Laser Textile Design: The Development of Laser Dyeing and Laser Moulding Processes to Support Sustainable Design and Manufacture

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Abstract

This research developed new creative opportunities for textile design by investigating CO_2 laser processing technology to achieve surface design and three-dimensional effects. A practice based and interdisciplinary textile design methodology was employed, integrating scientific and technical approaches with a reflective craft practice. It was found that the synthesis of design and science was imperative to achieving the research goal of evolving techniques that have opened new design opportunities for textile design whilst being viable and communicable for industrial and commercial application.

Four distinct *Laser Textile Design* techniques were developed in this research including: a laser enhanced dyeing technique for wool and wool blends; *Peri-Dyeing,* a laser dye fixation technique; a laser moulding technique; and a laser fading linen technique. Together these techniques offer tonal, multicolour, precise graphic processing and three-dimensional or relief surface design capabilities for wool, linen and synthetic substrates as evidenced through the creation of a commercially relevant textile design sample collection and garment prototypes. Thorough experimentation optimised the graphic processing capabilities of each technique, providing the ability to accurately define colour and three-dimensional shapes on textile substrates. The commercial viability of the research was confirmed through industry focus groups and technical testing that adhered to ISO international textile testing standards.

Development of the laser techniques considered textile design approaches that were found to eliminate or reduce consumption of water, energy and dye through enhanced material properties, dry processing or targeted dye fixation. In addition to supporting cleaner and more efficient textile practices, the research evidenced direct-to-garment processing opportunities. The potential for digital *Laser Textile Design* to contribute towards a sustainable, agile model for production and supply across the textile sector is discussed with relevance to bespoke and mass customisation services.

The research found that creative engagement with digital laser processes produced new aesthetic possibilities, and enabled innovation beyond creativity with relevance to design, manufacture and sustainability.

Keywords: Textile Design, CO_2 Laser, Sustainability, Textile Colouration, Surface Design, 3D Textiles, Direct-to-Garment Processing, Digital Design, Wool, Polyester, Linen, Interdisciplinary Textile Design Research

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Publications and Presentations

To date, the following publications and public presentations were produced by the author as a result of this research:

Morgan, L., Kane, F., Tyrer, J., Shen, J. 2016, Laser Moulding For Textiles: Supporting Sustainable Design and Manufacture. In Circular Transitions, Mistra Future Fashion Conference on Textile Design and the Circular Economy, November 23–24, 2016, Chelsea College of Arts & Tate Britain, London.

Morgan, L. 2016, Laser Textile Design Towards a Sustainable Tool for Manufacture and Design. In Behind the Threads: Unravelling the Sustainability of the Clothing Industry, Green Stems, April 2016, University of York, U.K. (Invited Presentation).

Morgan, L., Tyrer, J., Kane, F., Shen, J. 2015, Laser Enhanced Dyeing of Wool For Textile Design, in 13th International Wool Research Conference (IWRC-13) and AATCC Sustainability Symposium, June 10-14, 2015, Zhejiang Sci-Tech University, Hangzhou, China.

Morgan, L. 2015, Digital Laser Dyeing, LIA Today, 23 (4) pp12-14.

Kane, F., Morgan, L., Akiwowo, K., 2015, Textile Design Research: From Chemistry To Craft Towards Sustainable Design Innovation, in The Value of Design Research, 11th International European Academy of Design Conference, April 22-24th 2015, Paris, France.

Morgan, L., 2015, Proposing a Digital Laser-Design Supply Service, TechStyleLAB Symposium, 29-30th January 2015, Kent State University, Ohio, USA.

Morgan, L., Tyrer, J., Kane, F., Shen, J. 2014, Laser Enhanced Dyeing Of Wool For Textile Design, in Proceedings of Transition: Re-Thinking Textiles and Surfaces Conference Proceedings, University of Huddersfield, 26–27 November 2014, Huddersfield, U.K.

Morgan, L., Tyrer, J., Kane, F. 2014, The Effect of CO_2 Laser Irradiation on Surface and Dyeing Properties of Wool for Textile Design. in Proceedings of The International Congress on Applications of Lasers and Electro-Optics (ICALEO), October 19-23, 2014, San Diego, CA, USA. (Invited Plenary Paper and Speaker)

Morgan, L., 2014, Laser Enhanced Dye Performance for Surface Patterning of Woollen Textiles, FTC Association Research Event, 8th May 2014, Manchester School of Art, Manchester. U.K.

Exhibitions and Awards

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Laser Processing for Textile Texture Modification from MAS group and Loughborough University.

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Glossary Of Terms and Abbreviations

Action Research- A research strategy or disciplined process of inquiry conducted by and for those taking the action. The primary reason for engaging in action research is to assist the ‘actor’ (in this case designer) in improving and/or refining his or her actions (Sagor, 2000).

Agile Manufacturing- Manufacturing that is characterised by the ability to respond rapidly to customer needs and market forces, especially through the establishment of flexible relationships with suppliers (Oxford, 2014).

Auxiliary- A chemical assistant added to the dye bath at pre-determined stages of the dyeing process to achieve effective dyeing.

Biaxial tension- Tension in two directions (horizontal and vertical axis).

CAD- *Computer aided design*

CO_2 Laser- A device that generates an intense beam of coherent monochromatic light (or other electromagnetic radiation) by stimulated emission of photons from excited atoms or molecules derived from CO_2 gas (Oxford, 2014).

Colorimetry - The science and technology used to quantify and describe the human colour perception (Ohno, 2000). Quantified in this research using CIE colour space data (see Chapter 4.5).

Digital Laser Dyeing- an umbrella term to describe CAD controlled, laser-based dye techniques for textiles.

Direct-to-garment (DTG)- A design, print or finishing process applied directly to a finished ‘blank’ garment.

Engineered Textile Design- A print, pattern or surface effect that has been designed specifically to fit to the pattern piece or silhouette of an end product. The design placement accounts for the construction, seams and three-dimensional finished shape of the garment or end product, often eliminating wasted print from off-cuts.

Interdisciplinary Textile Design Research Methodology- The methodology developed in this research project that synthesises design, science and industrial collaboration to facilitate responsible material and process innovation.

ISO- *International Organisation for Standardisation*: An independent worldwide testing standards body comprised of 163 member countries. They provide and publish world-class standards or specifications for materials, products, services and systems that can be used consistently to ensure quality, safety and efficiency, fit for their purpose (ISO, 2016). For each of the ISO standards used in this research, the British Standards Institute (BSI) publication is referenced.

Laser Aesthetic- The visual appearance unique and specific to laser processing, unattainable by alternate design procedures.

Laser Energy Density- The amount of energy delivered to a surface by the laser per unit area, expressed in joules per square centimeter. Sometimes referred to as radiant energy density, or laser fluence.

Laser Fading- The colour fading or lightening of a substrate after laser irradiation that occurs at defined parameters.

Laser Resolution- A dots-per-inch measurement (dpi) used in laser processing. As the number of dots per inch increases, dots move closer together, eventually overlapping. The dot size remains the same relative to the laser beam spot size.

Laser Shibori- Three-dimensional and colouration surface design effects created by the combination of *three-dimensional laser moulding* and *Peri-dyeing*.

Laser Textile Design- Refers to use of the laser processing techniques developed in this research.

LCA- *Life Cycle Assessment,* an objective process to evaluate the inputs, outputs and potential environmental impacts associated with all stages of a product or process lifecycle from raw material extraction through materials processing, manufacture, distribution, use, repair, maintenance, and disposal or recycling. LCA is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. (BS EN ISO 14040:2006)

Nimble Manufacturing –See *agile manufacturing*

owf- *On weight of fabric*. Concentrations of dyes and dye auxiliaries are often measured and expressed as a percentage of the weight of fabric to be processed.

Peri-Dyeing- A laser dye fixation technique for textiles that takes place at the point of laser interaction. The prefix peri denotes around or adjacent. (Oxford, 2014). It involves applying dye locally to the surface of a textile substrate followed by laser irradiation. In this technique, the dye reaction takes place at the point of (or adjacent to) laser interaction.

Pyrolysis- Decomposition brought about by high temperatures (Oxford, 2014).

Reduction Clear- A wash-off procedure to remove surplus unfixed dye and/or dyeing auxiliaries from a textile so as to secure optimum fastness and the correct shade. In the case of disperse dyes on polyester, a *reduction clear* treatment commonly uses Sodium Hydroxide, while in the case of acid or reactive dyes on wool, ammonia is used as the reducing agent to remove unfixed dyestuffs and prevent further uptake of surplus dye (Burkinshaw & Kumar, 2008).

S.E.M- *Scanning electron microscope.*

Sustainable Textiles- (Clothing and) Textiles, which meet the needs of today's consumers, and are also made, transported, sold, used and disposed of in ways which do not adversely impact people or the planet – now or at any time in the future (Defra, 2011).

Tacit Knowledge- Understood or implied knowledge that is communicated without being stated (Oxford, 2014).

Textile Surface Design- The colouration, texturing and patterning of textile substrates for aesthetic and functional purposes.

Three-dimensional Laser Moulding- A tension assisted, heat-setting technique for synthetic stretch textiles developed in this research that results in three-dimensional, relief and surface texturing effects (Das, 2009).

True Resolution- A dots-per-inch measurement (dpi) used in digital graphics processing. As the number of dots per inch increases the dot size decreases providing a sharper image quality.

Uniaxial tension- Tension in a singular direction (horizontal or vertical axis).

CHAPTER 1 : INTRODUCTION

1.1 Introduction

This thesis presents a practice-led research project within the discipline of textile design. The research focused on developing new opportunities for textile design by harnessing digital laser technology, alongside the potential to discover more sustainable surface design techniques than currently available in equivalent textile processing. In order to establish the context for the research and methods used, this chapter will provide background on the overarching project and the author’s experience as a designer, the methodology and delimitations of the research. This chapter will also outline the aims and objectives of the research and research questions, concluding with an outline of the focus and structure of the thesis.

The sustainability of textiles is a salient concern in the textile industry and in current textile research. The industry is estimated to have a global economic value of over one trillion US dollars according to the department of the Environment, Food and Rural Affairs (Defra, 2008). With an industry so huge even a small reduction in energy and wet processing could equate to significant savings in wastewater effluent and consumed energy (Defra, 2010; Wrap, 2015). The use of laser processing in the field of textile design presents opportunities for cleaner and more efficient surface design without excessive water or chemicals and therefore has possible environmental benefits compared to equivalent textile processing methods.

Developments in laser technology for textile processing to date predominantly focus on textile engineering and as such, the digital design opportunities afforded by targeted and accurate processing of the CAD controlled laser provide a research opportunity. By reviewing the research carried out by textile design and engineering disciplines, it has been possible to build on technical research themes to identify possible textile patterning and three dimensional surface design opportunities resulting in the development of novel laser techniques for colouration, patterning and three-dimensional surface design. Through four diverse techniques, this project has investigated the design potential and performance properties of laser textile interaction. Links to industry provided a commercial focus to the work, and placed importance on technical understanding of the effects of laser interaction on material properties.

1.2 Research Background: The Lebiotex Project

This research formed part of an overarching project funded by the Arts and Humanities Research Council, entitled Laser Enhanced Biotechnology for Textile Design (LEBIOTEX). Lebiotex was a collaborative project between Loughborough University and DeMontfort University with an aim to discover new environmentally sustainable creative opportunities for textile design. The author's role was to research and develop novel surface design techniques using laser technology. DeMontfort University concurrently undertook research into enzyme treatments with the same design aim. As techniques from both projects were developed, results were shared with the Lebiotex team ensuring that the research direction remained relevant from a commercial perspective.

The industry partners involved in the Lebiotex project were from three distinct sectors of the textile industry. Camira Fabrics who manufacture, design and supply contract interiors; Speedo, a performance swimwear brand; and a final partner Teresa Green, a designer maker with a craft based practice. By keeping the research developments relevant to the industry partners, it was expected that results could be utilised across multiple sectors of the textile industry, accessible to industry, education and independent practitioner alike.

1.3 Researcher's Rationale

In order to provide context for the aims and approaches of this study, it is useful to comment on the background of the author and her motivations for undertaking this research. With a background in Textile Design, the author worked commercially in varied roles as a senior designer and design manager in the fashion and textiles industry. After six years working closely with international textile and garment manufacturers, she viewed the presented research as an opportunity to address sustainability in textile production processes by establishing new, environmentally sensitive textile design techniques with viable commercial applications through the use of laser technology.

The textiles and clothing sector represents the second biggest area of global economic activity in terms of intensity of trade (Defra, 2008) and approximately 7% of world exports (Allwood, 2006), so the sector's environmental impacts are significant. The chemicals used to achieve colour and pattern in traditional dyeing, bleaching, printing and finishing processes have been identified as key challenges to sustainability within the industry. In addition, large amounts of water and energy are used in many of these processes. Alongside legislation discussed in the literature review, an increased focus on efficiency has been recommended to improve environmental performance. In addition, the role of the designer has been recognised as central to the development of sustainable solutions (Forum for the Future, 2007).

It has been argued that responsibility could be placed on designers (Papaneck, 1971) to affect positive change in the industry by the choices made when designing new products, through to the materials used and the techniques applied (Bhamra, 2007). The following paragraph represents the author's reflections on working in design and product development roles in the fashion and textiles sector.

The fashion industry is by its nature frivolous, with seasonal trends resulting in a restless pace of changing styles. As is the case with most price sensitive industries, cheap costs often take precedence over environmental or ethical concerns. Working in industry, decisions often boil down to compromises based on monetary choices. Therefore, as a designer, trying to encourage sustainable practices can be difficult. Even in the creation of 'green' products, other stages of the manufacturing process are often left unaddressed. As an example, the benefits of using organic cotton becomes somewhat marred when the fabric must be shipped from factory to factory, where it is often combined with additional non-biodegradable components, the non-biodegradable off-cuts disposed in a landfill and the final product is freighted thousands of miles to be sold in the UK.

Disillusioned with the industry, the author saw the Lebiotex project as a rare opportunity to contribute towards a more sustainable textile sector by establishing new and environmentally friendly textile design techniques with viable commercial applications. The use of laser technology in this research has the potential to address sustainability by reducing water and energy use in production processes. Further advantages are addressed throughout the work.

1.4 Identification and clarity of Research Question, Aims and Objectives

A review of the literature and existing studies on laser modification for textiles has revealed a considerable amount of research on the topic. It was identified that gaps in this research topic remain for coloured and three-dimensional effects with a design led focus; these are discussed in detail in Chapter 2. Focusing on these gaps in knowledge, the following research question has been established.

> *To what extent can laser technology be used to modify textile substrates for the creation of novel, sustainable surface design techniques?*

The author's research is specifically concerned with affecting the surface quality of a range of fabric compositions using laser processing as design methods with potential to support textile sustainability.

The aim of the research is:

> **To develop new, sustainable, creative opportunities for textile design by investigating laser processing technology to achieve surface design and three-dimensional effects.**

The following objectives were used in order to meet the research aim.

OB1. Establish workshop conditions to ascertain the effect of laser parameters on textile substrates identifying colouration, pattern and three-dimensional design opportunities.

OB2. Develop and optimise laser processing techniques for textile colouration, pattern and three-dimensional surface design and characterise their usability, commercial viability and design potential through technical testing and design development.

OB3. Evaluate the developed *Laser Textile Design* techniques relevant to their suitability for manufacture, design, application and sustainability.

1.5 Definitions and Delimitations

The key terms that require definition for clarity of the research context are discussed in this section. Delimitations for the research are also addressed in this section, defining the scope of the study.

This practice based research is carried out from the perspective of a textile designer developing new techniques for surface design within the overarching field of textiles.

Textile design is broadly concerned with the tactile and visual characteristics of materials communicated through construction or surface design methods. This research is concerned with creating new surface design processes for existing material structures. Das (2009: 91) defines surface design of textiles as that, which '*constitutes appearance of the fabric surface in terms of its colour, texture and if applicable, pattern*'. For the purposes of this research, textile surface design refers to the colouration, texturing and patterning of textile substrates for aesthetic and functional purposes, both of which shall be reflected upon throughout this thesis.

Specific design effects and laser processing approaches that are pursued and excluded from the research are outlined in the Literature Review (Chapter 2.3). For example the work uses the laser for fibre modification, colouration and three-dimensional effects; it is not concerned with laser cutting processes, which have been thoroughly explored in existing textile design practice.

Textiles are recognised as ubiquitous in material culture (Dormer, 1997). As such, textile design is, by nature, an interdisciplinary subject; textile materials are rarely designed in isolation, without careful consideration of their end use, which includes diverse fields from fashion and interior products to medical and architectural applications. A textile designer's role therefore, must '*be the result of informed and purposeful thinking – to create something that is appropriate and of value in a specific context*' (Kavanagh, 2004: 3). The context of the *Laser Textile Design* techniques developed in this research considers design and processing opportunities for fashion and interior perspectives, specifically contract interior and performance swimwear applications. The commercial fit, aesthetic and technical performance standards have been addressed in this thesis, appropriate to the project's industry partners.

The selection of materials used within the research investigation reflects their use by the industry partners. Industrial partner Camira make heavy use of woven natural wool and linen fibres in the interior and furnishing fabrics they produce (Camira, 2015), while knitted synthetic polyester and polyamide are the predominant materials used in Speedo's performance swimwear garments (Speedo, 2015). Cotton, and non-woven structures were not investigated in this research. However, their importance to the textile industry is recognised and noted as an area for further work in Chapter 11.

The author assumes basic knowledge from the reader, of textile design terms in relation to traditional processes and construction principles. The work is aimed at an audience with an interest in textile innovation from design, technical, manufacturing or environmental perspectives. In order for the results to be appropriate, communicable and repeatable for textile design and production, this thesis presents detailed technical data and scientific analysis alongside insights and creative opportunities for designers.

While textile design may require an interdisciplinary mindset, it can be difficult for designers to access the scientific and technical facets of textiles, production or technology without the technical background. Typically, areas of textile design and textile engineering operate separately within the textile industry. However it has been recognised that collaboration and connections between fields can facilitate innovation. A report for the Crafts Council (KPMG, 2016) notes the ability for craft to support cross sector innovation and discovery in the UK. This places textile designers in a significant position to balance craft, design and technology to facilitate material innovation. Literature and research that bring together practical, scientific and aesthetic strands in equal depth are scarce. The research documented in this thesis presents an in depth study that brings together these attributes, noted as a distinct feature of the work. The specialist technical knowledge gained from working across textile design, optical engineering and fibre chemistry in this research was fundamental to developing textile design techniques using laser technology and to ensure context appropriate design outcomes. Discussions in this thesis highlight the relevance to textile designers, allowing the reader to examine the depth of the investigations and to gain design insights.

This research considers the potential for the *Laser Textile Design* processes to aid and improve sustainability for textile design. A report by the Department of the Environment (2011:01) defines sustainability in the sector as clothing and textiles,

> …*which meet the needs of today's consumers, and are also made, transported, sold, used and disposed of in ways which do not adversely impact people or the planet – now or at any time in the future*.

The measurement of sustainability is difficult to quantify. For example an organic cotton t-shirt may have an efficient and environmentally friendly production profile, but repeated laundering in the use phase has a negative impact. Conversely, a disposable product may reduce the impact of laundering but continual production would increase resource consumption and waste. Lifecycle assessment is one tool that offers a method to measure the environmental impact of production and use of products by comparative analysis. Conducting lifecycle assessment on the *Laser Textile Design* techniques was not within the scope or timeframe of this research study. However, addressing sustainability was a key motivating factor in the rationale for this research.

Considerations for sustainability were included in an analytical framework (Chapter 2.4.4 & 3.6.4). The framework was used to reflect on how the *Laser Textile Design* techniques developed in this research, may support improved sustainability in textile design and production through consideration of: material choices; water, energy, chemical and waste efficiency; and alternative production systems. As this study is concerned with production and design techniques, less emphasis is placed on sustainability during the use and end-of life phases of textile goods.

1.6 Research Methodology

An interdisciplinary textile design research methodology was used as articulated in Chapter 3. As a practice based study situated in textile design, the interdisciplinary research methodology employed drew on scientific knowledge frameworks used within optical engineering and dye chemistry, as well as design and craft based approaches. Both qualitative and quantitative methods were used, synthesising scientific and design research methods to ensure rigor across the interdisciplinary fields of study. Technical testing included ISO international standard testing, while design development and industry feedback explored the aesthetic, functional and commercial potential of each technique. Action research strategies were employed and an analytical framework was created to ensure the laser techniques were evaluated consistently relative to manufacture, design, application and sustainability. The combination of tacit knowledge gained from creative experimentation together with the technical knowledge gained from quantitative testing and analysis was imperative to achieving the research goal of evolving techniques, which can open new creative opportunities for textile design whilst being viable and communicable for industrial and commercial application. The combination of scientific and creative approaches were found to be essential in creating novel *Laser Textile Design* techniques and enabled innovation beyond creativity.

1.7 Contribution To Knowledge

The contribution and claims of the research outcomes are listed below.

Primary contributions: A catalogue of *Laser Textile Design* techniques:

- Laser enhanced dyeing of wool and wool blends for textile design
- Peri-dyeing, a laser dye fixation technique for textile design
- Laser faded linen
- Laser moulding for synthetic stretch textiles
- A methodology for practice based interdisciplinary textile design research, encompassing industy collaboration.

In addition, the research provided:

- An approach for achieving optimised graphic processing and controlled modification of textile substrates by harnessing laser irradiation.
- A *Laser Textile Design* collection and garment prototypes.
- A proposal for the use of laser technology beyond this research project.

1.8 Thesis Structure and Content

Figure 1.1 maps the thesis structure in relation to the research objectives. The topics to be addressed in each chapter of this thesis, are outlined below.

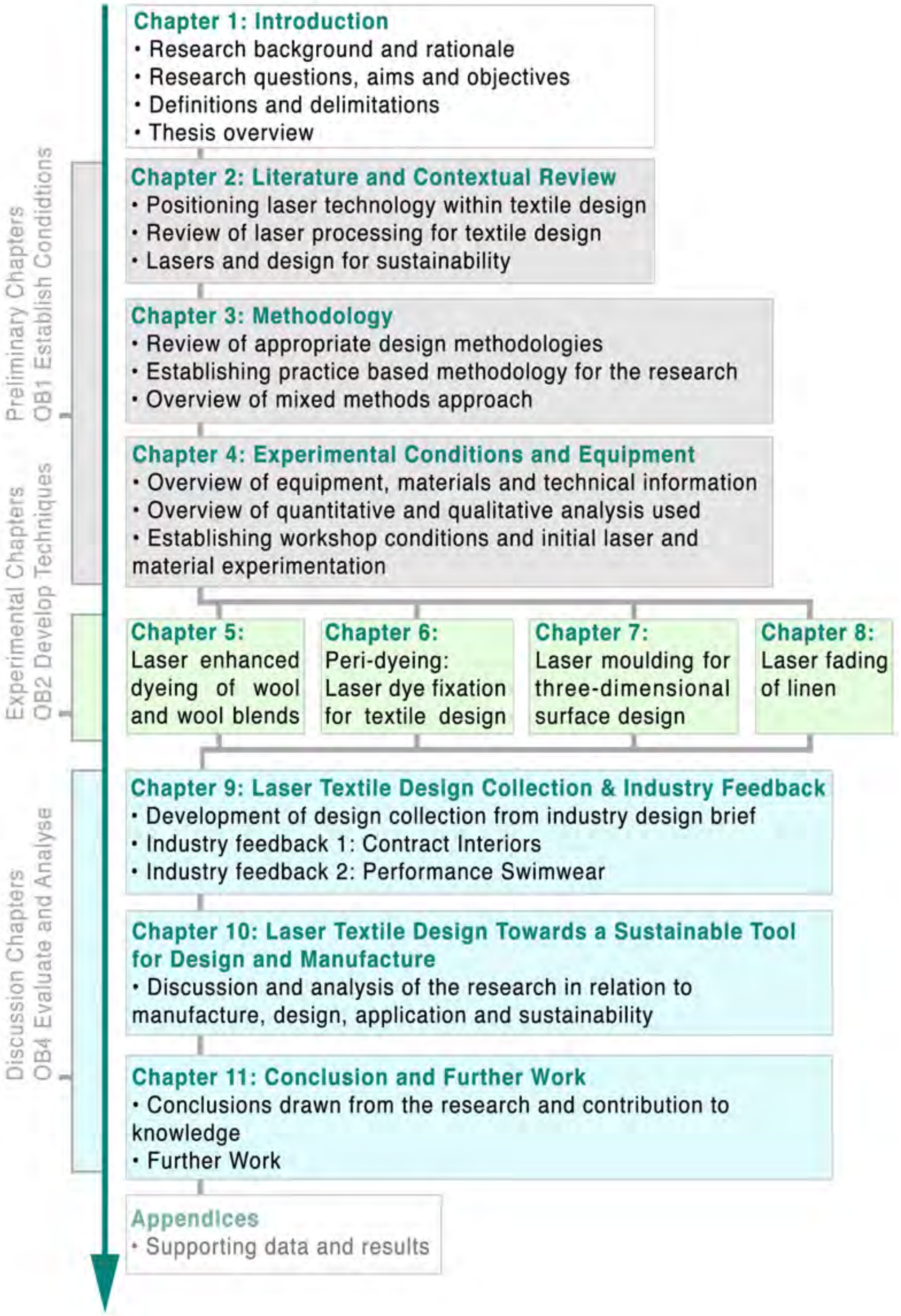

Figure 1.1 Thesis structure mapped against the research objectives

Chapter 2: *The literature and contextual review* positions laser technology as a tool for textile surface design and reviews current adoption of laser technology within the textile industry and in emerging textile research from design and engineering perspectives. In doing so, the review identifies gaps in knowledge and opportunities for furthering the development of *Laser Textile Design* techniques that may be filled by this research. Current and emerging models for sustainable design, efficient production and alternate modes of supply are discussed in relation to digital laser technology. Connections between sustainable design and innovation are made, expanding on the rationale for the project and developing a framework to examine how *Laser Textile Design* in this research, may support sustainability.

Chapter 3: *Methodology* The chapter articulates the interdisciplinary textile design research methodology established for this research. It discusses the relevance of practice based research and *Alternative Disciplinarity* (Rodgers & Bremner, 2011). In doing so, the chapter argues the case for an interdisciplinary approach to textile design in this research project, thus creating an alternate approach where scientific and design research are undertaken in parallel. In addition, the chapter highlights the mixed methods approach used, that combined qualitative and quantitative methods for problem formulation, data collection, analysis, evaluation and dissemination of the research work.

Chapter 4: *Experimental conditions and equipment* addresses the objective 'Establishing Workshop Conditions' (OB1) and documents the experimental conditions and equipment used throughout the research study. It describes how workshop conditions and parameters were established, detailing the qualitative and quantitative methods used. The testing of laser software is documented, detailing optimisation of laser parameters for consistent graphic processing. Affordances, constraints and potential design opportunities afforded by laser interaction with material properties are explored and recorded. The chapter concludes with a clear direction for the development of the laser textile techniques that are discussed in subsequent chapters.

Chapter 5: *Laser enhanced dyeing of wool and wool blends* describes the effect of CO_2 laser irradiation on the surface and dyeing properties of wool and wool blend substrates, presenting a laser pre-treatment technique for textile surface design. The chapter describes the development of techniques that can achieve and control multi-tonal, multicoloured and moulded relief surface designs through targeted laser processing. Analysis of the performance properties of treated substrates through ISO standardised testing addresses the potential commercial and sustainability advantages of the techniques.

Chapter 6: *Peri-dyeing: laser dye fixation for textile design* presents the investigation into a laser dye fixation approach to textile colouration and surface design. This led to the development of the 'peri-dyeing' technique. This technique considers the laser as a targeted energy source for 'on-the-spot' fixation, applying dye locally to the surface of a textile substrate followed by laser irradiation. The chapter details optimisation of parameters, dye application and graphic processing capabilities of the technique. Design potential of the technique is established and ISO standardised performance testing is carried out, providing an industry-focused analysis of the technique.

Chapter 7: *Laser moulding for three-dimensional textile surface design* describes the development of a new method for moulding synthetic stretch textiles. The chapter examines the use of photothermal energy of a CO_2 laser to induce a heat setting effect on polyester and nylon substrates, investigating three-dimensional effects through controlled tension and targeted laser irradiation. Important parameters were identified and explored leading to a system for predicting the three-dimensional effects to enable controlled design outcomes. Potential applications and advantages were discussed in relation to experimental laser moulded textile samples and avenues for potential further investigation were identified.

Chapter 8: *Laser fading of linen* describes investigation and testing of the effects of CO_2 laser irradiation on the aesthetic and durability properties of natural linen substrates. It discusses laser fading as a method to enhance the properties of linen fabrics, optimising the process and considering the advantages this may offer as a tool for surface design.

Chapter 9: *Laser Textile Design collection and industry feedback* provides analysis of the *Laser Textile Design* techniques developed in this research, as potential tools for manufacture and design through development of a design collection and industry feedback. In order to analyse and showcase the abilities of the techniques, a design collection was developed. The purpose of the collection was to validate and analyse the practical use and effectiveness of the laser techniques within the context of professional design practice. This was carried out using the author's background as a professional designer, which provided the appropriate skills and 'know-how' to carry out and answer a design brief. The chapter considers the success of the techniques and design collection through detailed industry feedback, recorded using focus group methods. This identified key themes of interest to the project's industry partners; a contract interior fabric manufacturer and a leading performance swimwear brand.

Chapter 10: *Laser Textile Design: towards a sustainable tool for design and manufacture* brings together discussion on each aspect of the research study, to reflect on the outcomes, experimental data, industry feedback and analysis from previous chapters, reviewing the merits of the project as a whole. The chapter determines to what extent the research outcomes answered the research question and met the research aim. The chapter considers *Laser Textile Design* as a tool for improved sustainability in the manufacture and design of textiles, reviewing efficient, responsive and direct-to-product processing opportunities and the levels of sustainable innovation they may offer. The research is analysed against the analytical framework developed in Chapter 2, considering the contributions and successes of the research in relation to design, application, manufacture and sustainability.

Chapter 11: *Conclusion and further work* presents conclusions from the research, overviewing the research and clarifying the contributions to knowledge. Avenues and opportunities for further work are listed.

The Appendices present a portfolio of design samples created during the research using the four developed *Laser Textile Design* techniques. In addition they contain supporting materials used within the research including testing results, numerical data, supporting materials from industry collaboration and coded transcripts.

CHAPTER 2 :
LITERATURE AND CONTEXTUAL REVIEW

2.1 Introduction

This chapter presents a review of current knowledge in relation to textile surface design, the use of lasers within textile processing and textile sustainability, providing a clear context for the research. The purpose of the review is to evaluate and critique current and emerging themes within the specialist subject area pertaining to *Laser Textile Design* to identify areas for the development of an original contribution to knowledge in the overarching field of textile design.

The chapter is presented in sections highlighting three key topics for review as detailed in Table 2.1. Section 2.2 introduces textile design and the related industry, positioning laser technology as a tool for textile surface design and finishing. As this research focuses on developing new textile surface design techniques, it is necessary to consider contemporary and traditional methods of surface design and colouration. This chapter briefly outlines key techniques for surface design noting existing craft and industrial textile processes. The purpose of this review is not to detail every individual textile process, many specialist texts and 'how to' guides exist that do so. Rather, it considers the advantages, limitations and opportunities for improvement that laser technology may facilitate.

Section 2.2 reviews the current adoption of laser technology within the textile industry and in emerging textile research from design and engineering perspectives. In doing so, section 2.3 maps out the capabilities of laser technology for textile surface design identifying gaps in knowledge and opportunities for furthering the development of *Laser Textile Design* techniques that may be filled by this research.

Section 2.3 considers the significance of the environmental impact of textile production and the role design can play in affecting positive change. Current and emerging models for sustainable design, efficient production and alternate modes of supply have been reviewed in relation to digital laser technology. The section concludes by developing a framework to examine the potential for *Laser Textile Design* in this research, to support sustainability.

Section 2.4 presents conclusions from the review clarifying the various opportunities for investigation to be addressed through this research.

Key Review Topics	Sub topics	Aim
2.2 Positioning Laser Technology within Textile Design and Finishing	Textile design and processing Textile surface design Laser technology	• To identify role of laser as a textile-processing tool in relation to traditional surface design and finishing methods. • To highlight issues, problems and advantages associated with current and traditional surface and finishing techniques to reveal possible areas for improved processing using lasers.
2.3 Review of Laser Processing for Textile Surface Design and Finishing	Laser cutting and etching in textile design Laser assisted 3D and relief effects Digital laser dyeing	• To review the adoption of lasers in the textile industry and laser research for textile manufacturing and design. • To map out the current capabilities of laser technology for textile surface design and identify further opportunities and gaps in knowledge that this research addresses.
2.4 Lasers and Design for Sustainability	Relevance of sustainable textile design research Impact of dyeing, printing and finishing Efficient technology and laser processing Lasers for sustainable design and manufacture	• To consider the environmental impact of textile production, particularly the role that digital laser design can play in affecting positive change. • To review important sustainability principles for consideration in the development of new textile design techniques within this research. • To examine laser technology as a sustainable tool for textile design and finishing.

Table 2.1 *Laser Textile Design*: Topics for Review

2.2 Positioning Laser Technology within Textile Design and Finishing

2.2.1 Textile design and processing

As discussed in the introduction, the research is set within the context of Textile Design. Design decisions can be made about a textile across all of its production stages (Wilson, 2001). Aesthetic and functional properties can be added in the developmental stages, from production of raw materials to the creation of yarn and the construction of fabric, or in the finishing phases (Gale & Kaur, 2002).

Figure 2.1 considers the points at which textile design intervenes within the textile production lifecycle. Constructed textile design happens towards the beginning of textile manufacture, which involves design of woven or knitted fabrics. The choice of construction and yarn can influence colour, pattern, texture and weight of fabrics. Surface design usually occurs in the textile finishing phases of textile manufacture and includes colouration, printing and embellishment. With digital design processes, opportunities emerge to move the design stage further down the production cycle allowing for later stage design decisions with potential for a more responsive approach to design, including design that is engineered towards an end product. While lasers can be utilised for heat treatments in fibre processing and yarn production (Putna et al., 1980), this review focuses on laser use within textile production. As such, *Laser Textile Design* can be positioned across the finishing and application stages within the textile life cycle. As with digital design, this creates an opportunity to move the design stage further down the production cycle.

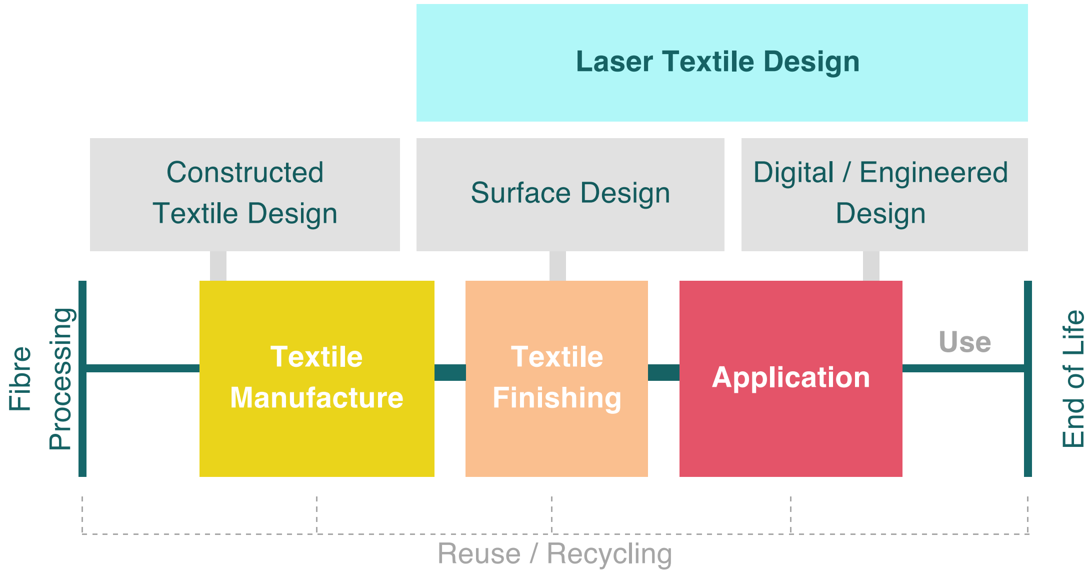

Figure 2.1 Positioning *Laser Textile Design* within the textile production lifecycle

Useful reviews of new advances in the field of surface design and digital processing techniques are well documented. For example, books such as Techno Textiles (Braddock & O'Mahony, 1998) detail recent textile innovations, while Bowles (2012) and Briggs-Goode (2013) extensively document digital printing and processing techniques. Current surface design techniques for textile design present challenges for sustainability and manufacture; this review highlights the issues associated with current and traditional surface finishing techniques that present possible areas for improved processing through the use of laser technology.

2.2.2 Textile Surface Design

Textile surface design is situated in the finishing phases of textile production for example, dyeing, printing and embellishment. Das (2009: 91) defines surface design of textiles as that, which '*constitutes (the) appearance of the fabric surface in terms of its colour, texture and if applicable, pattern*'. For the purposes of this research, textile surface design refers to the colouration, texturing and patterning of textile substrates for aesthetic and functional purposes, both of which shall be reflected upon throughout this thesis.

2.2.2.1 Colouration, Patterning and Digital Innovation

Colour, material and finishing play a significant role in offering design and aesthetic style to textile products (Kopla, 2014). Surface design effects are traditionally process-led with design aesthetic limited to process constraints, '*Textile design is heavily influenced by methods of manufacture*' (Briggs-Goode, 2013: 122). Process-led aesthetics relating to established textile techniques are still commonplace; for example, repeat patterns are necessitated in analogue printing processes as an economical means of patterning textiles, but have become a desirable and fundamental design feature for textile surface design. Finding new modes of textile design, such as laser technology, has the potential to innovate, providing its own aesthetic and distinct properties.

Textile designers achieve pattern through texture or colour by construction methods; where patterns are woven or knitted into the constructed surface by use of contrasting yarns and structures; or by surface design methods, which are applied to the textile after it's construction and include dyeing, printing and stitching processes. Differential dyeing of textiles make it possible to obtain tone-on-tone and multicolour effects on fabric via dyeing procedures. These can be achieved by using yarns of different fibre types in the fabric construction (Figure 2.2) or by resist dye methods. Resist dyeing can be achieved by pretreatment with compounds that either resist or improve dye uptake, or by shibori methods (see section 2.2.2.2 and Figure 2.5).

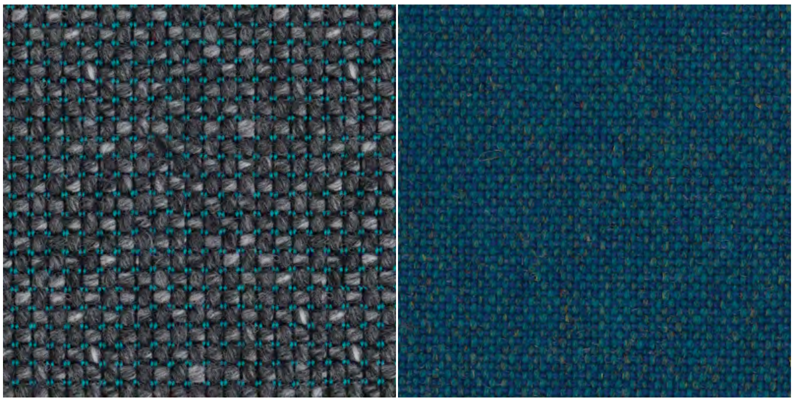

Figure 2.2 Differential dyeing in woven textiles (Camira, 2015)

Traditional textile methods often include time consuming loom set up for weaving, or screen or roller engraving for printing. Printing involves the application of colour onto a ground cloth, usually applied in the form of dyes in a printing paste or pigments. Economically, screen-printing is often limited in the number of colours that can be used, as a new screen is required for each colour change. After set up, the process can be fast at up to 120 meters per minute. However, with lead times of eight to twelve weeks combined with the significant costs of making each screen, large volumes are needed for the process to be economical (Briggs-Goode, 2013).

Digital textile techniques, controlled by computer-aided design, are becoming more prevalent in current markets. Examples of digital textile techniques include digital printing, laser cutting, 3D printing, digital embroidery, digital (jacquard) weaving and knitting. Couture fashion houses such as Iris van Herpen, Peter Perilatto (Figure 2.3a) and Anrealage (Figure 2.6) are making use of current digital textile innovations including 3D printing, digital printing and laser cutting, respectively. The opportunities for digital textile processing are vast; digital design offers ease of pattern change and duplication, unlimited colour and opportunities for engineering designs specific to end product (Figure 2.3b). While initial capital investment for digital equipment may be costly comparative to analogue apparatus, production advantages include reduced set up times and reduced cost per unit for individual production. This allows on demand production and shorter product runs to be economically viable. Digital technologies also offer sustainability benefits, discussed in section 2.4.

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a. b.

Figure 2.3 Digital textile design methods advancing graphic and production possibilities a) Pilotto (2013); b) Polvinen (2012)

Laser processing is a digital process that has potential to provide some advantages over traditional surface design techniques. The opportunities to improve on existing techniques include enhanced precision, offering ease of pattern change with new aesthetic and textural possibilities. Laser processing is a dry process that provides non-additive modifications to material properties, using no or low quantities of chemicals without the need for complicated equipment set up. For production they offer speed, versatility, combining process stages with less equipment, no moving parts to wear out, rapid prototyping, engineered and direct-to-garment processing opportunities. These advantages and developments in laser textile processing are further discussed in sections 2.3 and 2.4.

2.2.2.2 3D effects

In the design and construction of commercial and industrial textiles, three-dimensional surfaces are often used to provide beneficial properties to the fabric. Many traditional constructed, woven and stitched textile patterns exist for the enhanced properties they can offer for textile end-use. For example, honeycomb structures are traditionally used to provide increased absorption and insulation properties in textiles. Heightened absorption makes them common for towel fabrics. They also make strong insulators due to the pockets of air that can be trapped between the honeycomb areas of pattern. In a similar way, quilted surfaces trap air and padding between textile layers for insulating properties. Many functional finishes for textiles that were originally designed for high performance have become synonymous with high quality style, leading to their adoption in fashion and trend led textile products for their aesthetic appeal (Braddock & O’Mahony, 1998). Examples of contemporary three-dimensional finishes that show potential for aesthetic appeal combined with enhanced functionality include dimple patterns used within performance wear to provide aerodynamic texturing. Nike’s TurboSpeed performance sportswear (Figure 2.4) has textured surface patterns placed on specific areas of the athlete’s body. Nike claim the textured surface uses the same principle as dimples on a golf ball that reduce drag allowing it to travel further and faster (Nike, 2012).

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Figure 2.4 Nike Pro Turbo Speed Running Suit with dimples (Nike, 2012)

Traditionally, three-dimensional effects can be added during the construction of textiles such as weaving, or in the finishing phases through additive embroidery and stitching techniques. Some wet-techniques such as devoré, flocking, felting and shibori can also provide three-dimensional effects. Heat and heat-setting methods have long been used for creating three-dimensional forms on synthetic substrates. Shibori is a traditional resist dyeing technique that uses compression through stitching or clamps to prevent dye reaching the compressed areas of fabric. Following the heat of dyeing, the resulting fabrics often retain three-dimensional qualities combined with colouration effects as shown in Figure 2.5. A number of textile practitioners have investigated thermal effects to produce three-dimensional textile outcomes. Nigel Marshal researched vacuumed formed textile structures, woven using plastic films (Braddock & O'Mahony, 1998) however these did not have the drape and handle normally associated with fabric. Like other forms of heat moulding, vacuum forming requires a new mould to be cast for each new design. Isabel Dodd created formed textiles by baking printed rubber fabric adhesive on rayon stretch velvet at high temperatures to alter tension across the surface of her textile based accessories as shown in Figure 2.5 (Dodd, 1999). This resulted in effective sculptural fabrics, however the method would contaminate the materials rendering them non-recyclable.

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a. b.

Figure 2.5 3D textiles: a) Shaped shibori textile (Wade, 2002); b) Velvet scarf with handprinted large spot, Isabel Dodd (1999)

The examples discussed in this section documented three-dimensional effects that provided functional as well as aesthetic and textural attributes. The use of moulds for heat setting, complicated loom set up or additional materials, such as thread for stitching are traditionally used to produce three-dimensional forms. The use of laser technology to create three-dimensional textile forms may present processing advantages over traditional methods by instead offering, ease of equipment set up and pattern change through digital generation of designs and dry processing. Elimination of additional materials could improve ease of recycling at end of life.

2.2.3 Laser Technology

A laser is a device that emits an intense beam of light composed of electromagnetic waves that are in phase (coherent) and of the same wavelength (monochromatic) (Melles Griot, 2000). Infrared and ultraviolet lasers can be harnessed for their photothermal, and photochemical properties respectively. Lasers are used widely in manufacturing, for materials processing including cutting, marking, welding and drilling as well as for medical procedures and measurement applications (Berkmanns, 2010). The use of lasers in textile design is less widespread. However as research develops and the cost of machinery becomes more affordable for factories and educational institutions, their use has become well established (Hitz et al, 2001).

The laser used in this research study is a CO_2 laser that operates in the far infrared (IR) spectrum at a wavelength of 10,600nm; by contrast, Excimer and YAG lasers are examples of Ultraviolet lasers producing output wavelengths in the Ultraviolet (UV) spectrum (Hitz et al., 2001). Information from existing laser textile research was used to make informed choices on the most appropriate laser to use for marking and modifying textile substrates in this PhD research. A study from The Center for Research in Optics, Mexico, compared various lasers in the fading of denim (Oritz-Morales, 2001). It found that for marking textiles, the CO_2 laser was the most efficient system, allowing a desirable level of fading at minimum cost and energy levels. It was found that the YAG lasers (CTH:YAG / Ho:YAG) could achieve optimum results by gaining the greatest fading effect. However the power and cost used was unnecessarily large resulting in poor efficiency. These findings are echoed by Esteves & Alonso (2007) who report CO_2 laser technology offers higher processing efficiency over other laser-types. Chow et al. (2011) agree that CO_2 lasers offer textile processing advantages with larger beam size and ease of operation. In addition CO_2 is a non-toxic, fairly inexpensive lasing medium. Within the fashion and textile industry, CO_2 lasers are the predominant mode of laser processing for textile applications due to their commercial availability and relatively low processing outputs. For these reasons, this research makes use of the CO_2 laser, also considering potential ease of knowledge transfer to laser systems already established in a commercial textile context. The following section of the review discusses and examines textile design and finishing opportunities that make reference to both UV and IR laser systems.

2.3 Review of Laser Processing for Textile Surface Design and Finishing

The following section documents ways that laser technology has been utilised for textile surface modification in commercial, research and creative contexts to address the possibility for new textile design and mark making capabilities. The advantages of using these techniques over traditional textile processes are examined to assess areas for potential improvement from the perspective of environmental sustainability and production capability.

Laser materials processing for textiles is typically achieved in the following ways shown in Table 2.2.

<table>
<tr><th>Laser Processing Method</th><th colspan="2">Description</th><th>Examples</th></tr>
<tr><td>Cutting</td><td colspan="2">High Energy Density results in an incision through the entire depth of a material, resulting in a separation or removal of the processed surface.</td><td>Laser cutting (Section 2.3.1)</td></tr>
<tr><td>Engraving</td><td>A mark is achieved by an etching effect on the material, removing a thin surface layer from the textile substrate.</td><td rowspan="2">On textile materials, engraving and ablation are both concerned with removal of fibres or layers from the textile surfaces.</td><td>Denim (Section 2.3.2)</td></tr>
<tr><td>Ablation</td><td>A layer of material is removed to reveal the underlying substrate offering contrast and surface relief.</td><td>3D, devoré (Section 2.3.3.3)</td></tr>
<tr><td>Chemical Change</td><td colspan="2">Laser irradiation encourages a reaction and change of state, for example, the melting of synthetic materials or carbonisation of materials.</td><td>Laser dyeing
(Section 2.3.4)
Laser Welding
(Section 2.3.3.1)</td></tr>
</table>

Table 2.2 Laser Material Processing Methods

The following sections examine the extent to which each of the four approaches have been used in textile design and finishing. It examines how lasers have been used to provide cutting, fading, devoré, three-dimensional and colouration effects on textile substrates.

2.3.1 Laser Cutting in Textile Design

Laser processing offers efficient cutting without any wearing of tools and blades or laborious hand-cutting (Synrad, 2006). For textile design, laser cutting can be used for precision cutwork with high heat sealing or singeing fabric edges to prevent fraying. Laser cut design effects have been increasingly utilised across the fashion, accessory and home textile market sectors since couture textile designer Jakob Schlaepfer made pioneering use of industrial laser technology for his experimental mixed-media textiles in 1996 (Huddleston, 2009). As the technology has become more readily available, both couture and high street clothing sectors have embraced laser technology to create fashion-led effects, such as fringing, and as a form of garment embellishment. Laser cutting has been popularised by the commercial success of interior and fashion accessory designers such as Rob Ryan (2010), Tjorde Bjoonte (2004) and acrylic jewellery designers Tatty Devine (2011), who have all seen their work adapted for high street markets. As laser cutting technology has become standard equipment in university art and design departments, its creative use within textile design has grown. For example Hur (2010) used the laser to cut individual textile units to build customisable, modular fabrics, while Moriarty's (2004) layered laser cut rubber ‘lace’ gave a new aesthetic to the traditional textile process of lace making. Figure 2.6 shows a selection of laser cut products and textile goods.

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Figure 2.6 Laser Cutting in Textile Design.
L-R Top: Tjorde Bjoonte (2004); Tatty Devine (2011); Caroline Minar (2012); Dirk Bikkembergs (Glenisson, 2014); Bottom: Lauren Moriarty (2004); Ensuk Hur (2010); Eun Hong (2013); Anrealage (2013).

While laser technology excels in providing effortless, non-contact cutting, it can also be harnessed for the purpose of textile surface modification, discussed in the following sections. This research is not primarily concerned with cut, modular or folded textiles, which have been thoroughly explored in a textile design context, as this section has shown. Instead, surface modification of textiles for colouration, patterning and alternate ways to achieve three-dimensional effects on textiles using a laser, are explored.

2.3.2 Laser Etching in Textile Design

Laser technology has been adopted successfully in textile production in the denim and jeanswear industry in the manufacture of worn or weathered-look jeans. A CO_2 laser is used to fade the denim, removing indigo dye from the surface of the cotton fabric, revealing the white undyed fibre underneath (Kan et al., 2010). In comparison to traditional stone washing processes, this technique has replaced the use of chemicals and reduced the amount of water used by 85% when used to create Replay’s Laserblast denim (Replay, 2012), saving significant wastewater effluent (Costin et al., 1999). In addition to replacing stonewash effects, etching on the surface of the denim has been used to create faded patterns as depicted in Figure 2.7. Many studies and white papers have examined the indigo denim fading phenomenon (Kan, 2010; Ondogan, 2005; Oritz-Morales, 2001), providing detailed analysis of the effect of laser parameters on the colour strength and performance properties of treated denim.

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a. b.

Figure 2.7 Laser Engraved Denim: a) Liberty vs AG Denim (Kilcooley-O'Halloran, 2013); b) Replay Laserblast Jeans (Replay, 2012)

The successful adoption of laser fading techniques in the denim industry has led to the development of garment and textile-specific laser machinery. An example of laser processing equipment capable of processing fabric lengths can be seen in Figure 2.8a (Jeanologia, 2015). Direct-to-garment laser finishing equipment also exists, as shown in Figure 2.8b. In the example shown, a pair of inflatable legs hold the garment in its three-dimensional form as two infrared laser beams irradiate the fading design on each leg. The garment can be rotated for 360° processing. As the laser processing technology already exists for textiles, it facilitates potential ease of technology transfer for additional laser processing techniques, such as those developed in this research. Companies who already own such equipment may be well placed to uptake new laser techniques. If demand increases, the price of equipment is likely to drop, making it more feasible for textile or garment manufacturers to invest.

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a. b.

Figure 2.8 Laser Finishing Equipment: a) For Fabric Lengths; b) Direct-to-Garment Laser Finishing, (Jeanologia, 2015)

Despite the apparent commercial research interest, the focus of laser fading remains within the realm of cotton denim fabrics. Does the potential for fading alternate natural fibre sources provide potential for a new area of study?

This became the starting point for testing the effect of laser irradiation and its potential mark-making properties on a range of fabric substrates as detailed in Chapter 4. In this research study, linen was identified as a suitable substrate to impart laser fading. A literature search on the effects of laser irradiation on linen or bast fibres revealed a lack of study in this area. The effects of laser irradiation on linen have been documented in relation to research into the Shroud of Turin. Degradation over time caused by UV irradiation has been offered as one possible explanation of the mysterious markings on the linen shroud. To explain possible darkening effects Baldacchini et al. (2008) exposed a linen textile to a UV laser beam until discolouration occurred. Further discussion on laser-bast fibre interaction has not been documented, providing a gap in knowledge on the effects of laser irradiation on linen and other bast fibres for textile finishing and surface design.

2.3.3 Laser Assisted Three-Dimensional and Relief Effects

A laser moulding technique was developed during this research as discussed in Chapter 7. The use of laser technology to create three-dimensional textile forms may present processing advantages over traditional methods: for example, by the elimination of physical moulds or complicated loom set up in addition to ease of pattern change through digital generation of designs. The potential to use a CO_2 laser to heat set pre-determined shapes in a synthetic textile has not been previously explored. However, alternate laser techniques that generate textural and three-dimensional textile outcomes have been developed within the field of textile research, as discussed in this section.

2.3.3.1 Textural, Formed and Welded Three-Dimensional Laser Textiles

Designer, Jenny Addrison (2009) used the laser to affect the shine of a satin weave and produced alternating textures to pattern the surface of the cloth (Figure 2.9). Instead of removal, the synthetic woven yarns melted, and fused together altering the surface texture. The resulting areas were delicate and brittle, and therefore only useful as a decorative piece of cloth. There is potential for this technique to be refined with less damage to the integrity of the fabric. Yuan et al. (2012) exploited polyester melting effects to achieve a change in handle and colour, with a yellowing and darkening effect applied directly to fashion garments. Which other fabrics could be affected by laser irradiation to produce differential textural effects?

Figure 2.9 Laser Affecting the Shine of a Satin Weave, Jenny Addrison (2009)

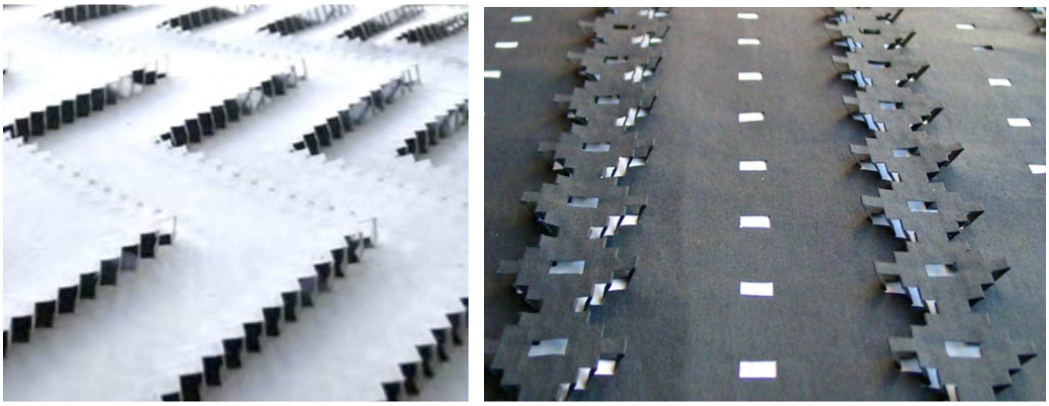

Figure 2.10 Laser assisted template pleating, Janette Matthews (2011)

Janette Matthews (2011) used a CO_2 laser to aid creation of origami inspired three-dimensional textiles (Figure 2.10). The laser was used to make templates and to score or cut fabric for complex folded shapes. The technique involved secondary steps in terms of folding the flat textile into its final 3D form. Is there potential to use the laser to heat set pre-determined shapes in a synthetic textile? This has not been explored in existing research.

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Figure 2.11 Laser Welding (Clearweld, 2012)

Laser welding has been used to bond seams in garment construction and in fashion. In the case of thermoplastic fibre fabrics such as polyester, lasers can be used to create stitch-less, water-resistant seams. As reported by The Welding Institute (TWI), this technique often requires an additive that is applied to the seam interface and reacts under the laser energy, melting and bonding the two surfaces together (Clearweld, 2012). Current uses of this technology include Airbags, medical and protective clothing and footwear with sealed seams. An example of laser welded seaming can be seen in Figure 2.11, with a second example showing the joining of two contrasting colour fabrics. Designer, Kate Goldsworthy has undertaken research into this area for textile design purposes. Goldsworthy (2009) explored laser welding technology to bond synthetics producing layered outputs that provided three-dimensional and relief qualities. Her work explored laser welding for mono-materials, using 100% polyester without an adhesive, encouraging non-contamination of the material. Traditional embroidery, bonding and printing techniques can render polyester products non-recyclable, as they are no longer pure. Using the laser welding process to bond polyester fabrics, Goldsworthy created decorative techniques and replicated traditional stitch effects, such as appliqué, quilting, and multilayered materials (Figure 2.12). Harnessing the laser for bonding and lamination of the fabrics, Goldsworthy was able to develop a range of surface decorating, and patterning methods while keeping the fabric 100% recyclable.

Figure 2.12 Laser Welded Effects on Synthetic Fabrics, Kate Goldsworthy (2009)

2.3.3.2 Lasers and Differential Shrinkage

Norbakhsh et al. (2011) reported on the laser's ability to reduce the shrinking and felting properties of wool. Laser irradiation to remove the scales of the wool fibre reduced felting and shrinkage, with results similar to that of wool treated using the traditional chlorination procedure. In Nourbakhsh's study, laser technology was discussed as a viable alternative method, which if applied on a commercial scale, could significantly benefit the environment by completely eliminating the hazardous chlorine compounds used in industry. In this case, laser processing was used as an all over treatment on the wool fabric, preventing overall shrinkage.

Differential shrinkage is a common technique used to create three-dimensional effects in weaving, when wool, elastane or high twist yarns are combined with non-shrink yarns. Three-dimensional effects are achieved when only the wool, elastane or high twist yarns shrink on release from the tension of the loom, or when washed. The difference in tension between yarns cause relief surfaces to be formed. The potential for Nourbakhsh's (2011) process to be used as a design tool, allowing targeted laser defined shrink reduction to achieve 3D surface and patterning effects was not investigated. However, design researcher Janette Matthews (2011) investigated the use of laser cutting to disrupt the surface of cashmere, as a pre-treatment to felting to achieve 3D surface pattern. The difference in tension across the woven cloth caused by the cut out areas formed bumps after felting, resulting in a textural relief surface (figure 2.13).

Figure 2.13 Laser cut and Felted Cashmere, Janette Matthews (2011)

There is further potential for the laser to generate three-dimensional textile moulding effects. For example, could differential tension effects be replicated by laser processing of synthetic textiles? Laser irradiation of synthetic stretch fabric under tension is examined in Chapter 7, addressing levels of detail, accuracy and control of three-dimensional effects and relief surface patterns.

2.3.3.3 Laser Devoré

Advancements in the field of surface design have been made using laser ablation for design purposes. Practitioners in the design research community have used laser ablation techniques on varied fabric substrates. For example, Stoyel (2007) used laser ablation to replicate traditional chemical devoré effects. She used a laser to remove the top layer from fabrics in a defined pattern, eliminating the need for devoré chemicals known to produce environmentally damaging waste. Payne (2010) further experimented with the laser for devoré effects on unconventional fabric compositions such as paper and wool or cotton and metallic fibres. The *laser devoré* technique was also applied to a screen-printed fabric to remove the printed surface layer, revealing the underlying woven fabric (Figure 2.14). The materials used were designed for the purpose of laser treatment, described by Payne (2010: 05) as, '*an effective way of combining two manufacturing techniques to create innovative textile design solutions*'. This suggests that other surfaces or coatings could be removed to reveal the underlying textile. Kane (2008) developed engineered non-woven materials. Her nonwovens were constructed so that laser removal of a top layer revealed underlying interest in the form of a contrasting colour, material or texture as shown in Figure 2.14.

Figure 2.14 Laser Devoré:

(L-R) Laser Patterned Nonwovens by Faith Kane (2008); Laser Devore on Velvet, Laser Etched Screen Print on Linen by Jessica Payne (2010); Laser Pile Removal on Cashmere by Janette Matthews (2011).

The Woolmark Company (2012) and Matthews (2011) explored laser devoré techniques for milled '*3D merino*' and felted cashmere, respectively. Woolmark reported no loss to fabric strength from the process, with digital design permitting late stage design decisions and intricate patterns that would be impossible to achieve using traditional jacquard weaving.

The textiles produced through laser ablation and laser devoré techniques shown in Figure 2.14, show a variety of aesthetic design outcomes including three-dimensional, textural and relief surfaces on natural and synthetic substrates. Adopting these techniques, Payne (2010) and Kane (2008) have allowed the addition of multiple colour effects to be achieved, unlike the monochrome properties usually achievable from raster laser marking. The techniques have not been explored with relation to additional dye effects. Making use of the enhanced dye properties of laser irradiated fabric could add combined three-dimensional and differential colour effects using a single laser process as a pre-treatment to dyeing.

The techniques discussed in this section, revealed that laser devoré and laser etching techniques have been broadly investigated for textile design; however, areas for potential further development have been identified. Working with fabric blends could allow for targeted removal or enhancement of one of the yarn components in the textile. Further processing, such as dyeing could allow the fabric to take on new properties. The effect of laser irradiation on material properties specific to textile fibre types are explored in this research in Chapter 4. Could laser engraving a milled woollen textile provide three-dimensional and differential colour effects using a single laser process as a pre-treatment to dyeing? This is explored in Chapter 5.

2.3.4 Digital Laser Dyeing

The term Digital Laser Dyeing was coined during Akiwowo's research project (2015: 13) as an umbrella term to describe CAD controlled, laser-based dye techniques for textiles. This term therefore has relevance to this research project as it seeks to further advance knowledge in this specialist area. Laser dye techniques developed in this research are discussed in Chapters 5 and 6, contributing to a significant proportion of the work completed within this research. As such, a detailed review of existing laser dye research is presented in this section.

Many researchers have harnessed the photochemical and photothermal properties that laser processing can provide to modify textile material properties. For example, laser irradiation has been found to modify synthetic fibres, allowing increased dye absorption (Montazer et al, 2012; Kan, 2008; Wong et al., 2007) and a reduction in temperature of the dyeing process (Periolatto et al, 2014; Xin et al, 2002). Studies examining the surface and dyeing properties of textile materials after laser irradiation are discussed in this section.

The effects of laser irradiation on synthetic polymer fibres have been reported to improve dye uptake on polyester (PET) (Esteves & Alonso, 2007; Kan, 2008; Akiwowo, 2015; etc.), polyamide (Esteves & Alonso, 2007, Bartlett, 2006) and polypropylene textiles (Shahidi et al, 2013). Increased dye affinity has been related to increased hydrophillia of the polymer fibres (Montazer et al., 2012) due to chemical and physical property changes after laser irradiation. Reported chemical changes responsible for improved dyeing include a more amorphous fibre structure after laser irradiation (Bahtiyari, 2011) and improved bonds from dyestuffs to fibre surface due to the creation of more functional groups after laser treatment (Shahidi et al., 2013; Bahtiyari, 2011). Morphological changes have also been reported in the form of a ripple-like structure on fibres after UV irradiation (Kan, 2008; Bahners, 1995; Stepankova et al., 2011) and increased surface roughness after IR laser irradiation (Shahidi et al., 2013; Esteves & Alonso, 2007) as shown in Figure 2.15 and Figure 2.16. Capacity for enhanced dyeing has been attributed to the increased surface roughness on fibres, providing increased surface area for improved adhesion of dye particles to fibre (Esteves & Alonso, 2007; Bahners et al., 1995; Wong et al., 2001; Atav, 2013; Shahidi et al., 2013).

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Figure 2.15 Polyamide and polyester before and after IR CO_2 laser irradiation (Esteves & Alonso, 2007)

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Figure 2.16 Polyester before and after UV Excimer laser irradiation (Kan, 2007)

Dye performance testing revealed that increasing energy density of laser treatment had an increasing effect on the colour difference values of synthetic fabrics after dyeing that relate to a significant increase in colour depth on the irradiated fabric surface (Montazer et al., 2012; Shahidi et al., 2013; Knittel, 1998). By controlling the energy density, the uptake of dye on the material can be controlled, allowing varied colour intensity across the textile surface (Bartlett, 2006; Akiwowo, 2015). However, as Kan (2008) reports, laser modification of textile fibres does not affect the bulk properties of the textile due to low penetration depths. Colourfastness tests of laser irradiated and dyed synthetic fabrics showed that higher-intensity laser irradiation increased the wettability, light, rubbing and wash fastness of the test fabrics, however, properties such as bending rigidity and tensile strength were negatively affected by an increase in laser intensity (Shahidi et al., 2013; Hua et al., 2002). Montazer et al. (2012) attribute low tensile strength to increased crystallinity with increased energy density.

On cotton, surface roughness and a ‘flaked’ appearance on cotton fibres after laser irradiation, improved water wicking properties. However, unlike synthetic fibres, laser modification was found to reduce the amount of direct dye absorbed, leading to decreased colour strength as laser power increases (Chow et al., 2011; Ferrero et al., 2002; Montazer et al., 2013). By contrast, the sponge-like swelling of cotton fibres that had been bleached prior to irradiation, increased dyeability and wettability (Montazer et al., 2013). Could this have potential to be exploited as a dye resist method? Do other proteinous fibre types, such as linen, display the same properties after laser irradiation? The effect of laser irradiation on linen is investigated in Chapter 8.

Potential has been revealed to apply alterative coatings via laser enhanced absorption on textile fibres. For example, Nourbakhsh and Ashjaran (2012) report that laser treated cotton attracted positively charged ions, such as silver nano particles, to improve antibacterial properties. Additionally, CO_2 laser irradiation has been found to provide an activating influence on absorption of fire protection treatment, accelerated by four to six times, compared to traditional padding application methods on synthetics, proteinous and cellulose fabrics (Besshaposhnikova, 2013). Besshaposhnikova reports this effect was improved when the fire protection treatment was applied before colouration, as dye competed for the same reactive groups on the textile fibre.

The aforementioned studies show potential for laser techniques to increase affinity for dye and alternate finishing treatments. What other properties could be engineered onto a fabric in this way? Could enhanced dye uptake act as an indicator to predict the increased affinity for alternate finishing treatments? Potential is discussed in subsequent chapters, however the scope for this research remains focused on laser colouration and texturing opportunities for textile design. Potential for laser finishing is discussed as further work (Chapter 11).

2.3.4.1 Potential For CO_2 Laser Dyeing of Wool

Fewer studies are available on the effect of laser irradiation on wool properties, however a small number have shown results including; laser irradiation to reduce felting and shrinkage of woollen textiles (Nourbakhsh et al., 2011) and UV irradiation to improve the dyeability of wool (Periolatto et al., 2014). A combination of laser and plasma treatments has also been used to increase hydrophillia as an all over treatment on woollen textiles (Czyzewski, 2012). Results achieved by allover UV treatment offers a potential opportunity for further research in examining the effect of the more commercially available CO_2 laser's infrared irradiation on woollen textiles.

UV irradiation was found to disrupt the cysteine disulphide bonds on wool fibres and increase surface oxidation leading to a reduced water wetting time (Sandu et al., 2009). This suggests that UV irradiation increases hydrophilic properties of wool fibres.

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Figure 2.17 SEM of untreated and plasma treated wool fibres (Kan et al., 1998)

Kan et al. (1998) reported an increase in the dyeing rate of plasma treated wool. He suggested that alteration of the fibre surface, as shown in Figure 2.17, was responsible, providing a pathway for ease of dyestuffs to diffuse into the fibre without significantly affecting the original bulk properties. Unlike plasma, a laser has the potential to target defined areas, in the form of patterns or graphic imagery controlled by CAD. Studying advances in plasma treatment for textiles offers potential to expand this research by revealing properties that lasers may be able to replicate in a targeted manner. Altered properties that can be achieved using plasma treatment include enhanced wettability or repellency, adhesion, affinity for dye and cleaning such as desizing (Tomasino et al., 1995).

Plasma and laser combinations have been used in a process called *Multiple Laser Surface Enhancement* (MLSE). Macbeth (2010), reports on the technology's potential to improve material properties such as hydrophobicity for waterproofing, hydrophilic properties for low temperature dying, fire retardancy, material cleaning and anti-microbial treatments on wool. Czyzewski (2012) describes the surface modification that occurs. It cleans the wool at the nanoscale, rearranging the tiny scales that make up each fibre so they more easily wick in water. Wool that undergoes this process can be dyed at a temperature of 70°C for three hours, using less aggressive chemical dyes. These reductions in dyeing time and temperature suggest cost and energy savings, which The Textile Centre identified as a reduction of 30% on heating costs, £22,000 reduction of chemical and effluent costs and an increase in selling price due to enhanced fabric performance (Brodie, 2011). The MLSE example reveals the extent of savings possible by laser enhanced textile processing, expanding the rationale for additional research in this area.

The research presented in Chapter 5 also identified greater dye uptake on wool after laser irradiation. However, unlike the MLSE treatments described above, the processes investigated in this research used a single laser treatment procedure prior to dyeing and can allow controlled graphic patterning. This research aims to prove that CO_2 laser processing can provide a viable dyeing and surface patterning technique on wool and expanded to include wool blends. Laser parameters, dyeing recipes, mark making, accuracy and pattern combinations were all investigated for this technique. Specialised testing equipment such as SEM was used to analyse changes to the fabrics.

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Figure 2.18 SEM micrographs of wool (a) untreated, (b) chlorinated, (c-f) laser treated with increasing energy density (Nourbakhsh et al., 2011)

Nourbakhsh et al. (2011) showed that laser treated wool reduced felting shrinkage through modification of wool scales, as shown in Figure 2.18, at a level similar to that of wool fabric treated using a traditional chlorination procedure. Smith et al. (2010) found successful results removing scales from the surface of wool fibres by means of a chemical treatment. In his study, he found that the effects of subsequent enzyme treatments on wool were significantly increased. In the experiment, described by Smith et al., they found that the effects of the enzyme treatment Protease on wool were significantly increased after a pretreatment to make the fabric more hydrophilic. The study showed how the alkaline and CTAB pretreatment removed the lipid (fat) on the surface of the wool fibres allowing greater water uptake. Could the use of laser pre-treatment replace the need for the alkaline and CTAB allowing for a greater effect to take place when the fabric undergoes subsequent treatments such as dyeing? Could dye act as a visual indicator to predict the increased amount of enzyme or other chemical uptake, such as waterproofing?

The potential for the CO_2 laser, as an effective surface design tool for wool has not been fully explored in previous studies, nor has the correlation between laser parameters and the effect on dyeing a woollen textile. Herein lies an opportunity for investigation; to ascertain the effect of CO_2 laser irradiation at altered parameters on the surface and dyeing properties of 100% wool and wool blend substrates, and secondly; for results to be analysed in relation to their potential as a technique for textile surface design, discussed in Chapter 5.

2.3.4.2 Design perspectives on Laser dyeing

The proliferation of scientific papers on the subject, show that technical frameworks dominate existing laser textile research. Because of this, emphases on the surface design opportunities of these technical processes are not often highlighted. The aforementioned studies go a long way to test and explain the phenomenon on synthetic textiles, concentrating on an improved overall performance, while only a few have discussed the possibility of design outcomes from targeting specific areas of the textile substrate. Textile design research carried out by Bartlett (2006), Addrison (2009), Perliatto et al. (2014) and Akiwowo (2015) begin to address laser dye techniques from a design perspective.

Perliatto et al. (2014) suggest potential for design outcomes using stencils to mask all-over UV irradiation on wool. The stencils resulted in selective UV exposure on the substrate. Cross dyeing techniques were then used to gain a two-colour result as shown in Figure 2.19.

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Figure 2.19 UV treated wool fabrics cross dyed with metal-complex and acid dyes (top side, untreated; lower side, UV treated), (Periolatto et al., 2014).

There is a history of research on digital laser dyeing at Loughborough University with Bartlett (2006), Addrison (2009) and Akiwowo (2015) having studied the effects of laser irradiation on colouration for textile design. They began to explore potential for pattern, facilitated by tonal differentiation that can be achieved through laser pre-treatment when dyeing synthetic fibre fabrics.

Drawing on the digital graphic potential of CO_2 lasers, Bartlett (2006) identified the potential for using an increased dye uptake on synthetic textiles with the graphic capabilities of laser technology, while Addrison (2009) harnessed the properties of blended polyester/cotton fabrics to achieve multicoloured designs. When dyed in a mixture of different coloured disperse and direct dyes, uptake in the laser marked areas provided the disperse dye colour, while the cotton content was dyed by the direct dye colour as shown in Figure 2.20. The results were effective in achieving multicoloured areas on the same piece of cloth from a mixed dye bath, however the fabrics were delicate, so further testing could prove useful to develop a more functional technique that results in a more robust finished textile. The technical investigation of the process was limited in Addrison's work therefore the scope to expand the analysis and design potential of laser irradiation on blended fabrics exists. Other blend combinations have been explored in this research; specifically wool polyester blends, as discussed in Chapter 5.

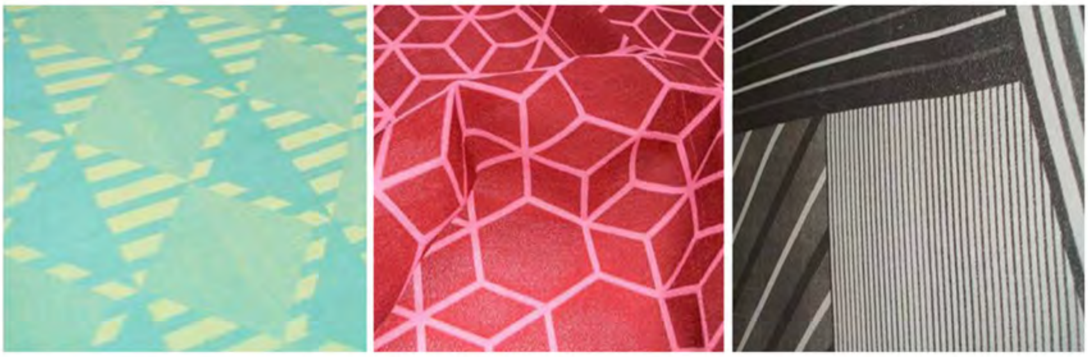

Figure 2.20 Multicoloured Polycotton and Polyester, Jenny Addrison (2009)

Recently completed work by Akiwowo (2015), sought to further develop a laser based pre-treatment for PET textiles adding to existing knowledge of laser colouration by further combining design development and technical inquiry. Akiwowo considered the improved dye uptake as an alternative colouration and patterning method for textile design on polyester fabrics. She reported the use of the laser beam as a dots-per-inch tool enabling digital dyeing, exploiting tonally varied dye uptake through controlled parameter settings. Akiwowo begins to investigate the commercial relevance of the technique by carrying out performance testing at an ISO standard, specific to her own designs, and reports potential advantages including potential for engineered design and patterning across garment seams as shown in Figure 2.21.

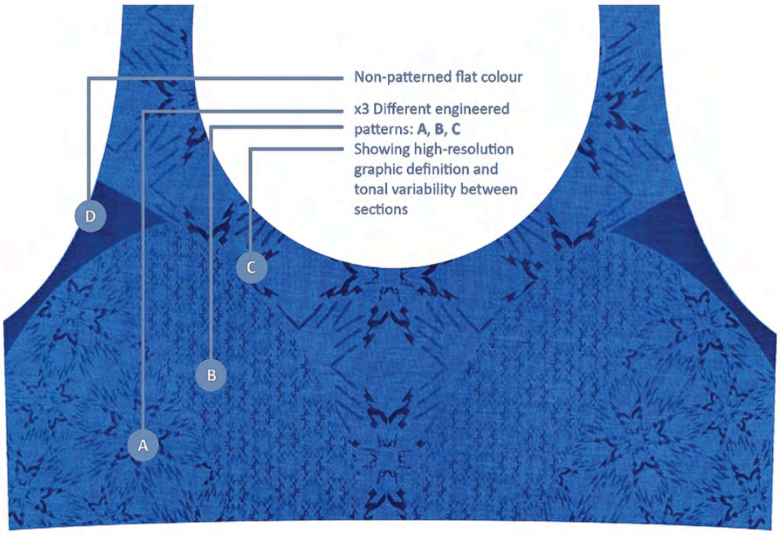

Figure 2.21 Laser dyed polyester garment, Kerri Akiwowo (2015)

2.3.4.3 Laser Dye Fixation Approaches To Textile Colouration And Design

All reported laser dyeing studies indicate a delicate balance of textile properties effected by laser treatment and highlight the importance of finding the correct laser parameters to work effectively on different fabric substrates due to the capacity for CO_2 laser processing to cause thermal damage (Kan, 2008; Montazer, 2011; Stepankova & Dembicky, 2010; Shahidi et al., 2013; Esteves & Alonso, 2007; Akiwowo, 2015). While laser pre-treated textiles have shown that greater affinity for dyeing is possible, mechanical tests have shown that the thermal stress applied to the substrate is ultimately a damaging action (Chow, 2012; Bahtiyari, 2011). Understandably, the referenced researchers have not focused on this negative aspect of the technique to a great extent in their papers, but this may account for the lack of commercial uptake of the laser dyeing techniques, despite proliferation of research into the subject for synthetic textiles mentioned in this literature review thus far. Akiwowo (2015) and Bahners (1995) suggest limiting the process to the use of lower laser energy densities as an approach to prevent loss of tensile strength. Consequently, only colour at lower depths of shade may be achieved for tensile strength to remain acceptable. Therefore, laser dye techniques have scope for improved performance, addressed by this research study through the peri-dyeing technique developed during this research and discussed in Chapter 6.
The previous studies discussed in sections 2.3.4.1 and 2.3.4.2 use a fibre

modification approach to enhance the substrate's affinity for dye. In this research an alternate approach considers the laser as a targeted energy source for 'on-the-spot' fixation, with dye reaction taking place at the point of laser interaction.

Attempts towards a laser dye-fixation approach to surface design of textiles can be recognised in a small number of studies. Examples discussed in this section include Kearney & Maki (1994), Bartlett (2006) and Fall (2015), who have all reported some success in introducing dye at the point of laser irradiation. Kearney and Maki reported a system for fixing fibre reactive dye to cotton by way of an argon-ion laser (Kearney & Maki, 1994). Their method applied the dye by screen-printing in the form of a paste. While the study provided a feasible low heat dye fixation method, the scope of the study was limited. At a maximum speed of 0.6mm/s, the process was very slow and the screen-printing stage of the process negated the advantage of remote, non-contact laser processing.

Textile dyeing company, Zaitex and Textile equipment company Tonello have developed a system for adding pattern to cotton textile garments using a laser (Billian, 2015). Their *Garment Flash Printing* involves a laser, pigments and a polymeric binder to add colour to cotton fabrics (Fall, 2015). The process involves use of a laser to fix the pigment that is applied as an even all over treatment to cotton fabric in the form of a resin. Tonello have developed the method from a commercial perspective, specifically focusing on application for denim garment finishing. Therefore the application outcomes of the method are currently limited to cotton textiles. At the time of writing, further information on the technique was not available, however the image shown in Figure 2.22 shows the effects of the process on cotton jeans.

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Figure 2.22 Garment Flash printing on cotton jeans, Tonello (2015)

Sivithri Bartlett considered the effects of laser treating a fabric wet with dye in her doctoral thesis (Bartlett, 2006). Her preliminary results identified a slight increased uptake within the dye bath (Figure 2.23), however the work was not furthered.

Akiwowo (2015) painted dye onto fabric, which was dried followed by laser irradiation using a CO_2 laser. Her results showed increased uptake after washing compared to the untreated control sample, however like the fibre modification approaches discussed in previous sections, this method induced thermal fibre damage. The true potential of a dye reaction that takes place at the point of laser interaction was not fully explored and leaves open a wide gap for experimentation into technical refinement of a laser dye fixation technique and its creative potential.

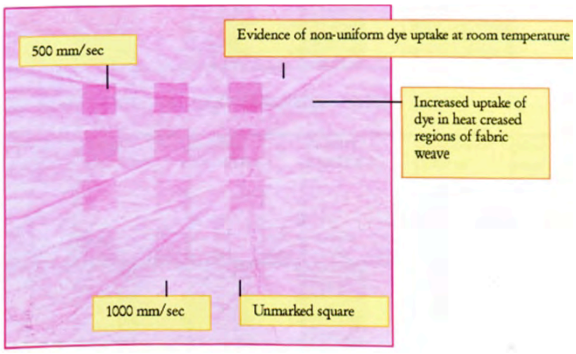

Figure 2.23 Dye Uptake on Laser treated Polyamide (Bartlett, 2006)

Each of the methods discussed in this section suggest potential for laser irradiation to activate a dye reaction on a textile substrate in a targeted manner that could be suitable for the design and patterning of textiles. However, to date a rigorous study has not been published that adequately explores the design potential of a laser dye fixation method on a variety of textile substrates; nor have they developed a coherent technique that may be replicated; or carried out any appropriate testing to suggest the process may be suitable for commercial application. The Peri-dying technique discussed in Chapter 6, developed a laser dye fixation method for wool and synthetic textile substrates. Design potential and standardised performance testing are also carried out in this research, addressing the gaps in knowledge identified in this review.

2.4 Lasers and Design for Sustainability

2.4.1 Relevance of Sustainable Textile Design Research

As discussed in the introduction, Chapter 1, improving the sustainability of textile design techniques was a crucial motivating factor in the development of this research project. Indeed, the sustainability of textiles is a salient concern in current textile research, with sustainable fashion and textile design a common agenda for industry and academic research. A report by the Department of the Environment (Defra) defines sustainability in the sector as clothing and textiles,

> …*which meet the needs of today's consumers, and are also made, transported, sold, used and disposed of in ways which do not adversely impact people or the planet – now or at any time in the future* (Defra, 2011:01).

In 2008, the global textile industry was estimated to have an economic value of over one trillion US Dollars (Defra, 2008). Sustainable initiatives and Government commissioned studies have identified several areas of concern across a textile product’s life cycle (Wrap, 2015; Defra, 2008; Forum for the Future, 2007). Figure 2.1 shows how these main concerns are broken down into each stage of production through to end of life. As highlighted by Bhamra (2007), it is a complex scale, where more efficient manufacture, does not always mean a more sustainable end product due to durability, consumer washing habits and finally disposal/ recyclability.

This research is concerned with the application of colour and 3D surface design in the finishing stages of textile processing. By considering how and when these techniques are applied within the textile product’s lifecycle, widens the remit for sustainable improvement. Laitala and Boks note that sustainable initiatives often focus on the use of resources during production rather than the *‘experience and longevity of use*’ (Laitala and Boks, 2012:127). Therefore it is important to consider ways in which production systems, supply, end-use and end of life factor into sustainable choices as well as simply striving for more efficient manufacturing and production techniques, often referred to as lifecycle thinking. However, as Gwilt points out while designers may strive to improve the environmental and ethical impacts of a product, ‘*the issue of over-production is a difficult point to address when the success of a* (fashion) *label traditionally relies on increasing product sales’* (Gwilt, 2013: online).

Stevels (1997) four levels of sustainable innovation are listed in Table 2.1. Considering the levels in relation to this research, draws attention to, not only the small changes that can be made to improve sustainability, but also the wider picture across multiple sections of the textile lifecycle. Levels 1 and 2 refer to improvements in existing products and systems, for example reductions in energy and improved efficiency. Level 3 looks at designing sustainability into new products or services from the outset. Finally, level 4 is about creating new systems that change and challenge modes of production or consumption.

Level 1	Incremental improvements	Level 1
Level 2	Re-design existing	
Level 3	Functional sustainability designed into products from outset	
Level 4	Systems: changing modes of production or consumption	Level 4

Table 2.3 Stevels Levels of Sustainable Innovation (adapted from Stevels, 1997)

Considering where design fits into this framework in the context of textile production and supply, the diagram in Figure 2.24 identifies where textile design intervenes within a textile lifecycle, this in turn, can indicate where textile designers have the potential to play a role in improving sustainability.

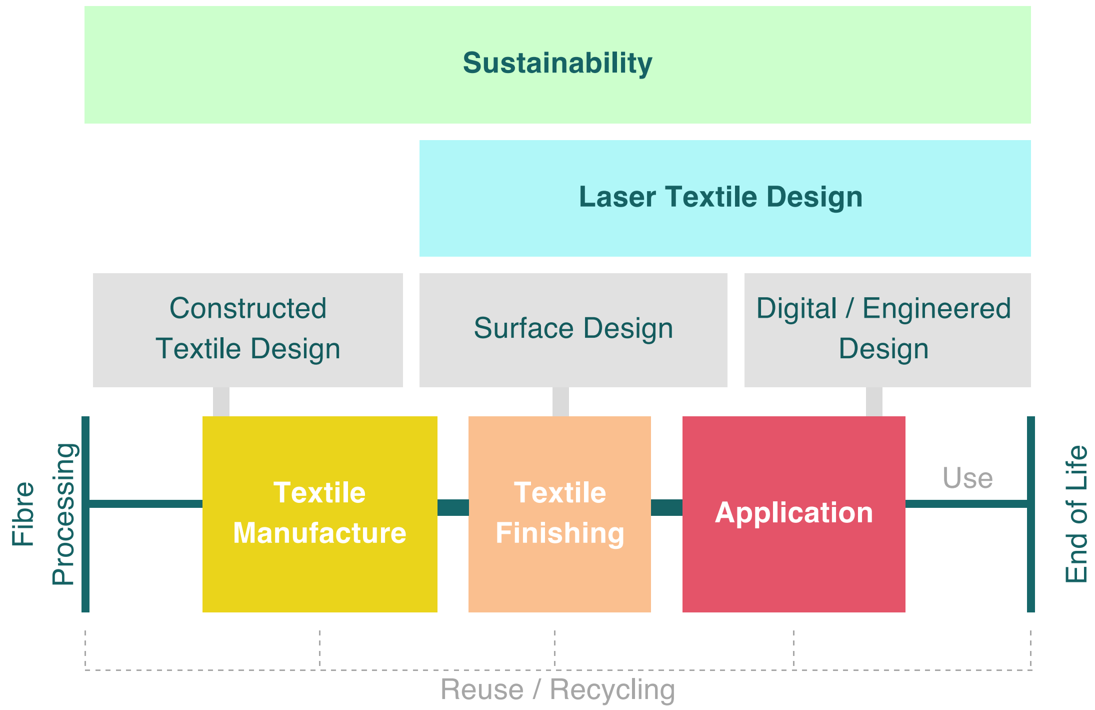

Figure 2.24 Design Stages in a textile lifecycle indicate where design can influence sustainability

For many decades the writings of design academics, such as Victor Papanek (1971; 1995), have highlighted the importance of the designer's role and responsibility in creating products that are sensitive to environmental and societal futures. Which adds further relevance to this research project in the context of textile design. Niinimäki and Hassi (2011) argue that making use of design strategies could be of critical importance to facilitating change, to reduce the environmental impact of textiles and clothing. Kane et al. (2015) discuss sustainable innovation with reference to design, arguing that an interdisciplinary approach, combining knowledge from both science and design, is crucial in fostering sustainable innovation for textile design.

Models and theories describing ways that sustainability could be implemented have emerged in textile research literature and government best-practice initiatives (Bamhra, 2007; Forum for the Future, 2007; DEFRA, 2011; McDonnagh, 2002; Politowicz, 2013; Wrap, 2015; Allwood, 2006). Each of these texts points towards key changes in systems and perceptions, which may be facilitated by on-going design research. The emphasis is placed on designers' role and design choices to consider sustainability from the outset. The sources cited above agreed that ongoing research into ways to limit use of chemicals and reduce waste and energy is needed in the textile industry. Bhamra (2007) suggests that in designing a new product or process a designer should consider if it offers improved sustainability from reducing energy or hazardous waste to increasing product value through longer life spans, ease of repair or recyclability. Only when the majority of these features apply to the new product, will the design be seen as an improvement.

Within each step of a textile product's lifecycle, from manufacture to end of life, improvements could be made to increase sustainability. If end of life is factored into design decisions, material choices to allow ease of re-use or recyclability may lend to a truly circular economy. To date, design researchers have contributed to the discussion and development of innovations across this spectrum from new materials that make use of industrial waste products (Mestre, 2014; Hijosa, 2016); new techniques such as non-chemical dyeing (Colorzen, 2014; Otsuki & Raybin, 2010; Huntsmann, 2014) and new systems such as on-demand design (Unmade, 2015), proposals for cyclability (Goldsworthy, 2014) or upcycling (Earley, 2007) to improve the environmental profile of functional and decorative textile goods.

By considering the ecological potential of laser technology in relation to the key environmental issues reviewed in this section, a framework for analysis may be drawn for the alternative design and finishing techniques developed in this research project. As suggested by Bhamra (2007) and Stevels (1997), the success of new techniques can be measured against their potential for sustainable innovation and improvement.

2.4.2 Impact of textile dyeing, printing and finishing

The environmental impacts involved in the dyeing, printing and finishing stages of textile production are highlighted as water and energy intensive, often inducing waste and chemical discharge (Defra, 2011). 40,000 to 50,000 tons of dye effluent is reportedly released as effluent into the environment globally each year (Better Thinking, 2006). Recent government legislations and recommendations by environmental organisations (REACH, 2006; Sustainable Europe Research Institute, 2000; Friends of the Earth, 2011, Greenpeace, 2012) have raised global awareness of the issues faced at this stage of production. Therefore, reducing the use of chemicals, water and energy has been identified as a key challenge in textile production (Wrap, 2015; Forum for the Future, 2007).

Wool and polyester fibres, used in this research, possess hydrophobic properties. Water repellence can be a desirable property in fashion and homewares, but presents a barrier for dyeing and printing of textiles. To obtain a desired shade of colour when dyeing and acceptable fastness properties that are required commercially, dye must completely penetrate through the textile fibres. High temperatures and long processing times are required for an optimum dye reaction to take place (Lewis, 1982). Traditionally, problems are overcome using additional chemical wet pre-processes. For example, scouring, bleaching, and steaming are all common processes used to improve dyeing and printing of wool. These processes are associated with high levels of wastewater and chemical effluent in industry, consequently the development of more environmentally friendly pre-treatments or enhanced processing opportunities are desirable for manufacture.

Energy is cited as one of the main cost factors in the textile industry, with wet processing a major energy consumer used for heating and steaming (Hasanbeigi & Price, 2015). Among the recommendations for improving energy efficiency in wet processing, Hasanbeigi and Price suggest reducing time and temperature and combining preparatory treatments to reduce the amount of thermal energy used. Cowell (2015) notes that sustainable solutions for the textile industry need to find a balance between ecology and economy, *'sustainable value can only be feasible if both ecological and economic priorities are also being met'.* Enhancing the quality and value of a product while reducing the environmental impacts can be referred to as eco-efficiency, or '*The ratio of product or service value to its environmental impact' (United Nations, 2009).* Fortunately, methods to improve environmental efficiency in wet processing such as laser treatment can also provide economic efficiency through reduced energy, water and dye or chemical requirements.

Cowell (2015: 40) reports that the increased search for more sustainable solutions for textile processing by retailers, brands and manufacturers is '*driving new technologies*' including reduced-water dyeing, digital printing and innovative pre-treatments to encourage improved uptake of dyestuffs. The use of laser technology to enhance colouration and surface design has relevance in this discussion. It has been reviewed in the previous section that laser modification of natural and synthetic fibres may offer enhanced dye uptake through dry pre-processing methods. Localised dyeing, combining colouration and patterning and reducing temperature have all been identified as avenues for further investigation in this research, showing relevance to water, dye chemical and energy reduction, identified as key to reducing the ecological impact in textile dyeing, printing and finishing.

2.4.3 Efficient Technology and Laser Processing

Emergent technological and engineering advancements are adding to sustainable improvements in manufacture. Scaturro (2008: 475) highlights the '*significance of technology's role in the evolution towards a more sustainable fashion system*.' This section acknowledges technological advances occurring in the industry, seeking to identify the advantages and limitations that laser processing offers over emerging colouration and surface design innovations. To what extent does laser processing have a place in the future of sustainable manufacture?

Reports suggest new technologies are one way to boost sustainability of production. In the realm of fashion and textiles, Sarah Scaturro (2008) has referred to the use of sustainable technology as *Eco-Tech Fashion*. She reasoned that advances in technology could be used as a fundamental aid to the development of environmentally friendly processes, describing an ideal where future technological systems are more sustainable than those that currently exist in manufacturing. Allwood (2006) proposes a number of alternative scenarios by which the processing of a garment, from raw fibre to finished product could be changed to offer a commercially viable more sustainable form of production. She suggests that the impact of new specialist technologies on the textile industry, could bring areas of production and manufacture back to the UK, where higher labour costs, could be offset by less intensive level of manpower required.

As well as the environmental benefits, digital technology and production systems may also offer other commercial benefits: such as allowing production of smaller batches, including made-to-order production of individually designed and sized garments, and pattern customisation at supplier or even consumer level, without the need for expensive setup costs (Allwood, 2006). Cie and Joseph (2010) describe this as ‘*nimble manufacturing*’.

The laser is one such *nimble* or *agile* technology that has sustainable potential. It is a digital technology that offers dry processing and potential for combining processing stages, for example, laser cutting combined with laser processed surface design could reduce the number of separate steps necessary to produce garments. Further environmental, economical and practical processing advantages of laser technology for textile design are discussed in the following section.

2.4.4 Lasers for Sustainable design and Manufacture

How can laser processing offer sustainability for textile design and manufacture? The aforementioned publications throughout section 2.4 provide a number of ‘best practice’ initiatives for improving sustainability in the textile lifecycle (Bamhra, 2007; Forum for the Future, 2007; Defra, 2011; McDonnagh, 2002; Politowicz, 2013; Wrap, 2015; Allwood, 2006). These suggestions have been used to compile Table 2.4. It shows a number of sustainability principles that have relevance to laser processing of textiles and potential to address the problems faced by current textile surface design and colouration techniques.

Sustainability Principle	Stevels Level
Material Choices	Level 1
Energy and Water Reduction	
Chemical Reduction	
Waste Reduction	
Sustainable Systems	Level 4

Table 2.4 Sustainability Principles relative to Stevels Levels

Each of these sustainability principles and their relevance to this research, are discussed in the following sections. The five principles have been selected with the intention that highlighting and using these principles from the outset would keep sustainability at the forefront of the study. A framework was created from the five principles to aid decision-making and analysis of the work, aimed to enhance the overall sustainability of this research as laid out in Chapter 3: Methodology, and reviewed in relation to the developed laser techniques in Chapter 10.

2.4.4.1 Material Choices

The specificity of laser fibre modification on material properties means that material choices are significant in this research. This research aims to enhance material properties via laser irradiation for further processing efficiency, potentially improving the sustainable profile of the textiles.

Literature on sustainable textiles highlight the importance of material choices and their effect on natural resources during production (Fletcher, 2008; Allwood, 2006; Forum for the Future, 2007) and at the end of their useful life (McDonough, 2002; Goldsworthy, 2014).

Cotton and polyester are the most widely produced textiles, accounting for 80% of the textile market globally (Defra, 2007). The current intensity of production for these two fibre types requires high levels of energy, water and in the case of cotton, pesticide use (Forum for the Future, 2007). Fletcher (2008) discusses material diversity; the use of a wide variety of materials instead of intensive production of just a few. A case study demonstrating the benefits of material diversity explains that substituting polyamide yarns for British wool in a carpet would reduce the environmental impact by 65% (Allwood, 2006). Wool is a key fibre used in this research. Finding new techniques to enhance the properties of wool may make it more attractive as a fibre type to the furnishing and clothing industries. This, in turn could lead to similar environmental benefits as described in the above case study. There are many other fibre types that could spread out the use of resources. A Forum for The Future UK (2007) report suggests the textile and clothing industry should consider alternative natural fabrics. Other fibre types considered in this research include linen that has the potential to be harvested and manufactured locally. Similar to the example of British wool, using linen as a substitution has potential to reduce environmental impact.

Material choices also have an impact at the end of a textile's life. A report by Forum for the Future (2007:13) suggests designers and developers should use, '*alternative natural and renewable fabrics (*and*) design clothing for recycling or disassembly*'. *Cradle-to-Cradle* is a principle, by which zero waste is considered from the very inception of a new product or material (McDonough & Braungart, 2002) with an aim to create a closed loop of manufacture and use. McDonough and Braungart propose a product that has reached the end of its lifespan should be returned to the industrial cycle, as a raw material for new products, with no decline in quality. This system encourages materials to be used in a pure state. Without contamination, the materials can either be returned to the industrial cycle easily, or if the material is biodegradable, it can be returned to the earth to decompose. Goldsworthy (2014) discussed *design for cyclability* in relation to laser processing for textiles as discussed in section 2.3.3.1 of this review. Her laser finishing process retained their mono material properties to allow a closed loop textile lifecycle. She proposes that synthetic textile products should be designed for recovery at end of life; that is, they should remain uncontaminated for repeated cycles of use and recycling. This proposal has relevance to this research project, through the development of laser techniques that negate additive processes, such as stitching (see Chapter 7). Keeping fabrics pure to one fibre type only, would allow outcomes to be recycled responsibly, or biodegrade, vastly increasing the overall sustainability of the work.

2.4.4.2 Energy, water and chemical reduction

Recent advances in sustainable dyeing processes have addressed the issue of water consumption through new waterless dyeing technologies that have been developed for all-over colouration on cotton (ColourZen, 2015) and synthetic textiles (Otsuki & Raybin, 2010; Huntsman, 2015). In addition, digital printing has provided industry with efficiency for textile patterning. The use of CO_2 lasers as a dry process, also offers positive implications for reduction of wastewater and processing time of textile production in comparison to traditional wet finishing methods (Costin & Martin, 1999). These advantages have been beneficial to denim manufacture in creating laser-faded effects on denim (Ortiz-Morales, 2002; Ondogan, 2005) with up to 80% reduction of water reported in garment production (Replay, 2012). The use of laser technology on other textile substrates presents numerous further opportunities for sustainability in the field of textile research. In Chapter 4 for example techniques developed in this research suggest that lower dyeing temperature and time could significantly reduce water and energy. Combining printing and dyeing in one step as discussed in Chapters 4 and 5, could also remove extra wet processes from the production chain, or eliminate them completely as discussed in Chapter 8. For the purposes of this research, it is hoped that a reduction of energy and water in the processing of textile surface designs would provide a process with less environmental impact than equivalent surface design methods.

2.4.4.3 Waste reduction

While this research is not primarily concerned with textile waste, design strategies that make use of digital technology, such as laser processing in this research, have potential to aid waste reduction.

With reference to the sustainability benefits of digital textile printing, Allwood (2007) discusses the ability for digital technologies to allow small-batch and made-to-order production, *'cost of stock-holding and the need for end-of-season price reductions would be reduced if production was fast and close to the retail outlet, as there would be no requirement for advance ordering of large batches'* (Allwood, 2007:13). Where digital technologies allow for engineered printing, a *zero waste* approach can be employed to reduce or eliminate production waste (Politowicz, 2013). Tefler (2012) reported a 23% improvement on material usage through intelligent pattern layout, an approach that laser precision could facilitate. As an example of a laser engineered design, Akiwowo (2015) created a laser-dyed prototype garment, shown in Figure 2.21.

Ondogan (2005) describes a number of advantages of laser technology over the wet methods for denim, such as the ability for placement of designs and detailed imagery to be applied easily and identically from product to product. He notes that increasing repeatability and production standards in mass production adds value by reducing 'seconds' where identical worn effects could not be achieved by traditional methods. These advantages of using a laser compared to traditional methods in the denim industry act as an example, showing how the use of laser technology could be of similar benefit in other textile production models and within this research.

In addition to the design approaches to reduce waste discussed above, the laser offers mechanical waste saving with no mechanical or moving parts to wear out or consumables to replace (Synrad, 2006).

2.4.4.4 New Systems

Nimble or agile manufacture and fashion on demand have been cited as key ways to achieve a more sustainable fashion industry by changing the mode of supply and production (Barnes & Lea-Greenwood, 2006). Within their manifesto, ‘Ted’s Ten’ suggest ‘*Design to dematerialise and develop systems and services’* could be used as a strategy for improving sustainability in the field of Textiles (Politowicz, 2013).

H and M (2015) recently published a sustainability report that states they are going to reward business to suppliers who can help to offer them more responsive supply. If more brands follow suit the demand for new, more responsive systems is likely to increase. For manufacture and supply chains responsive supply means reducing lead times and minimum orders. As mentioned in the previous section, if suppliers can be responsive to their customers needs, then there is an opportunity for reduced stock holding and surplus stock reduction. For retail, responsive supply can mean adoption of ‘on-demand’ production. With reference to digital technology, Cie and Joseph (2010) suggest print on demand could offer *‘the ultimate in stock control, with print engineering, where textile designs are printed on pattern pieces to fit specific products, limiting fabric waste’*.

There has been an increase in the number of companies who are following an on-demand model. Services such as these allow individual customer interaction and a move towards customisation and personalisation of garment ‘blanks’. For example digital and sublimation printing companies like YR Store (2015); Print All Over Me (2015) (Figure 2.26); and Knitwear company ‘Unmade’ (2015) (Figure 2.26) provide ‘design your own’ blank products or templates that allow customers to design and create their own garments. This kind of personal interaction means a final garment is only created when it has a buyer; this may facilitate *aesthetic sustainability* (Harper, 2012) helping consumers to form a stronger connection to their clothes, with an aim to increase the garment lifespan (Fletcher, 2008).

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Figure 2.25 Customer customisation on knitwear (Unmade, 2015)

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Figure 2.26 On-demand Garment Printing (YR Store, 2015; Print All Over Me, 2015)

The potential for laser technology to provide responsive supply as a digital manufacturing tool has been implemented in denim manufacture (Jeanologia, 2015) and acknowledged in textile design research by Stoyel (2003), Ondogan (2005), Goldsworthy (2014) and Akiwowo (2015). According to Onogan (2005), the laser was shown to accelerate production, and repeatable designs could be used on CAD systems, sent via the Internet across the world. Accurate duplication of designs from the design studio across the supply chain can be a challenge in the fashion and textiles industry. Designs for laser processing saved as digital files can be stored, changed and duplicated easily. This allows very small production runs, with the ability for 'quick response' or fast fashion manufacture in response to demanding markets. As discussed in this review, the laser provides non-contact processing that offers flexibility for application on 3D forms and finished garments (Shahidi et al., 2013). An on demand or customisation laser service has potential to provide direct-to-garment or direct to product processing that would be enhanced by further development of *Laser Textile Design* techniques as discussed in this research. This requires repeatability and control over the laser as a design and surfacing tool for transferability to on demand production systems, addressed within the research via testing that meets international standard regulations as discussed in Chapters 4 to 8.

2.5 Chapter Summary

The literature review has revealed the laser as an effective tool with increasingly diverse textile applications. Lasers provide an energy efficient means of material processing and have been shown to have fibre modification capabilities that can enhance and improve dyeability without excessive water or chemicals and therefore have potential environmental benefits compared to traditional textile dyeing processes. For graphic processing, they enable specificity and control by digital generation of imagery.

The effect of laser irradiation on different textile substrates varies dependent on the method of application and the material. In this way laser techniques could be said to be process led, however unlike other surface design techniques, multiple effects can be achieved by the same equipment. The advantages of digital control mean a vast scope for the type and scale of the imagery processed. The high level of control and microscopic precision capabilities coupled with non-contact processing of the laser offer a unique benefit not achievable by other means. It is these unique attributes and controllable parameters of the laser that offer potential for novelty and innovation through consideration of brand new processes and opportunities for textile design.

Based on the research presented, several areas of investigation have been identified where the effects of laser irradiation on specific fibre types could be explored in relation to the research aims. This research is ultimately looking for a more sustainable way to produce surface design on fabrics, while also carefully considering the fibre choices. The aim was that this would lead to relevant design outcomes, using the laser as a more sustainable method of production. Questions posed highlight gaps in knowledge for laser modification of textiles to develop and further the work, leading to a distinct research outcome.

Questions raised from the literature review that have been selected for research in this study are summarised in Table 2.5 The table shows a summary of surface design effects that have been achieved through different laser processing methods in the reviewed textile engineering and design research literature. The reviewed literature demonstrates that laser irradiation can be used for cutting, fading, devoré, three-dimensional, and colouration effects including increased dye uptake on synthetic textiles. Gaps in knowledge exist that provide opportunities to expand research into laser surface modification, multicolour, 3D and textural effects.

The study presented in this thesis investigates the effects of CO_2 laser irradiation for colouration and three-dimensional surface design opportunities, exploiting the design potential of the laser as a digital graphic processing tool. The questions and opportunities identified in Table 2.5 formed a basis for investigation into: colouration opportunities using the laser as a thermal source to modify textile fibres (Chapter 5); to induce dye fixation at the point of laser irradiation (Chapter 6); laser fading linen (Chapter 8); and to facilitate precision heat moulding of synthetic materials (Chapter 7). The methodology used is discussed in the following chapter.

Laser Process	Examples of laser surface design effects achieved in existing textile research			Questions identified from Literature Review	Gaps selected for research in this study	Additional Questions
	Design Effect	Colour	Relief/ Texture			
Cutting	Cut work patterns	Multicolour achieved indirectly by layering	Yes			• What design opportunities and graphic capabilities exist for any new laser techniques and how they are best achieved: What levels of mark making and quality of line, tone, colour and three-dimensional effects are achievable? • What are the advantages for manufacture are offered over existing design techniques? • What are the sustainable advantages of the techniques? • What are the potential applications?
Engraving	Fading of denim	Tonal faded effects	No	• Can laser fading techniques be used on alternate fabric substrates such as linen and other bast fibres?	Fading and marking Linen substrates	
Ablation	Devoré	Multicolour Indirectly by engineered composite materials	Yes	• Can devoré effects enhance wool dyeing?	Combining relief and dye effects	
Chemical Change	Dye effects	Tonal effects can be achieved by laser dyeing or multicolour on blends	No	• Can infrared laser irradiation be used as an effective pre-treatment to dyeing wool for increased uptake? • Are differential levels of dye uptake achievable on wool/ wool blends without degradation to the fabric substrate? • Can time or temperature of dyeing be reduced? • Can a dye fixation approach be used to induce dye uptake at point of laser irradiation? • Can targeted laser irradiation be used to achieve 3D moulding of synthetics by heat setting?	Laser Enhanced dyeing of Wool Multicoloured dyeing Laser Dye fixation Moulding 3d, heat setting ISO testing and parameter optimisation	
	Inducing phase change in synthetics (Melting)	No	Texture and Sheen			
	Welding	Multicolours can be achieved by welding 2 colours together	Layering and stitch effects			

Table 2.5 Opportunities for Laser Textile Research identified in the Literature Review

CHAPTER 3 : AN INTERDICIPLINARY TEXTILE DESIGN METHODOLOGY

3.1 Introduction

This chapter highlights the key points of discussion around approaches to research informed by design, relevant to this study. It goes on to articulate the methodology established for this PhD. As a practice based, multidisciplinary study situated in textile design, the research methodology employed draws on scientific knowledge frameworks used within optical engineering and dye chemistry, as well as design and craft based approaches. It has therefore been necessary to outline the approach used, in context to the different areas of study. This crossing of boundaries has led to a thorough investigation of the subject, maintaining rigor across all straddled fields.

The first part of this chapter aims to provide a critique of approaches to research for textile design, touching on existing literature relating to design, materiality, craft and tacit knowledge. It considers how a multi-disciplinary approach might benefit each stage of the research from development to outcomes. In doing so, it reflects upon the relationship between design and scientific methods in defining a specific methodology. The second part of this chapter will highlight the key methods used for problem formulation, data collection, analysis, evaluation and dissemination of the research work.

In a traditional sense, scientific research is investigative, setting out to prove or disprove phenomena. '*Science is analytic, design is inventive*' (Gregory, 1966). Textile design research makes use of design specific approaches, which will be discussed in this chapter.

Rogers and Bremner note that focusing on the distinctions between design and science approaches in research may not be productive discourse for practitioners. Instead they argue the case for *Alternative Disciplinarity*, where methods are not determined through discipline based values, but are '*project based'* (Rodgers & Bremner, 2011: 1). This chapter will argue the case for an interdisciplinary approach to textile design in this research project thus creating an alternate approach where scientific and design research are undertaken in parallel. Nonetheless, it remains important to outline some of the key areas of thought on the subject of design research to support and clarify how design practices have informed and benefited the work.

3.2 The role of practice in design research

The idea that a specific *designerly* way of thinking exists has been widely discussed in academic literature in the field of design (Dorst, 2011; Kimbell, 2011; Cross, 2007; Durling, 2002). Debates about what constitutes a 'design approach' have acknowledged that a distinction exists between research in design and research within sciences and humanities (Cross, 2007; Archer, 1995). Design thinking has been referred to as a specific type of knowledge, an epistemology that is described by Cross as a '*designerly way of knowing*'. It has been explained as a bringing together of *'practical and theoretical kinds of knowledge*' (Newbury, 1996: 16) while Cross

(1999: 06) observes: '*Design knowledge resides in its processes: in the tactics and strategies of designing*'. The importance of design processes is reflected by Scrivener (2002: 1) who believes knowledge is produced through the process of making, noting this as a, *'knowledge independent of the actual art objects produced'*. This brief overview highlights the diversity in descriptions of the term *design thinking*, used to portray knowledge, approach and process within design. Kimbell (2012: 144) recognises that discussion in the field of design thinking often separates *doing, knowing and saying* but instead we should focus on a practice approach. She acknowledges that *Design as practice* encompasses design knowledge, activity and problem solving all together.

Niedderer & Roworth-Stokes (2007: 3) seek to define practice as follows; '*Practice is the application of skills, knowledge and expertise, through action or exercise'*. Practice-based research can be identified as distinct from general design practice (Cross, 1999; Durling, 2002) in that the acquisition of new knowledge is the goal (Archer, 1995). This has led Durling and Neidderer to refine the definition of design practice within research as '*investigative designing*' (Durling & Niedderer, 2007: 16). Frayling (1993: 05) positioned design research as taking several forms: '*research into design, research through design or research for design'*. The research discussed in this thesis can be described as *Research through design*, where creative practice was used as an essential part of the research both in conducting the investigation and as a means of expressing the results. The multiple uses of practice in this research reflect Durling's (2002: 82) sentiment that design practice can be used as an '*interrogative process'* if used as a structured method for data collection or reflection on practice.

3.3 Relevant strategies for practice based research

Emergent research methodologies for design are ones in which strategies are not always predetermined, but emerge from action over time (Barrett & Bolt, 2007). An emergent strategy compliments the idea of a 'project based' methodology, discussed in the introduction of this chapter, in that problem finding and research activity can be developed as the practice progresses.

Action research (Lewin, 1946) and grounded theory (Glaser & Strauss, 1967) are examples of emergent research methodologies. With origins in social science disciplines, the strategies typically relate to social practice. Despite this, they offer some relevant approaches for design research and as such examples of design research that make use of these approaches exist (Archer, 1995; Neidderer, 2009; Mestre, 2014).

Action research has relevance for practice based research, described as a research methodology that enables the researcher to bring about an improvement in their professional practice (Birley & Moreland, 1998). Bruce Archer (1995:11) defines action research in relation to *research through practice*, as *'systematic enquiry conducted through the medium of practical action; calculated to devise or test new* *information, ideas, forms or procedures and generate communicable knowledge'*. The Action Research paradigm has several identifiers; the topic usually focuses on changing an existing social practice *(AR_1)*; it involves participatory activity *(AR_2)*; collaboration *(AR_3)*; and comprises of documented reflective cycles *(AR_4)* (Swann, 2002: 55). The reflective cycles can be divided into four steps; planning, action, observation and reflection (Zuber-Skerritt, 1996).

Reflective practice is the cyclical process used to evaluate professional practice during (*reflection in action*) and after (*reflection on action*) practical action (Schon, 1983). In both instances critical reflection informs the next actions to be taken and the process repeats. Donald Schon (1983: 97) describes the design process as, '*a reflective conversation with the situation'*. Swann (2002) notes the similarities between the design process and the process of action research. Employing design practice within research makes use of research strategies that are familiar to designers (Gray, 1996) drawing upon the practitioner's design expertise (Grocott, 2012) and resulting in outcomes that are a direct result of the practitioner's action (Archer, 1995). Compare this to scientific study; one that is conducted under strict controlled conditions in such a way as to avoid influence from the investigator on the subject being studied. The interpretive approach is catered for through action research and can be noted as a factor that differentiates design research from scientific research; the individual researcher becomes integral to the research process (McNiff, 1988).

As a design-led research project, the action research model provides some appropriate strategies for this PhD. The research aim to develop new techniques for textile design (and therefore for textile designers) was effectively seeking to change and improve existing textile design and laser processing practices *(AR_1)*; the research process used design practice and scientific experimentation as action *(AR_2)*; the project involved a number of stake holders/ proposed end-users in the form of industrial partners who have contributed to the research development and evaluation throughout the project *(AR_3)*; and reflective practice was used to develop, refine and optimise practice and process through iterative cycles *(AR_4)*.

If a personal influence informs the enquiry, it becomes important that the researcher's position should be made explicit. Archer (1995: 11) notes it is '*good practice to make clear exactly what was the theoretical, ideological and ethical position the investigator took up in making the intervention, observations and judgements'*. In this PhD, the research question was approached from the position of a textile designer with a marked interest in sustainability. In this case, what are the characteristics of practice-based research that are familiar to that of a textile designer and how did this influence the methodological approach? The following section addresses that question and discusses the notion of a specific 'textile approach' with reference to strategies used within existing textile design research.

3.4 Textile Design Approach

Recent researchers have alluded to a distinct textile design approach. Drawing from within the broad spectrum of design research, textile knowledge encompasses tacit knowledge (section 3.4.2) with further concerns linked to a craft approach, focusing on materiality. Igoe (2010: 2) notes textile design as a '*sub-discipline of design with it's own specific methodologies*'. While Philpott and Kane (2016: 252) describe 'textile thinking' as: *'a unique strand of design thinking and makes a significant contribution toward flexible and connective ways of problem solving'.* Studd (2002) aimed to map the design process specific to a textile designer noting five phases (planning, research and analysis, synthesis, selection, production) in the design process that were common to professional textile design practices from freelancers and design studios to retailers and global suppliers. While Studd's research maps the process stages and methods used, it fails to comment on, or give an insight into the overall approach to design specific to textiles. Igoe (2013) articulates a poetic definition of textile thinking focusing on the emotional and taciturn nature of materials. However, this also stays away from mapping out key aspects of a textile approach to research. In order to articulate a particular way of thinking distinct to textile design practice, it is necessary to review the work of recent textile design researchers.

In reviewing the methodologies from a selection of studies by recent practice-based textile design researchers, similarities were observed. Several commented on the creative process as essential to the problem finding or development stages of research (Nimkulrat, 2012; Philpott 2010; Carden 2011; Igoe, 2010), whilst most made reference to tacit or experiential knowledge playing a key role in their practice (Nimkulrat, 2012; Philpott 2012; Carden 2011; Igoe, 2010; Kane 2008, Vuletich 2014). To emphasise it's importance, Bye (2010: 11) claims that one of the goals of textile design research should be '*to make tacit knowledge accessible to advance the understanding of textiles as a design research discipline'.*

Harris (2012), Nimkulrat, (2012), Kane, (2008) and Vuletich (2014) all profess to taking a 'craft' approach from the stand point of a designer-maker. Whereas Philpott (2010), Carden (2011), Mestre (2014), Goldsworthy and Paine (2014) discuss ways in which they have used craft as an intervention to keep a 'hands-on' connection to the textiles while using digital or industrial tools. Of the reviewed projects, creative opportunities were articulated in the aims of the project with visual and tactile communication considered key factors in evaluating the success of outcomes (Philpott 2010; Akiwowo, 2014; Goldsworthy and Paine 2014; Kane 2008; Bartlett, 2006). Igoe (2010: 4) extols the use of visual and sensorial qualities, insisting that textile design '*must use all its performative, decorative and seductive characteristics in order to communicate its exquisiteness to patrons'*. Philpott (2010: 2) also encourages the use of a textile methodology within research to '*expand the discourse beyond purely functional parameters, suggesting alternative futures where beauty, utility and intuition all play a role*'.

Textile design researchers also expressed the interdisciplinary nature of their inquiry, each stating crossovers with different fields specific to their research project (Matthews, 2011; Bartlett, 2006; Philpott, 2010; Kane 2008; Akiwowo, 2015; Goldsworthy & Paine 2014). Recurring themes have placed textile practice at the boundary between commercial design, engineering and a more skills based craft with the following characteristics: an approach to problems; 'tacit' or 'experiential' knowledge; craft and material knowledge; the importance of aesthetic; and function. The diagram in Figure 3.1 shows how textile design characteristics are positioned in relation to design, craft and engineering disciplines. The following section discusses each of the characteristics in turn and how they have informed or been catered for in the research strategy for this research project. The case for an interdisciplinary approach is discussed in section 3.5.

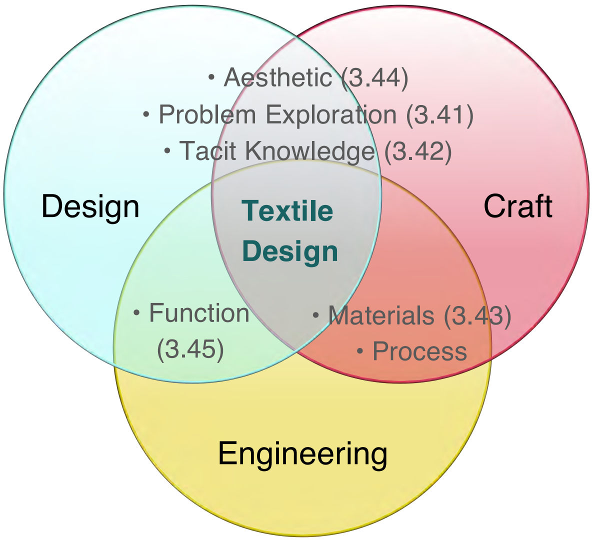


Figure 3.1 Characteristics of a Textile Design Approach

3.4.1 A specific approach to problems: exploration

Fatima Saikaly (2005) noted a distinct approach to design research after she reviewed fourteen case studies from practice-based research projects in design, across the world. Saikaly's (2005:11) study found all the reviewed projects to have similarities in their '*fuzzy*' starting point and in their '*ongoing construction of research processes*'. This PhD project began with a 'fuzzy' or 'wicked' problem (Rittel & Webber, 1974); the wider aim to develop new sustainable aesthetic opportunities for textiles using laser technology. It was 'wicked' in the sense that it had multiple priorities (sustainability, aesthetics, textiles, laser processing) and varied stakeholders with the potential for multiple solutions. Dorst (2011) argues that the ability to re-frame a problem, is significant to a designerly way of thinking. Designers create new approaches to solving a problem that can lead to innovation, not focusing solely on a solution. Emergent research strategies allow for fuzzy problems to be tackled '*without rigid methodological requirements'* (Haseman, 2006: 101), therefore multiple avenues can be explored from the outset of the project. It could be argued that here lies another particularity of design research; the starting point. For example, rather than beginning with a narrow problem that needs solving, a creative, more *playful* approach in the initial stages of this research allowed discoveries to emerge, which could then be further refined. Laser techniques were not predetermined, rather they emerged and were refined as the research and knowledge of materials and equipment progressed.

Rachel Philpott (2007: 2) discusses exploratory play in relation to design as '*a process of knowledge generation…which allows practice-led research to flourish and advance beyond that which could be achieved by scientific research methods used in isolation*'. Reflecting Philpott's comment, Durling and Niedderer (2007:16) identify creative exploration as a way of using creative practice to work through a research problem. In practice-based research, designing is not simply used as a demonstration or assessment of a theory, but it is used to, *'reveal new avenues and opportunities for development, and to gain new insights and understanding'.* It was through a *playful* phase in this research project that a familiarity between laser settings, graphic elements, material weight and composition was established. It was also through playful exploration that the *affordances and constraints* of a new medium could be learnt intuitively (McCullough, 1996), which built upon a cumulative tacit knowledge of material and medium properties.

3.4.2 Tacit knowledge

In reference to the subject of research discovery, scientist Michael Polyanyi (1966) proposed that tacit knowledge involves the foresight to anticipate a solution to an undetermined, or hidden problem. The idea of a tacit knowledge has been recognised as a feature present in creative and practice based research disciplines as charted by Neidderer and Imani (2008). Igoe (2010) also believes tacit knowledge to be *embodied* in textile design through the designer's process and practice.

If the knowledge generated through practice is in part tacit or experiential, this could be difficult to communicate. Neidderer and Roworth-Stokes (2007) state that reflection on the design practice is how experiential and tacit knowledge can be understood and communicated. In this research project, documentation in logbooks became important, not only for recording technical data and parameter settings, but also for recording design insights and intuitive interference with the laser machinery to try and capture the information gained through experiential knowledge. For example, knowing by sight when a material had received an optimal amount of laser irradiation and stopping the process. The number of laser passes and the visual attributes could then be recorded by written and photographic accounts to allow replication of the results. Similarly experiential knowledge of laser and material interaction helped to intuitively determine the range of parameters to work within for each new design, material weight or construction.

3.4.3 Craft and Material knowledge

A craft approach can be said to be that which, involves hands on creativity, engaging with materials (Leader, 2010) and mastery of tools or medium (Adamson, 2007) yet serves a practical purpose. Textile practice is often informed by a craft approach due to the focus on materiality and the hands-on making approach taught on most textile design degree courses.

Both Adamson and Carter discuss the importance of materiality to the craft practitioner identifying a specific type of knowledge described as '*thinking through craft*' (Adamson, 2007: 7) and '*material thinking*' (Carter, 2005: 5) respectively. The material knowledge gained through practice has been key, enabling understanding of physical properties and processes through material experimentation used in this research.

Pye (1968) refers to the '*workmanship of risk*' noting it is not the involvement of hand processes over machines or technology, rather the skill and risk involved in a task that defines it as a craft process. When McCullough (1996) writes about the abstraction of craft through the use of digital tools, he notes that it is the degree of *personal participation* that maintains the crafted element distinct from merely operating machinery. During the research in this PhD, personal participation with the digital laser technology was maintained by establishing control of each variable dependent on desired design effects on a case by case basis, rather than by using pre-set conditions. It was through these personal interventions and *craft approach* that an important connection to the materials and making process could be maintained.

3.4.4 Aesthetic: A new 'laser aesthetic'

Aesthetic and tactile properties are noted as particularly important for textile design, described as a design discipline that must consider *visual, tactile and emotional* qualities (Gale and Kaur, 2004). Igoe (2010: 5) notes: '*pleasure-giving qualities of textiles may be subtle and tactile or decorative and sensorial'.*

Materials, processes, end-use, trends, design briefs and practitioner preference have influence on aesthetic and tactile qualities and must be considered during textile design practice. As noted in the literature review, methods of manufacture traditionally have the most significant effect on textile aesthetics (Briggs-Goode, 2013) when design aesthetic is limited by process constraints. However, process-led textile design has become a universally familiar language. For example, repeat patterns are necessitated in analogue printing processes as an economical means of patterning textiles, but have become a desirable and fundamental design feature for textile surface design across modes of manufacture. Therefore finding new modes of textile design, such as laser processing, has the potential to innovate, providing its own aesthetic and distinct properties. Aesthetic and tactile properties are particularly significant for this research, as it examines new ways to affect and control the three-dimensional, tactile and graphic processing capability of laser technology.

3.4.5 Function

Function can encompass use, application and performance properties of a textile.

These can be engineered or designed in to a textile, or may be present in the material properties. Within industry, for commercial fit, textiles must meet performance and functional needs as well as aesthetic ones. A textile designer's role therefore, must '*be the result of informed and purposeful thinking – to create something that is appropriate and of value in a specific context*' (Kavanagh, 2004: 3).

Design and research of the functional aspect of textiles often requires crossovers into other disciplines such as product or fashion design, engineering or chemistry, dependent on the functional requirements. For example, this research made use of technical textile testing, optical engineering, and textile, dye and fibre chemistry. These fields are outside of typical textile design practice, but ensured the functional, performance and commercial viability of the textile outcomes were considered.

3.5 Interdisciplinary Research

Having expressed the theoretical context of textile design research, this section argues the case for interdisciplinarity or Alternative Disciplinarity; the crossing of fields in order to bring new knowledge and innovation to textile design. Research undertaken by Matthews (2011), Philpott (2010), Akiwowo (2014), Goldsworthy (2014) mentioned previously had to face similar cross-boundary issues. Working from a standpoint routed in textile design, they too had research goals to develop new processes for the field necessitated by the performance and functional goals of industry. Kane et al, comment on the value of interdisciplinarity,

> *Whilst both technical and creative studies contribute critically to the expanding field of textiles, we propose that when working with newly established technical processes within a design context, an interdisciplinary approach that embraces both scientific and artistic research methods can support sustainable innovation.* (Kane et al, 2015: 1).

In an example of designing as a synthetic process combining both technical and conceptual development, Durling and Niedderer (2007: 16) claim, '*exploration of the material through designing has demonstrated superior qualities which could not have been predicted from the scientific data alone*'. As a designer working in a different discipline, there is potential to use experiential knowledge to bring fresh perspectives and alternate priorities to different fields. In laser processing of textiles for example, what may be deemed as an accidental burn mark to the laser engineer could be seen as an opportunity for surface design from a textile designer's point of view: a way to create meaningful marks. Rachel Philpott reflects how this affects textile designers working with new technologies,

> *In contemporary textile practice (technology) has subtly shifted focus of the means of production from experiential craft to design engineering. This presents the challenge to exploit automated production processes and CAD/CAM technologies, whilst retaining the valuable embodied knowledge gained through hand making and the opportunities for innovation that this*

> *hands-on practice affords.* (Philpott, 2012:59)

In this research, a purely scientific approach may have resulted in an improved dye performance for the textile substrate such as described in the literature review (for example, Bahtiyari, 2011). However, following a desire to create a new surface design tool encouraged breaking the 'rules' of optimal processing. Laser technology was designed for cutting solid metals and plastic substrates, not for modifying highly delicate textile substrates. Strategies for overcoming processing problems were developed through creative experimental and systematic technical approaches combined. This *creative (mis)use* of the laser system allowed new ways of processing textiles to be discovered.

Goldsworthy and Paine (2014:50) discuss how they overcame the barriers of using new technologies by utilising a textile craft practice, *'Often new skills borrowed from a scientific field become essential to deepening understanding and developing a new techno-craft approach*'. This was also found to be true of this research project. A further in-depth technical knowledge can be gained from working to a rigorous scientific line of questioning, allowing an insight and thorough understanding into the workings of laser technology and associated software, as well as an elevated understanding of the chemical and physical effects that can be achieved on fabric substrates.

Comparable to the stonemason or weaver learning the technical processes of their craft to become a master craftsperson, so too does the technical understanding of the laser system allow the technology to become a tool with which to create. The processes that have been developed have allowed a freedom to design using a brand new 'toolbox' of techniques. McCullough also alludes to a freedom that can be found by the crafts person using either manual or digital tools when he describes mastering the technology '*to the point where it becomes transparent'* (McCullough, 1996:55). The combination of tacit knowledge gained from creative experimentation together with the technical knowledge gained from quantitative testing and analysis provided the appropriate understanding of the laser as a tool, imperative to achieving the research goal; to evolve techniques to open new creative opportunities for textile design whilst being viable and communicable for industrial and commercial application.

Typically, the interdisciplinary areas of textile design and textile engineering operate separately within the textile industry. However it has been recognised that collaboration and connections between fields can facilitate innovation. A report for the Crafts Council (KPMG, 2016) notes the ability for craft to support cross sector innovation and discovery in the UK. This places textile designers in a significant position to balance craft, design and technology to facilitate material innovation.

It is through this alternative disciplinarity, that a specific methodology for this research has evolved, borrowing from action research principles with design specific skills identified as key to advancing the research, together with systematic rigor of controlled experimentation. In addition, this research considers industrial input from the project industry partners. This adds further depth to the study in terms of commercial validation and relevance. Defining a specific strategy for this research has been characterised by a fusion of scientific research methods and design research methods as discussed in the following section.

3.6 Methods

This research has been conducted using a mixed methods approach. A mixed methods approach involves integrating both qualitative and quantitative data to inform and analyse the research inquiry (Cresswell, 2014). The use of multiple methods to examine one complex research issue allows a more significant result to be obtained adding rigor to the study. Triangulation of multiple methods provides less likelihood for bias or anomaly if each of the methods used corroborate the research findings (Grey & Malins, 2004). In addition, the use of mixed methods complements the interdisciplinary approach discussed in the previous section, making use of methods that have roots in both design and scientific fields.

The methods used in this study can be categorised into five stages of the research process as articulated by Neidderer (2009). These are: Problem formulation, Methods of data collection, Methods of analysis, Evaluation and Dissemination. These stages correlate with the stages of the proposed action research paradigm; Planning, Action, Observation, Reflection and Documentation (Zuber-Skerritt, 2006) and can be used in the formation of an action plan for this research. Table 3.1 shows the role of methods used in this research adapted from Niedderer's *'Framework for analysing role of methods in research'* (Neidderer, 2009:14).

The diagram in Figure 3.2 shows the action plan for the research, broken down into the five phases of work. It shows how the combination of textile design practice (in the form of creative sampling) and scientific experimentation (in the form of systematic sampling) were used as methods of data collection for research into materials and developing new processes for existing laser technologies. The diagram indicates how textile design practice was used to develop and to analyse data. Critical reflection on each phase informs practice whist employing and building on tacit knowledge and technical understanding. Material samples and written documentation were generated throughout.

Work created as part of the practice then became the data for analysis and each set of action and reflection formed an iterative body of physical samples and a subject knowledge that could be explicitly documented in the form of samples and written results. The textile designs as data allowed qualitative analysis to reveal the suitability of the laser techniques for design opportunities, assessing aesthetic, tactile and emotional qualities through reflection and structured industry feedback; quantitative data was used to analyse parameter optimisation, functional and performance standards.

Stage	Method	Purpose/Aim	Type	Additional
Phase 1 Problem Formation *(Planning)*	Contextual Review	Review existing research in the field and Identify knowledge gaps	Mixed	Information from design and technical literature.
Phase 2 Data Collection *(Action)*	Creative Sampling	Identification of design opportunities	Qualitative	Observation on samples & exploratory design practice.
	Systematic Sampling	Identify effect of laser on textile substrates and optimise techniques	Mixed: observation & numerical data	Scientific experimentation, technical samples & numerical data
	Technical Testing	Test functionality of techniques	Quantitative	Numerical data from ISO/ established tests.
	Log book and technical file documentation	Record numerical parameters and design insights	Mixed	Written notes, numerical data, sketches, photographs
Phase 3 Analysis *(Observation)*	Reflective practice	Analyse processes and insights to inform further work	Qualitative	Insights leading to refined action.
	Analysis of testing results	Analyse success of material performance	Quantitative	Formulas, graphs and tables.
	Focused design practice	Analyse design opportunities gained from laser techniques	Qualitative	Design Collection to answer industry brief.
	Industry feedback using focus group methods	Analyse success of design and commercial fit	Qualitative	Transcripts, brainstorming & ranked samples
Phase 4 Evaluation *(Reflection)*	Analytical Framework	Ensures outcomes are measured against consistent criteria	Mixed	Measures success against design attributes, contextual viability & sustainability
	Triangulation of technical and creative results	Evaluate success of techniques	Mixed	Comparison of design specific and scientific data. Advantages and Disadvantages.
Phase 5 Dissemination (Documentation)	Written documentation/ conference presentations	Communicate new knowledge	Mixed	
	Exhibition	Provide evidence and showcase samples	Qualitative	
	Project meetings and presentation	Provide progress updates of the work to industrial partners.	Qualitative	Feedback informs subsequent direction of the work

Table 3.1 Role of methods used in Lasers for Textile Design Research

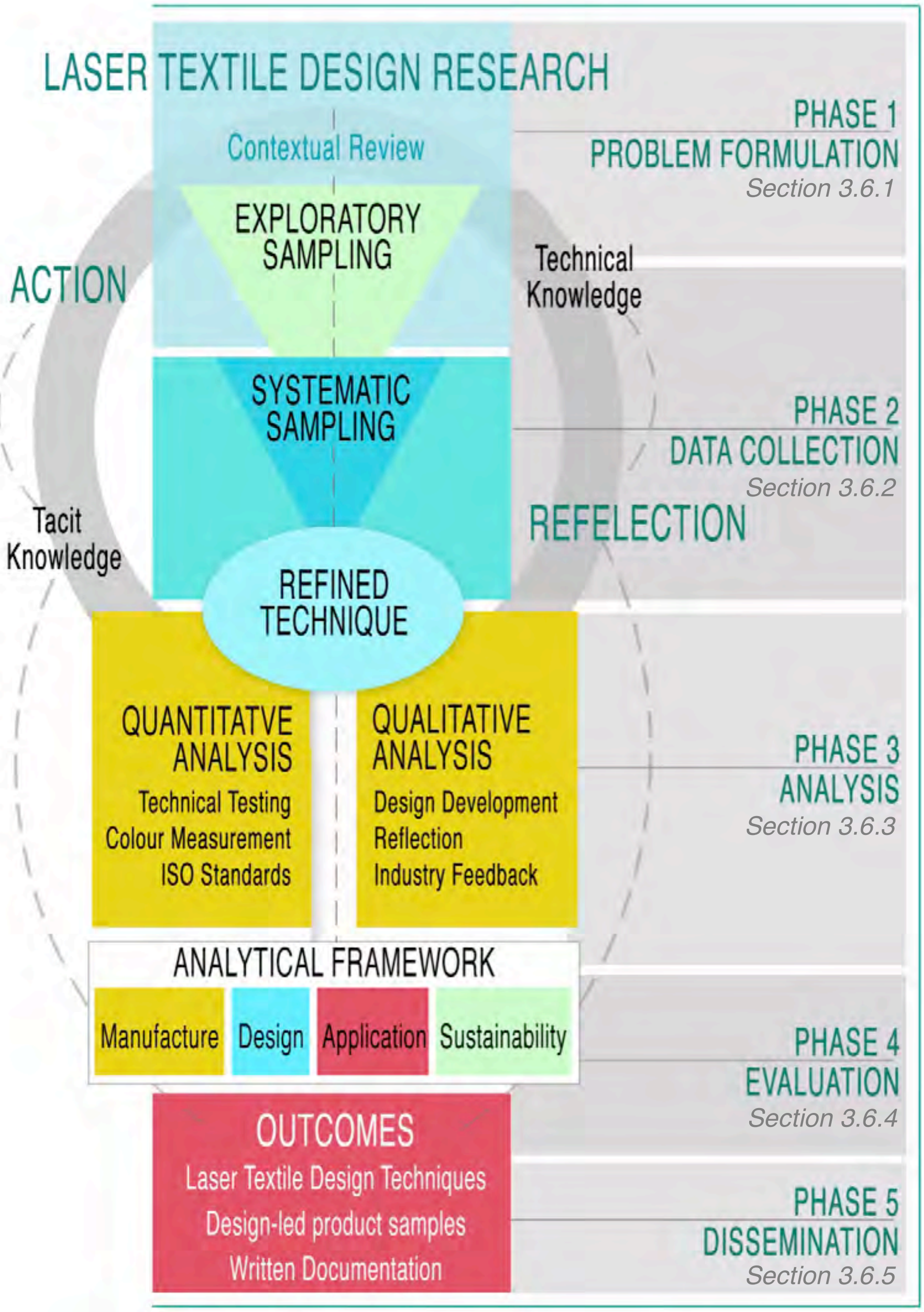


Figure 3.2 Action Plan for *Laser Textile Design* Research

With reference to the diagram in Figure 3.2, the following section describes how the methods are used in each phase of the research.

3.6.1 Problem formulation (phase 1)

The first Phase 1 began with the broad aim of achieving novel and sustainable methods of applying surface design by modifying textile substrates by use of laser technology. A literature and contextual review (Chapter 2) was conducted to identify areas for improvement and gaps in knowledge leading to the research concept development. This included a review of academic and technical literature, design projects and innovations in the field of textiles for surface patterning, sustainability and laser processing. Visits to trade fairs, industry partner's companies, and conferences were also used to review industrial technology and processes as well as historical, current and predicted future trends for textile processing.

3.6.2 Data Collection (phase 2)

Whilst establishing workshop conditions for this research, an initial exploratory and somewhat 'playful' phase allowed experimentation with a wide range of parameters and materials (Chapter 4). Reflections from this early stage fed back into Phase 1, helping to inform the problem formulation. A technical understanding of the process and fabrics is also vital for this research. Thus, experimentation carried out took the form of systematic sampling, creative sampling and technical testing, described as follows.

- **Exploratory Creative sampling**: Used the designer's skills and experiential knowledge to explore design effects, aesthetic and tactile opportunities afforded by laser irradiation on textiles. This 'playful' phase also generated tacit knowledge of the affordances and constraints of materials in relation to the use of laser technology.

- **Systematic sampling**: The iterative, logical experiments carried on textile substrates to prove or disprove the effect of laser interaction. These experiments used a scientific approach, with set material and procedural boundaries to test a single variable. Systematic sampling was generative as each set of sampling informed progression of subsequent experiments.

- **Technical Testing**: Tests adhering to ISO international standards were carried out to quantify the functional performance of laser treated textile samples. In addition, specialist scientific equipment was used to observe and measure the dye performance, colour change and fibre modification caused by laser irradiation on textile substrates.

Niedderer & Roworth-Stokes (2007) draw on Miles and Huberman (1994: 278), the Arts and Humanities Research Council (2003) and Biggs (2005: 5), to identify how practice can be used with rigor within a research setting as a method to generate knowledge, or an outcome to embody knowledge only when accompanied by a written analysis and account to be recognised as research. Cross (1999) also emphasises the need for the communication of reflection on research practice. Documentation in this research has been used to record both qualitative and quantitative data. Logbooks and technical files were used to record parameters, measurements, reflections and design insights. Creative and technical aspects of the making or experimental processes were also captured by photography. Sketchbooks, mood boards, photographs and CADs, were used to document the design development process for the creation and choice of graphics for laser processing. Descriptions of tests, materials and equipment used for data collection in the research are detailed in Chapter 4.

3.6.3 Analysis (phase 3)

As discussed previously, reflective practice was used as a form of analysis and applied throughout this research. This is shown in Figure 3.2 as circular, passing through and feeding into each phase. The reflective process was integral to decision making to provide direction and generate ideas during and after practical work also known as '*reflection in and on action'* (Schon, 1983:97). In both instances critical reflection informs the next actions to be taken. Questions arising from practice prompt further practical exploration, and the process repeats.

> *The field of the project creates a space for the practitioner where each move offers a step toward becoming better informed about the topic under investigation*. (Grocott, 2012:19)

Analysing the quantifiable measurements from Phase 2 reflected the technical language of engineering and industry testing standards (described in Chapter 4). Again this circular process fed back into further action allowing technical refinement of the effects, providing proof of concepts as well as the ability to quantify and explain the effects achieved on textile substrates, allowing techniques to be controlled and replicated.

The processes were also tested for their design potential through focused design practice. A design brief, provided by the industry partners, resulted in a focused design collection in answer to the brief. The function of design in this instance was used to analyse how an aesthetic design language may be translated to fabric using the newly established techniques.

Industry feedback was collected using focus group methods including group discussions, written, brainstorming and ranking activities. Focus group data was collated and transcripts were coded to analyse the success of design, function and commercial fit of the *Laser Textile Design* techniques and sample collection, and to establish areas of commercial interest. Focus groups, meeting feedback and personal logbooks allowed a more ethnographic approach and allowed the research to move forward, not only on successful technical and aesthetic results, but also on feedback relative to those with vested commercial interest. The specific focus group methods used for conducting and analysing feedback from industry are discussed in Chapter 9.

3.6.4 Evaluation: Analytical Framework (phase 4)

To ensure consistent evaluation of the research outcomes, an analytical framework was used (Grey & Malins, 2004). This provided '*measurable success criteria'* to judge the success of the outcomes (Blessing et al., 2009: 27). Figure 3.3 shows the analytical framework compiled for this research. Four strands of analysis were used to evaluate and measure each technique against the considerations and advantages for manufacture, design, application and sustainability. These four strands emerged as appropriate factors on which to measure the success of *Laser Textile Design* through formal discussions with industry with relevance to the research aim.

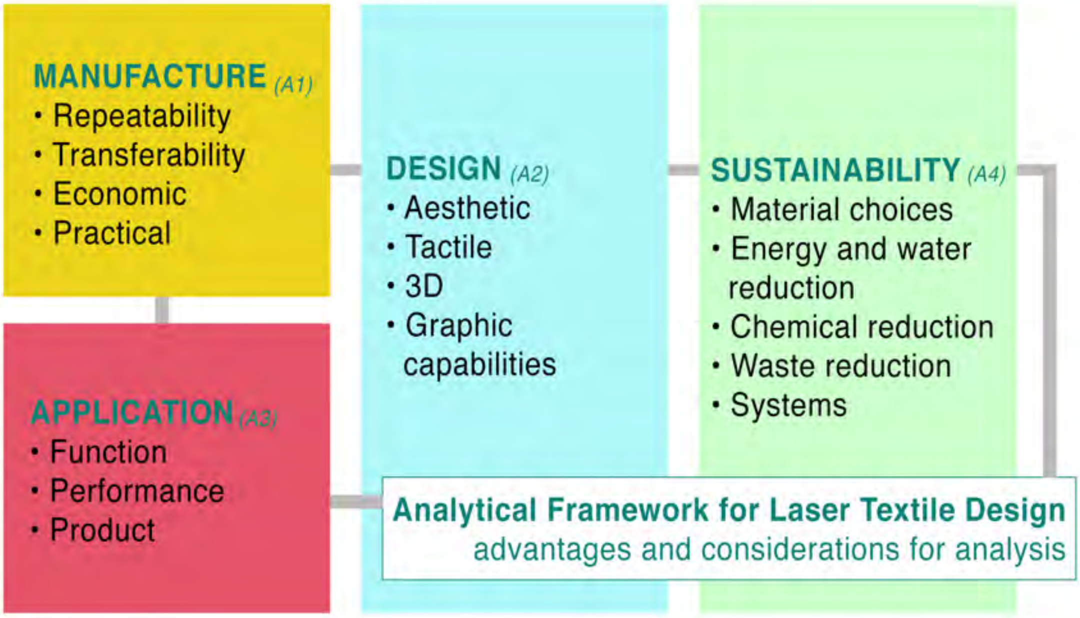


Figure 3.3 Analytical Framework Summary for *Laser Textile Design*

The results from each technique, the *Laser Textile Design* collection and the findings from industry feedback were brought together in order to evaluate the research as body of work. Technical testing and systematic sampling results were used to evaluate the repeatability, consistency and transferability of the techniques from a manufacturing perspective (*A1*). A design collection and experimental samples were used to evaluate the design opportunities (*A2*) through visual and tactile means. Industry standard testing results informed evaluation of the techniques in relation to their application opportunities (*A3*), with aesthetic and functional properties together revealing viability for their potential commercial context. The measures of success of sustainability (*A4*) refer to the list of criteria compiled in Chapter 2. Potential for reduced environmental impact compared to equivalent textile processing techniques is considered against each criteria.

3.6.5 Dissemination (phase 5)

Using the developed process, physical designs were created and informed the discussion and documentation of potential advantages, impacts and viability. This took the form of conference papers, reports, presentations and exhibition of the work. Project meetings, regular presentation and discussion with industry professionals, as well as attending conferences also provided feedback that informed subsequent direction of the work.

3.7 Chapter Summary

This chapter has reviewed issues regarding practice-based research and discussed the suitability of using Action Research principles. It has identified the characteristics of a 'textile design approach' and argued the case for interdisciplinarity relevant to this research. The methods used have been charted (Table 3.1) in relation to each phase of the research resulting in an action research plan (Figure 3.3).

An interdisciplinary, textile design approach was used in this practice-based and design-led research study, borrowing strategies from action research. A mixed methods approach used both qualitative and quantitative data, synthesising scientific and design research methods to ensure rigor across the interdisciplinary fields of study. The research included industrial collaboration using focus group methods to gain formal feedback from the project's industry partners. The feedback from performance apparel and interior markets ensured commercial relevance and appropriateness across textile market sectors. An analytical framework was created to ensure the environmental, aesthetic, tactile and functional performance of the laser techniques were evaluated consistently for manufacture, design, application and sustainability.

Research that brings together practical, scientific and aesthetic strands in equal depth are infrequent. The interdisciplinary textile design methodology documented in this thesis enabled an in depth study that brings together these attributes, while considering commercial relevance and responsible innovation. This can noted as a distinct feature of the methodological approach.

CHAPTER 4 :

EXPERIMENTAL CONDITIONS AND EQUIPMENT

4.1 Establishing Workshop Conditions

This Chapter documents the experimental conditions and equipment used throughout the research study and describes how workshop conditions and parameters were established. A technical approach was used to confirm and test parameters using testing equipment and established methods of analysis thus the equipment, materials and technical Information are described herein. A sound technical knowledge of equipment, materials and processes was imperative to understanding and later predicting the laser effect on textile materials. This was gained in four ways: though literature (Chapter 2); revising fibre, dye and laser properties; technical testing of laser treated textiles; and through tacit knowledge, which was developed though practice during the course of the research by sampling, observing and material handling. A material-led exploratory approach was used to establish affordances and constraints for each tested substrate and to explore potential design opportunities afforded by laser interaction with material properties. This Chapter addresses the objective 'Establishing Workshop Conditions' (OB1) and is divided into six sections as described in Table 4.1.

Section	Aim / Focus	
4.2 Laser system	Details the CO_2 laser equipment used for this research including the specific conditions and set up required for this research.	Technical Information
4.3 Materials	Details the materials used for this research and highlights important material properties of each fibre type.	
4.4 Textile Dyeing	Details the equipment used to ensure controlled dyeing conditions and the dye recipes used in this research.	
4.5 Analysis	Quantitative: Details the quantitative methods, equipment, and equations used for analysis and ISO standard testing throughout this research. Qualitative: Details the qualitative methods used for development, documentation and analysis of the laser techniques and resulting *Laser Textile Design* collection.	Analysis Methods
4.6 Establishing Laser Parameters for Textile Design	Details the laser software parameters and discusses the best practice that has been developed for laser processing and graphics handling for textile substrates used in this research. Also notes troubleshooting for inconsistent laser processing issues.	Establishing Workshop Conditions
4.7 Effect of Laser Irradiation on Textile Fibres: A Material-led Investigation	Details the initial material-led, exploratory sampling and investigation to establish the effect of laser irradiation on a range of textile fibres. Leading to identification of textile design opportunities and clear directions for further investigation.	

Table 4.1 Experimental conditions and equipment: Chapter contents and rationale

4.2 Laser System

4.2.1 CO_2 Lasers

A laser is a device that emits an intense beam of light composed of electromagnetic waves that are in phase (coherent) and of the same wavelength (monochromatic). This differs from natural light or light from a light bulb where many different wavelengths travel in different directions (Melles Griot, 2000). The word ‘LASER’ is an acronym for ‘Light Amplification by Stimulated Emission of Radiation’. This describes the process by which a laser beam is formed (Laserline 2010). Stimulated emission is the process whereby an electron in an excited state meets a photon, or light wave, resulting in the electron producing another photon of the same wavelength, phase and direction (Melles Griot, 2000).

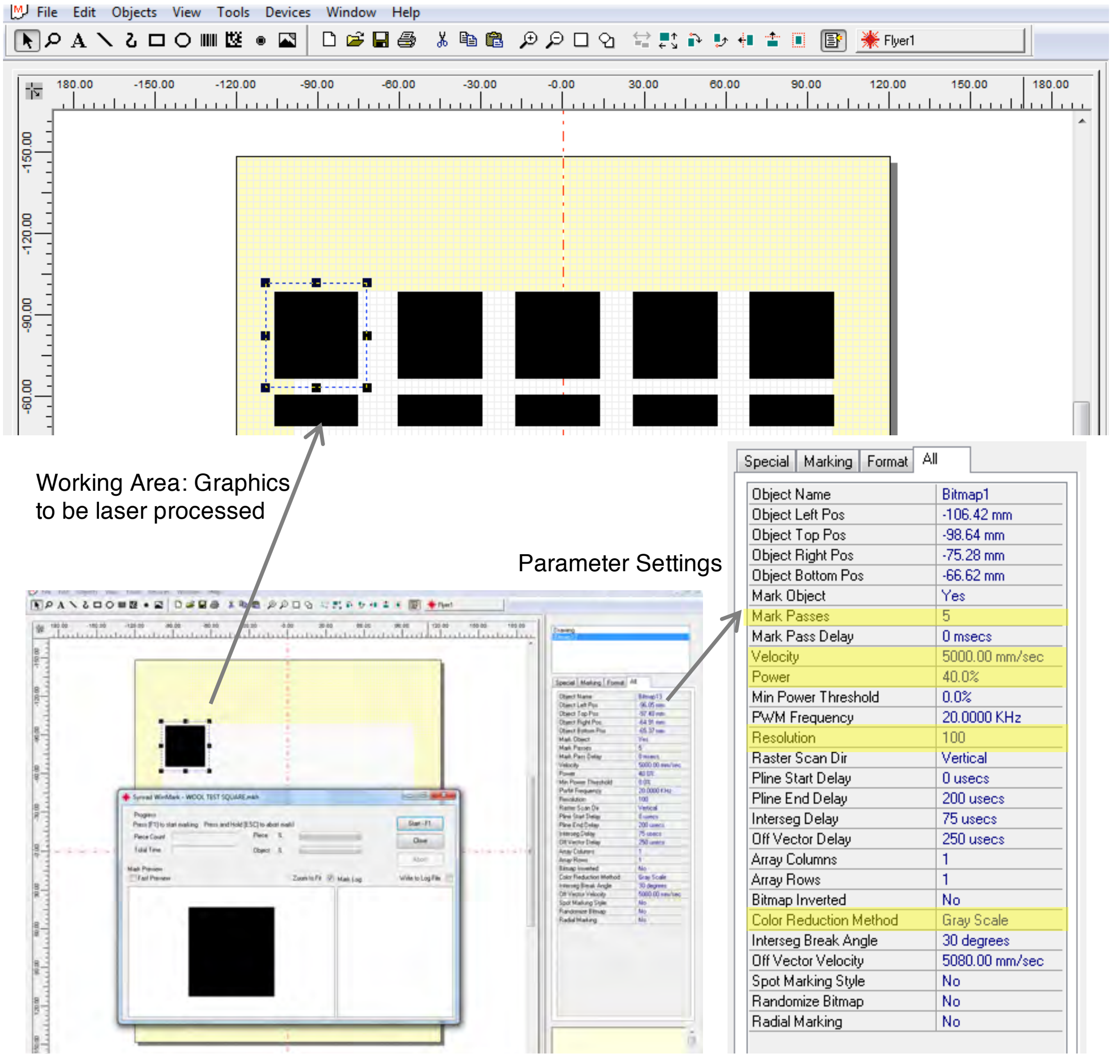
This process is facilitated using a lasing medium in a sealed tube. A CO_2 laser has a lasing medium containing a mixture of CO_2, helium and nitrogen gasses. Electrical energy is applied to the tube to excite the electrons of the CO_2 molecules. When duplicate photons are emitted by stimulated emission, they in turn can stimulate further emissions from neighbouring atoms in in the lasing medium. This results in a cascading effect with multiple replications of identical photons, known as light amplification (Melles Griot, 2000). A small percentage of these identical photons travelling in parallel are allowed to escape from the tube via a partially transmitting mirror, this forms the laser output beam. Laser types operating at different wavelengths originate from alternate lasing mediums. For example a CO_2 laser operates in the far infrared (IR) spectrum at a wavelength of 10,600nm, while an Excimer laser produces an output wavelength of 246nm in the Ultraviolet (UV) spectrum (Hitz et al, 2001). Infrared and ultraviolet lasers can be harnessed for their photothermal, and photochemical properties respectively.

Figure 4.1 Synrad CO_2 Laser Marker Used in this Research

The laser marking process for this research was conducted using a Synrad carbon dioxide (CO_2) source laser shown in Figure 4.1. This laser operates at a wavelength of 10.6µm producing a continuous wave beam in the far infrared spectrum with a maximum power of 100 Watts. An infrared Laser was chosen to harness the photothermal properties to modify chosen textile fibres. The laser has a beam diameter of 0.03cm at a fixed focal length, which was established prior to experimentation. All experiments were carried out with the laser beam in focus on the surface of the textile substrate.

4.2.2 Laser Software

The laser in this study was digitally controlled through a computer software package called Winmark. Winmark allows control of multiple variable parameters for graphics handling. Figure 4.2 shows the software control panel. The effect of the highlighted variables will be discussed in relation to their effect on laser materials processing in greater detail later in this chapter. They include: power; velocity; resolution; colour reduction; and mark passes.



Working Area: Graphics to be laser processed

Parameter Settings

Object Name	Bitmap1
Object Left Pos	-106.42 mm
Object Top Pos	-98.64 mm
Object Right Pos	-75.28 mm
Object Bottom Pos	-66.62 mm
Mark Object	Yes
Mark Passes	5
Mark Pass Delay	0 msecs
Velocity	5000.00 mm/sec
Power	40.0%
Min Power Threshold	0.0%
PWM Frequency	20.0000 KHz
Resolution	100
Raster Scan Dir	Vertical
Pline Start Delay	0 usecs
Pline End Delay	200 usecs
Interseg Delay	75 usecs
Off Vector Delay	250 usecs
Array Columns	1
Array Rows	1
Bitmap Inverted	No
Color Reduction Method	Gray Scale
Interseg Break Angle	30 degrees
Off Vector Velocity	5080.00 mm/sec
Spot Marking Style	No
Randomize Bitmap	No
Radial Marking	No

Figure 4.2 Winmark software interface

Laser power, laser scanning speed (velocity) and laser resolution are variables that have the most significant effect on laser processing of materials (Synrad, 2006). Additional variables allow further control by fine-tuning the manner in which digital graphic files are processed by the laser machinery (see section 4.6).

4.2.3 Laser Power Output

A power meter is a device that can be used to accurately measure the power output of a laser beam. Settings within the Winmark computer software allow varied control of the laser power output expressed as a percentage power. The accuracy of the software power percentages were determined using a power meter. The laser beam was fired directly at the power meter for 10 seconds, providing a minimum, maximum and average (mean) power reading in Watts. Readings were taken for the laser, fired at intervals of 10% for increasing power outputs from 0-100%. Figure 4.3 shows a graph of the results. It can be seen from the graph that powers of 30-100% reflect an accurate representation of the actual power output in Watts. For example, at 30% power, the output corresponds to 30W. However from 0-30% the percentage power does not correspond to an accurate actual power reading. As a result of this, further power readings at intervals of 0.2% between 0-20% were recorded to determine the accuracy of lower percentage powers, shown in Figure 4.4. The graph can be used to determine the actual power output obtained from the software by reading the corresponding figure on the Power axis (y). For example a software power of 10% gives an average actual power output of 4.4W. Fluctuations in the graph show that percentage powers below 30% are inconsistent. Consequently, to retain the most accurate and repeatable results, powers of 30W and above were chosen in this study where possible.

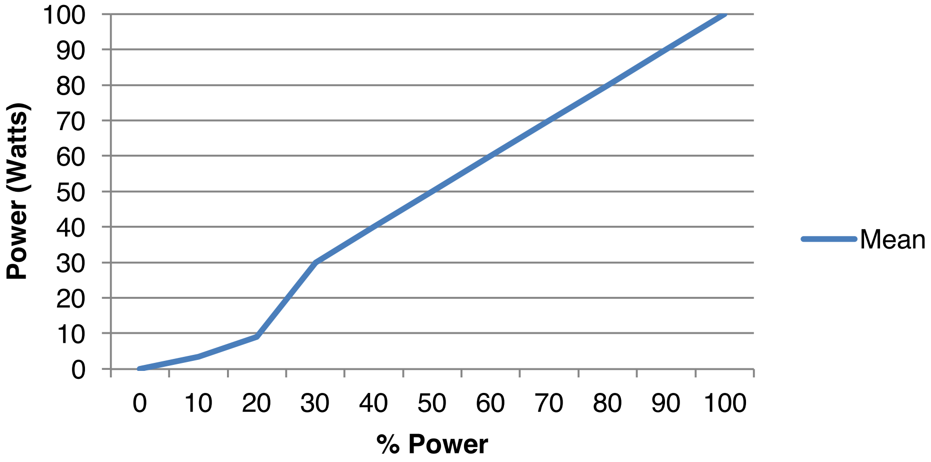


Figure 4.3 Synrad CO_2 Laser Power Output (0-100%)

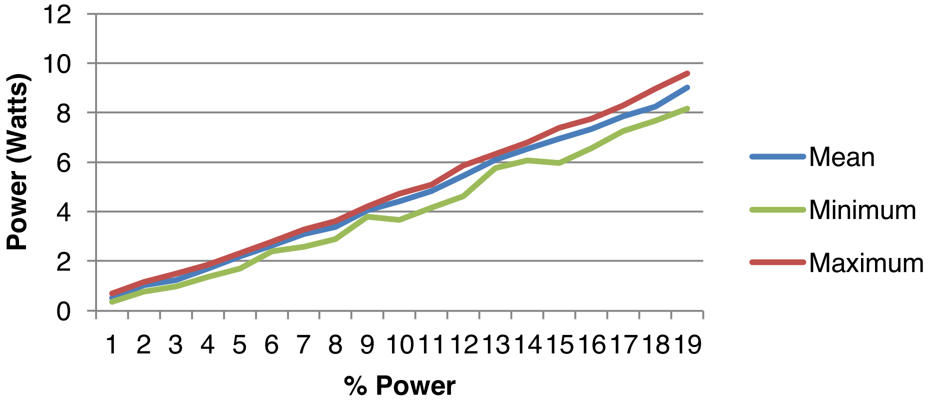


Figure 4.4 Synrad CO_2 Laser Power Output (0-20%)

4.2.4 Energy Density

Energy density is a measurement that can be used to quantify the energy delivered to a substrate via the laser beam. Also referred to as laser fluence, the measurement takes into consideration multiple parameters that can affect laser processing to provide a single number. This allows replication of results across varied laser systems, where power outputs and velocity capabilities may differ from machine to machine. Thus was used as a measurement throughout this research. Provided that the total energy density delivered to a substrate remains constant, the effects achieved on the material substrate should also remain consistent. To calculate the energy density of a laser beam, the total energy in Joules (J) must first be determined. The total energy varies depending on the chosen laser power and velocity parameters. It can be calculated as shown in Equation 1.

$$\text{Total Energy} = P \times T$$

Equation 1 Total Energy

Where P is the output power of the laser in Watts (W) and T is the time in seconds (s) that the focused laser beam will be in ‘contact’ with the substrate. The time will vary in relation to the chosen velocity of laser beam scanning. For example at a scanning speed of 700cm/s it will take 0.4×10^{-4}s to traverse an area equivalent to the laser beam spot size (0.03cm). When total energy has been determined, the energy density of the laser beam can be calculated as shown in Equation 2.

$$\text{Energy Density} = \text{Total Energy} / \text{Area}$$

Equation 2 Energy Density

Where Energy Density is measured in J/cm^2, total energy in Joules (J) and area relates to the laser beam size in cm^2. A beam spot size of 0.03cm used in this research relates to a beam area of 0.71×10^{-3}cm^2.

4.3 Materials

Fibre Category		Fibre Type	Textile	Construction	Supplier
Natural	Protein Fibres	Wool (100%)	1. Wool 1: 19 microns 2. Oxygen 3. Blazer 4. Worsted Wool 5. British wool	Plain weave Crepe Weave Milled Twill Twill	1. Drummond Parkland, Hudderfield UK 2. Camira, Huddersfield UK 3. Camira, Huddersfield UK 4. Whalleys, Bradford UK 5. Whalleys, Bradford UK
	Cellulose Fibres	Cotton	Denim (used in parameter tests only)	Twill	Whalleys, Bradford UK
		Linen / Flax (100%)	5. Valencia Natural Linen 6. Natural Linen 2	Plain Weave	Whalleys, Bradford, UK
Man-Made	Synthetic Polymers	Polyester (PET) (100%)	7. Endurance + (p4p)	Jersey Knit	Speedo, Nottingham UK
		Nylon (Polyamide)	8. 80/20 Nylon/ Elastane (p4p)	Jersey Knit	Speedo, Nottingham UK
Blended		Wool/ Polyester Blend	9. 45/55 Wool/Polyester 10. 30/70 Wool/Polyester	Plain Weave	9. Inotex, Slovenia 10. Whalleys, Bradford, UK

Table 4.2 Overview of textile fibres types and substrates in this research

Table 4.2 provides an overview of the textiles used in this research, categorised by the textile fibre type. Natural fibres include protein (animal hair) or cellulose (plant based) fibre types. Man-made fibres are made up of polymers that can be synthetic in origin or from regenerated natural sources. The predominant fibre types used in this research are highlighted in the table, including natural fibres; wool and linen, and synthetic fibre types; polyester and polyamide (nylon). These fibre types were chosen for study to reflect their use by the industry partners. Industrial partner Camira make heavy use of natural wool and linen fibres in the interior and furnishing fabrics they produce (Camira, 2015), while synthetic polyester and polyamide are the predominant fibre types used in Speedo's performance swimwear textile goods (Speedo, 2015).

An understanding of fibre properties was essential to this research, as the physical properties of a textile are determined by the fibre composition, structure and morphology. Therefore, it was necessary to review the composition and properties of the fabrics used in this study, in order to understand and predict the effect of laser irradiation on material properties and to evaluate the modification that occurs. The fibre types, their properties and dyeing behaviors are introduced in this section. In addition, potential opportunities for improving material properties by laser processing are highlighted.

4.3.1 Wool

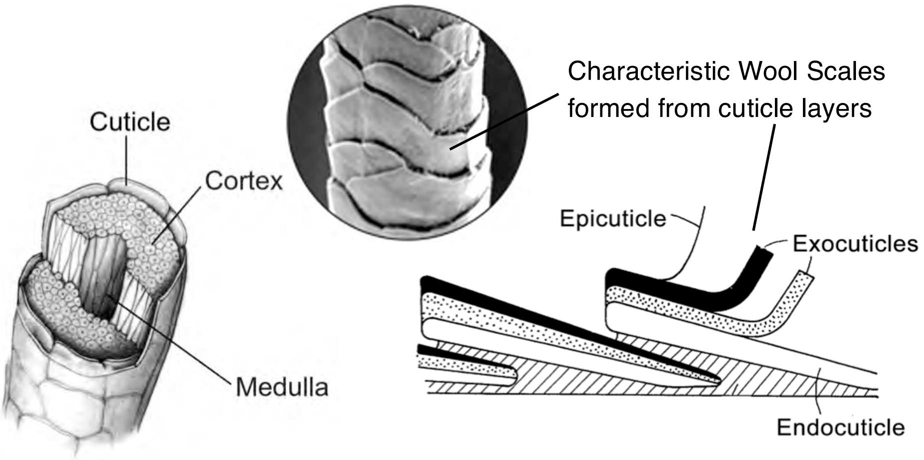


Figure 4.5 Simplified wool fibre structure diagram (Lewis & Rippon, 2013)

Wool is a complex protein fibre originating from sheep's wool. It has a highly complex fibre structure, compared to synthetic polymers, such as polyester or cellulose structures such as cotton fibres.

The fibre is made up of a hydropillic cortex, this mostly consists of amporhous keratin fibres. The cortex is surrounded by layers of cuticles that make up the characteristic scales on the surface. On the outer layer of the epicuticle a thin layer of lipids, or fats is covalently bond to the surface, responsible for the wool's natural hydrophobia. Water repellence can be a desirable property in fashion and homewares, but presents a barrier when dyeing and printing of woollen textiles.

To obtain a desired shade of colour when dyeing wool and the decent fastness properties that are required commercially, dye must completely penetrate through the fibre. The diffusion of dye molecules occurs through the small gaps between the cuticle scales. In order to aid this process, standard temperatures of 100°C are used to relax and open up the gaps between the cuticle layers. Long processing times are required for an optimum dye reaction to take place (Lewis, 1982; Huntsman, 2007).

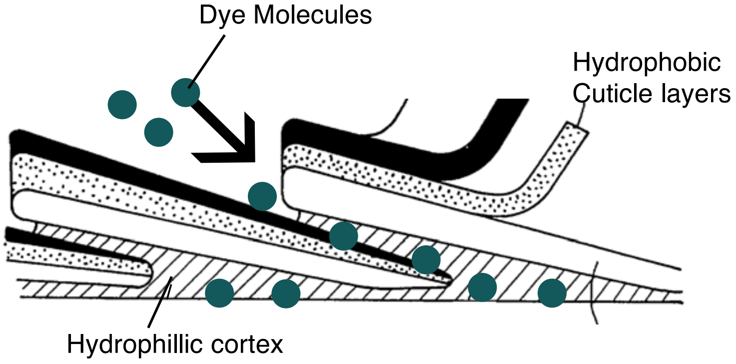


Figure 4.6 Dye molecules penetrate wool fibre between hydrophobic scales

Traditionally, problems are overcome using additional chemical wet pre-processes. Scouring, bleaching, chlorination and steaming have all traditionally been common processes used to improve dyeing and printing of wool (Broadbent, 2001). These processes are associated with high levels of wastewater and chemical effluent in industry, consequently the development of more environmentally friendly wool pre-treatments are desirable for manufacture. While the literature review documented that developments of more environmentally friendly dyeing processes are being made in the textile industry, it also identified laser processing of wool as a potential avenue for investigation that may provide a more efficient pre-treatment; a potential that is explored through experimentation in this research as detailed in chapters 5 and 6.

The predominant wool substrate that was used for technical testing in this research is referred to as Wool 1 in Table 4.2. This pre-scoured woven 100% wool fabric supplied by Drummond Parkland (Huddersfield, UK) was used throughout the experimentation. The fabric is a plain weave construction with a mean fibre diameter of 19.7 microns. Samples measuring 4cm x 1.2cm at a weight of 1.25g were used for testing purposes. This standardised wool was used for systematic sampling as a fixed variable to allow results to be comparable and rigorous. A number of alternate wool substrates were used during the design development stage to test new techniques on a variety of weights, constructions and textures as detailed in Table 4.2. Using a variety of wools also provided proof that the results were not limited or specific to the standardised wool only.

4.3.2 Linen

Linen textiles are made from plant based, flax fibres. The plant of origin, *Linum usitatissimum* can be grown in temperate climates; as such linen has a heritage of local production in the UK (Collier, 1980). Long fibres are extruded from the straw-like plant before being spun into yarns. Linen fibres can be wet or dry spun providing differences in lustre and finish. Wet spun linen uses long fine fibre strands (line) and the yarn is typically used for finer fabrics, providing a smooth sheen appearance. Dry spun linen uses shorter fibres (tow) and the yarn is regularly used in heavier weight fabrics with a course, rustic appearance. Flax fibres show a higher strength than many alternate textile fibres, and as such, linen is often used for applications requiring repeated laundering and strength. Cellulose fibres show good resistance to thermal degradation compared to other fibre types (ibid), exemplified by the high temperatures needed for ironing and dyeing.

Due to the naturally mid-brown colour of linen, bleaching is common for commercial linen textile goods. However, bleaching of linen presents difficulty due to the linen lignen content, traditionally overcome by strong chlorination processes or multiple bleaching treatments (Hickman, 1994; Abou-Okeil et al, 2010). Legislation restricting the use of environmentally unsound chemicals, chlorine included, means that alternate methods are required (Hickman, 1994). This research has identified a method by which laser processing can fade natural linen, presenting opportunities as an alternate dry finishing technique. Alternate methods to pattern and improve linen material properties and their potential benefits are discussed in Chapter 8.

4.3.3 Polyester and Polyamide

Polyester and Polyamide are both synthetic polymer fibre types. Polymers in molton or solution are extruded into long continuous filaments through small holes in a metal plate called a spinneret. Rapid cooling of the polymers forms solid polymer filaments. The dyeing mechanism for synthetic polymers involves holding temperatures above the glass transition temperature. This results in molecular movement within the polymers allowing dye diffusion and fixation to take place.

Polyester is the name given to textiles made from the polymer *polyethylene terephthalate* (PET). PET polymer fibres are hydrophobic and with a high glass transition temperature, they require high temperatures (usually 140^{o}C) for dye diffusion to take place. Nylon or polyamide is a polymer fibre. Its glass transition temperature is considerably lower than that of polyester and the amine groups which make up the polymer provide reactive sites for ease of dyeing by reactive, acid and disperse dyestuffs.

The dyeing and heat setting properties of these two fibre types was investigated in relation to laser processing during this research. The PET and Polyamide knitted jersey constructions used for experimentation in this research (see Table 4.2) were provided in prepared for print (p4p) format, meaning the fabrics had not undergone any prior finishing treatments. Provided by Speedo, both fabric substrates are used in their performance swimwear collections.

4.3.4 Wool Polyester blended fabrics

Blended fabrics are common in textile goods due to their ability to provide material property benefits from both fibre types. Wool and polyester blended fabrics were used in this research study. In a blended fabric, the fibre types can be combined by spinning two fibres types together into a single yarn, or through the use of two different (single fibre type) yarns combined into the textile during fabric construction. The predominant blended substrate used in this research was a plain weave fabric, woven from a blended wool and polyester yarn at a ratio of 45% wool and 55% polyester.

4.4 Textile Dyeing

A Datacolor *Ahiba Nuance* infrared dye machine was used in the dyeing phase of experimentation. This machine allowed controlled temperature and agitation throughout the dyeing process. Dyeing occurs by adding dye, fabric sample and auxiliaries in airtight cylinders with each fabric sample occupying its own vessel; this process is known as exhaust dyeing. Concentrations of chemicals used during the dye process were expressed as a percentage on weight of fibre (owf). Standardised dye recipes as recommended by the dye manufactures are presented below.

Figure 4.7 Datacolour *Ahiba Nuance* Infrared Dye Machine

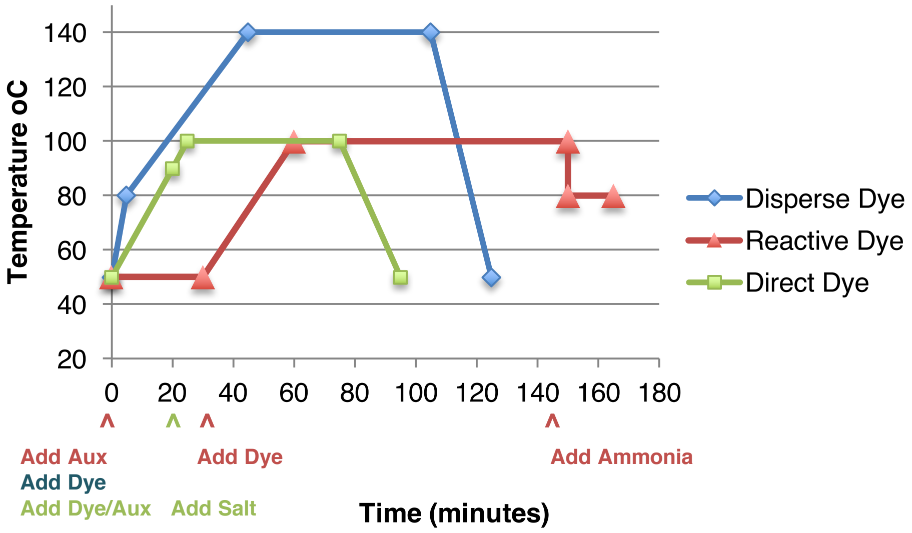


Figure 4.8 Schematic for Optimal Dyeing with Disperse (polyester), Reactive Dyes (wool) and Direct Dyes (Linen)

Figure 4.8 shows a schematic of the standard dyeing procedure for optimal dyeing conditions for: the reactive dyeing of wool; the disperse dyeing of polyester; and the direct dyeing of linen. The procedure used for dyeing each substrate was as follows.

- Recipe 1: Reactive and acid Dyes for wool and wool blends

  The dye recipe used Lanasol Blue CE Reactive dye from Town End Dyes, UK, at a 4% dye concentration and the auxiliaries as recommended by the manufacturer (Huntsman, 2007). Fabric undergoes a 15-minute pretreatment at 50^{o}C in a 1:100 liquor ratio containing 2% owf acetic acid, 5% owf sodium sulfate (Glauber's Salt), 1% owf Albegal B and water. Dye is then added and the dye bath warmed to 100^{o}C for

90 minutes. Finally 1% owf ammonia is added and processed at 80°C for a further 15 minutes. After dyeing, the samples are removed from the dye bath, rinsed and allowed to air dry.

Experiments described in Chapter 5, examine the effect of varying the time and temperature and concentration of dyeing from the standard shown in Figure 4.8.

- Recipe 2: Disperse dyes for polyester fabrics
  Synthetic fabrics dyed under standard dyeing conditions used a 4% owf disperse dye at a liquor ratio of 1:100. Textile samples to be dyed were added to the dye liquor and the dye bath held at a maximum temperature of 140°C for 60 minutes.

- Recipe 3: Reactive or direct dyes for dyeing Linen fabrics
  Linen fabrics dyed under standard dyeing conditions used a 4% owf direct dye at a liquor ratio of 1:100 containing 5% owf sodium sulfate (Glauber's Salt) and 2% owf sodium carbonate. Textile samples to be dyed were added to the dye liquor and the dye bath held at 90° for 20 minutes. Salt was added and the dye bath held at a maximum temperature of 100°C for a further 50 minutes.

4.5 Analysis

The following equations, tests and equipment were used to assess and analyse the effects of laser irradiation on textile properties, the dyeing process and design outcomes. This section is presented under the headings of Quantitative Analysis and Qualitative Analysis. As discussed in Chapter 3: Methodology, the use of multiple forms of data and analysis in the study provided rigour through triangulation of results. For quantitative data, each experiment was repeated a total of three times and the mean and standard deviations recorded.

4.5.1 Quantitative Analysis

4.5.1.1 Energy saving

An approximation of the energy saved during the dyeing process by reducing time and/ or temperature was estimated using the appropriate curves in the dye schematics, on the assumption that the power required to heat the dye bath is proportional to the temperature, and Energy = Power x Time. The relative energy saving can be approximated from the difference in the areas under each curve.

$$\% \text{ Energy Saving} = 100 \times (A_a - A_b) / A_a$$

Equation 3 Energy Saving

Where A_a is the area under graph line a, the standard dyeing profile, and A_b is the Area under graph line b, the reduced time and/ or temperature dyeing profile.

4.5.1.2 Reflectance Spectrophotometry

CIE colour space is a colour evaluation method that compares the sample to be tested to a standard (white). Numerical data was recorded using a reflectance spectrophotometer to measure CIE L*a*b* values shown in the diagram in and described as follows:

L*	Black = 0 (Lightness/ Darkness) White = 100
a*	Red = Positive Value Green = Negative Value
b*	Yellow = Positive Value Blue = Negative Value

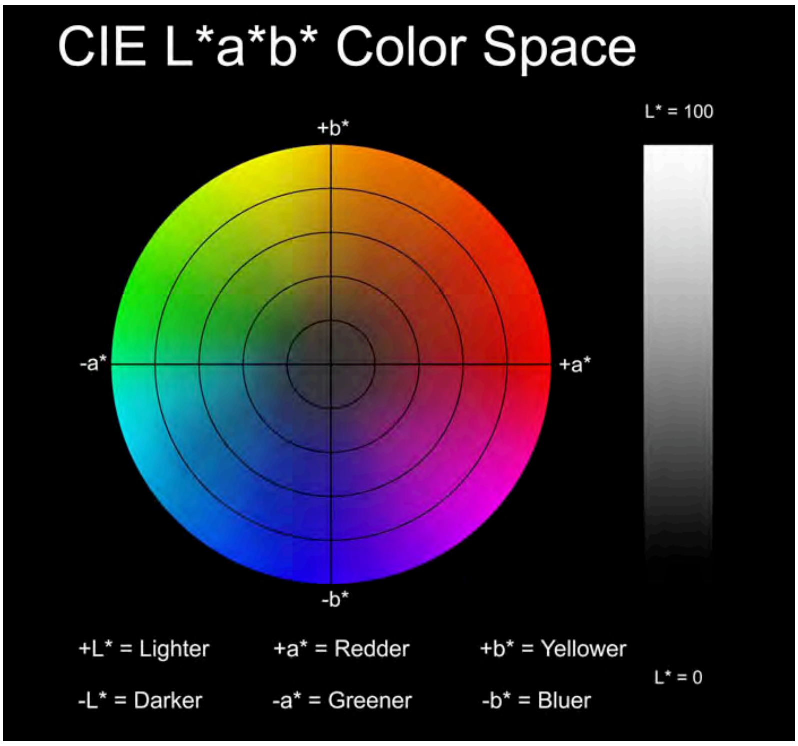


Figure 4.9 CIE L*a*b* Colour Space diagram

Testing for this experiment was performed using a Data Colour Spectraflash 600 Plus-CT. Each sample to be treated was folded into four before being placed beneath the aperture to prevent light transmission through the sample. Measurements were repeated three times per sample and rotated by 90° degrees between each measurement and the mean calculated. The Figures were then used to calculate colour difference values (ΔE*) using Equation 4.

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{\frac{1}{2}}$$

Equation 4 Colour Difference

Where ΔL*, Δa* and Δb* are the differences in colour measurements between laser irradiated front and untreated reverse sides of the textile samples.

4.5.1.3 Dye Exhaustion and Fixation

Dye Exhaustion is the percentage of dye absorbed by the fabric from the dye bath solution. In this experiment a Unicam SP1800 UV/visible spectrophotometer was used, set at 610nm, the maximum absorbance wavelength specific to the chosen dye. Three absorbance measurements were taken from each exhausted dye bath and an average was used to calculate Exhaustion (%E) using the following equation (Equation 5).

$$\%E = 100 \times (Abs_0 - Abs_1) / Abs_0$$

Equation 5 Dye Exhaustion

Where Abs_0 is absorbance of the original dye bath solution at a wavelength of 610nm and Abs_1 is absorbance of the remaining dye bath liquor after the dyeing process has taken place.

The total fixation efficiency represents the percentage of the original dye concentration applied to the fabric that became covalently bonded (fixed) to the test substrate. It was calculated by considering the absorbance values before and after the dye reaction had taken place as well as the absorbance value after a secondary wash off procedure or reduction clear, calculated using Equation 6.

$$\%T = 100 \times (Abs_0 - Abs_1 - Abs_2) / Abs_0$$

Equation 6 Total Fixation Efficiency

Where Abs_0 is absorbance of the original dye bath solution at a wavelength of 610nm and Abs_1 is absorbance of the remaining dye bath liquor after the dyeing process has taken place, and Abs_2 is the absorbance after a secondary wash-off procedure or reduction clear.

The percentages of exhaustion and total fixation efficiency were used to quantify the fixation of the absorbed dye. The fixation values were calculated using Equation 7.

$$\%F = \%T / \%E \times 100$$

Equation 7 Dye Fixation

Where %T is the total fixation efficiency and %E is the dye exhaustion as discussed in the previous section.

4.5.1.4 Colour Fastness to Washing

The standard test method *BS EN ISO 105-C10: 2007* was used to determine the effect of washing on colour fastness of the laser irradiated and dyed samples. A multi fibre strip as shown in Figure 4.10a, was attached to each sample. Each sample with its attached strip was in placed in a separate vessel in a soap solution (5g/l). The vessels as shown in Figure 4.10b were agitated under controlled conditions of time and temperature. Table 4.3 shows the conditions used for each test, A to D.

Figure 4.10 a) Multi FIbre Strip b) Wash Fastness Testing Carried out in Controlled Conditions (SDC, 2003)

Wash Test	Temperature (^oC)	Time (mins)	Steel Balls	Sodium Carbonate
A	40	30	0	0
B	50	45	0	0
C	60	30	0	(2g/l)
D	95	30	10	(2g/l)

Table 4.3 Wash Test Conditions for BS EN ISO 105-C10: 2007

After rinsing and drying, colour change of the fabric sample and the staining on the adjacent fabric are assessed by comparison to the original fabric. Grey scales are used for assessing change in colour (*BS EN ISO 105-A02: 1993*) and for assessing staining (*BS EN ISO 105-A03: 1993*). A value from 1 to 5 is awarded using the appropriate grey scales shown in Figure 4.11, where 5 is no loss of colour or no staining.

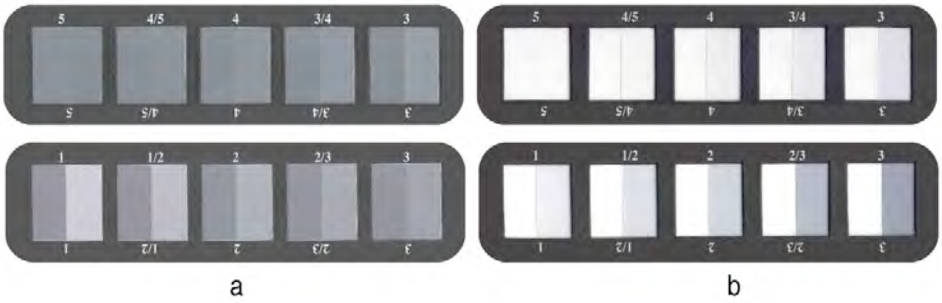


Figure 4.11 Grey scales used for assessing a) staining and b) colour change (SDC, 2003)

4.5.1.5 Colour Fastness To Rubbing

Colour fastness to rubbing under both wet and dry conditions was determined by the *BS EN ISO 105-X12: 2002* standard test method. Test samples were rubbed with a dry cloth and a wet cloth using a crockmeter, as shown in Figure 4.12, which provides a constant rubbing pressure of 9N. The staining of the rubbing cloths were then assessed using the grey scale method.

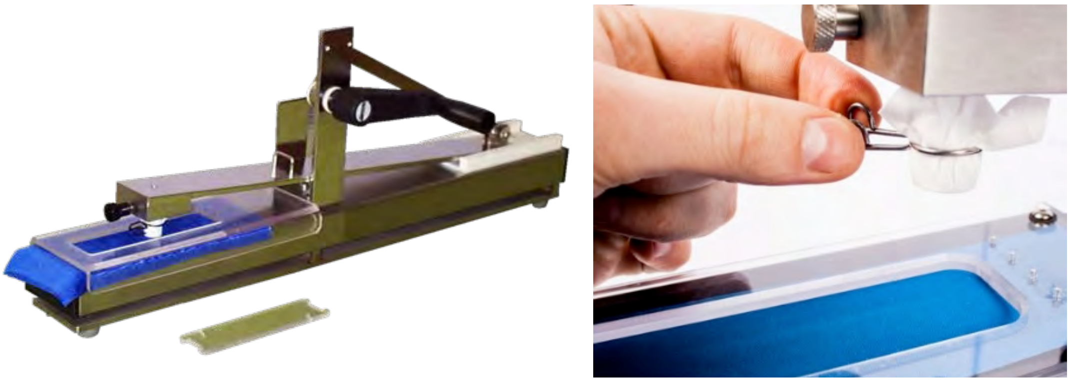


Figure 4.12 Crockmeter apparatus and rubbing cloth (Heal, 2009)

4.5.1.6 Tensile Strength

Standard test method *BS EN ISO 13934-1: 1999*, determines the elongation at maximum force using the strip method. The test was used in this research to assess the effect of laser irradiation on the tensile strength of woven fabrics. Ten 5 x 30cm laser irradiated specimens were prepared. Each sample was clamped into the jaws of an Instron Tensile Tester apparatus and extended at a constant rate until it ruptured (Figure 4.13). The maximum force and elongation were recorded and the mean and standard deviation were calculated for each set of results.

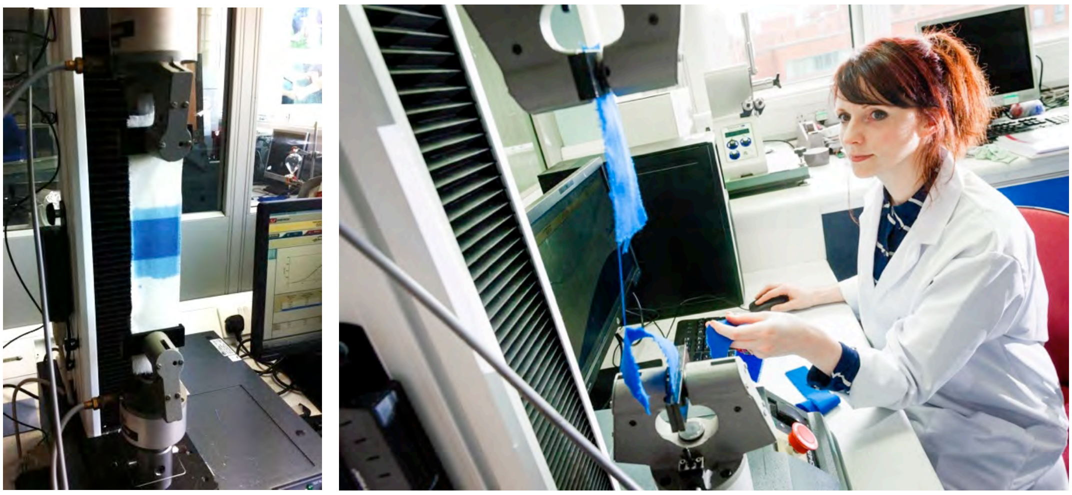


Figure 4.13 Instron Tensile Strength Testing

4.5.1.7 Burst testing

The standard test method *BS EN ISO 13938-2: 1999* is a pneumatic method for determination of bursting strength and distension. The method was used to assess the effect of laser irradiation on the strength of knitted fabrics in this research. Ten laser irradiated specimens were prepared. Each sample was clamped over the diaphragm of a Heals Burst Tester apparatus. Compressed air was used to distend the diaphragm until the fabric specimen burst. The bursting strength and bursting distension were recorded and the mean and standard deviation calculated for each set of results.

Figure 4.14 Burst Strength Testing

4.5.2 Qualitative Analysis

4.5.2.1 Observation, Reflection and their documentation

Observation and reflection were used to aid decision-making, to provide direction and to generate ideas during and after practical work throughout this research (see Chapter 3). Documentation in this research has been used to record and reflect upon both qualitative and quantitative data. Logbooks and technical files were used to record parameters, measurements, observations, reflections and design insights. Creative and technical aspects of the practice-based and experimental processes were also captured by photography. Sketchbooks, mood boards, photographs and CADs, were used to document the design development process for the creation and choice of graphics for laser processing.

Figure 4.15 Documentation of sampling in technical file, observation and written reflection

4.5.2.2 Microscopy

A Nikon Optiphot optical microscope was used to examine the effects of laser irradiation on treated fabric samples at a magnification of 10x. A Phenom Scanning Electron Microscope (SEM) at a magnification of 5000x allowed further analysis of the effects of laser irradiation on individual textile fibres. Extended depth of field (EDF) software on an optical microscope allowed high quality micrographs to be recorded. EDF software records the area of the examined substrate in focus as the microscope moves through focus. The resulting compound image allows differing heights on the surface of the substrate to remain in focus, allowing the surface morphology of the textile fibres to be examined and recorded with detail and clarity.

4.5.2.3 Graphic Test Sheet

A mark making test sheet was created using graphic software as shown in Figure 4.16. Knowledge of mark making qualities that can be attained by textile processes is essential for designers for the creation of suitable designs. For example if only one tone is achievable in a certain process, only monochromatic designs will be successfully processed using the technique. For this reason, the test sheet includes a range of linear, block filled shapes and halftone effects to test the quality of line and achievable detail, while gradiated, painterly and photographic marks are included on the sheet to test the level of tonal differentiation that can be attained.

Figure 4.16 Mark Making Test Sheet

4.5.2.4 Design Development

Design practice in this research was used to develop and validate laser techniques for textile design. For example, design samples were used alongside experimentation to analyse the aesthetic, tactile and graphic potential of the laser textile techniques. Visual and contextual research, including sketching, mood boards and colour palette aided design development towards a final collection of textile samples, as documented in Chapter 9.

4.5.2.5 Design Brief

An industry design brief for a *Laser Textile Design* collection was complied for this research project in collaboration with Camira fabrics (see Chapter 9). In professional design scenarios, design briefs are given to provide designers with the necessary background information and instructions required to complete the piece of work. Design Briefs may be specific, detailing the scope, aims and objectives of a project (Studd, 2002; Phillips, 2004) or they may provide a broad outline and direction allowing a greater freedom of interpretation for the designer (Brown, 2009). In the case of this research, the design brief provided a broad overview; it detailed relevant company trend directions including guidance on aesthetic themes, colour palettes, materials, intended market and delivery deadlines. The brief enabled an appropriate industry focused response to be delivered in the form of a final design collection that would:

- collect qualitative data, validating the laser techniques as appropriate textile design tools.
- provide qualitative data in the form of samples to be analysed through reflection and formal industry feedback.

4.5.2.6 Industry Feedback Using Focus Group Methods

Industry feedback was collected during this research using focus group methods, conducted to analyse the success of design, function, commercial fit and potential future directions of laser textile techniques and the resulting sample collection. Langford and McDonagh (2002) describe the effective use of focus groups for specifically for product development. They define focus groups as a qualitative research method involving groups of people engaging in a planned discussion or structured interview on the topic of interest.

Focus group methods were particularly useful for dealing with information that could not otherwise be easily measured, in the case of this project, two groups comprised of members of staff within the industrial partners (a performance swimwear brand and a contract interior manufacturer) were used to capture discussion on the success of the *Laser Textile Design* collections. This included capturing '*less tangible issues'* (ibid: 3) such as how the participants 'felt' about the samples, as well as establishing what qualities made designs suitable for the context of their company and customers. The specific methods used for conducting and analysing the feedback including the moderator's guide, group activities, coding and thematic analysis of transcripts are discussed in Chapter 9.

4.6 Establishing Laser Parameters for Textile Design

4.6.1 Laser software parameters and graphics handling for textiles

Many currently available laser processing systems, including the 100W CO_2 laser used in this research, are engineered for cutting and processing of plastics and metals instead of sensitive textile substrates. Consequently, conditions must be managed and parameters specific to each textile substrate must be established to ensure effective and consistent laser processing. Although Matthews (2011), Bartlett (2006) and Akiwowo (2015) have all reported on the use of laser software and associated file formats for textile processing, it has nonetheless been an important part of establishing workshop conditions to systematically test software parameters, thus confirming and/or improving laser textile practices. The experiments and information provided in the remainder of this chapter aided technical understanding and assisted the development of tacit knowledge. Developing familiarity of the look, handle and sound of appropriate processing and reaction have all been important. This has allowed new conclusions to be drawn regarding the most appropriate laser and software parameters for graphics handling and laser textile processing.

Figure 4.17 Graphics handling on Winmark laser processing software

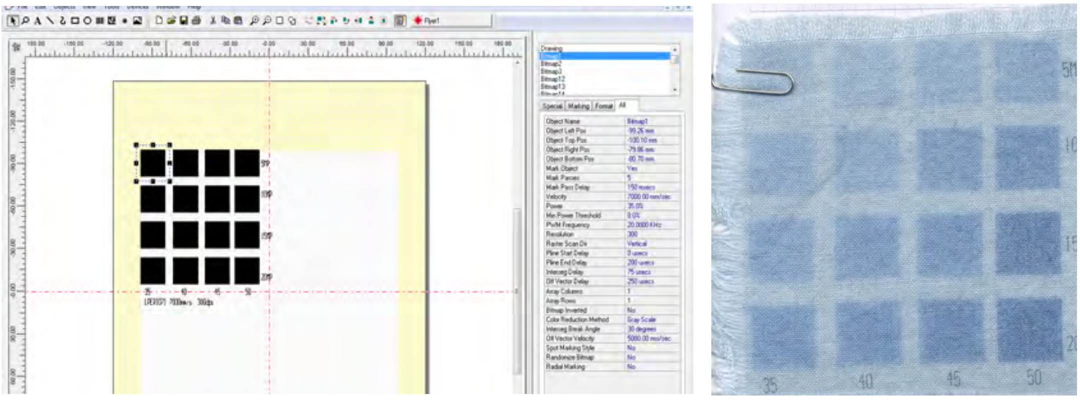
4.6.2 Power, velocity and energy density

Laser power can be controlled as a parameter for laser processing. On Winmark software, power is expressed as a percentage of the overall output power (Synrad, 2006:44). As shown in the laser power output graphs in section 4.2.3, the laser used for this study showed inconsistent actual power outputs at laser power parameters below 30%. The laser beam scanning velocity has an affect on the power received by the substrate. For example, a slow velocity may cause burning when the heat of the laser beam has more time to penetrate the substrate. It is possible to maintain the equivalent energy density by using high power at a fast velocity, or using a lower power at a slower velocity. To overcome inconsistencies in power output at power parameters below 30%, increasing the velocity would allow the higher (30%+) powers to be used on delicate textile substrates.

In this research, chosen power and velocity settings were used to calculate the laser energy density as described in section 4.2.4. For each experiment the laser parameters are expressed and documented as laser energy density to aid transfer of results to an alternate CO_2 laser set up.

4.6.3 Calibrating Laser Parameters for Textile Substrates

Laser processing is a multi-variable process. Variables include laser power, velocity, laser resolution, and the number of laser mark passes. Parameter grids can be used to “calibrate” this information. Parameter grids were used in this research to determine optimal settings to treat each different substrate. Parameters below the optimal settings did not provide sufficient energy density to cause effect on the surface of the substrate. Parameters above the optimal settings caused significant thermal damage, burning and finally ablation.



Object Name	Bitmap1
Object Left Pos	-99.26 mm
Object Top Pos	-100.10 mm
Object Right Pos	-79.86 mm
Object Bottom Pos	-80.70 mm
Mark Object	Yes
Mark Passes	5
Mark Pass Delay	150 msecs
Velocity	7000.00 mm/sec
Power	35.0%
Min Power Threshold	0.0%
PWM Frequency	20.0000 KHz
Resolution	300
Raster Scan Dir	Vertical
Pline Start Delay	0 usecs
Pline End Delay	200 usecs
Interseg Delay	75 usecs
Off Vector Delay	250 usecs
Array Columns	1
Array Rows	1
Bitmap Inverted	No
Color Reduction Method	Gray Scale
Interseg Break Angle	30 degrees
Off Vector Velocity	5000.00 mm/sec
Spot Marking Style	No
Randomize Bitmap	No
Radial Marking	No

Figure 4.18 Parameter Matrix on Winmark Software and resulting sample

Throughout this research, *laser power/velocity* and *laser power/mark pass* matrices were used to determine the range of parameters to cause effect on the textile substrate without causing significant thermal damage. Visual and microscopic examination of the irradiated matrix was used to identify optimal parameter combinations or the parameter range in which to work, for each new textile substrate. An example is shown in Figure 4.18. The most appropriate range of parameters was found to be specific to each textile substrate depending on fibre type, material weight or composition. The effects of laser material interaction are further discussed in section 4.7.

4.6.4 Raster and Vector

Laser software can process information in two ways, through raster or vector marking. With vector files, the laser beam follows straight or curved lines between two points on an x-y axis (Synrad, 2006). Vector information cannot read tonal values. With raster processing, the laser scans the entire image area. However, the laser beam only fires in areas where raster objects are present. Figure 4.19 shows the same sets of shapes with arrows indicating the difference in paths taken by the laser beam when controlled by a) a vector file b) a raster file. Raster files can read tonal information and can therefore be used to replicate photographic imagery. The laser will process changes in tone as changes in power output. For example a tonal value of 100% black would be processed at the power output of the user's chosen parameter. However, a tonal value of 50% black would produce half the power output. It is possible to choose the power range in which to operate for raster files. Parameter testing is necessary to determine the minimum and maximum power outputs required to correspond to 0% black as minimum to 100% black as maximum.

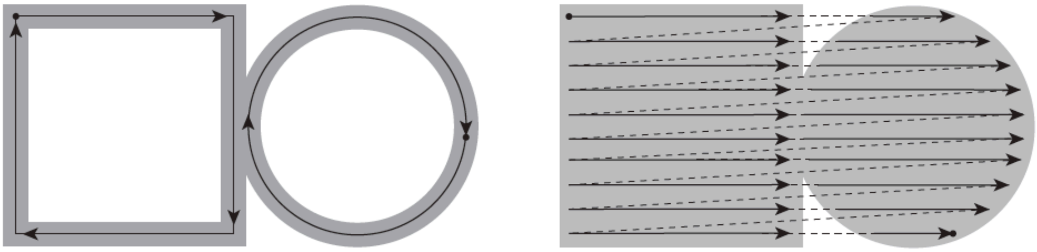


Figure 4.19 Difference in the paths of vector and raster objects (Synrad, 2006)

4.6.5 Raster Colour Reduction Methods.

Designs and imagery produced as pixel based CAD files contain rich colour and tonal information. When importing an image file, the laser requires tonal information to be translated to a suitable format for laser processing. Winmark software can simplify or reduce this information in two ways:

1. By reducing the image to 8-bit and assigning changes in tonal information to a change in laser power (greyscale). Chosen power settings determine the power output for a black tonal value. Power output will be automatically altered to reflect percentage saturation of the greyscale (Synrad, 2006). For example, if a power of 60W is chosen, white will be 0% (power off); mid grey will be 30W; and black will provide full chosen power setting of 60W.

2. By reducing the image to monochrome and assigning changes in tonal information to changes in the size, shape or spacing of pixels, with laser power remaining constant (halftone, error diffusion, bayer dithering). These reduction methods provide the appearance of shading similar to methods using in newspaper production (Synrad, 2006).

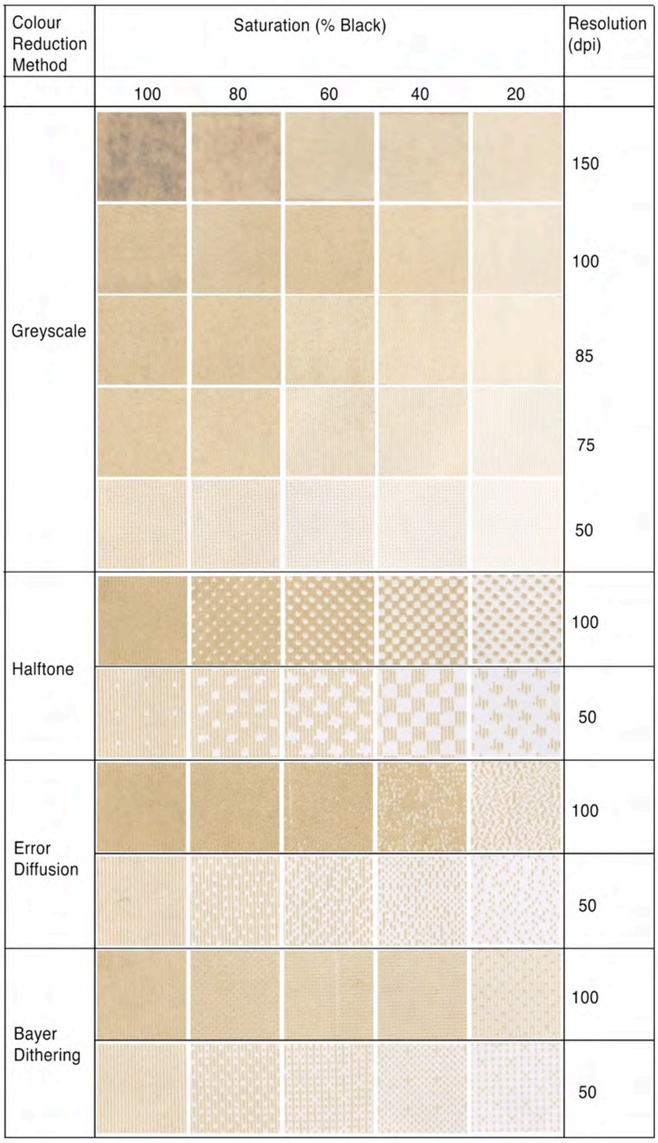
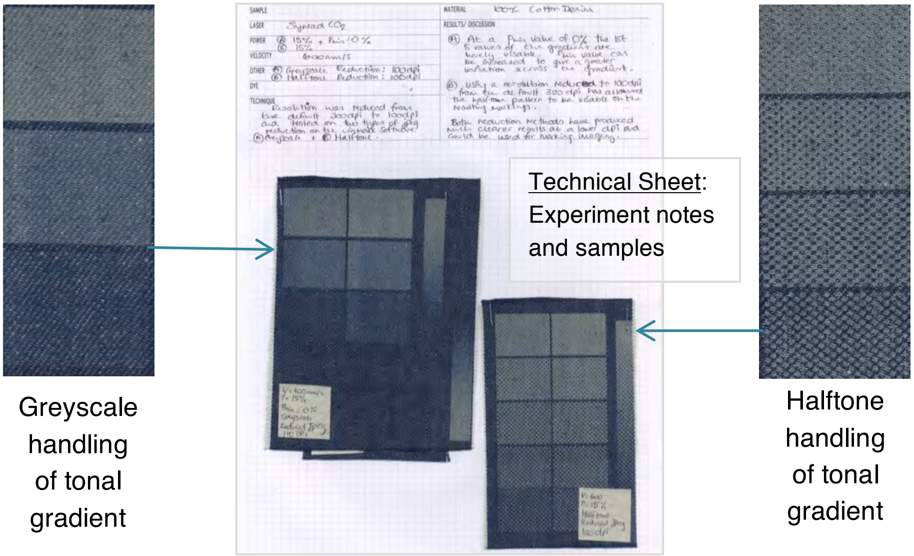


Table 4.4 Colour Reduction Methods

The colour reduction options described above were tested to establish the most appropriate method for textile processing. The methods are compared in Table 4.4 and Figure 4.20 after laser processing on paper and cotton denim respectively. Halftone, error diffusion and bayer dithering methods all represent changes in tonal information through disruption of the original uniform ‘flat colour’ adding a different aesthetic. For this reason, they were unsuitable for the purposes of this research. With the greyscale method, consistency remains undisturbed by altering tonal values; changes in tone are instead controlled by energy density. It can be seen that greyscale reductions at resolutions between 75-100dpi provide the most consistent, uniform squares, therefore the most appropriate image processing parameters. Controlling resolution within a greyscale reduction means that consistent all over coverage can be achieved, allowing the graphic potential of digital image processing to be realised.



Greyscale handling of tonal gradient

Halftone handling of tonal gradient

Figure 4.20 Laser greyscale and halftone reductions: tonal gradients on denim fabric

4.6.6 Resolution

Resolution is often a representation of image quality, measured in dots per inch (dpi). For traditional print media, higher resolution corresponds with a higher image quality and clarity. For print media 300dpi is the standard minimum for a high quality print output. In digital processing, a true resolution of 300dpi will house 300 dots in an inch. To increase the resolution and therefore to increase the number of dots per inch, smaller dots are generated. By contrast, in laser processing the number of dots that can fit into an inch is determined by the laser beam spot size. Where the laser beam spot size is a fixed variable, to increase laser resolution, therefore to increase the number of dots per inch, the dot spacing must be brought closer together, eventually overlapping (Synrad, 2006). The differences in approach to dpi handling between true resolution and laser resolution are shown in Figure 4.21.

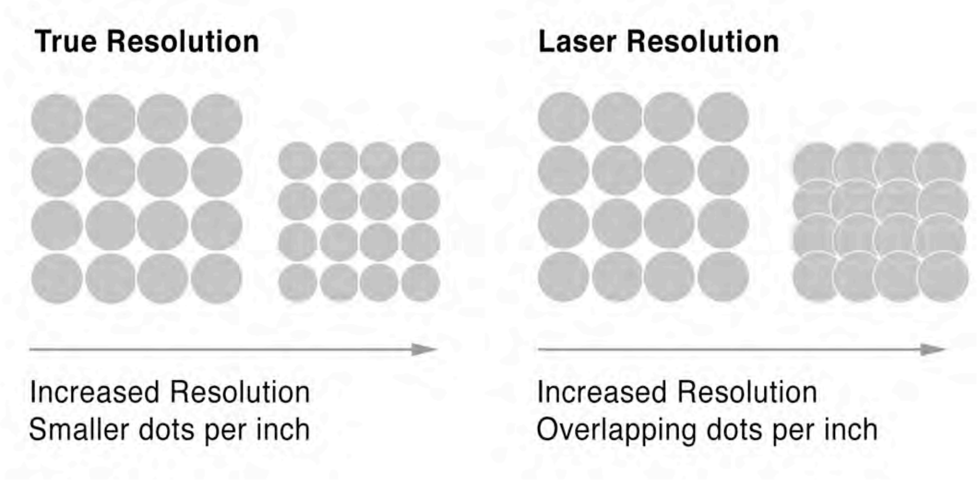


Figure 4.21 Difference between True Resolution and Laser Resolution

The default setting when importing raster image files to Winmark software is set at a resolution of 300dpi, however it was shown to cause inconsistent processing that impeded the changing of tonal qualities. As discussed in the previous section, problems faced by line spacing of less than 0.03cm for vector graphics caused overlapping lines that resulted in over processing. Similarly, higher laser resolution resulted in the overlapping of dots.

The laser used for this research had a beam spot size of 0.03cm. It can be calculated that this spot size can fit 84.67 times within an inch (2.54cm) without overlapping. If overlapping leads to inconsistencies in image processing, it can be concluded that a resolution of 85dpi may produce the highest quality image. This was confirmed experimentally as shown in the following figures. Experiments were carried out to examine the effect of laser resolution on graphics handling. Image files with tonal gradients were laser processed at laser resolutions from 50-300dpi as shown in Figure 4.22

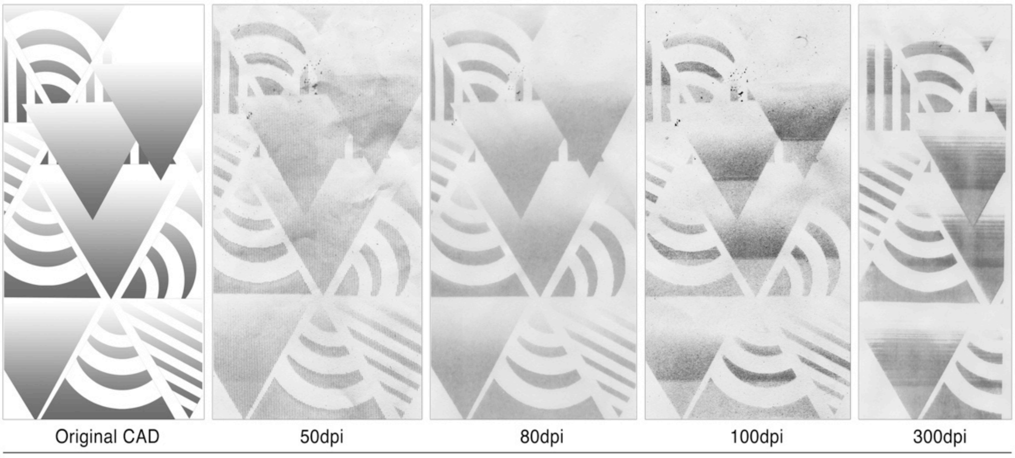
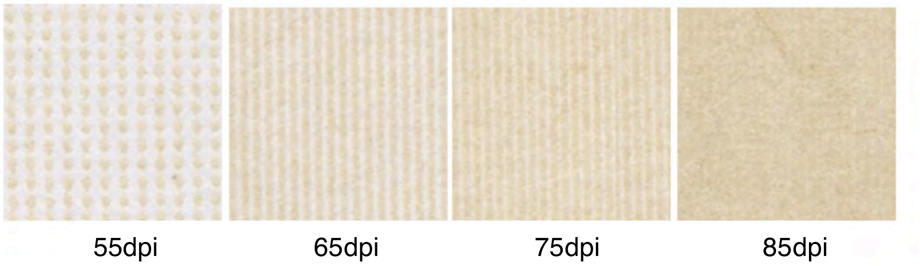


Figure 4.22 The effect of laser resolution on tonal gradients

It can be seen that a resolution of 80dpi provides the most appropriate raster image processing to achieve smooth tonal gradients. At 50dpi the resolution is low, and the space between dots can be seen. At 100 and 300dpi tonal gradients are not processed smoothly, with visible bands across the artwork. At 5x magnification, further examination of processing quality at laser resolutions between 50-100dpi confirmed the optimal dot spacing to be 85dpi as shown in Figure 4.23. At this optimal laser resolution, dots met without overlapping, providing a smooth consistent coverage. Below 85dpi, the dot spacing was visible resulting in a striped appearance. Consequently, a resolution of 85dpi was used throughout this research to mark solid raster shapes for parameter testing and for all over laser marking. Graphics were also processed at a resolution of 85dpi, unless otherwise specified, using a greyscale reduction to convert images to laser ready files.



55dpi 65dpi 75dpi 85dpi

Figure 4.23 Effect of laser resolution on processing quality (x5 magnification)

4.6.7 Vector Line Spacing

When processing a filled vector shape, it is not possible to select a scanning resolution. The default settings were found to give uneven processing. However, it is possible to obtain a more uniform processing result by dictating the laser-scanning path. Comparable to resolution, which controlled the spacing of raster laser beam scanning, line spacing can be used to control vector laser beam scanning. This can be achieved by drawing shapes with multiple vector lines, or by using the Winmark software ‘wobble’ function for block filled vector shapes. The line spacing method was also reported by Akiwowo (2015). The line spacing method was investigated to determine its relevance to this research, as discussed in the following experiment.

Figure 4.24 Line Spacing Parameter Grid

A parameter grid of line spacing at varied sizes against laser power was used to determine the most suitable parameters for consistent laser processing. The grid showed that altering the density of line spacing could represent tonal information, as shown in Figure 4.24. Microscopy revealed a line spacing distance of 0.03cm provided a result where lines did not overlap, consistent with the laser beam spot size (0.03cm) allowing an even marking result. To alter tonal values using this method, it is necessary to use line spacing below 0.03cm, to achieve darker tones.

This relies on over-processing that can lead to burning in the areas where lines begin to overlap. To achieve lighter tones, the spacing between lines must be increased and resulting in a striped appearance. For this reason, it was decided that altering line spacing was not the most appropriate method to achieve consistent and even laser processing in this research.

Instead of altering line spacing, energy density can be used to control tonal variation. This technique was tested on a series of circles with a fixed line spacing equal to 0.03cm, resulting in consistent laser processing as shown in Figure 4.25. However, difficulty was encountered in translating vector line spacing into detailed or photographic imagery. While the line spacing method provides relevance for improved vector laser processing, the transferability for all types of digital graphics is limited. Consequently, for the purposes of this research, using raster based graphics with controlled resolution and greyscale reductions provided more appropriate image processing controls. The consistency of raster laser processing using a greyscale reduction remained undisturbed by altered tonal values, as they maintained a fixed beam scan spacing; thus tone could be controlled by energy density.

Figure 4.25 Line spacing/ dye uptake experiment (Sample: Uptake 23.1)

4.6.8 Multiple laser passes

It has been discussed that increasing laser energy density provides an increasing effect on irradiated substrates. However, high energy densities can lead to thermal damage. Winmark software settings allow the quantity of laser 'mark passes' to be chosen. The user manual states: "*In some cases, several low-power passes are preferable to a single high-power pass*" (Synrad, 2006:152). Experiments with multiple laser passes were undertaken in this research, to ascertain if increased energy density could be delivered to a textile through layered processing. It was found that multiple laser passes could be used effectively for dye fixation (Chapter 6).

4.6.9 Summary of Laser Parameters for Textile Design

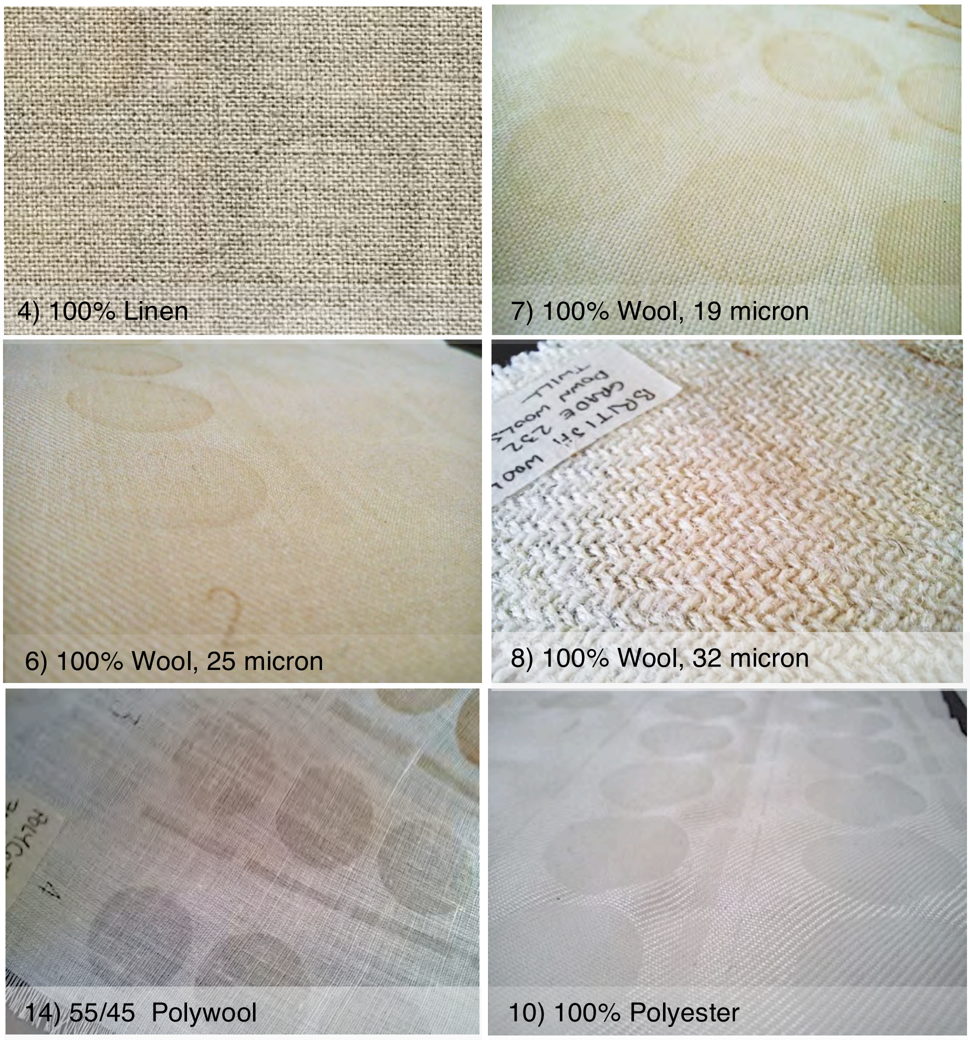
Appropriate laser software conditions and parameter settings for optimal graphics handling have been established in this section. This has furthered the work of previous laser textile research (Bartlett, 2006; Matthews, 2011; Akiwowo, 2015) by describing the optimal conditions for laser resolution for smooth image control, improving on the halftone and line spacing methods described by Akiwowo (2015). While the halftone reduction method can be used to represent tonal information, it does not replicate the original design file accurately. Through experimentation and sampling, this research has shown that by using greyscale reductions, levels of grey in a raster image are translated more appropriately into smooth gradients. This process is consistent with alternate raster processing software (such as Photoshop), allowing results to be easily replicated across different machines. It has been discussed how resolution in a laser processing context differs from that of resolution in digital printing processes to facilitate understanding of the laser marking process.

It is also useful to recognise the parameters with most significance for application of the laser techniques. In this study, the potential contexts, or end users, for the laser techniques were established as textile designers and industry. In order to compete with traditional techniques in such a market place, speed and consistency were seen as two factors of significant importance for textile processing, where 'time is money'. The highest processing speeds available for the laser marker were used in this research, at processing velocities of 500-700cm/s.

Raster processing allowed ease of transfer from CAD's containing multi tonal information to laser software. The most suitable resolution for consistency and quality of image was chosen at 85dpi. Further experimentation determined the exact values relevant to each substrate. Identifying the desired parameters for velocity and resolution allow these to become fixed variables. In order to narrow down the range of settings with the remaining variable parameters; laser power and mark passes, it is noted that consistency of the actual laser power output is poor below 30% so power settings between 30 and 100 should be used to improve repeatability. Parameter grids should be used for each new fabric substrate to calibrate the most appropriate laser processing parameters. This chapter has offered a method of calibrating laser parameters that can be followed on any laser machine, regardless of total wattage, speed capability or software.

4.7 Material-led investigation into the effect of IR Laser Irradiation on Textile Fibres

Material-led, exploratory testing was carried out at the initial phase of this research to determine the effect of laser irradiation on a number of textile substrates. A range of textile constructions and compositions including paper, denim, linen and a variety of woollen and synthetic textiles were used in this exploratory phase. The aim of the initial experiments was to identify any design opportunities that may arise from laser-material interaction and to confirm and compare the effects of laser irradiation on the substrates. Each sample was laser irradiated with a number of test markings, dyed and examined under a microscope. Observations and reflections were recorded before and after dyeing. A selection of initial samples is shown in Figure 4.26. Some known laser effects documented in the literature review were confirmed as accurate; for example, enhanced dye uptake on polyester. Other effects were unexpected; for example, linen fading. A selection of the most significant results is presented in Table 4.5. which describes the samples that provided influence on the subsequent direction of the research. Reflections and design opportunities that arose from the samples are recorded in the table together with the laser and dye parameters used.



4) 100% Linen

7) 100% Wool, 19 micron

6) 100% Wool, 25 micron

8) 100% Wool, 32 micron

14) 55/45 Polywool

10) 100% Polyester

Figure 4.26 Initial Laser tests on varied textile fibre types (undyed)

Sample/ Ref	Substrate	File	J/ cm^2	Dye Recipe	Testing	Notes	Design Opportunities	Further work?
1 / Fading 25.1	100% **Cotton Denim** Twill	Vector Squares	3.2-3.6	(undyed)	-	• Steady increase in fading with energy density w/out damage. Yellowing.	Faded patterning	• Parameters • Washing remove the yellowing
2 / Fading 25.2, 25.3		Raster Greyscale	3.2-3.8	(undyed)	-	• Subtle greyscale • Yellowing of the denim occurs.	Tonal fading	• Increase range of greyscale, • Mark making/ quality of line
3 / Fading 25.4- 25.5		Raster Pattern	3.6	(undyed)	-	• Reduced resolution eliminates burning reveals white cotton	Defined fading. Graphic imagery	Determine optimal resolution for laser for all subsequent experiments.
4 / Fading 4:1	Valencia Natural **Linen** Plain Weave	Vector Shapes	3- 3.8	(undyed)	-	• Fading at small parameter range. • High power = darker marking effect	Faded patterning	• Faded after washing to remove burnt debris? • Further parameter tests • Dyeing.
5 / Fading 7.11		Raster Marking	3.4	3% Solar BG Yellow Direct	-	• Faded areas retain lighter appearance after dyeing.	Two tone pattern	Colour data. Rub/wash fast testing. Brighter colour after dyeing? Alternate to bleaching?
6 / Uptake 7.1	100% Worsted **Wool** Twill	Vector Circles	2.6-3.4	Acid: 3% 3G Coomassie Turquoise	• Microscopy Reveals darker colour on surface of dyed fabrics, as power increases, charring occurs and dye fixes to burnt debris. Debris comes off with abrasion.	• Successful increased uptake with strong differential colour • Higher energy density for raster files • Differential slight across greyscale	Multi-tonal design	• Mark Making • Mechanical testing • Colour data • dye concentrations • dye times • SEM • Reduce dye time or dye concentration to achieve greater contrast
7/ Uptake 17.2	100% **Wool** 19 microns Plain Weave	Raster Greyscale						
8 / Conc. 19:1-19:6	100% **Wool** 19 microns Plain Weave	Vector Squares		0.5- 3% Reactive Blue		0.5% too low for differential dyeing. 1.5% optimum. 3% min difference.		• Reduced dye temp/ time improve contrast?
9 / Uptake 8.1-8.5	**Wools:** Twill, Wool/ lycra, Crepe, Jersey	Vector Circles		2% Lanasol Reactive Blue		• Greater dye uptake across all wool constructions • Lower ED for thinner fabrics.	Tonal design on range of wool fabrics	• Test mark making capabilities/ quality of line
10 / Uptake 7.10	100% **Polyester** Twill	Vector Circles	2.6-3.4	3% Dispersol Rubine C-B	Microscopy: increased melting. At high ED melted poly reformed into solid surface. Fibre damage.	• Surface texture altered.• Stiffness/ damage occurs at higher ED. • Strong dye uptake after irradiation. • Inertia caused over-processed outlines. Line spacing approach improved processing- no outliines.	Surface Texture. Warped Surface. Strong colour contrasts after dyeing. Clear multi-tonal definition,	Possible to affect dye uptake without fibre damage? Exploit / control warped surface texture to create 3D surface? Heat setting?
11 / Uptake 23.1	100% **Polyester** (Endurance+) Jersey knit	Line-space Vectors	3.2-3.6	2% Red HWF-3BF Synolon Disperse				
12 / Surface Marking 6:2 - 6.9	**Synthetic Knits:** AquaBlade, Fastskin & S200: 50/50, Nylon /Lycra. Kira : 80/20, Endurance+: PET **Wovens**: Paga-strong: 65/35 Nylon/Lycra. LZR: 75/25	Vector Shapes	2.6-3.4	(undyed)	-	• Visible marking occurs on fabric surface. • Highest powers lead to brittle fabric, which breaks upon stretching. • Subtle markings at lower powers do not tear. • Thicker fabric responds favourably to laser irradiation as damage to the fabric strength does not appear to occur easily.	• Iridescence and altered surface relief. • mark making at optimum parameters	• Further mark making tests could be tried at noted optimum parameters • Mechanical testing should check fabric strength after lower power irradiation. • Dyeing should reveal increased uptake.• Could a striped texture effect akin to existing calendaring methods be achieved?
13 / Uptake 7.5	30% **Wool,** 70% **Polyester** Twill	Vector Circles	2.6-3.4	3% Dispersol Rubine	• Microscopy shows disperse dye uptake in laser treated/ acid dye uptake on non treated. • Fibre melt at higher ED solidifies, forms thin layer on surface loosing woven structure definition.	• Prior to dyeing no burning apparent. Higher powers caused fabric stiffening. • Strong uptake of disperse on laser marked, slight staining on untreated • Lower ED = subtle shades/ marl effect. • Excellent colour contrast between areas; w/out damage.	• Strong colour contrasts: screen print effect. • Marl / vintage look. •Multicoloured design and pattern	• Test mark making capabilities and quality of line achievable to establish most appropriate designs. • Do the higher powers negatively affect the mechanical properties of the fabric? • Test alternate colour ways and dye combinations. • Test for wash and rub fastness. • Test patterns and mark making. • 2 step dyeing: reactive then disperse dye
14 / Uptake 10.1	45% **Wool,** 55% **Polyester** Plain Weave			3% Solar Yellow Acid & 3% Dispersol Rubine				
15 / Uptake 14.4	45% **Wool**, 55% **Polyester** Plain Weave			2% Lanasol Reactive Blue		• Melting of poly content at high ED. Laser areas remain white, acting as resist to reactive dye.	• Faded mark making, multi-tonal pattern.	

Table 4.5 Initial Testing: Laser - Material Interaction

Figure 4.27 Laser fading experiment: Laser Resolution (*sample 3*): a) 300dpi; b) 85dpi

Experiments on paper and denim aided the ‘troubleshooting’ of laser processing. Samples from these experiments can be seen throughout section 4.6. For example in Table 4.4, laser parameter testing on paper revealed the appropriate software settings for consistent graphics handling. Samples shown in Figure 4.27 and documented in the table as *sample 3* show the effect of laser resolution on fading denim. It was found that choosing the appropriate laser resolution was essential in achieving a white, faded appearance regardless of energy density settings. This sample highlights the importance of laser resolution for the appearance of laser processing on textile substrates. It was found throughout the research that processing problems could be overcome by addressing the laser resolution. No new textile design opportunities were identified for cotton denim at this stage of the sampling process, and therefore denim was not further investigated during this research.

Initial laser processing on natural linen revealed a fading effect over a small range of parameters as shown in Figure 4.26 (14) and Figure 4.28. At higher energy densities burning led to a darkening effect on the substrate. Due to the fabric weight, the burning effect did not appear to damage or weaken the bulk properties of the sample. The laser fading effect was further examined as a textile surface design technique for linen in chapter 8.

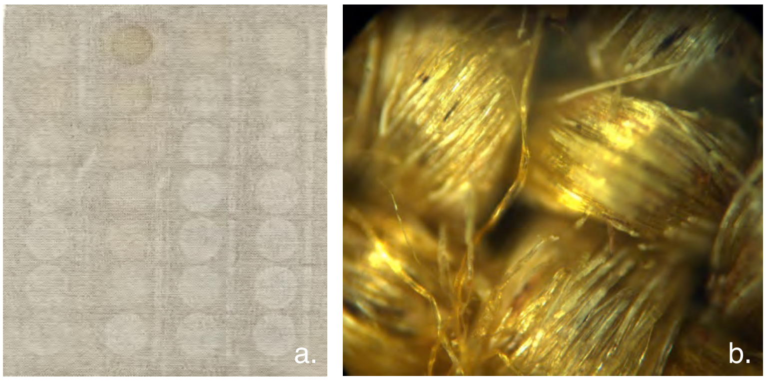


Figure 4.28 Laser faded natural linen (*samples 4 & 5*) a) parameter test b) micrograph (10µm)

The effect of laser irradiation on wool was explored. Initial testing established the range of parameters to cause effect on a number of woolen textile constructions as documented in Table 4.5. Figure 4.26 (6 & 7) show laser processed wool prior to dying. Subtle visual changes to the surface are apparent as laser energy density increases, beyond a certain threshold burning occurs on the wool surface resulting in carbonization and debris that can be removed by gentle abrasion. After dyeing, the laser processed areas of the textile were darker in colour, indicating potential enhanced dye uptake. Microscopic examination of the textile (Figure 4.29) showed the laser irradiated fibres to be darker shades of blue. However, fibre damage (b) and burnt debris (c) are evident compared to the untreated areas (a). These samples have revealed enhanced dyeing opportunities for wool, further developed in chapter 5 to impart a controlled textile surface design effect.

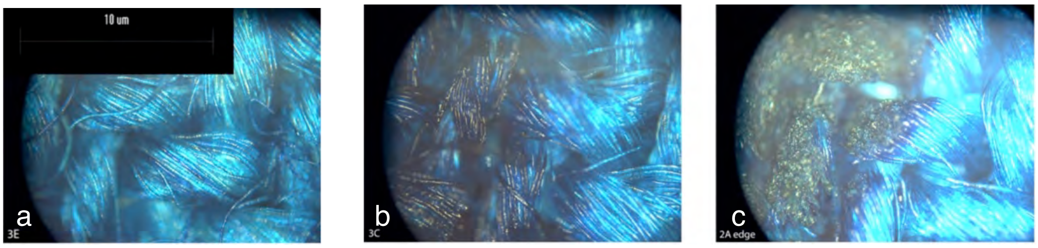


Figure 4.29 Micrographs (10µm) of laser irradiated 100% worsted wool twill at increasing energy densities (*sample 6*)

The effect of laser irradiation on polyester and nylon substrates revealed visual and textural changes to the textile surface as shown in Figure 4.27(10) and Figure 4.30. As laser energy density increased, so too did the transparency of the fabric resulting in delicate and brittle material properties. Laser irradiation on these samples was also found to affect the surface tension and dimensional stability of the entire textile sample leaving a warped, rippled silhouette as shown in Figure 4.30.

Figure 4.30 Altered surface qualities of polyester textile after laser irradiation (*sample 10*)

Microscopic examination revealed high levels of fibre melting with increased energy density (Figure 4.31). Melted polyester fibres solidified, modifying the surface properties (c-d). At energy densities beyond this point, high levels of melting lead to a complete reformation of the substrate and definition of the original woven structure is lost (e-f). The work in this section confirmed the findings of research cited in the literature review on the effects of IR laser irradiation of synthetic substrates (for example: Addrison, 2009; Bartlett, 2006; Akiwowo, 2015). After dyeing, the laser treated polyester showed a significant increase in uptake in the laser treated areas with increased fibre-melt providing the darkest colour result. To progress the findings, the textural changes in surface tension were further examined in chapter 7, to create controlled three-dimensional effects that can be combined with dyeing processes.

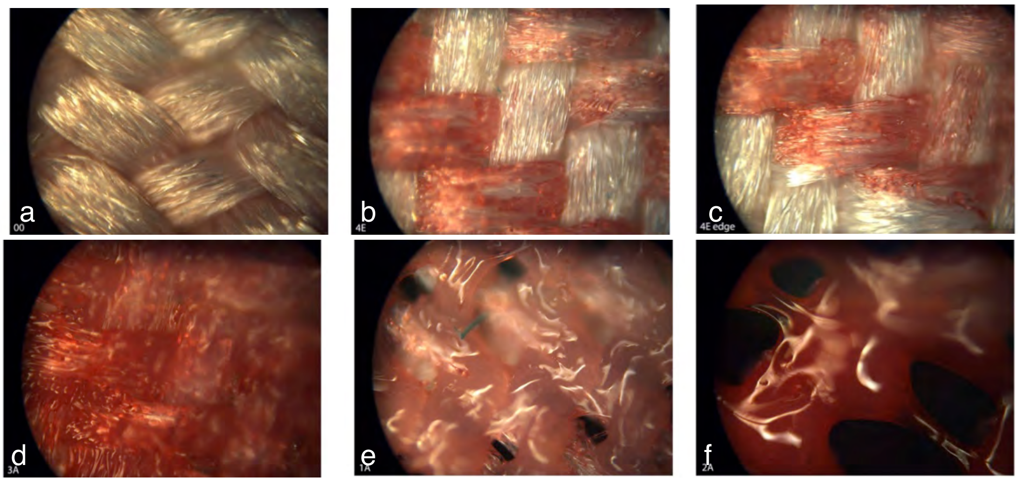


Figure 4.31 Micrographs (10µm) of laser irradiated 100% Polyester twill at increasing energy density (*sample 10*)

The effect of laser irradiation on wool/polyester blended textiles showed increased melting of the polyester content of the substrate as energy density increased. Like polyester, the surface appearance of the textile was altered in the laser irradiated areas resulting in transparency at the highest tested energy densities as shown in Figure 4.26(14). After dyeing with disperse dye at temperatures below 100^{o}C, only the laser irradiated areas showed uptake of the dye colour (Figure 4.32a). With the laser irradiated areas displaying polyester property traits, design opportunities through differential dyeing may arise. An initial experiment to test this mixed acid and disperse dye in a single dye bath providing a two colour result (Figure 4.32b). Further investigation in chapter 5 develops the process as a multicolour dyeing technique for wool / polyester blend textiles.

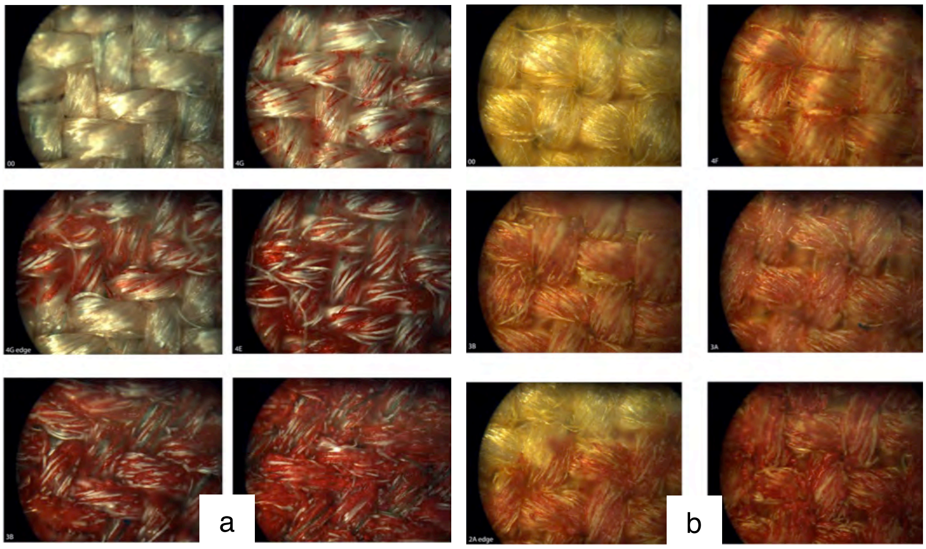


Figure 4.32 Laser irradiated polywool micrographs (10µm) a) disperse dye (*sample13*), b) mixed bath acid and disperse dyes (*sample 14*)

A summary of findings from the initial material-led exploration is documented in Figure 4.33. The diagram lists the key findings relating to colour and texture for each tested substrate, noting the changes in material properties brought about by controlled laser irradiation. This relates to phase 1 of the research, ‘exploratory sampling’. Design opportunities were identified from this, including: enhanced dyeing opportunities; dye fixation opportunities; controlled surface texturing opportunities; and fading and marking opportunities. Each design opportunity led to the development of a new *Laser Textile Design* technique, which are further explored in phase 2 and 3 of the research. Further work was identified to progress and refine each of the techniques, listed in the diagram as phase 3. The techniques are discussed in subsequent chapters of this thesis (Chapters 5-8).

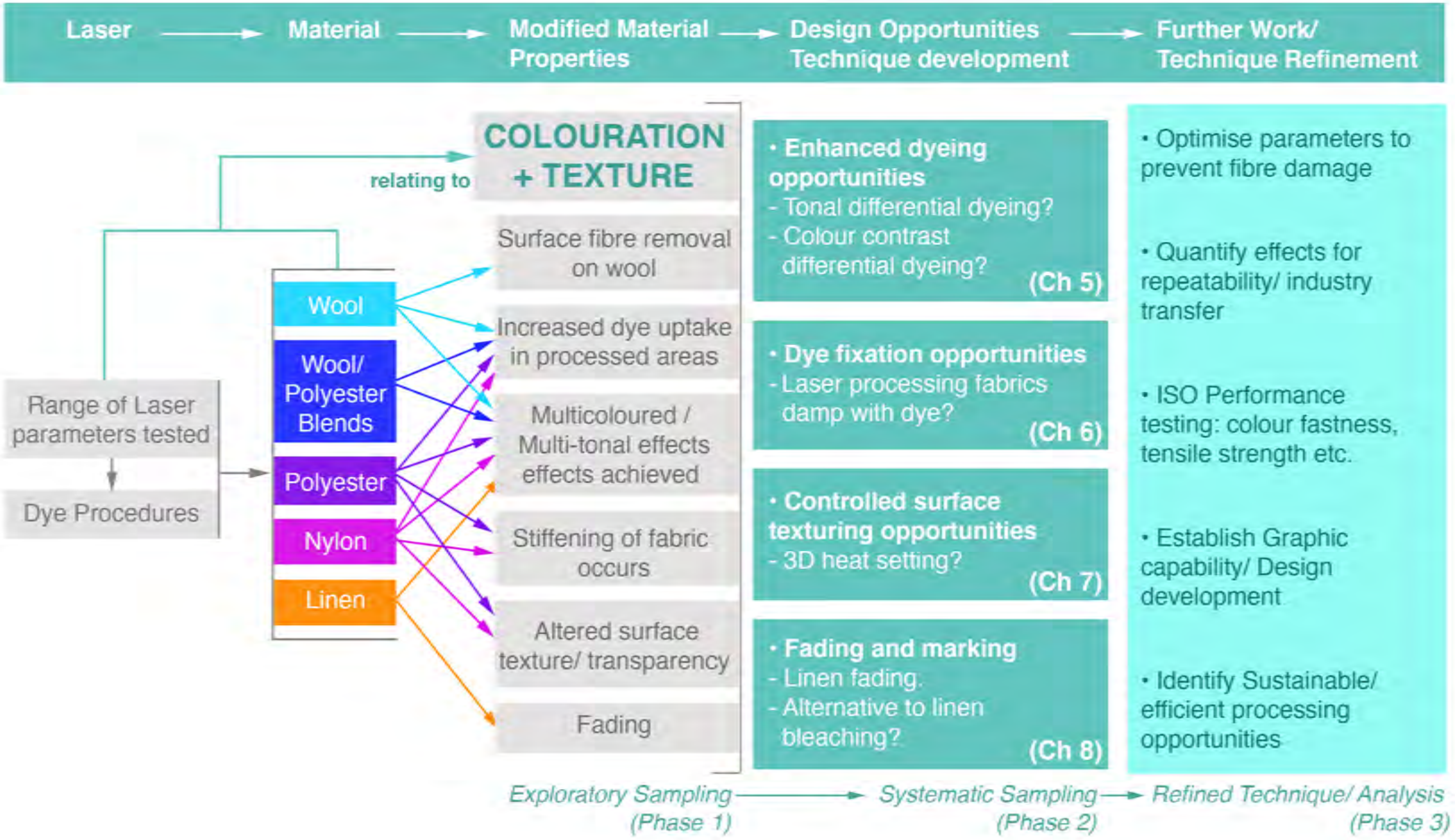


Figure 4.33 Laser Textile Research directions: identified from material-led exploration

4.8 Chapter Summary

This chapter answered the objective ‘Establishing Workshop Conditions’ (OB1) by providing a comprehensive overview of;

- Equipment and technical information required for this research
- Qualitative and quantitative analysis methods used in this research
- Experimental and workshop conditions established for this research

The chapter described the technical background of the laser system, materials and dyeing procedures required throughout this research. In addition, it provided an overview of qualitative and quantitative analysis methods, including all testing equipment and established textile testing procedures used. This led to a sound technical knowledge of equipment, materials and processes that was imperative to understanding and later predicting the effect of laser irradiation on textile materials.

Appropriate laser software conditions and parameter settings for optimal graphics handling were established. The information provided in this chapter has relevance beyond this research, offering a method to calibrate laser parameters for textile substrates and to troubleshoot laser processing issues for optimal image quality.

A material-led investigation into the effect of laser irradiation on textile fibres used an exploratory approach to establish affordances and constraints for each tested substrate and to explore potential design opportunities afforded by laser interaction with material properties. The effect of altering laser parameters was explored, enabling a range of aesthetic and tactile responses from the material properties. This led to the identification of four distinct areas for further investigation described in subsequent chapters of this thesis including new approaches to laser colouration and texturing of textiles as follows:

- Laser modification of fibres, as a pre-treatment to dyeing: *Laser Enhanced Dyeing of Wool and Wool Blends* (Chaper 5)
- Laser dye fixation: *Peri-dyeing* (Chapter 6)
- *Laser Moulding* (Chapter 7)
- Laser as post-treatment to fade natural linen fabric: *Laser Fading Linen* (Chapter 8)

CHAPTER 5 : LASER ENHANCED DYEING OF WOOL AND WOOL BLENDS

5.1 Introduction

Initial experiments, discussed in the previous chapter, showed that laser irradiation on wool and wool blend substrates had the potential to provide an enhanced colour effect after dyeing. This chapter describes further experimentation to control and analyse the effects of laser treatment for enhanced colouration and for use as an accurate design tool on wool and wool blend substrates.

As discussed in Chapter 2, many researchers have harnessed the photochemical and photothermal properties that laser processing can provide, to modify textile material properties. For example, laser irradiation has been found to modify synthetic fibres, allowing increased dye absorption (Montazer et al, 2012; Kan, 2008; Wong et al., 2007) and a reduction in temperature of the dyeing process (Periolatto et al, 2014; Xin et al, 2002). The proliferation of scientific papers on the subject, show that technical frameworks dominate existing laser textile research. Because of this, emphases on the surface design opportunities of these technical processes are not often highlighted. The aforementioned studies go a long way to test and explain the phenomenon on synthetic textiles, concentrating on an improved overall performance, while only a few have discussed the possibility of design outcomes from targeting specific areas of the textile substrate. Textile design research carried out by Perliatto et al (2014), Akiwowo (2015), Bartlett (2006) and Addrison (2009) begin to address laser dye techniques from a design perspective.

Fewer studies are available on the effect of laser irradiation on wool properties, however a small number have shown results including; laser irradiation to reduce felting and shrinkage of woollen textiles (Nourbakhsh et al., 2010) and UV irradiation to improve the dyeability of wool (Periolatto et al., 2014). A combination of laser and plasma treatments has been reported to increase hydrophillia as an all over treatment on woollen textiles (Czyzewski, 2012). Results achieved by allover UV treatment reveals an opportunity for further research; to examine the effect of the more commercially available CO_2 lasers' infrared irradiation on woollen textiles. The potential for the CO_2 laser, as an effective surface design tool for wool has not been fully explored in previous studies, nor has the correlation between laser parameters and the effect on dyeing a woollen textile. Herein lies an opportunity for investigation.

The aim of the following investigations was firstly, to ascertain the effect of CO_2 laser irradiation on surface and dyeing properties of wool and wool blend substrates, and secondly for results to be analysed in relation to their potential as a technique for textile surface design. Using a 10.6µm, 100 Watt CO_2 laser, optimum laser processing parameters for treating the substrates were determined. Analysis of the performance properties of treated substrates through ISO standardised testing and potential sustainability advantages of the techniques are also presented. The techniques described in this chapter explain how multi-tonal, multicoloured and moulded relief surface designs can be achieved and controlled through targeted laser processing of wool and polywool textiles.

5.2 Surface and Dyeing properties of laser pre-treated wool for textile design

The research presented in this section examined the effect of infrared laser irradiation, as a pre-treatment to dyeing 100% wool and its potential as a design tool for textile processing. Investigations revealed CO_2 laser irradiation could be used to increase dye uptake on the fabric surface. After dyeing, the laser marked areas appeared tonally darker on the surface of the cloth. This tonal differentiation was then used to examine quality of line, texture and mark making that can be achieved to impart surface patterning on woollen textiles.

5.2.1 Laser

The photothermal properties of the infrared laser were harnessed to modify woollen fibres. The laser has a fixed focal length, which was established prior to experimentation. All experiments were carried out with the laser beam in focus on the surface of the textile substrate. Winmark software was used to mark solid raster shapes for parameter testing and for all over laser marking using the method described in Chapter 4. Graphics were processed at a resolution of 100dpi using a greyscale reduction to convert images to laser ready files. The window of laser processing parameters to cause effect on the material properties for wool was expected to be small. This was confirmed experimentally to range between 3-4J/cm^2, as described in Chapter 4. Below this, insufficient energy density is delivered to the fabric to allow a phase change to occur. Above this, pyrolysis negatively impacts material properties. Therefore, laser irradiation of fabrics was carried out at energy densities of 3.06J/cm^2, 3.23J/cm^2, 3.40J/cm^2 and 3.57J/cm^2 and an untreated control at 0J/cm^2. To ensure an even processing of the substrate surface, the laser irradiation passed over the fabric 5 times at a constant laser scanning speed of 5000mm/s.

5.2.2 Surface Observation

To examine the effect of laser treatment on the surface properties of wool, laser irradiation at increasing energy density outputs was performed prior to dying the wool with reactive dye, including an untreated, 0J/cm^2 control. Prior testing had established the range of laser parameters in which to operate.

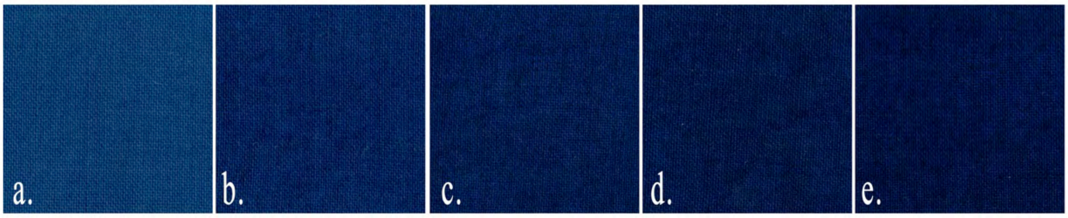


Figure 5.1 Laser pre-treated, dyed wool samples subject to energy densities of a.) 0, b.) 3.06J/cm^2, c.) 3.23J/cm^2, d.) 3.4J/cm^2, e.) 3.57J/cm^2

Visually, a change in colour can be seen between each of the laser treated samples and the untreated control as shown in Figure 5.1. As laser energy density increases, the colour change appears to show increasingly darker shades of blue. On the lowest parameter settings this change is subtle. On the highest settings, pyrolysis becomes evident on the wool fibre.

Figure 5.2 shows microscopic images of laser treated wool before and after dyeing at increasing laser energy densities. Figure 5.2a shows the untreated control. Here there is a consistent, even tone across the fibres. In Figure 5.2b and Figure 5.2c however, it can be seen that individual fibres, which have been subject to the laser irradiation, are darker in colour. In Figure 5.2b the contrast between lighter and darker fibres is subtle. In micrograph Figure 5.2c, where a higher energy density has been used, the contrast has increased significantly. Increased carbon can be seen in micrograph Figure 5.2d. The darker colour is a result of pyrolysis followed by dyeing however; these areas of burnt debris sit on top of the damaged wool surface and are easily removed by gentle abrasion. As well as degrading fabric structure, this may result in poor colour fastness to washing and rubbing.

The results indicate improved dye performance on the surface fibres of wool that has been subject to laser irradiation. As the laser energy density increases, so too does dye performance on the substrate. However, too high an energy density will begin to discolour and degrade the wool fabric, as the heat begins to burn and char the surface. The results indicate a delicate balance of textile properties effected by laser treatment and highlight the importance of finding the correct laser parameters to work effectively on each fabric substrate. In this case energy densities beyond 3.57J/cm^2 are excessively damaging to the woolen fibres, therefore not suitable for the aims of this investigation.

The morphology of the irradiated surfaces was further examined by scanning electron microscopy (SEM). SEM was carried out on an area of the wool fabric that had been subject to laser irradiation of 3.4J/cm^2. The micrograph in Figure 5.3 shows the wool fibre strands in the processed area. Two particular fibre strands of note, labeled A and B can be seen. The characteristic scales of natural wool fibre can be seen on Strand A, this strand was not subject to laser irradiation. On Strand B however, the scales on the surface of the fibre appear less pronounced; they have been ablated by laser irradiation.

The scales on a woollen fibre are formed from a tough slightly hydrophobic lipid layer. The removal of the scales of a wool fibre allows easier penetration of the dye into the core of the fibre (Smith et al, 2010:330). The darker colour properties seen in Figure 5.1 can be attributed to improved dye absorption by the laser modification of wool fibres.

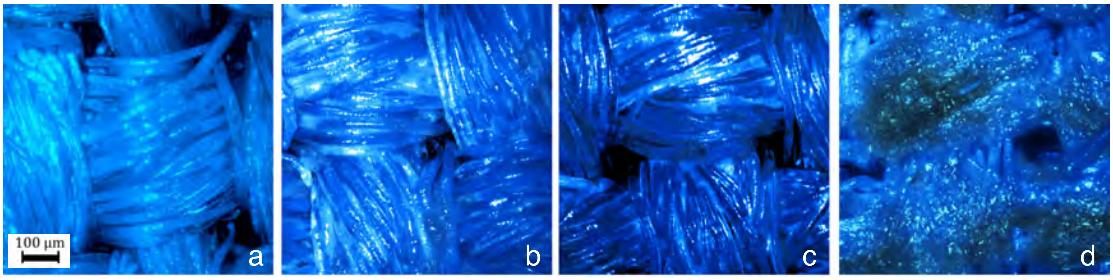


Figure 5.2 Micrographs 10x magnification of laser pre-treated, dyed samples subject to energy densities of a.) 0J/cm^2, b.) 3.06J/cm^2, c.) 3.4J/cm^2, d.) 3.57J/cm^2

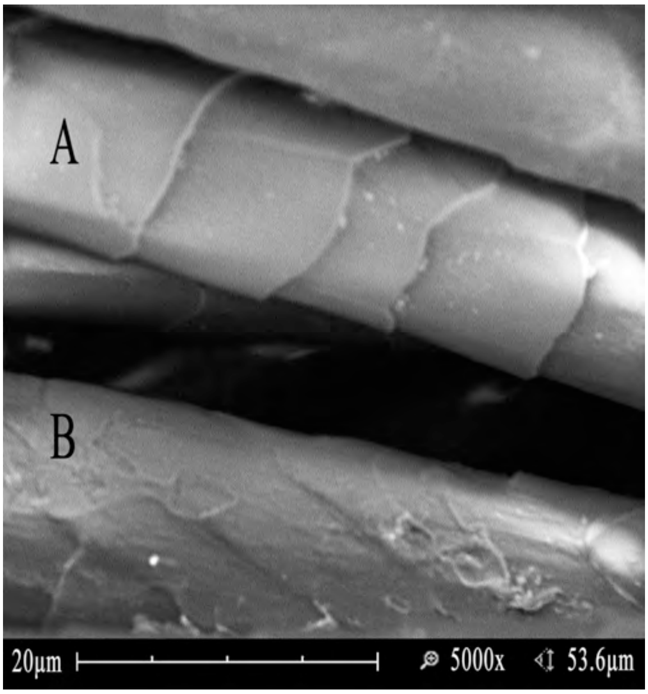


Figure 5.3 SEM micrograph of laser irradiated wool. a.) Untreated wool fibre, b.) Laser irradiated wool fibre

From SEM and optical microscopic evaluation, laser parameter settings suitable for further testing were identified and the effect of laser irradiation on individual wool fibres has been discussed.

5.2.3 Effect of Dye Temperature and Energy Saving

Laser treated wool was dyed at temperatures of 55 °C, 70 °C, 80 °C and 100°C and the colour data recorded. The colour difference was calculated using Equation 4 (as described in section 4.5.1.2). On initial visual inspection, it appeared that the greatest colour difference could be seen at the sub-optimal temperatures of 70°C-80°C as shown in Figure 5.4. After further analysis, colour data revealed that while the highest depth of shade was achieved at 100°C, the highest colour difference between laser irradiated and non-irradiated areas was identified at 70°C, as shown in the graph in Figure 5.5. In order to exploit design opportunities, the highest colour difference offers greatest contrast to achieve pattern on the textile surface.

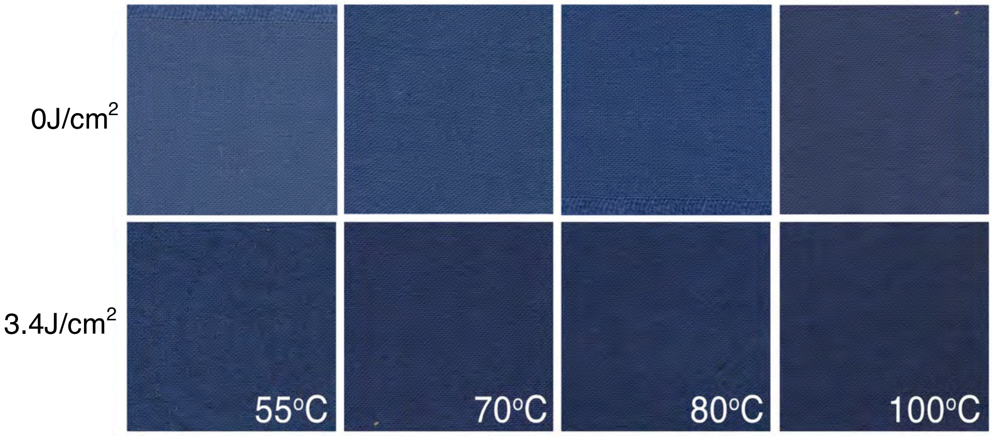


Figure 5.4 Laser pre-treated, dyed wool samples, dyed at varied temperatures

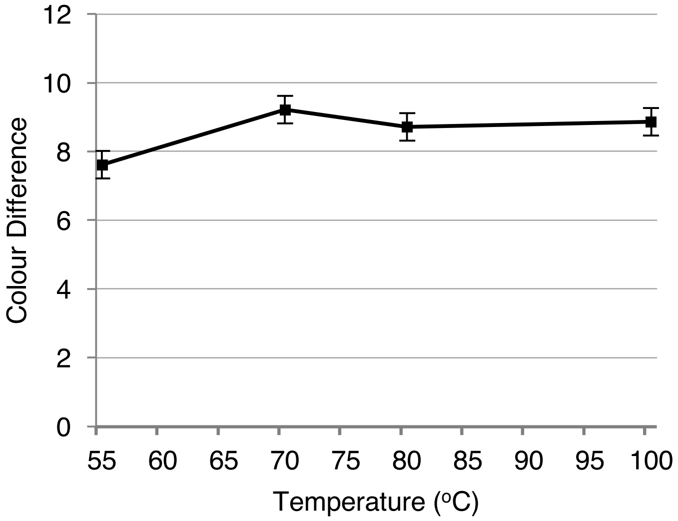


Figure 5.5 Effect of dye temperature on Colour Difference of laser irradiated samples

Figure 5.6 shows a schematic for dyeing wool with reactive dye. Line a, shows the standard procedure for optimal dyeing conditions, as described by the manufacturer (Huntsman, 2007), where the dye bath is held at a peak temperature of 100°C for 90 minutes. The processing temperature of 80°C was chosen for further testing throughout this study, as it offers a high depth of shade combined with a significant colour difference. The dyeing profile of 80 °C held for a reduced overall dyeing time is shown in green on the schematic in Figure 5.6, line b.

The associated energy saving of the dye profile used in this study was calculated using Equation 3 (as described in section 4.5.1.1). The reduced time and temperature for dyeing the laser treated wool equates to a 54% reduction in energy during the dyeing procedure, showing potential for a significant economical and environmental advantage, further discussed in section 5.4.

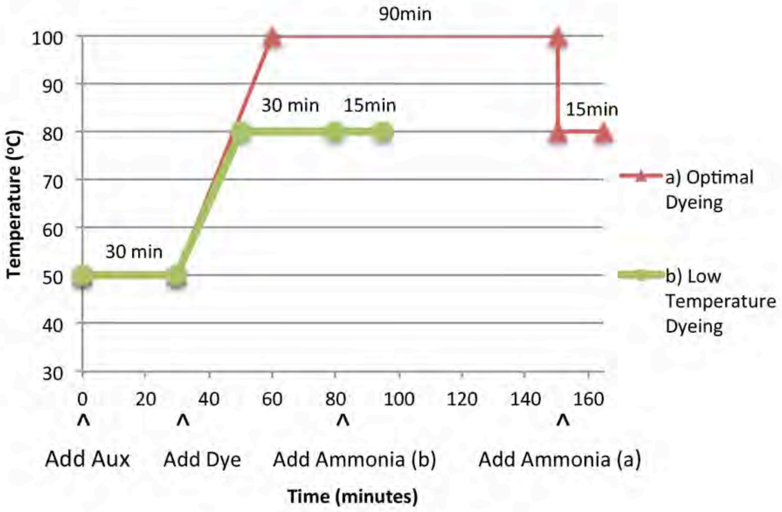


Figure 5.6 Dyeing Schematic for Reactive Dye comparing optimal dyeing conditions for wool with low temperature dyeing conditions used after laser irradiation.

5.2.4 Dye Exhaustion.

The energy densities 3.06J/cm^2 to 3.57J/cm^2 were chosen to provide a range of results for testing purposes without causing thermal damage to the woollen textile. The samples were then dyed with Lanasol blue reactive dye in controlled conditions. At optimal conditions of 100^{o}C, 90 minutes, the dye bath has the potential to be fully exhausted at the end of the dyeing process (Huntsman, 2007). A fully exhausted dye bath would result in insufficient dye remaining in the liquor for adequate absorption readings to be taken using a spectrophotometer. To ensure only partial exhaustion, a high concentration of dye at 4% owf was chosen and the dye bath held at sub-optimal dyeing conditions of 80^{o}C for 30 minutes.

After dyeing, the absorbance of the remaining liquor from each of the five parameters was measured using a spectrophotometer. This was then used to calculate percentage exhaustion relative to the initial dye bath concentration, before dyeing. The results show an overall increase in exhaustion of the dye bath as laser energy density increases as seen in the graph in Figure 5.7. This indicates a corresponding increased dye uptake by the fabric substrates. At the lower than optimal temperatures of 80^{o}C, exhaustion of dye has increased by a significant 9-10% on all laser treated samples.

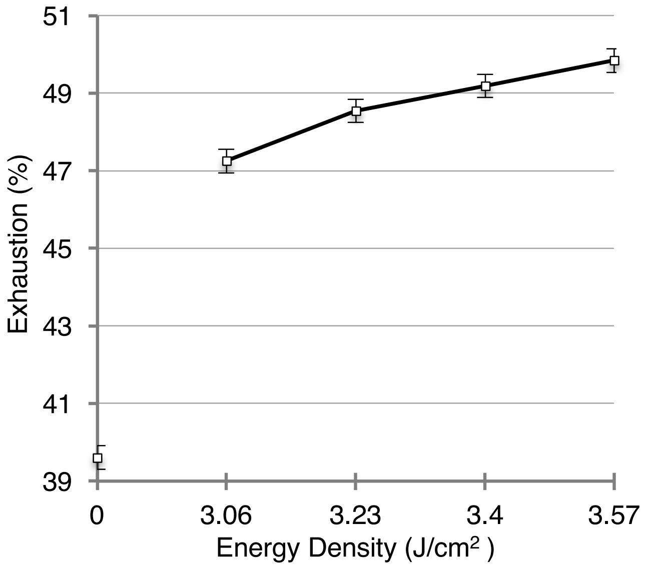


Figure 5.7 Graph Showing % Exhaustion of Dye from Dye Bath at Increasing Laser Energy Densities

5.2.5 Colour Measurement

The laser irradiated samples were measured before and after dyeing, using a reflectance spectrophotometer for CIE L*a*b* values (Table 5.1). The colour difference values were recorded and plotted on the graph in Figure 5.8, examining competitive dying between laser irradiated front, and untreated back of samples. For a controlled comparison, it was important to examine the colour measurement results of the laser irradiated, undyed samples. Therefore before dyeing, the colour difference between laser-treated parameters and untreated control was measured. This is represented on the graph as ΔE_0 line 3 (Figure 5.8), which shows a very shallow fluctuating line with values below 1, up to 3.4J/cm^2. Beyond this energy density, the colour difference soars to a difference value of 6.71 revealing the threshold laser parameter before discolouration through burning occurs. This result has significance proving laser discolouration prior to dyeing did not cause effect or influence on the colour levels after dyeing at energy densities up to and including 3.4J/cm^2.

The increasing difference values after dyeing are visualised in graph form, showing rising curves for each of the difference values ΔE_1, ΔL*, Δa* and Δb* (Figure 5.8). 3.06J/cm^2 shows a significant increase in colour difference (ΔE_1*) and darkness (ΔL*) of the laser treated substrate, which continued to rise with increased laser energy density. There is a less significant rise in a* and b* values (Δb*) indicating blue and green hues were reduced as the samples became darker. Both a* and b* values rose steeply after 3.4J/cm^2. The graph patterns indicate a consistent increase in all difference values for dyed samples at energy densities of 3.06J/cm^2 and above. However, after 3.4J/cm^2, a steep slope in the graph indicates a significant increase in colour difference, suggesting that dye uptake intensified significantly beyond this energy density. The highest colour difference in the tested range that did not cause discolouration or thermal damage to the textile surface was identified as 3.4J/cm^2. We can conclude this to be the optimum setting to gain greatest dye uptake without causing unwanted degradation to the wool fibre. Beyond this parameter, discolouration and unwanted pyrolysis prior to dyeing has been observed.

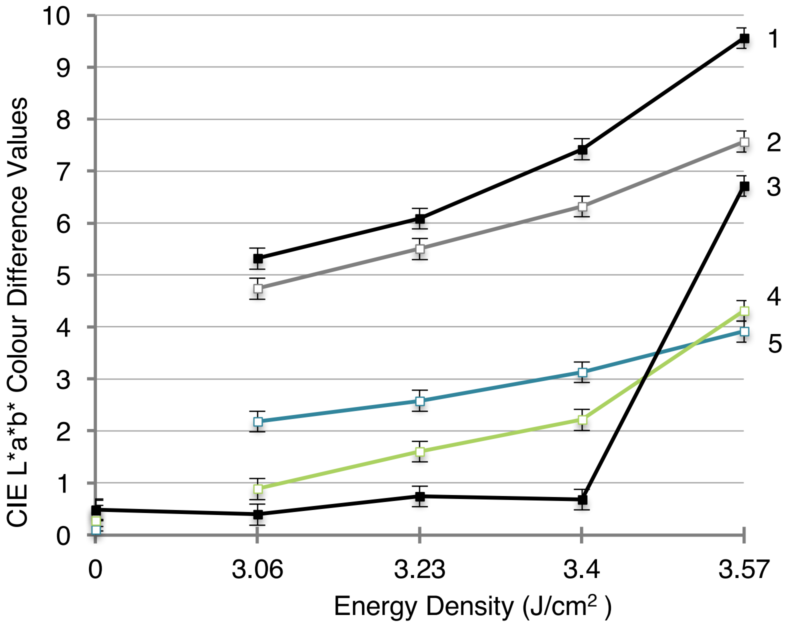


Figure 5.8 CIE L*a*b* Colour Difference: 1) ΔE_1 2)ΔL^* 3)ΔE_0 4)Δa^* 5)Δb^*

Table 5.1 shows CIE L*a*b* values for both front and reverse of the samples. It can be seen that colour remains consistent between untreated reverse sides and the control across all samples with a SD of less than 0.5. If competitive dyeing were taking place we would expect the reverse side samples to show decreasing colour levels proportional to the increase on the laser treated front. Together with the morphological information derived from the SEM images, this suggests that the laser modification of wool fibres allows more dye to enter the fibres on the laser treated surface. The increased dye exhaustion verifies that a greater affinity for dye is attained.

Sample	**Energy Density [J/cm^2]**	**Colometric Data Laser Irradiated Un-dyed**	**Colometric Data Untreated/ Dyed Back**			**Colometric Data Laser Irradiated/ Dyed Front**				**Fastness to Washing** BSEN ISO-C10: 2007 Test B			**Fastness to Rubbing** BSEN ISO 105-X12: 2002			**Tensile Strength** BSEN ISO 13934-1: 1999			
		ΔE_0	**L^*_0**	**a^*_0**	**B^*_0**	**L^*_1**	**a^*_1**	**b^*_1**	**ΔE_1**	**Cotton**	**Wool**	**Nylon**	**Dry**	**Wet**	**Colour Removal**	**Load at Break (N)**	**Tensile Strain at Break (%)**	**Max Load (Kg)**	**Tensile Strain at max load (%)**
a	0	0.49	30.40	-9.18	-23.17	30.40	-9.18	-23.17	0.47	4/5	4/5	4/5	4/5	4	4	339.03	30.96	342.11	29.48
b	3.06	0.40	29.83	-8.72	-23.20	25.09	-6.53	-22.32	5.32	5	5	5	4/5	4/5	4/5				
c	3.23	0.74	30.92	-9.05	-23.24	25.42	-6.47	-21.64	6.09	5	5	5	4/5	4/5	4/5				
d	3.4	0.68	30.23	-9.14	-23.02	24.22	-6.03	-20.80	7.42	5	5	5	4/5	4/5	5	228.11	17.72	229.70	17.39
e	3.57	6.71	30.76	-9.08	-23.09	23.19	-5.16	-18.78	9.56	5	5	5	4	3/4	3				
SD			0.43	0.18	0.09	2.78	1.50	1.68											

Table 5.1 Results for colometric, fastness and strength properties of laser irradiated /dyed wool

5.2.6 Fastness Properties

To examine the effect of laser treatment on the functional properties of wool, laser irradiated samples at increasing energy densities were tested to determine their colour fastness to washing and rubbing.

The international standard test method, *BS EN ISO 105-C10: 2007*, was used to determine the effect of washing on colourfastness of the laser irradiated and dyed samples. A multi fibre strip was attached to each sample, which was then agitated under controlled conditions of time and temperature in a soap solution. After rinsing and drying, colour change of the fabric sample and the staining on the adjacent fabric were assessed by comparison to the original fabric. A value from 1 to 5 is awarded using the appropriate grey scales (see Chapter 4), where a score of 1 is a poor colour fastness result and a score of 5 equates to no loss of colour or no staining.

Colourfastness to rubbing under both wet and dry conditions was determined by the *BS EN ISO 105-X12: 2002* standard test method. Test samples were rubbed with a dry cloth and a wet cloth using a crockmeter, which provides a constant rubbing pressure of 9N. The staining of the rubbing cloths are then assessed using the same grey scale scoring system as above (described in detail in Chapter 4).

The results in Table 5.1 show that fastness performance has not been negatively affected by washing or rubbing. Fastness results of the laser pretreated samples at the reduced time and temperature are consistent with the dye manufacturers results at the recommended higher dye temperature and time (Huntsman, 2007). The untreated control shows slight loss in fastness performance, suggesting that the laser irradiated samples give improved fastness to washing and rubbing at lower temperatures. Therefore this laser dyeing technique provides a means to reduce dyeing temperature without compromising colour fastness quality. At the highest laser energy density we begin to see a reduction in fastness to rubbing. This is due to the onset of pyrolysis with higher thermal energy as observed under microscopy. Loose burnt debris was removed by the rubbing test (*BS EN ISO 105-X12: 2002*). The results show that laser parameters between 3.06J/cm^2 and 3.4J/cm^2 are suitable for dye uptake improvement without loss of colour fastness or thermal degradation of the woollen fibres.

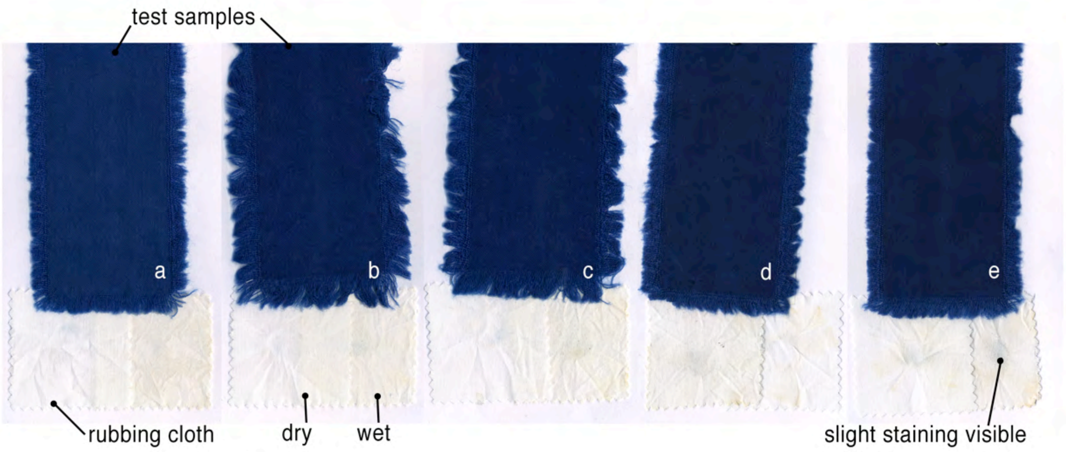


Figure 5.9 Fastness to rubbing of laser irradiated, dyed wool: a.) 0 J/cm^2, b.) 3.06J/cm^2, c.) 3.23J/cm^2, d.) 3.4J/cm^2, e.) 3.57J/cm^2

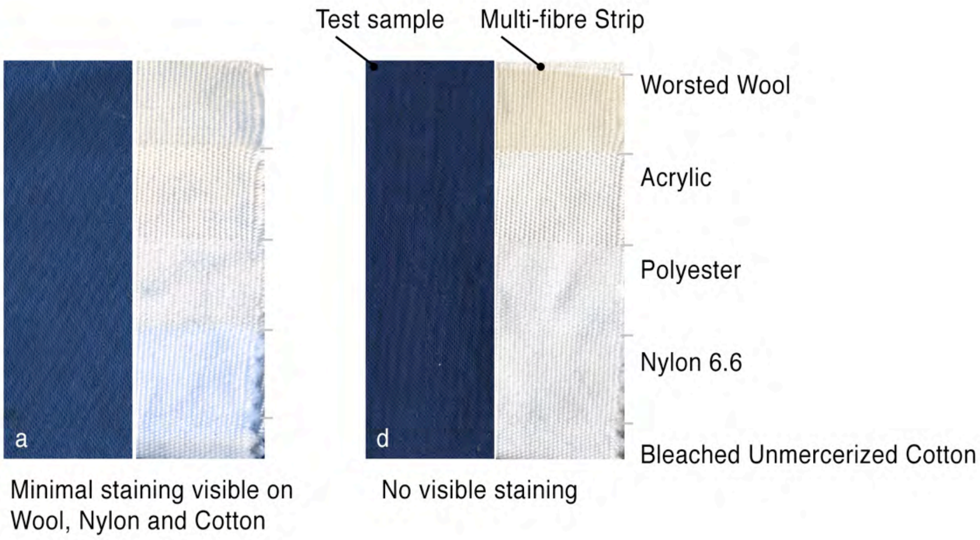


Figure 5.10 Fastness to washing of laser irradiated, dyed wool: a.) 0 J/cm^2, d.) 3.4J/cm^2

5.2.7 Tensile strength

Twenty 5 x 30cm 100% wool strips were prepared; ten were laser-irradiated at the highest optimal laser/dyeing parameter which was determined as 3.4J/cm^2, and ten remained untreated as controls. Each strip from both sets was tested for tensile strength, with the load and strain recorded using the standardised test (*BS EN ISO 13934-1: 1999*) on Instron tensile testing apparatus, as described in Chapter 4. The table of results (Table 5.1) shows the mean figures for both sets of tested samples. Results of tensile strength testing reveal laser irradiation to have a negative effect on the overall tensile strain that can be applied to wool. While the bulk properties of the textile on the non-laser irradiated areas remain intact, the laser-removal of scales on the surface fibres of the wool causes some weakness in the laser irradiated areas. The results show a reduction in tensile strength by 39%, which is below the recommended tolerance of +/-2% (Camira, 2015) when compared to the untreated control. However, the fabric was able to withstand forces of 228N before breaking, which is within minimum tolerated levels for a range of woven interior and apparel fabrics. For example, 150N is reported as an acceptable load in commercial specifications for a standard shirt or dress, 180N for bedding and 200N for a blazer or trousers (Qvc, 2012). A minimum breaking load of 22kg remains compliant with guidelines set by the Association for Contract Textiles, ACT (2014) for a woven upholstery fabric. Therefore, if this laser dye technique was to be used for commercial application, a fabric of the tested weight would remain well within commercially tolerated minimums.

Optimal parameters have been discussed in this chapter, to maximise the colour effect while minimising thermal damage. However, it is worth noting strategies to further reduce negative impact on the fabric strength. The results shown provide the tensile strain for the darkest tonal values. Lower values could be used to achieve improved overall strength. In addition, ways to manage and overcome laser-induced damage can be designed into the digital graphics used to process the textile substrate. The tested samples were subject to all-over laser irradiation. The use of pattern spacing could ensure laser marked areas were not densely concentrated. This would avoid creating points of weakness in the design. Alternatively, lower energy densities could be used within the range to cause enhanced dye uptake, albeit with a more subtle colour change result.

5.2.8 Laser Pre-treatment to dyeing for Textile Design

The colour difference between treated and untreated areas of the fabric substrate are most significant at 3.4J/cm^2, showing potential for CAD controlled laser treatment to be used as a design tool/technique through targeted processing. A mark making test sheet was created using the graphic software, Photoshop, with a range of patterns and imagery as shown in Figure 5.11. The test sheet includes a range of linear, gradiated and photographic marks to test the quality of line and tonal differentiation that can be achieved using the laser assisted dyeing technique.

Wool fabric was laser marked with the test markings using a CO_2 laser with an energy density of 3.4J/cm^2. After dyeing with blue reactive dye, the laser marked areas appeared tonally darker on the surface of the cloth. Examination of the sample reveals that tonal gradients, and a precise level of detail are achievable for linear, block filled shapes and halftone effects. Subtle tonal information has also been possible allowing painterly and photographic imagery to be processed.

From the results of the test sheet (Figure 5.11), the most effective graphics were chosen to take forward for design development. Geometric patterns consisting of solid and linear shapes were laser marked on 100% wool fabric, followed by dyeing with reactive dye. The resulting samples, shown in Figure 5.12, give a two tone all over pattern. The technique has the potential to be used on woollen textiles of varied constructions and weights that could be suitable for fashion or interior applications.

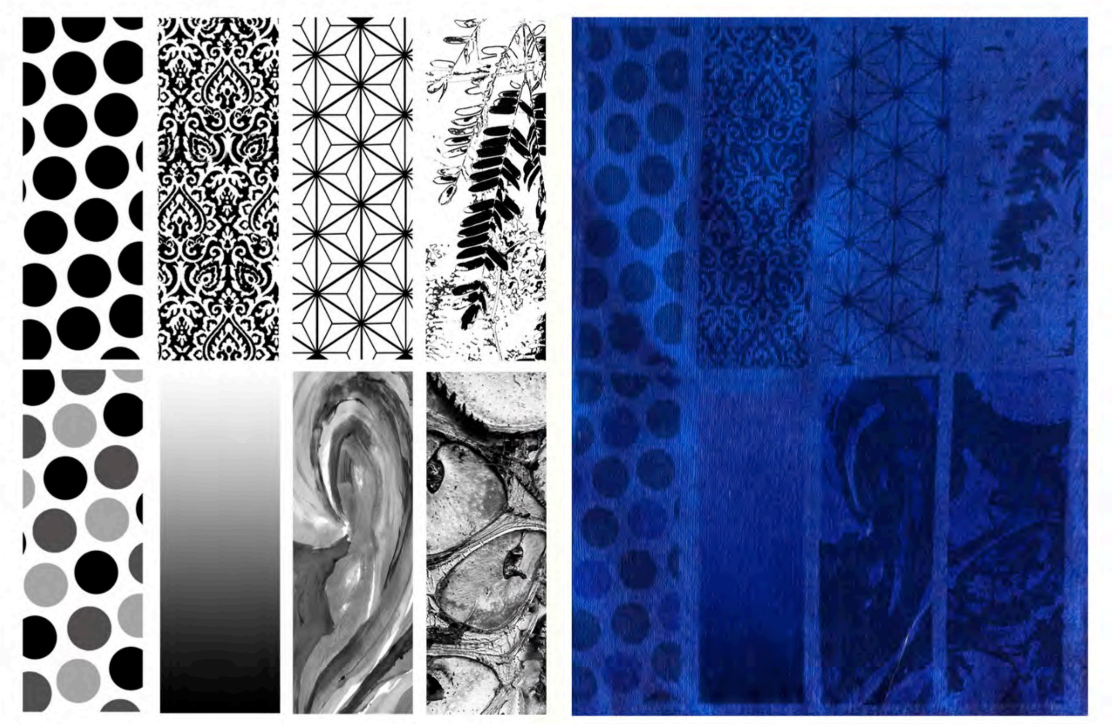


Figure 5.11 Laser marking test sheet as a CAD and processed on a wool textile sample.

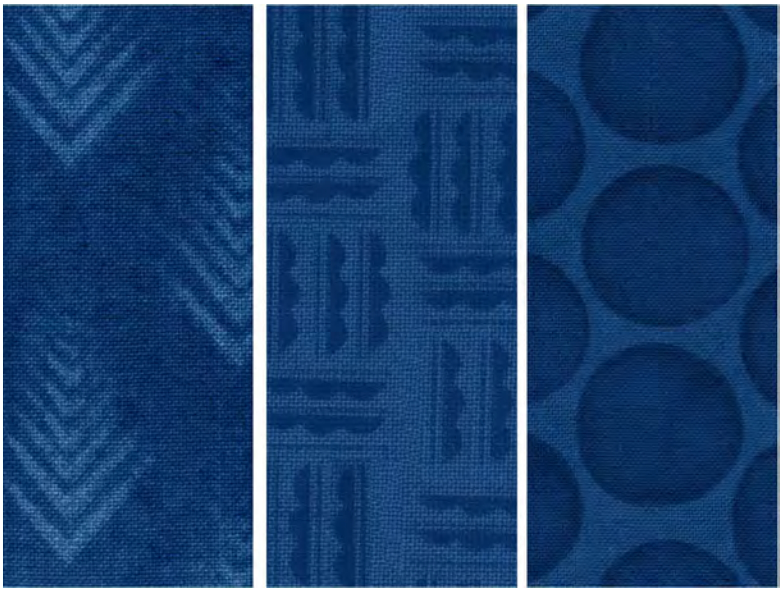


Figure 5.12 Design Samples: CAD controlled tonally darker areas produced by laser irradiation prior to dyeing.

5.2.9 Laser pre-treatment of textured Wool Surfaces

Having established the technique on a plain weave, 19 micron wool, alternate wool fabric weights and constructions were tested. The following images show successful results on a 25 micron worsted wool twill (Figure 5.13b) and a thicker 32 micron British wool (Figure 5.13a).

Figure 5.13 a) Laser Pre-treated and dyed 100% British Wool Heavy Woven Twill b) Laser Pre-treated and dyed 100% Worsted Wool Twill

5.2.10 Laser Moulded Wool

The effect of laser irradiation on a milled wool fabric was examined. On testing of laser parameters, it was found that thicker brushed or milled wool fabric could withstand increased laser energy density and surface burning without affecting the bulk properties of the fabric. At energy densities in excess of 3.57J/cm^2, increased burning on the surface left a layer of carbon debris on the laser irradiated areas, which could be removed by gentle abrasion. It was shown that laser engraving could be used to remove or ‘burn off’ the felted or brushed surface fibres of milled wool, revealing the underlying woven structure. On removal of the burnt debris, the underlying woven structure was revealed, undamaged. This technique provided contrasting relief, where the surface layer of fibres was removed as well as a contrast in texture between the laser engraved and non-engraved areas. Figure 5.14 shows the contrasting surface relief effects of varied parameters of laser irradiation, after the burnt debris was removed.

Figure 5.14 Contrasting relief on milled wool sample after varied parameters of laser irradiation, after removal of burnt debris

Figure 5.15 shows a geometric pattern laser etched into the brushed wool fabric; a) shows the sample during the process of removing the burnt debris, b) shows a close up of the sample after the burnt debris was removed. It can be seen that the brown carbon debris has stained the fabric surface. The sample was then washed in a gentle cycle of equivalent to wash fastness test *a* (see chapter 4), using a non-ionic detergent to remove any remaining staining or burnt debris trapped between the surface fibres. Washed samples that have been patterned by the laser can be seen in Figure 5.16, where the subtle change in relief and surface texture provides an effective surface design on the brushed wool textile.

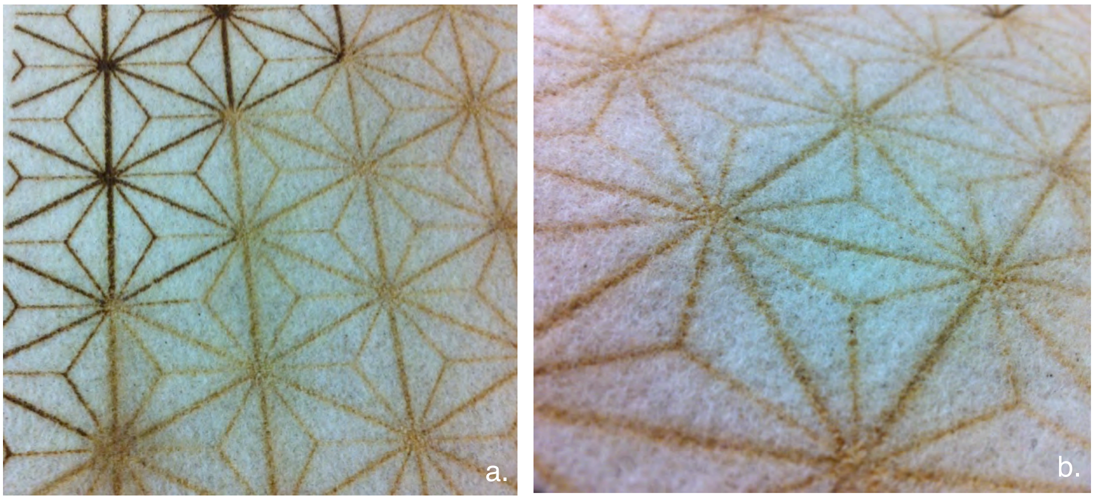


Figure 5.15 a) Removal of burnt debris of laser irradiated geometric pattern on milled wool. b) Close up detail shows brown carbon staining after debris removed.

Figure 5.16 Laser engraved milled wool design samples, after washing.

A similar laser engraving technique was described by Matthews (2011) on felted Cashmere, and by Woolmark Company (2012) on felted Merino. However, the processes they described was solely a textural effect. The work discussed in this section furthers the process through colouration techniques on milled wool. With the knowledge gained from previous laser pre-treated wool experiments described in this chapter, a selection of laser moulded brushed wool samples, were dyed at 80°C. As hypothesised, dyeing the laser moulded samples resulted in an increased uptake in the laser engraved areas to provide multi-tonal patterning combined with contrasting texture and relief effects on the surface of the cloth. Figure 5.18 and Figure 5.17 show a selection of laser moulded and dyed samples, providing three- dimensional relief surfaces in addition to multi-tonal design effects.

Figure 5.17 Laser engraved and dyed milled wool design samples.

Figure 5.18 Laser engraved and dyed milled wool design samples.

5.2.11 Discussion of Wool Results

This study has found that a CO_2 laser marker can be used to irradiate wool fabrics prior to dyeing to achieve differential dye uptake across the surface of the cloth. A technique has been developed allowing a pattern to be marked on wool using a CO_2 laser followed by dyeing. After dyeing, the laser-marked pattern will appear tonally darker on the surface of the cloth. Microscopic analysis has shown that laser irradiation removes the outer scales from individual wool fibres on the surface of a woollen textile. It has been discussed how the modification of these scales allows easier penetration of dye into fibre, so that laser marked areas will allow an improved dye absorption compared to the non-treated areas. Usually, high temperatures and long processing times are required to achieve maximum dye uptake on wool (Lewis, 1982). However, this study has shown that dyeing laser pre-treated wool at a reduced temperatures can achieve an elevated level of dye uptake.

As well as an apparent visual effect, dye exhaustion results have indicated an increasing amount of dye uptake is achieved as the laser energy density delivered to the fabric is increased. Colour data testing corroborates, increased colour intensity occurs after dyeing as laser energy density increases. Analysis of CIE L*a*b* colour difference values of laser treated wool before dyeing confirms that increased colour difference is a result of increased dye uptake, not from laser discolouration, up to an energy density of $3.4 J/cm^2$. This is the optimum energy density to achieve greatest colour difference before pyrolysis begins on the surface of the wool fabric. Up to this optimum level, parameters can be chosen to achieve a variety of mark making and gradiated tonal effects without loss to performance properties of the fabric from washing or rubbing to an ISO standard.

The lower temperature and reduced dyeing time is estimated at a significant 54% energy saving when compared to the manufacture's recommended dyeing process (Huntsman, 2007).

The study has shown through CIE L*a*b* measurement that colour can be defined through laser energy density selection. After calibration, this could be used by designers to define exact colour values or pantones with a level of control that ensures repeatability. The technique can be used to create halftone, linear and monochrome effects on wool textile substrates. A method for laser engraving the surface of milled wool fabrics was also described which provided three-dimensional relief surfaces in parallel with the colouration advantages.

5.3 Surface and Dyeing Properties of Wool Blends for Textile Design

Recent studies have shown that photothermal properties of laser irradiation has the ability to affect the surface of textile fibres on a microscopic level, altering polymer structures of synthetic fibres thereby allowing an increased affinity for dye on the substrate (Montazer et al, 2012; Kan, 2008; Wong et al, 2007; Bartlett, 2006; Akiwowo, 2015) as Discussed in Chapter 2. Previous studies have evidenced that laser treatment increases dye uptake in wool (in section 5.2 above) and polyester (by technical papers discussed in Chapter 2). However these techniques have limitations in colour patterning allowing only monochromatic results.

Blended fabrics can offer advantages over virgin materials allowing properties of both fibres to increase the desirability and performance of the textile. Furthermore, introducing single (mixed) bath dyeing into the process offers potential for further significant reductions in waste water effluent, energy and processing time for blended fabrics. The following study examined the effect of CO_2 laser irradiation as a pre-treatment to dyeing wool-polyester blended fabrics (polywool) using reactive and disperse dyes. The laser technique was explored for it's potential to achieve multicoloured design outcomes on blended textiles.

5.3.1 Laser Parameters

Three sets of polywool fabric were laser irradiated at energy densities of 2.89-3.9J/cm^2 at 5000mm/s and an untreated, 0J/cm^2 control. Prior testing had established the range of laser parameters in which to operate. Each set of samples was dyed in a separate vessel containing either; Lanasol Reactive Blue dye, Disperse Blue dye or a mixed bath containing Lanasol reactive Red and Disperse Blue Dye prepared at a dye concentration of 4%. After dyeing, the samples were examined to determine the effect of laser irradiation on the surface and dyeing properties of polywool fabric. From visual observation of the resulting samples, shown in Figure 5.19, depth of shade appeared to increase as the energy density delivered to the substrate increased, corroborating with results from the previous study on wool. Microscopic examination was carried out, with an aim to further identify the observed effects, discussed in the following section.

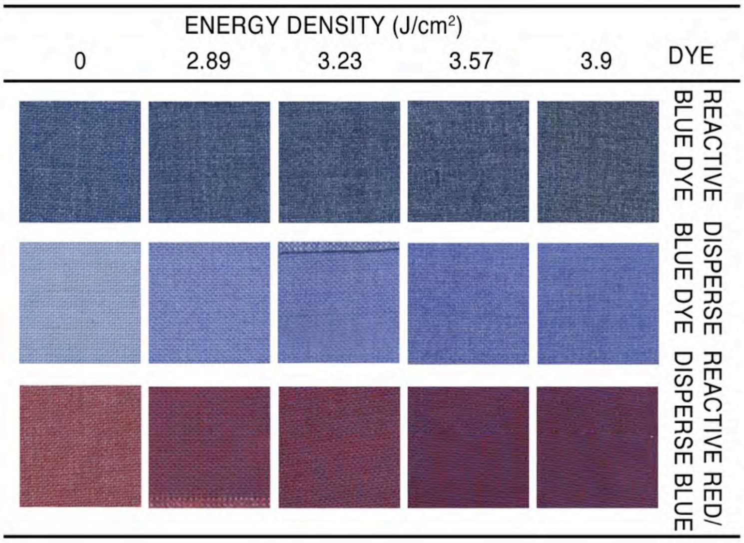


Figure 5.19 The effect of laser irradiation on dyeing behavior of polywool

5.3.2 Surface Observation.

Figure 5.20 shows a series of micrographs of the laser irradiated polywool dyed in a reactive dye bath. Reactive dye has specificity towards natural fibres, allowing the wool to uptake the dye while the polyester remains undyed. In Figure 5.20, The blue strands indicate the dyed wool fibres, while the polyester can be seen in white. Micrograph *a* shows the untreated control, with a clear definition between the wool and polyester fibres. Individual fibre strands can be identified. By contrast, as the laser energy density increases in micrographs *b-e*, it can be seen that individual polyester fibre strands loose their definition as the white polyester begins to melt under the heat of the laser. As the energy density increases further, increased melting can be observed. The polyester fibres that have melted and re-solidified have formed together, expanding and eventually protruding on to the blue wool fibres. The expanded area of polyester on the surface of the cloth shifts the balance of colour. More of the white polyester can be seen on the surface, visually resulting in a lightened effect at the higher energy densities.

A colour change effect can also be seen across the laser parameters in Figure 5.21, which shows polywool samples dyed in a disperse dye bath. In this series of micrographs, the wool fibres remain undyed (white), while the blue areas indicate dyed polyester due to disperse dye’s specificity towards synthetic fibre types. As discussed in the literature review Chapter 2 and Experimental conditions Chapter 4, laser irradiated polyester has an increased affinity for dye uptake. As laser energy density increases, the areas of polyester in the polywool show increasingly darker shades of blue.

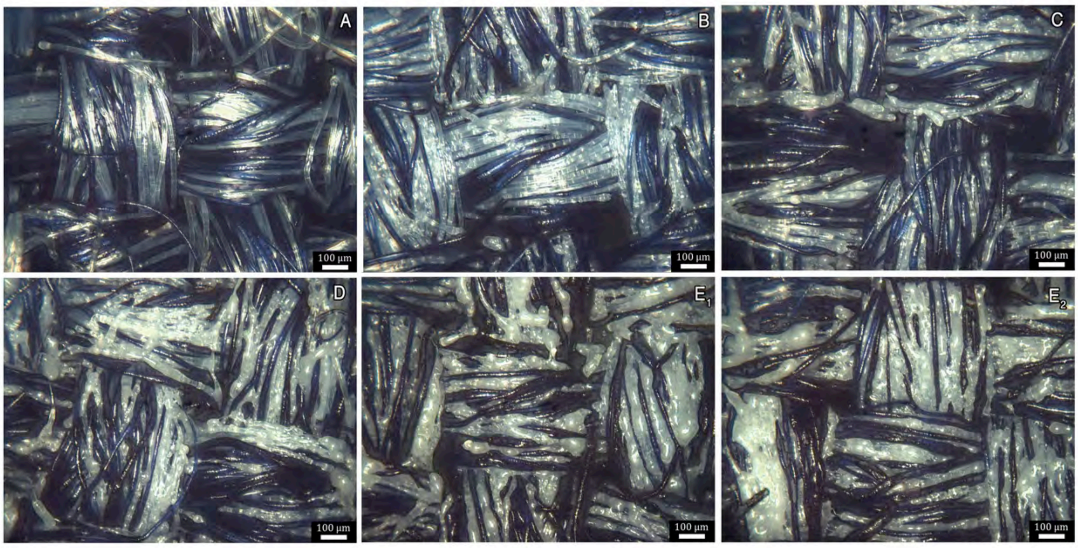


Figure 5.20 Micrographs of Poly/Wool dyed with Blue Reactive dye after laser irradiation at a) 0J/cm^2 b) 2.89J/cm^2 c) 3.23J/cm^2 d) 3.57J/cm^2 e) 3.9J/cm^2

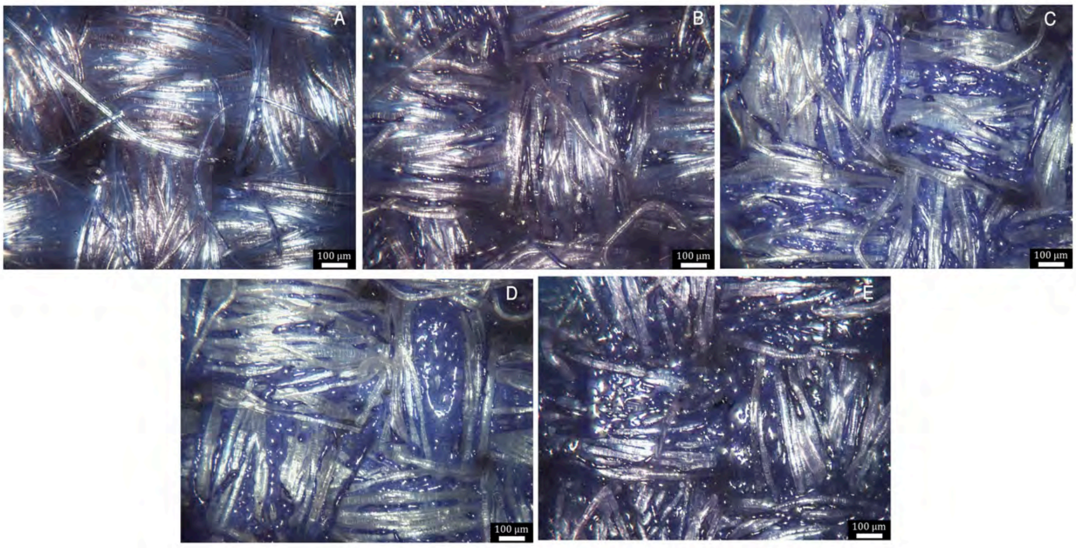


Figure 5.21 Micrographs of Poly/Wool dyed with Blue Disperse dye after laser irradiation at a) 0J/cm^2 b) 2.89J/cm^2 c) 3.23J/cm^2 d) 3.57J/cm^2 e) 3.9J/cm^2

Figure 5.22 shows the micrographs from a laser irradiated polywool dyed in a mixed dyebath of blue disperse and red reactive dye. The specificity of the two dyestuffs corresponds to the resulting blue polyester and red wool fibres as shown in the micrographs. Similar conclusions can be drawn from these micrographs as from Figure 5.20 and Figure 5.21. At temperatures of 70°C, the polyester remains undyed in the untreated control allowing the red to visually dominate the surface colour. However as laser energy density increases, the uptake of disperse dye improves. In micrographs d and e increased melting and expansion of the reformed polyester combined with increased affinity for dye in the laser treated areas, result in a strong blue predominating over the red wool. The shift in colour balance shows how the polyester properties dominate the laser treated areas at these higher energy densities. The clear differentiation between wool and polyester dyed with contrasting colours combined with the shift in dominant fibre properties between laser irradiated and untreated areas of the substrate could be exploited for design purposes. Targeting the laser irradiation in a defined pattern followed by dyeing in a mixed dye bath, could impart multicoloured designs on a polywool textile.

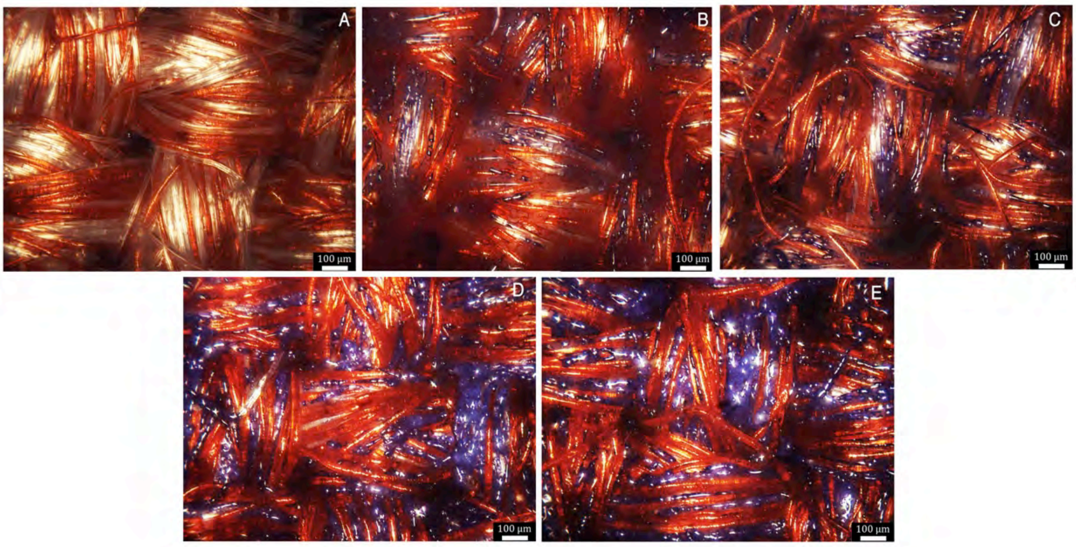


Figure 5.22 Micrographs of Poly/Wool dyed in a mixed dye bath of Blue Disperse and Red Reactive dyes after laser irradiation at a) 0J/cm^2 b) 2.89J/cm^2 c) 3.23J/cm^2 d) 3.57J/cm^2 e) 3.9J/cm^2.

5.3.3 Effect of Dye Temperature

To optimise the mulitcolour effects achieved by laser pre-treating and dyeing a polywool substrate, the effect of dye temperature on the colour results was examined. Table 5.2 shows the ‘palette’ of colour samples achieved by altering dye temperature and laser energy density. This colour chart can be used as a shade card or guide for designers wishing to achieve a mixture of shades.

5.3.4 Colour Measurement.

The colours achieved as a result of altering dye temperature and laser energy density were quantified using the CIE l*a*b* colour space system. This measured the colour levels and determined the most effective parameters for achieving a multicolour effect.

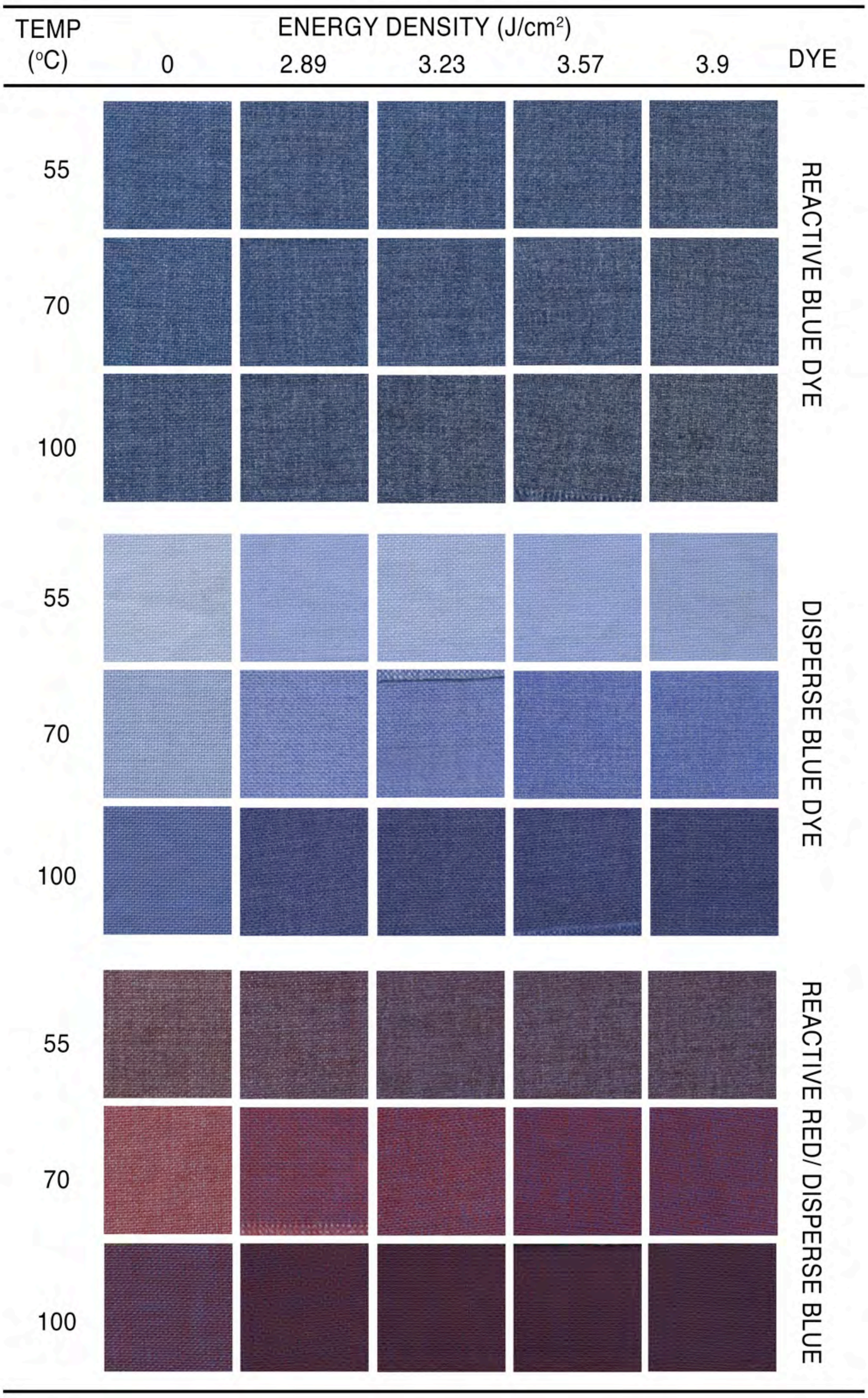


Table 5.2 Table showing colour of dyed and laser irradiated polywool samples at varied temperature in reactive, disperse and mixed dyebaths.

The colour data from the reactive dyed polywool at all tested temperatures reveals an initial decrease in L values indicating that colour darkens after laser irradiation (Figure 5.23). However after this initial increase, both the L and b values increase signifying a lightening of colour which gets progressively less blue (Figure 5.24). This is consistent with the observation from the micrographs, which show an increase in polyester characteristics with increasing laser energy density. Where the polyester properties dominate, the reactive dye becomes less effective resulting in reduced uptake after laser irradiation. The colour difference results (Figure 5.25) reveal all tested temperatures to provide a consistant increasing level of colour difference with increasing laser energy density on reactive dye.

The colour data from the disperse dyed polywool shows a decrease in L values (Figure 5.26) indicating that colour gets darker with increased laser energy density at all tested temperatures, while b values show a significant drop (Figure 5.27) corresponding with an increased in blue colour after laser irradiation. The results show fluctuations in b values as laser energy density increases. In combination with the surface observation and L values, it can be concluded that this was due to a high depth of shade of the disperse dye moving toward a deep navy colour therefore less of a ‘pure’ blue colour was obtained, as dye uptake increases. The colour difference results (Figure 5.28) reveal 70°C to provide the highest level of colour difference between laser irradiated and non-treated areas of polywool dyed with disperse dye. The difference is significantly higher at 70 °C.

The colour data from the mixed dye bath containing red reactive dye and blue disperse dyed polywool shows that laser irradiation results in darker colour result, indicated by a reduced L value across all temperatures, however the L* values then remained consistent with increasing laser energy density (Figure 5.29). A decrease in a* values across all temperatures indicates the colour result becoming less red as laser energy density increases (Figure 5.30), while the decrease in b* values corresponds to a general trend of increasing levels of blue (Figure 5.31). At 100°C the b* value fluctuates, as described in discussion of the disperse-only graph, this is due to the dark shades achieved moving towards navy at high temperatures. The colour difference graph (Figure 5.32) for the mixed dyebath reveals a sharp increase in colour difference with laser irradiation across all temperatures, with a significantly higher colour difference result occurring at 70°C. The results confirm 70°C to be the optimal dye temperature to achieve a high contrast colour result.

Figure 5.33 plots the a and b values of laser irradiated polywool dyed in a mixed dyebath of red reactive dye and blue disperse dye at 70°C. The shift in colour balance on the textile is visualised on the graph as it moves from red through purple towards blue with increasing laser energy density.

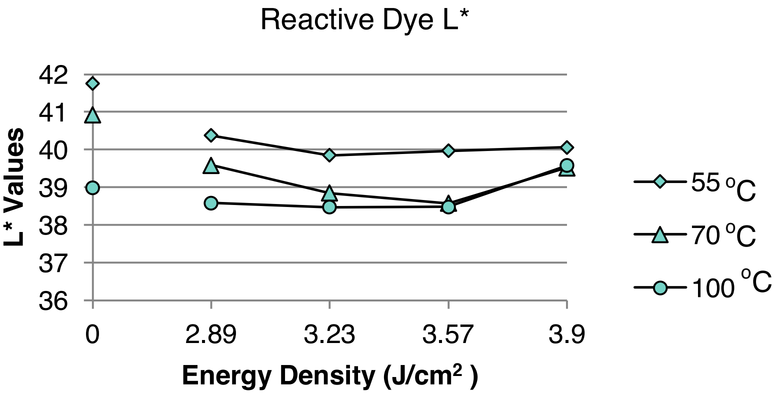


Figure 5.23 L* Values of polywool dyed in 4% blue reactive dye at 55, 70 and 100°C

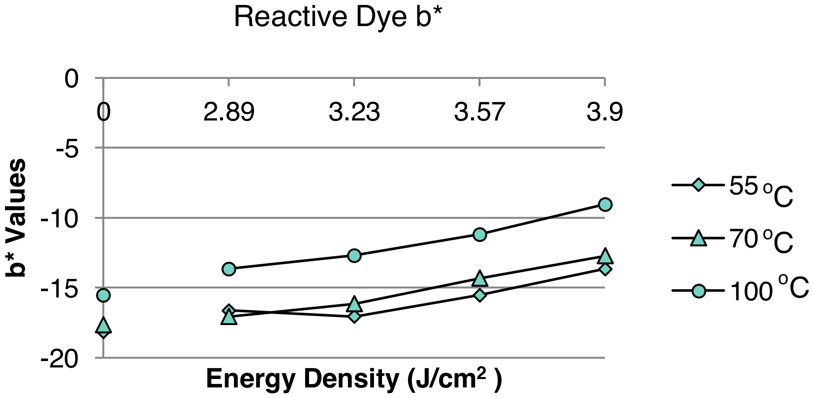


Figure 5.24 b* Values of polywool dyed in 4% blue reactive dye at 55, 70 and 100°C

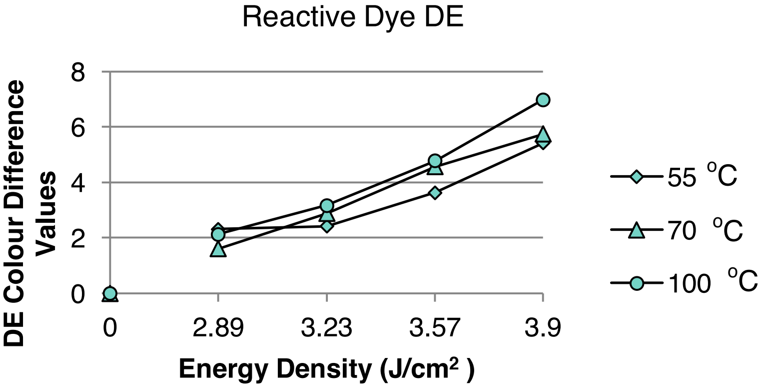


Figure 5.25 L* Colour Difference of polywool dyed in 4% blue reactive dye at 55, 70 and 100°C

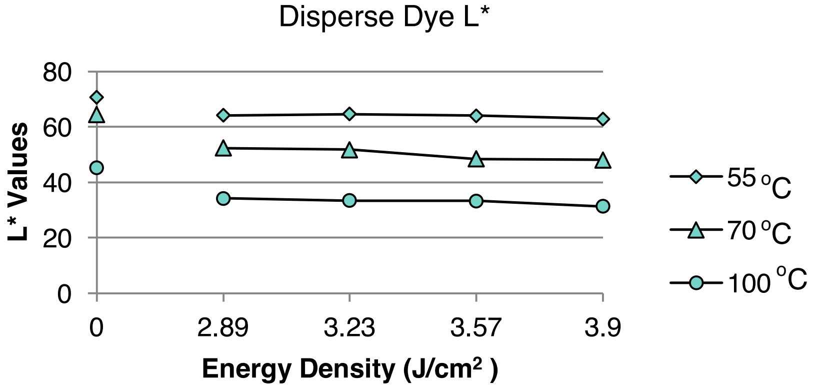


Figure 5.26 L* Values of polywool dyed in 4% blue disperse dye at 55, 70 and 100°C

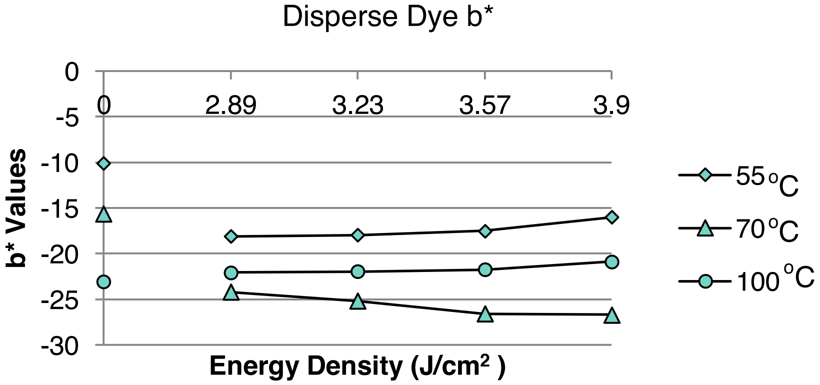


Figure 5.27 b* Values of polywool dyed in 4% blue disperse dye at 55, 70 and 100°C

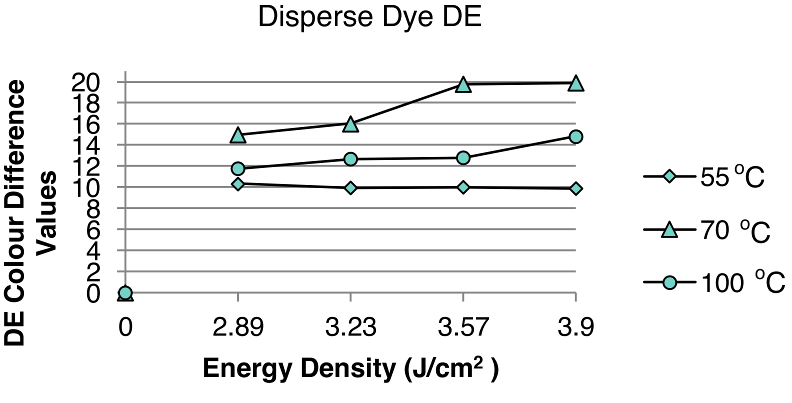


Figure 5.28 Colour difference of polywool dyed in 4% blue disperse dye at 55, 70 and 100°C

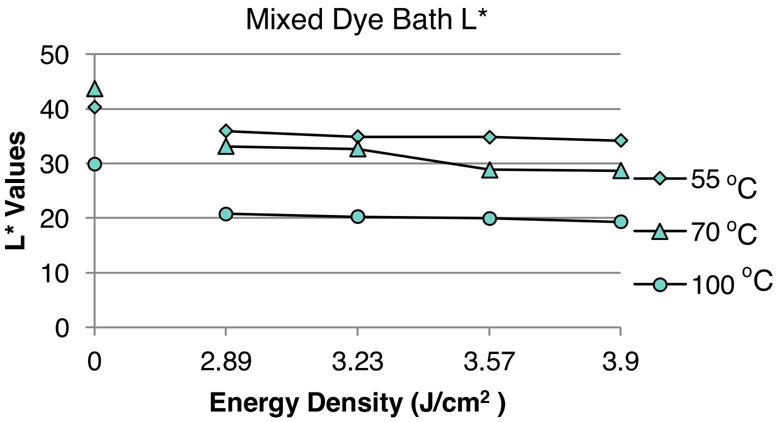


Figure 5.29 L* Values of polywool dyed in mixed red reactive/ blue disperse dye at 55, 70 and 100°C

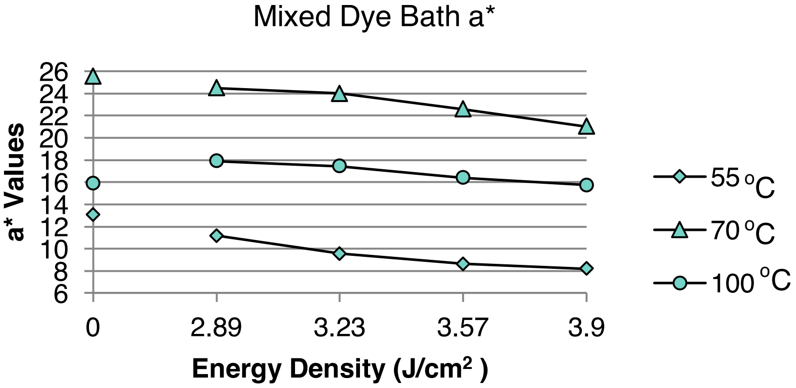


Figure 5.30 a* Values of polywool dyed in mixed red reactive/ blue disperse dye at 55, 70 and 100°C

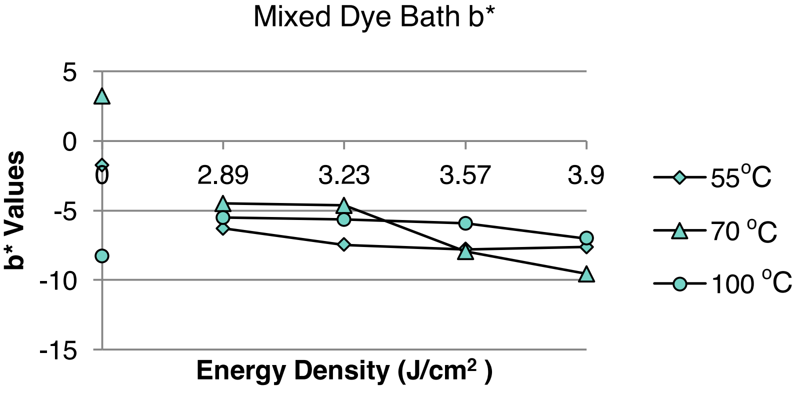


Figure 5.31 b* Values of polywool dyed in mixed red reactive/ blue disperse dye at 55, 70 and 100°C

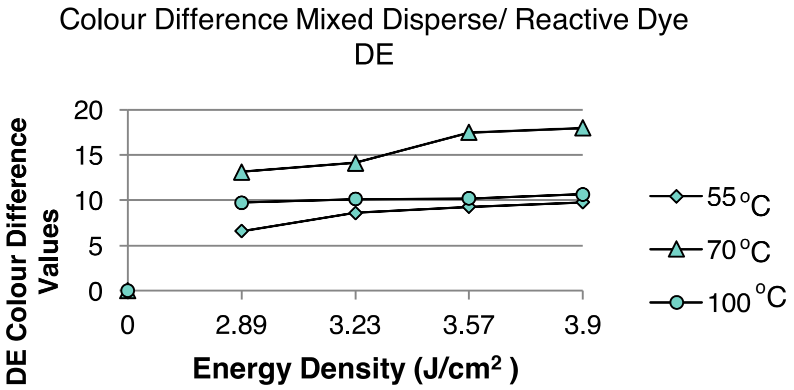


Figure 5.32 Colour difference of polywool dyed in mixed red reactive/ blue disperse dye at 55, 70 and 100°C

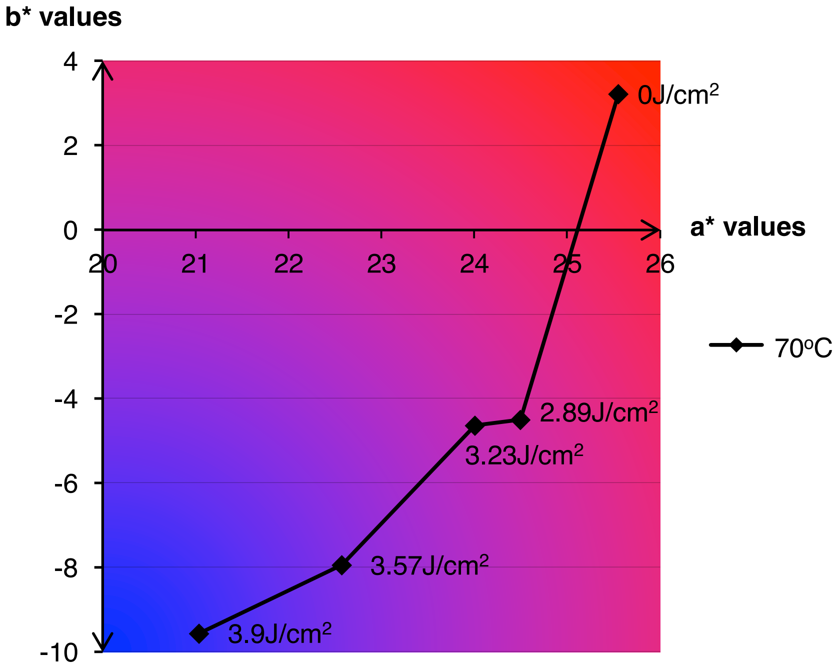


Figure 5.33 Effect of laser irradiation on colour values of polywool dyed in mixed red reactive/ blue disperse dye at 70°C

5.3.5 Fastness Properties

The results in Table 5.3 show that fastness performance has not been negatively affected by washing or rubbing. Fastness results of the laser pretreated samples at the reduced time and temperature are consistent with the dye manufacturers results at the recommended higher dye temperature and time (Huntsman, 2007). The untreated control shows slight loss in fastness performance, suggesting that the laser irradiated samples give improved fastness to washing and rubbing at lower temperatures. The results show that all tested laser parameters are suitable for colouration effects without negatively affecting the fastness properties of polywool.

Sample	Energy Density $[J/cm^2]$	**Fastness to Washing** BS EN ISO 105-C10: 2007 Test B				**Fastness to Rubbing** BS EN ISO 105-X12: 2002		
		Cotton	**Wool**	**Nylon**	**Polyester**	**Dry**	**Wet**	**Colour Removal**
a	0	5	4/5	4/5	5	4/5	4/5	5
b	2.89	5	5	4/5	5	5	5	5
c	3.23	5	5	4/5	5	5	5	5
d	3.57	5	5	5	5	5	4/5	5
e	3.9	5	5	5	5	4/5	4/5	5

Table 5.3 Results table for laser irradiated polywool

5.3.6 Tensile Strength

As discussed in the microscopic analysis, laser irradiation of dry textile goods in the energy density range used in this study was seen to cause microscopic thermal damage (melting) to fibres on the surface of the laser processed area. It is known from previous studies that laser induced fibre damage has a negative impact on the tensile strength of a laser treated textile (Chow, 2012; Bahtiyari, 2011). Melting of synthetics results in recrystalisation, leading to a harder, more brittle surface. Therefore, if melting occurs over a sufficient area of the textile, it can act as a point of weakness under strain. As discussed previously, ways to manage and overcome laser-induced damage can be designed into the digital graphics used to process the textile substrate. The use of pattern spacing can ensure laser marked areas are not densely concentrated. This would avoid creating a point of weakness in the design. Alternatively, lower energy densities can be used within the range to cause enhanced dye uptake, albeit with a more subtle colour change result.

5.3.7 Design and Colour

An experiment was carried out to reveal the most effective colour combinations for mixed dyeing of laser irradiated polywool. Fourteen dye baths were prepared containing acid and disperse dyestuffs at a concentration of 4% owf in the following colour combinations as shown in Table 5.4. An X in the table represents the dye combinations tested on 55/45 poly/wool samples (Figure 5.34). A Y in the table denotes dye combinations used in the subsequent experiment on 70/30 poly/wool samples (Figure 5.35).

Dye Type and Colour			Disperse Dyes				
			D1	**D2**	**D3**	**D4**	**D5**
			Orange Foron Brilliant Orange ERL 200	Blue Serilene Brilliant Blue	Violet C.I. Dispersol Violet 1	Red Foron Brilliant Scarlett S-RL	Turquoise Sandolan Turq. E-US 300
Acid Dyes	**A1**	Yellow Coomassie Yellow R	X Y	X			X Y
	A2	Magenta III Acid Magenta	Y	X	X	X	Y
	A3	Orange Coomassie Orange G			X	X	X
	A4	Green Nylosan Green E-GL	X				X

Table 5.4 Tested dye colour combinations for laser pre-treated polywool

The colour difference of the dye combinations was calculated. Higher colour differences have potential to indicate the combinations with greatest colour contrast, however visual inspection and the use of designer's tacit knowledge was deemed more appropriate for choosing colours for design development. Consequently, the fabric swatches shown in Figure 5.34 present the results in the form of a colour palette. The table can be used to determine the laser and dye parameters needed to achieve the chosen colour selection. To achieve the desired shade in a design, the corresponding energy density should be used to irradiate those areas of the design, followed by dyeing in the associated mixed dye combination.

The polywool used for experimentation had a composition of 55% polyester and 45% wool. Different ratios of wool/polyester may offer different colour results. A smaller range of colours was tested on a fabric with a blend ratio of 70% polyester, 30% wool at a dye concentration of 2%. The dye colours used are denoted with a Y in Table 5.4. The resulting swatches are shown in Figure 5.35. Despite the lower dye concentration and resulting lighter depth of shade compared to the previous experiment, a strong contrast between colours was demonstrated. These samples showed no 'muddying' of colours through dye staining, as occasionally evident when the composition ratio was narrow.

Colour combinations inspired by the palette tables were explored within a small range of design samples shown in Figure 5.36 to Figure 5.38. The laser patterned polyester / wool blend samples show that a range of aesthetic effects are possible, from subtle tonal shifts to strong colour contrasts suitable for designing textiles.

Figure 5.34 Laser irradiated 55/45 poly/wool samples: Colour swatch chart

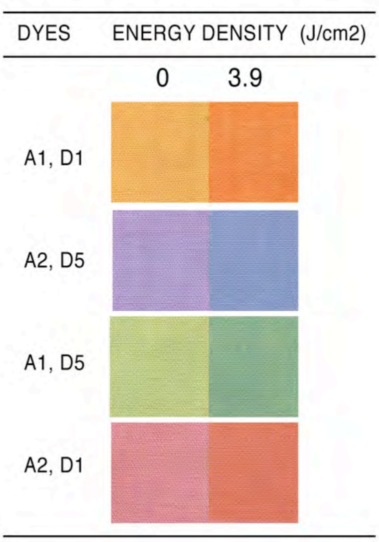


Figure 5.35 70/30 poly/wool colour swatch chart

Figure 5.36 Laser Patterned 55/45 Poly/Wool design samples

Figure 5.37 Laser Patterned 55/45 Poly/Wool design samples

Figure 5.38 Laser Patterned 55/45 Poly/Wool design samples dyed with contrasting disperse and acid dye colours.

5.3.8 Discussion of Polywool results

This study examined the effect of CO_2 laser irradiation as a pre-treatment to dyeing polywool blended fabrics using reactive or acid and disperse dyes. The results showed a novel method for generating multi-coloured textile surface design furthering the work of Addrison (2009) and Akiwowo (2015) through the use of polywool textiles, robust testing, detailed examination and explanation of the phenomenon.

The results indicated potential for generating textile surface design. Using a 10.6µm, 100 Watt CO_2 laser, optimum laser processing parameters for treating the fabric blend, were determined. Tests were then performed to analyse the effectiveness of the laser pre-treated and dyed fabric. Reflectance spectrophotometry, dye exhaustion and colour difference values were calculated, revealing that laser treatment has an increasing effect on the uptake of disperse dye while reducing the uptake of reactive or acid dye. Microscopic analysis of the laser treated fabric showed an increased area of synthetic polyester on the surface of the blended textile, reducing visibility of the wool fibres.

Laser irradiated samples were dyed in a mixed dye bath combining contrasting coloured disperse and acid or reactive dyestuffs. The polyester content in the untreated areas remained unaffected by the disperse dye at temperatures of less than 100^{o}C, therefore at lower temperatures, the wool properties dominated the non-treated areas. The opposite was true of the laser irradiated areas, where increasing laser energy density was shown to have an increasing effect on the uptake of disperse dye while reducing the uptake of reactive or acid dye. Investigations concluded that CO_2 laser irradiation lead to a change of state of the polyester content of the blended fabric. The polyester melted under the photothermal heat of laser irradiation. On cooling, the polyester reformed, expanding onto the wool fibres, in turn causing the polyester properties to dominate the laser irradiated area.

The laser marked area, with it's increased affinity for dye, allowed uptake of the disperse dye colour at lower temperatures. The shift in fabric properties across laser irradiated and non-treated areas of the textile combined with the specificity of the different dyestuffs resulted in a clearly defined multi-colour result. The technique was used to examine the design qualities that could be achieved to impart successful surface patterning on blended textiles as shown through design samples and colour palette tables.

5.4 Advantages for Sustainability and Manufacture

These techniques offer sustainable innovation in a number of areas. Laser enhanced dyeing offers potential reductions in energy and wastewater effluent through reduced dyeing temperatures and improved dye performance. Low temperature processing reduces overall dyeing time and temperature from standard practice, displaying potential for an estimated 54% reduction of energy during dye production in the case of the laser pre-treated/dyed wool (as shown in section 5.2.3). The ability to reduce energy used in dyeing by over half would offer exceptional savings with both economic and environmental benefits.

The laser marking operates a remote, non-contact set-up with the ability to place designs on finished products and across garment seams. This also offers potential for manufacturers to customise garment blanks to meet the requirements of retailers and consumers. This kind of responsive manufacture has the potential to reduce surplus stock. Furthermore, combining the functionality of the laser to perform multiple production tasks at once, such as pattern cutting or laser engraving milled wool as well as the laser dyeing techniques, would allow additional environmentally sustainable benefits to the process compared to outsourcing each individual stage of the production process, for example, fabric manufacture, screen printing and garment production in addition to storage and transport between these phases. Combining techniques in one stage has potential to offer fast response in today's fast changing market, with easily changed CAD files allowing smaller product runs than financially permitted by exposing individual screens for screen printing or die cutters for product pattern cutting. Therefore, as well as meeting the aim to offer sustainability through reduced temperatures and improved dye performance, laser technology could offer additional advantages through a potential change in production systems.

The laser technology used is commercially available and accessible to small businesses as well as to the larger manufacturer. This means that the techniques developed could be transferred to creative textile businesses including fashion and homeware applications. The results could enable design innovation and customisation to manufacturing and retailing businesses, alongside contribution to developing environmental strategies, thus increasing their competitiveness within the global market.

5.5 Chapter Summary

Novel methods of textile surface design for wool and wool blend textiles have been presented with design examples. Additional sustainability benefits and positive impacts for manufacturing have also been discussed.

Results have established that an increased dye uptake is achievable on the surface of fabrics by laser irradiation. Experiments have shown that CAD files can be used to mark out targeted areas to create specified designs. The reason for the increased dye uptake has also been explained. The tested substrates show high fastness to washing and rubbing, indicating that the dyeing quality meets current industry and consumer standards. It has been shown that the technique reduces overall dyeing time and temperature from standard practice, displaying potential for an estimated 54% reduction of energy during dye production. The study has resulted in new techniques to achieve multi-tonal and 3D relief surfaces on wool and multicoloured dye effects on polywool blends, providing new surface design tools for the textile designer through the use of laser technology.

Enhanced colouration through laser modification of textile fibres makes use of a photothermal reaction, which can cause unwanted fibre damage. Optimal parameters to avoid excessive fibre damage have been presented in this chapter, however potential for further improvement exists. The following chapter discusses the development of an alternate technique for laser dye colouration, using a dye fixation approach.

CHAPTER 6 : PERI-DYEING: LASER DYE FIXATION FOR TEXTILE DESIGN

6.6 Introduction

Existing techniques for digital laser dye colouration and patterning of textiles employ the laser as a pre-treatment to dyeing using a fibre modification approach to enhance the substrate's affinity for dye. While previous studies have shown that laser enhanced dyeing is possible, mechanical tests have shown that the thermal stress applied to the substrate is ultimately a damaging action (Chow, 2012; Bahtiyari, 2011). Chapters 2, 4 and 5 discussed scope for improved performance of existing laser dye techniques and identified an area of further work to explore a laser dye fixation approach to textile colouration. This led to the development of the 'peri-dyeing' technique. The prefix peri denotes *around* or *adjacent.* (Oxford, 2014). This technique considers the laser as a targeted energy source for 'on-the-spot' fixation. It involves applying dye locally to the surface of a textile substrate followed by laser irradiation. In this technique, the dye reaction takes place at the point of (or adjacent to) laser interaction.

As reviewed in Chapter 2, attempts towards a laser dye-fixation approach to surface design of textiles can be recognised in a small number of studies. For example, Kearney & Maki (1994), Bartlett (2006) and Fall (2015) have all reported some success in introducing dye at the point of laser irradiation (see pg 36). However, the true potential of a dye reaction that takes place at the point of laser interaction has not been fully explored and presents a gap for experimentation into technical refinement of a laser dye fixation technique and its creative potential.

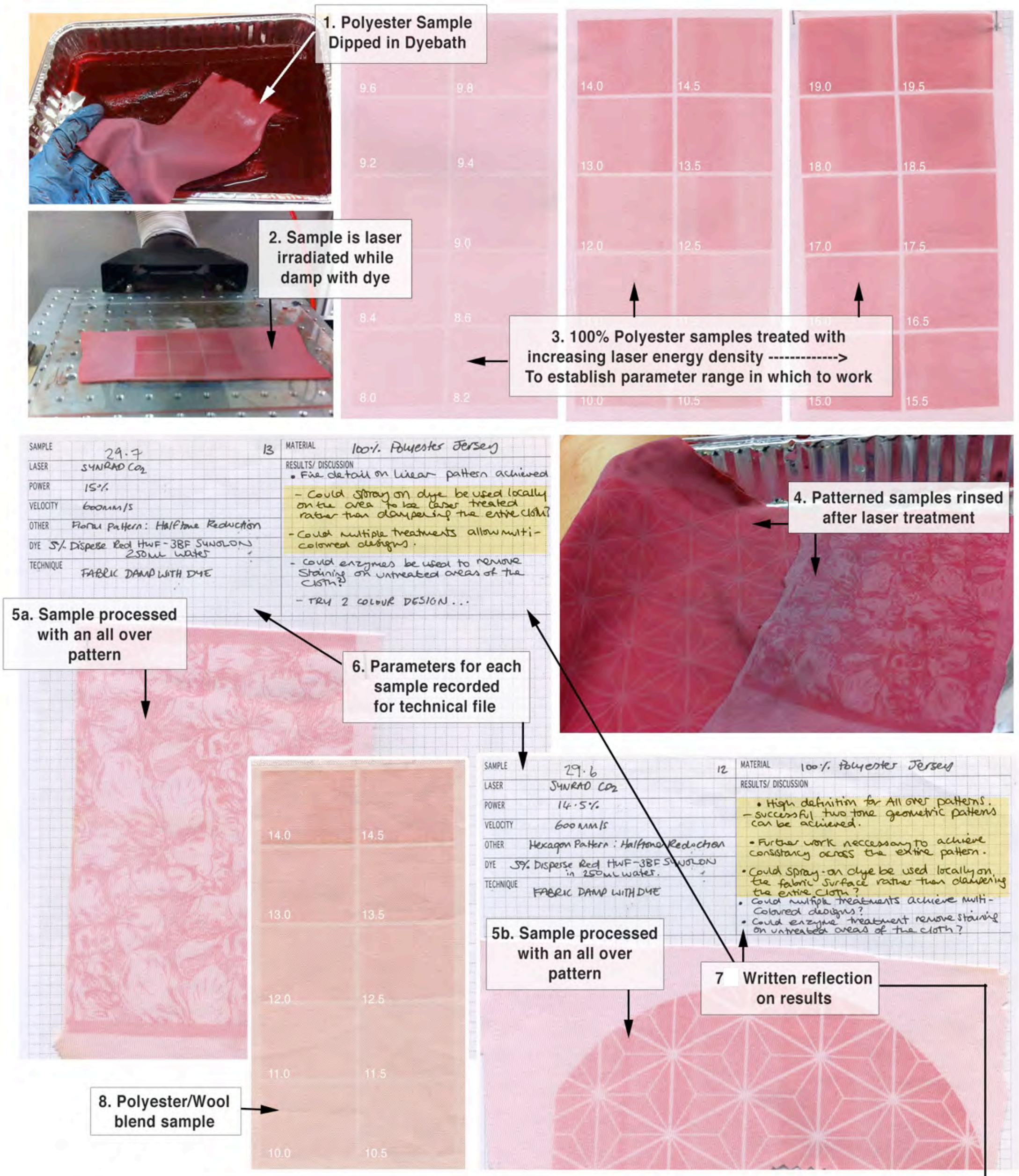
Textile dyeing is an energy dependent process, therefore the photothermal properties of the infrared laser irradiation presents potential to activate a dye reaction on a textile substrate in a targeted manner that could be suitable for the design and patterning of textiles. However, to date, a rigorous study has not been published that adequately explores the design potential of a laser dye fixation method on a variety of textile substrates; nor have they developed a coherent technique that may be replicated; or carried out any appropriate testing to suggest the process may be suitable for commercial application. The peri-dying technique discussed in this chapter addresses gaps in knowledge identified in the literature review towards the development of a laser dye fixation method for wool and synthetic textile substrates. Design potential and standardised performance testing are also carried out in this research.

6.6.1 Establishing the Peri-Dyeing Technique

In Chapter 5, it was discussed how laser modification of textile fibres could enhance dye uptake. This resulted in a successful design technique but with some limitations. On wool, only tonal effects could be achieved, on polywool some multicolour effects can be achieved. Tonal effects can also be achieved on polyester, as reported in the Literature Review (Bartlett, 2006; Akiwowo, 2015 etc.) and confirmed in Chapter 4 of this thesis. However, on all substrates, to achieve a high depth of shade is detrimental the tensile strength of the material.

The CO_2 laser beam, with a wavelength in the Infrared spectrum, is absorbed effectively by water. It was hypothesised that laser irradiating a damp fabric may reduce thermal damage on the treated substrate. Further to this, Laser irradiation of a fabric that is damp with dye may have the potential to incite a dye reaction at the point of laser fibre interaction. Bartlett (2006) sampled a similar experiment that showed potential for a dye fixation by laser irradiating a polyamide substrate wet with dye. However, the work was not furthered, optimised, or tested for permanence or design potential.

A series of initial experiments in this research explored the potential for such a technique as shown in Figure 6.1. These experiments were conducted using a hands-on method; dipping the textile samples in a dye bath of Synolyn Red disperse dye with a fixed concentration of 5% owf (on weight of fabric). After immersion, samples were wrung to remove excess dye liquor and placed on the laser bed for irradiation. After laser irradiation, the samples were rinsed until the water ran clear and allowed to air dry. Written reflections on these initial experiments noted the technique could be used to achieve significant dye uptake. An increasing depth of shade was achieved as energy density increased on 100% polyester knitted fabric and a polyester/wool blend woven fabric. It was observed that tonal gradients could be achieved by altering energy density. During further sampling, laser irradiated all-over-pattern CAD files resulted in two-tone designs with fine linear detail. These initial samples provided proof of concept and identified areas for further experimentation to refine the technical procedure and explore design opportunities. These included: improving the consistency of laser processing for dye uptake by refining laser parameters; testing the technique on alternate substrates and textile constructions; testing layered treatments to achieve multicoloured designs; and examining the most appropriate application of dye onto fabric.



1. Polyester Sample Dipped in Dyebath

2. Sample is laser irradiated while damp with dye

3. 100% Polyester samples treated with increasing laser energy density ------------> To establish parameter range in which to work

4. Patterned samples rinsed after laser treatment

5a. Sample processed with an all over pattern

6. Parameters for each sample recorded for technical file

SAMPLE 29.7 13
LASER SYNRAD CO_2
POWER 15%
VELOCITY 600mm/s
OTHER Floral Pattern: Halftone Reduction
DYE 5% Disperse Red HWF-3BF SUNOLON 250mL water
TECHNIQUE FABRIC DAMP WITH DYE

MATERIAL 100% Polyester Jersey
RESULTS/ DISCUSSION
- Fine detail on Linear pattern achieved
- Could spray on dye be used locally on the area to be laser treated rather than dampening the entire cloth?
- Could multiple treatments allow multi-colored designs.
- Could enzymes be used to remove Staining on untreated areas of the cloth?
- TRY 2 COLOUR DESIGN...

SAMPLE 29.6 12
LASER SYNRAD CO_2
POWER 14.5%
VELOCITY 600 MM/S
OTHER Hexagon Pattern: Halftone Reduction
DYE 5% Disperse Red HWF-3BF SUNOLON in 250mL water.
TECHNIQUE FABRIC DAMP WITH DYE

MATERIAL 100% Polyester Jersey
RESULTS/ DISCUSSION
- High definition for All over patterns.
- successful two tone geometric patterns can be achieved.
- Further work neccessary to achieve consistancy across the entire pattern.
- Could spray-on dye be used locally on the fabric surface rather than dampening the entire cloth?
- Could multiple treatments achieve multi-Colored designs?
- Could enzyme treatment remove staining on untreated areas of the cloth?

5b. Sample processed with an all over pattern

7 Written reflection on results

8. Polyester/Wool blend sample

Significant Reflections from Initial Sampling

Design Insights:
- Successful two tone patterning.
- Fine detailed Linear qualities achieved.
- Could multiple treatments achieve multicoloured designs?

Technical Insights:
- Could dye be applied locally rather than applying to entire cloth? Could spray-on dye be used?
- High definition all over pattern achieved- further work needed to improve processing consistency.

- Increased Energy density = increased depth of shade (can be used for multi-tonal designs)
- Technique effective across multiple substrates. Try technique on wool? Different fabric weights?

Figure 6.1 Initial Sampling for Peri-dyeing Technique

6.7 Dye Application for Peri-dyeing

6.7.1 Controlled Dye Application

Regarding the application of dye onto fabric, it was necessary to add rigour to the process by using a repeatable and measurable dye application method. Applying a measured amount of dye locally to the fabric sample would allow control and repeatability as well as reducing dye-liquor waste. A pipette was chosen as a reliable dye delivery tool at laboratory scale that allowed quantifiable amounts of dye to be applied to textile samples in a targeted manner. It was confirmed experimentally that 1ml dye liquor was sufficient to cover an area of $10cm^2$. This equates to a measurement of $0.1ml/cm^2$ and was used for each subsequent experiment in this chapter unless otherwise stated. Quantities of dye liquor below $0.1ml/cm^2$ did not provide sufficient coverage. Samples that remained partially dry resulted in thermal fibre damage and uneven processing after laser irradiation. Quantities above $0.1ml/cm^2$ rendered the textile sample excessively wet resulting in insufficient dye uptake after laser irradiation. Figure 6.2 shows the pipette application process. In this example, 2ml of dye liquor was applied to a polyester sample measuring $20cm^2$. The final image in the series shows the sample after laser irradiation. Successful dye uptake is clearly visible in the laser irradiated area, indicating that an appropriate quantity of dye had been used.

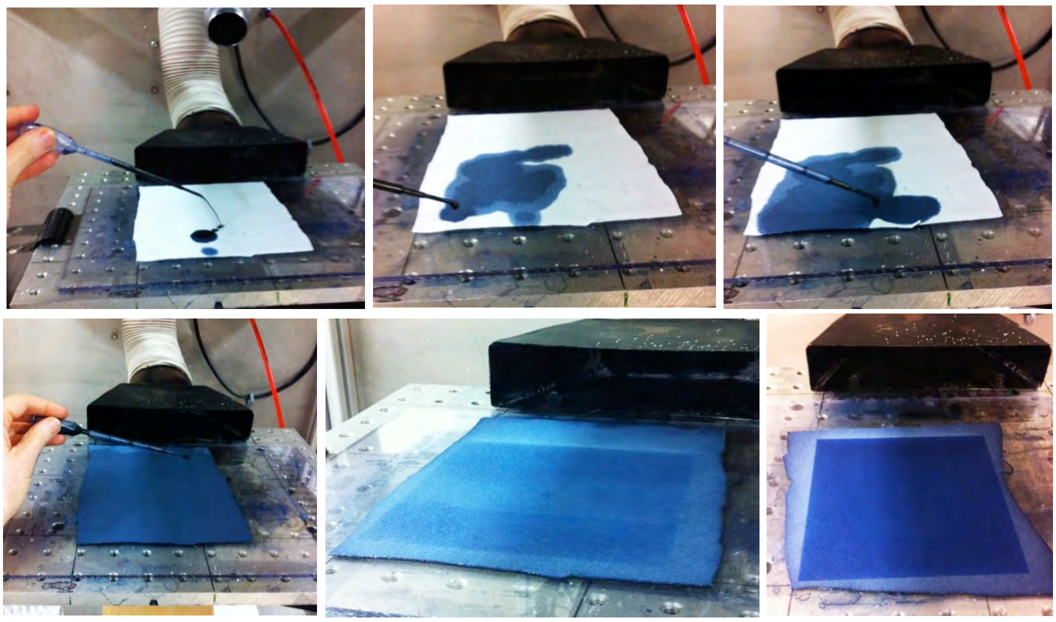
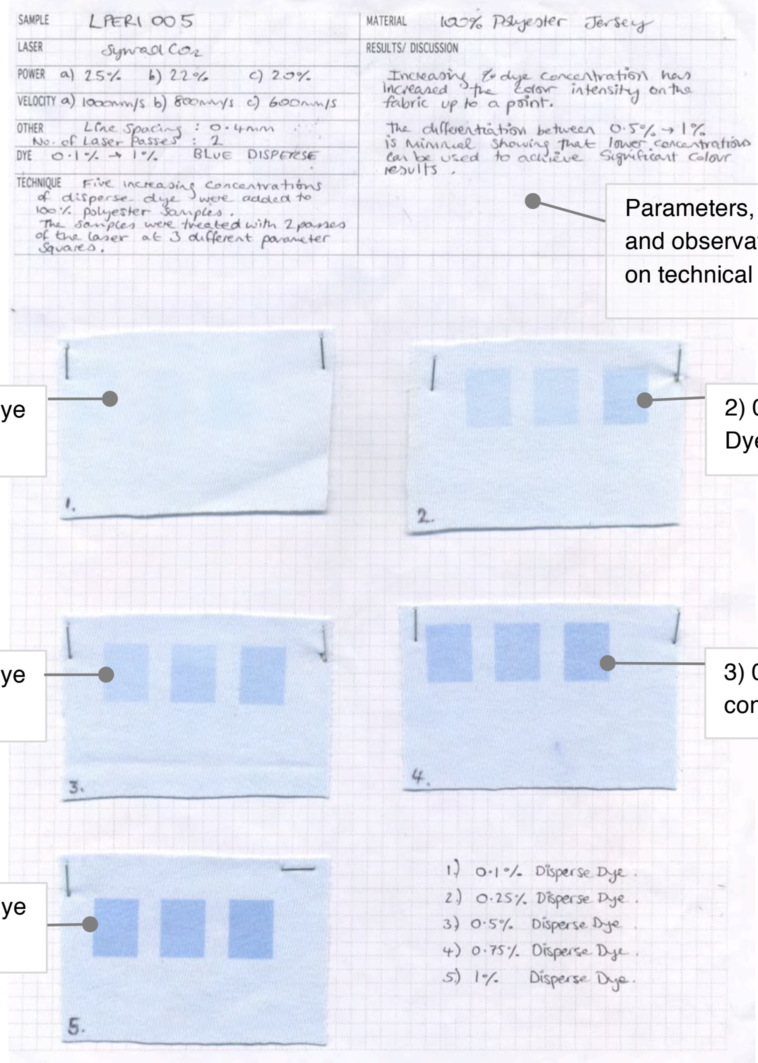


Figure 6.2 Applying Dye to Fabric with a Pipette followed by Laser Irradiation

6.7.2 Dye Concentration for Peri-Dyeing

In initial sampling (see Figure 6.1), it was observed that the final dye colour did not reflect the depth of shade that would be achieved through a conventional dyeing process at a dye concentration of 5% owf Therefore, the relevance of dye concentration to dye application and uptake in the peri-dyeing process was identified as another important area to be investigated and refined.

In order to determine the effect of dye concentration on the colour result from peri-dyeing, dye concentrations between 0.1 and 1% disperse blue dye were applied to 5 polyester samples. Each sample received 1ml of dye, immediately followed by laser irradiation. The resulting samples and technical sheet are shown in Figure 6.3. From visual inspection, an increased depth of shade was observed as dye concentration increased from 0.1-0.75% as expected. However, with minimal colour differentiation between 0.75% and 1%, it can be concluded that maximum uptake has occurred for this set of laser parameters. Therefore, further increasing dye concentration does not provide a higher depth of shade. From this experiment it can be concluded that low dye concentrations can be used to achieve significant dye uptake results. Dye concentrations of 1% were used for subsequent experimentation. At 1% dye, it is known that a significant colour result can be achieved, with scope for uptake improvement. The most appropriate range of laser parameter settings should be identified to further optimise dye uptake as discussed in the following section.



SAMPLE LPERI 005
LASER Synrad CO2
POWER a) 25% b) 22% c) 20%
VELOCITY a) 1000mm/s b) 800mm/s c) 600mm/s
OTHER Line Spacing : 0.4mm
No. of Laser Passes : 2
DYE 0.1% → 1% BLUE DISPERSE
TECHNIQUE Five increasing concentrations of disperse dye were added to 100% polyester samples. The samples were treated with 2 passes of the laser at 3 different parameter squares.

MATERIAL 100% Polyester Jersey
RESULTS/ DISCUSSION
Increasing ~~to~~ dye concentration has increased the color intensity on the fabric up to a point.
The differentiation between 0.5% → 1% is minimal showing that lower concentrations can be used to achieve significant colour results.

1) 0.1% Disperse Dye.
2) 0.25% Disperse Dye.
3) 0.5% Disperse Dye
4) 0.75% Disperse Dye.
5) 1% Disperse Dye.

Parameters, reflections and observations recorded on technical sheet.

1) 0.1% Disperse Dye concentration

2) 0.25% Disperse Dye concentration

3) 0.5% Disperse Dye concentration

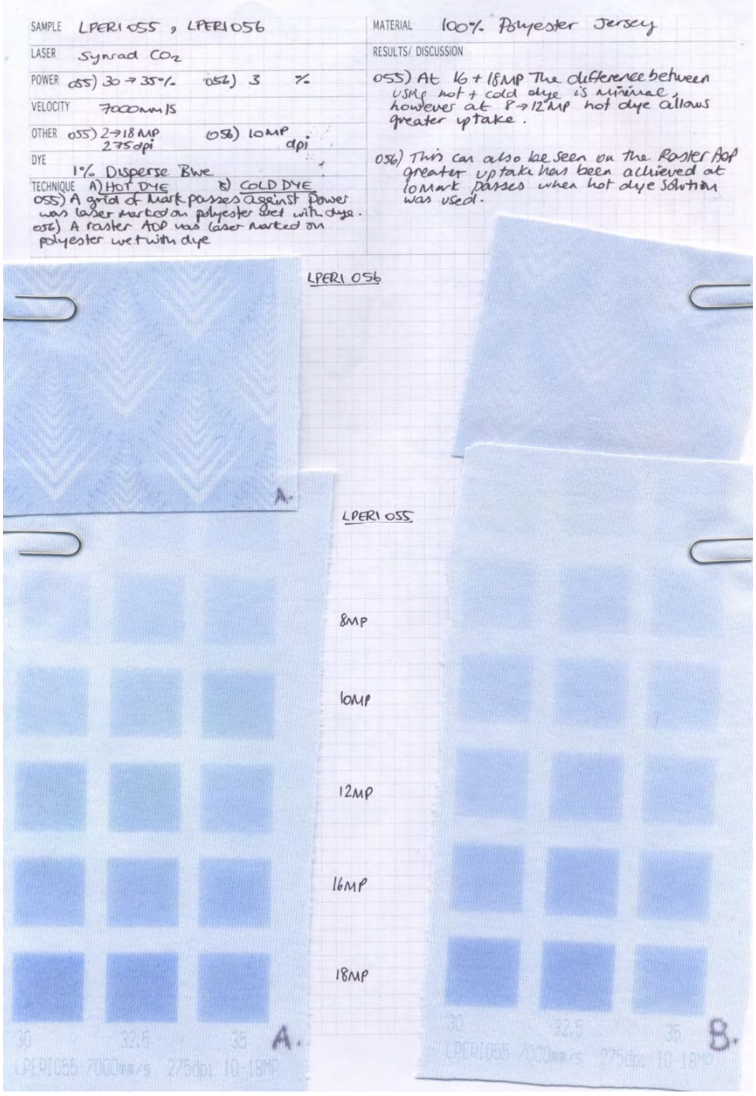
3) 0.5% Disperse Dye concentration

3) 0.5% Disperse Dye concentration

Figure 6.3 The effect of dye concentration on Peri-dyeing

6.7.3 Effect of Dye temperature for Peri-Dyeing

Textile dyeing is an energy dependent reaction between dye molecules and textile fibres. It was hypothesised that increasing the temperature of the dye that is applied to the textile during the peri-dyeing process may facilitate the rate of reaction. An experiment was carried out to determine the effect of dye temperature on peri-dyeing as shown in.



SAMPLE LPERI 055 , LPERI 056
LASER Synrad CO_2
POWER 055) 30 → 35 % 056) 3 %
VELOCITY 7000mm/s
OTHER 055) 2→18 MP 275dpi 056) 10MP dpi
DYE 1% Disperse Blue
TECHNIQUE A) HOT DYE B) COLD DYE
055) A grid of Mark passes against Power was laser marked on polyester sheet with dye.
056) A raster AOP was laser marked on polyester wet with dye

MATERIAL 100% Polyester Jersey
RESULTS/ DISCUSSION
055) At 16 + 18MP The difference between using hot + cold dye is minimal, however at 8→12MP hot dye allows greater uptake.
056) This can also be seen on the Raster AOP greater uptake has been achieved at 10Mark passes when hot dye solution was used.

Figure 6.4 Effect of dye temperature on peri-dyeing

The samples showed peri-dyeing with warm dye provided a greater depth of shade at lower laser parameters, reducing the potential for fibre damage. It can be seen that lower energy densities processed with warm dye can achieve the same visual colour result as those gained from cold-water dye at higher powers. When the dye liquor was applied at a higher temperature, less energy density was required to heat the dye to 120-140°C for the dye reaction to take place. However, facilities within the laser lab did not allow for controlled consistent temperatures to be maintained for comparative testing. In addition, using warm dye on alternate substrates, such as wool and nylon may lead to dye staining before laser irradiation, as these substrates will begin to accept dye at lower temperatures. To maintain controlled conditions for further experimentation in this research, dye liquor was used at room temperature. Nonetheless, increasing the initial temperature conditions of the dye liquor, or of the substrate to be treated provides an area for further investigation with potential to increase the speed of processing.

6.8 Refining Laser Parameters for Peri-dyeing

The textile dyeing mechanism is an energy dependent process. It involves heating the substrate above its glass transition temperature; consequently, significant energy is required to facilitate dye diffusion. The laser used in this study is capable of output temperatures in excess of 400°C. Therefore, fast and accurate application of heat is easily achievable. However, the application of high laser energy density to facilitate the dye process on textile substrates can result in fibre damage. When the textile is damp with dye, the aqueous dye liquor absorbs some of the laser energy. This in turn heats the substrate via the dye liquor in a similar process to that of a dye bath, but with a laser, this occurs on a targeted micro-scale. To achieve the high temperatures required for dye diffusion (120-140°C for polyester), a fine balance must be met between providing enough energy to sufficiently heat the dye liquor, and too much energy that may result in fibre damage. A series of experiments were undertaken to determine the optimal parameters for peri-dyeing as discussed in this section.

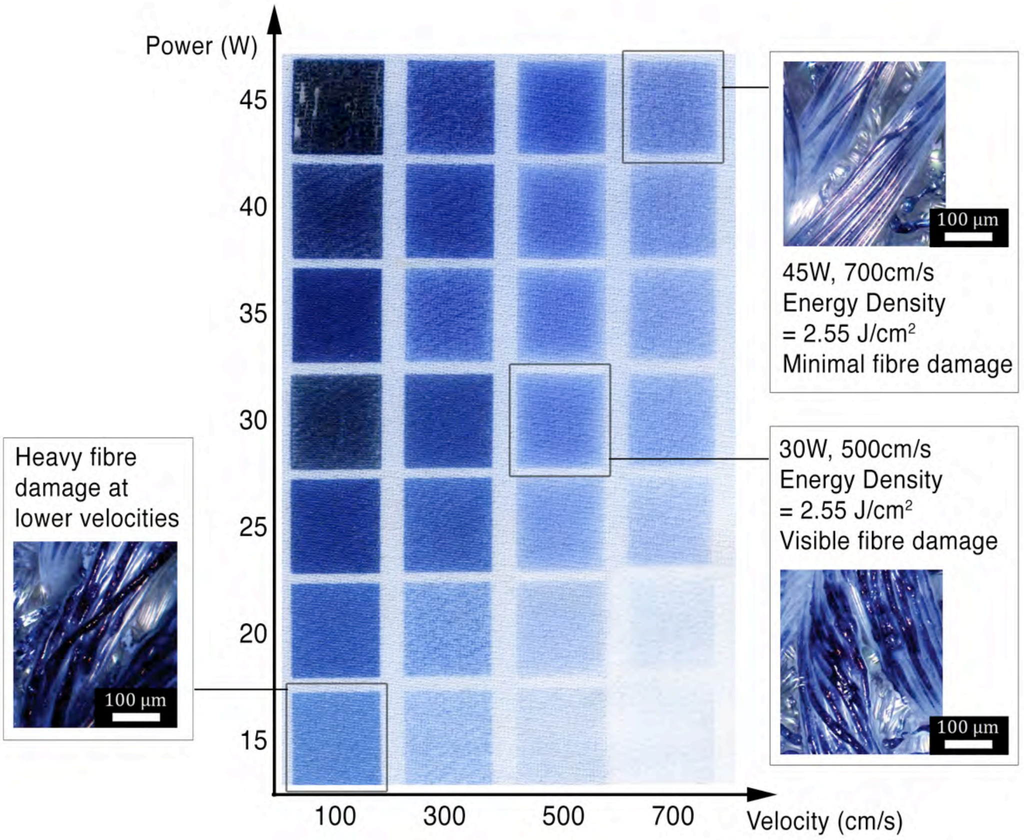


Figure 6.5 Peri-dyed parameter grid showing velocity against laser power

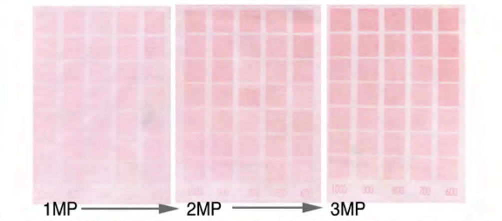
A parameter grid of laser power against velocity was produced using the peri-dyeing process on polyester with a 1% disperse dye concentration. The resulting sample is shown in Figure 6.5. A greater depth of shade was obtained as laser power increased. Increasing laser velocity had the reverse effect. Consequently, higher laser powers were required to produce the same colour effect at higher velocities. These results are supported mathematically by the energy density equation.

Calculations reveal that power of 30W and a velocity of 500cm/s provides an energy density of 2.55J/cm^2. If the same energy density is delivered to a substrate at 700cm/s, a higher power of 45W must be used. Microscopic examination of these parameters revealed visible fibre damage on the substrate at a lower velocity. By contrast, minimal fibre damage was seen at the equivalent energy density at a higher velocity as shown in Figure 6.5. From this, it was concluded that processing at higher velocities allowed higher laser power to be used, obtaining a strong depth of shade without causing significant fibre damage. Consequently, the maximum parameter for the laser used in this study, 700cm/s, was used as the optimal velocity for peri-dyeing.

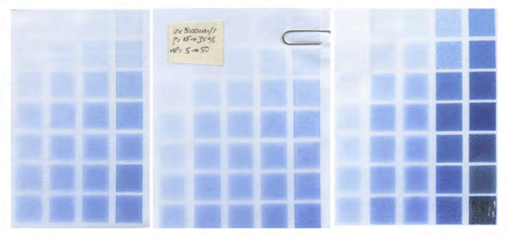
It has been shown that increased laser energy density provides an increasing dye uptake in the peri-dyeing process. In addition, high velocity and high power parameter combinations were shown to provide an optimal colour result with the least amount of fibre damage. However, as discussed when high energy densities were used, some fibre damage could be seen on the surface of the textile. Experiments with multiple laser passes were undertaken in order to ascertain if increased energy density could be delivered to the textile through layered processing.

6.8.1 Utilising a multiple laser mark pass approach

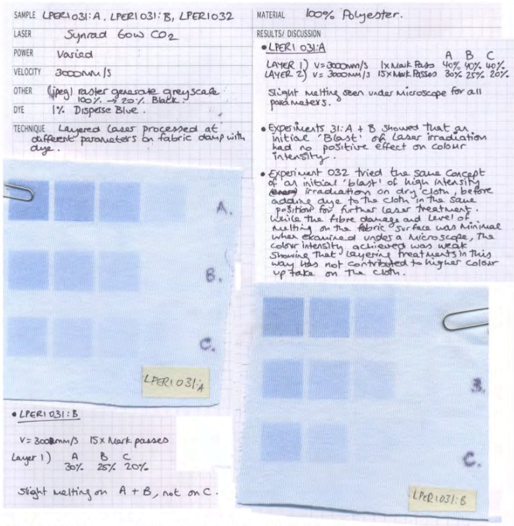
Systematic sampling was carried out with the aim to further refine the peri-dyeing process and assess the relevance of a multiple laser mark pass approach. The series of experiments is shown in Figure 6.6. These experiments trialed the effect of multiple laser mark passes in relation to other laser processing variables. In trial *a*, a velocity/power grid was repeated with an increasing number of mark passes. It can be seen that the colour intensity improves with multiple passes. Based on the results from *a*, trial *b* used a fixed velocity of 700cm/s and parameter grids of energy density against mark passes were processed. A suitable parameter range was identified that provided a range of tonal values through altering the number of laser mark passes. In trial *c*, an initial ‘blast’ of laser energy followed by laser irradiation with lower energy density was tested. It was considered that an initial large amount of energy may provide enough heat to ‘kick-start’ the dye reaction, after which subsequent layers may require less energy to continue the dye reaction. However, in this experiment, it was found that the initial higher blast initiated fibre damage, which was only exacerbated by further mark passes. The same conclusions were drawn from the trials in experiment set *f*, where ranges of energy densities were altered between mark passes. It was found that layering treatments at varied energy densities did not contribute to higher dye uptake. In trial *d*, the use of multiple mark passes was tested on raster squares and vector line-spaced squares. It was found that repetition of the line spaced vectors intensified the inertia problem as described in Chapter 4, thus raster processing was identified as more appropriate for peri-dyeing. Trial *e* tested the reapplication of dye between mark passes. It was found that this led to drenching of the fabric, with excessive dye liquor leading to poor dye uptake.



a) Mark Pass Trials: Velocity against power parameter grids processed with increasing mark passes.



b) Mark Pass Trials: parameter grids of power against mark passes to find suitable parameter range.



SAMPLE LPERI 031:A, LPERI 031:B, LPERI 032
LASER Synrad 60w CO2
POWER Varied
VELOCITY 3000mm/s
OTHER (jpeg) raster generate greyscale 100% → 20% Black.
DYE 1% Disperse Blue.
TECHNIQUE Layered laser processed at different parameters on fabric damp with dye.
MATERIAL 100% Polyester.
RESULTS/ DISCUSSION

- LPERI 031:A

			A	B	C
LAYER 1)	V=3000mm/s	1x Mark Pass	40%	40%	40%
LAYER 2)	V= 3000mm/s	15x Mark Passes	30%	25%	20%

Slight melting seen under Microscope for all parameters.

- Experiments 31: A + B showed that an initial 'Blast' of laser irradiation had no positive effect on colour intensity.
- Experiment 032 tried the same concept of an initial 'blast' of high intensity ~~[illegible]~~ irradiation on dry cloth, before adding dye to the cloth in the same position for further laser treatment. While the fibre damage and level of melting on the fabric surface was minimal when examined under a Microscope, The colour intensity achieved was weak showing that layering treatments in this way has not contributed to higher colour uptake on the cloth.

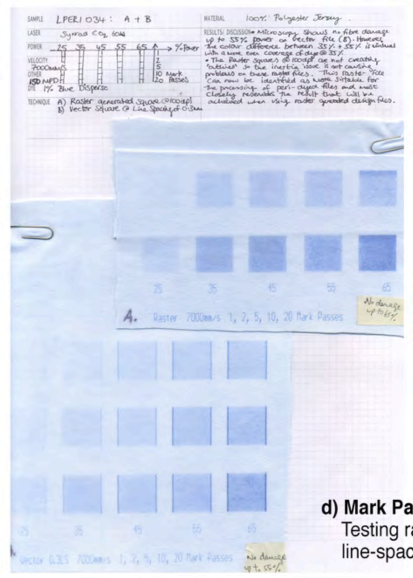
- LPERI 031:B

V= 3000mm/s 15x Mark passes

	A	B	C
Layer 1)	30%	25%	20%

Slight melting on A + B, not on C.

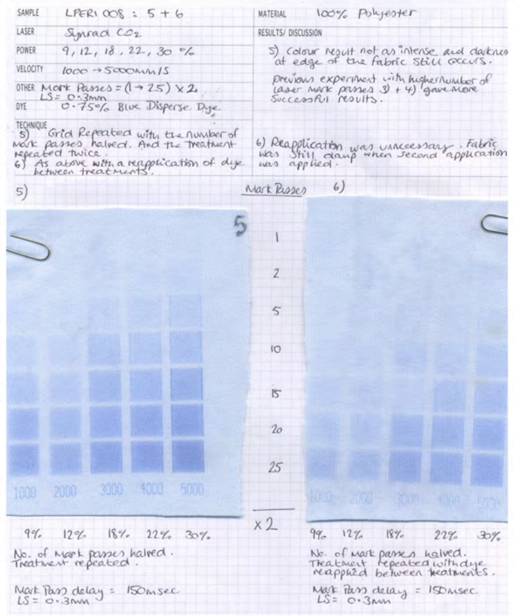
c) Mark Pass Trials: Initial laser 'blast' of high power.



SAMPLE LPERI 034 : A + B
LASER Synrad CO2 60W
POWER 25 35 45 55 65 → % Power
VELOCITY 7000mm/s
1 2 5 10 20 Mark Passes
OTHER 150 MPD
DYE 1% Blue Disperse
TECHNIQUE A) Raster generated square @1000dpi
B) Vector Square @ Line Spacing of 0.3mm
MATERIAL 100% Polyester Jersey.
RESULTS/ DISCUSSION

- Microscopy shows no fibre damage up to 55% power on vector file (B). However, the colour difference between 35% + 55% is minimal with a more even coverage of dye @ 35%.
- The Raster squares @ 1000dpi are not creating 'outlines' so the inertia issue is not causing problems on these raster files. This raster file can now be identified as more suitable for the processing of peri-dyed files and most closely resembles the result that will be achieved when using raster generated design files.

d) Mark Pass Trials: Testing raster vs line-spaced vector.

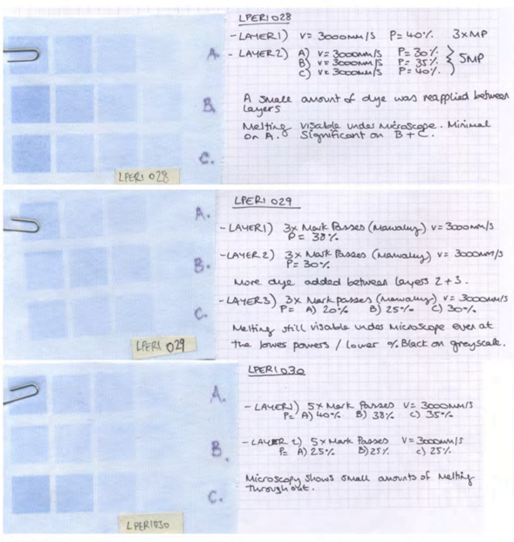


SAMPLE LPERI 008 : 5 + 6
LASER Synrad CO2
POWER 9, 12, 18, 22, 30 %
VELOCITY 1000 → 5000mm/s
OTHER Mark Passes = (1 → 25) x 2
LS= 0.3mm
DYE 0.75% Blue Disperse Dye
TECHNIQUE
5) Grid Repeated with the number of mark passes halved. And the treatment repeated twice.
6) As above with a reapplication of dye between treatments.
MATERIAL 100% Polyester
RESULTS/ DISCUSSION
5) Colour result not as intense and darkness at edge of the fabric still occurs.
Previous experiment with higher number of laser mark passes 3) + 4) gave more successful results.
6) Reapplication was unnecessary. Fabric was still damp when second application was applied.

5) No. of Mark passes halved. Treatment repeated.
Mark Pass delay = 150msec
LS = 0.3mm

6) No. of mark passes halved. Treatment repeated with dye reapplied between treatments.
Mark Pass delay = 150msec
LS= 0.3mm

e) Mark Pass Trials: Reapplication of dye between passes.



LPERI 028
- LAYER 1) V= 3000mm/s P= 40%. 3xMP
- LAYER 2) A) V= 3000mm/s P= 30%
B) V= 3000mm/s P= 35%
C) V= 3000mm/s P= 40%
5MP

A small amount of dye was reapplied between layers

Melting visable under Microscope. Minimal on A. Significant on B + C.

LPERI 029
- LAYER 1) 3x Mark Passes (Manualy) V= 3000mm/s P= 38%
- LAYER 2) 3x Mark Passes (Manualy) V= 3000mm/s P= 30%

More dye added between layers 2 + 3.

- LAYER 3) 3x Mark passes (Manualy) V= 3000mm/s P= A) 20% B) 25% C) 30%

Melting still visable under Microscope even at the lowest powers / lower % Black on greyscale.

LPERI 030
- LAYER 1) 5x Mark Passes V= 3000mm/s P= A) 40% B) 38% C) 35%
- LAYER 2) 5x Mark Passes V= 3000mm/s P= A) 25% B) 25% C) 25%

Microscopy shows small amounts of melting throughout.

f) Mark Pass Trials: Altering laser power between passes.

Figure 6.6 Mark Pass Trials: Samples, reflections and technical notes.

From these experiments it was concluded that choosing a fixed energy density and varying the number of mark passes could improve uptake. The results from these tests, showed that extra processes such as reapplication of dye, an initial higher blast of laser energy, or altering energy density between mark passes were unnecessary to achieve optimised processing.

Having identified the potential of utilising a multiple laser mark pass approach to improve the peri-dyeing process, further experiments and sampling were conducted. A parameter grid of energy density against laser mark passes was peri-dyed onto polyester as shown in Figure 6.7. Microscopic analysis showed minimal or no fibre damage at the highest parameters, which provided the darkest depth of dye shade. It can be seen that increasing the number of laser mark passes can increase the intensity of colour without causing significant melting or damage to the laser irradiated polyester fibres.

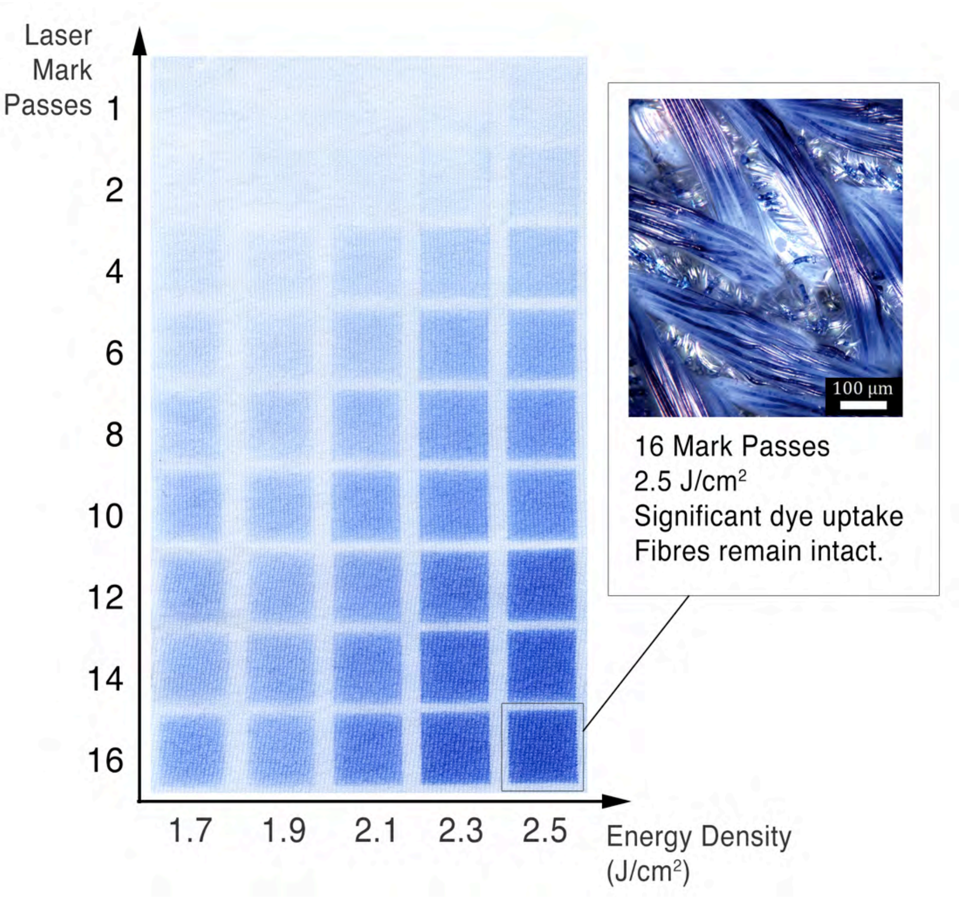


Figure 6.7 Peri-dyed parameter grid: Energy density against number of laser mark passes

An all over pattern (AOP) was peri-dyed onto polyester at an energy density of 2.3J/cm^2 The resulting samples are shown in Figure 6.8. It can be seen that dye depth of shade increases as the number of mark passes increase. In addition, clarity and definition of the pattern improves as mark passes increase.

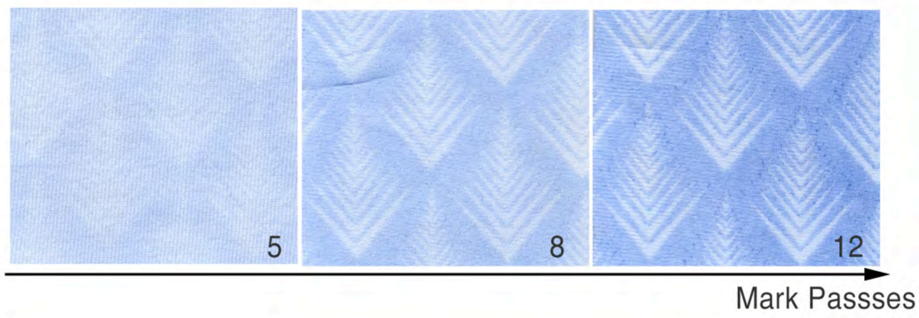


Figure 6.8 All over pattern: peri-dyed at increasing laser mark passes

Figure 6.9 shows further sampling to compare graphics handling at altered energy density and mark pass settings. A high number of mark passes combined with a low energy density (30MP, 1.4J/cm^2) resulted in a high depth of dye shade in the laser irradiated area. However, the graphic detail of the AOP was lost, showing as a faint pattern with poor definition. In contrast, by increasing the energy density to 2J/cm^2 a similar depth of shade was produced with high definition graphic handling after only 10 laser mark passes. Calibration to find the optimum graphics handling for each new substrate and pattern may be required; made possible through simple parameter tests as evidenced in this section.

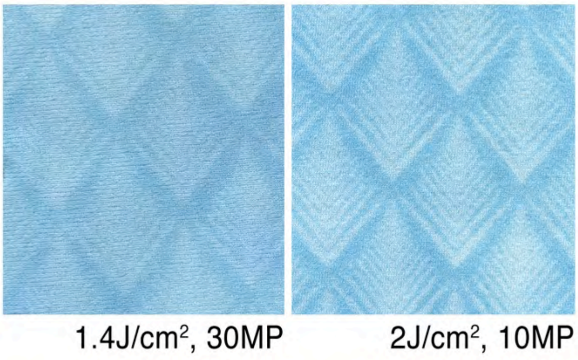


Figure 6.9 All over pattern peri-dyed parameter comparison

Microscopic comparison of laser parameter options revealed the most effective laser energy density settings to allow for greatest uptake of dye without causing significant damage to the textile fibres, facilitated by the use of multiple mark passes. Having established the appropriate range and combination of processing parameters for polyester, the same parameter grids can be used to determine the most appropriate range of parameters for processing alternate substrates and fabric constructions. The grids below show that peri-dyeing can be successfully performed on nylon and woolen textiles. It can be seen that wool requires a higher set of energy densities to achieve a high depth of shade.

6.9 Peri-dyeing Wool

Utilising the findings from experiments on peri-dyed polyester, a parameter grid of mark passes against energy density was laser irradiated on wool using the peri-dyeing process with 1% reactive dye solution. All over pattern swatches were also sampled. The resulting samples are shown in Figure 6.10. Potential for the process to transfer to woolen textiles was identified; significant dye uptake was observed. A number of alternate wool textile constructions were peri-dyed to determine the suitability of the process across varied textile textures and constructions. The results showed significant dye uptake across all tested substrates (Figure 6.11). However, both sets of samples, shown in Figure 6.10 and Figure 6.11, require processing to be improved to achieve consistent, level dyeing and higher quality graphics handling.

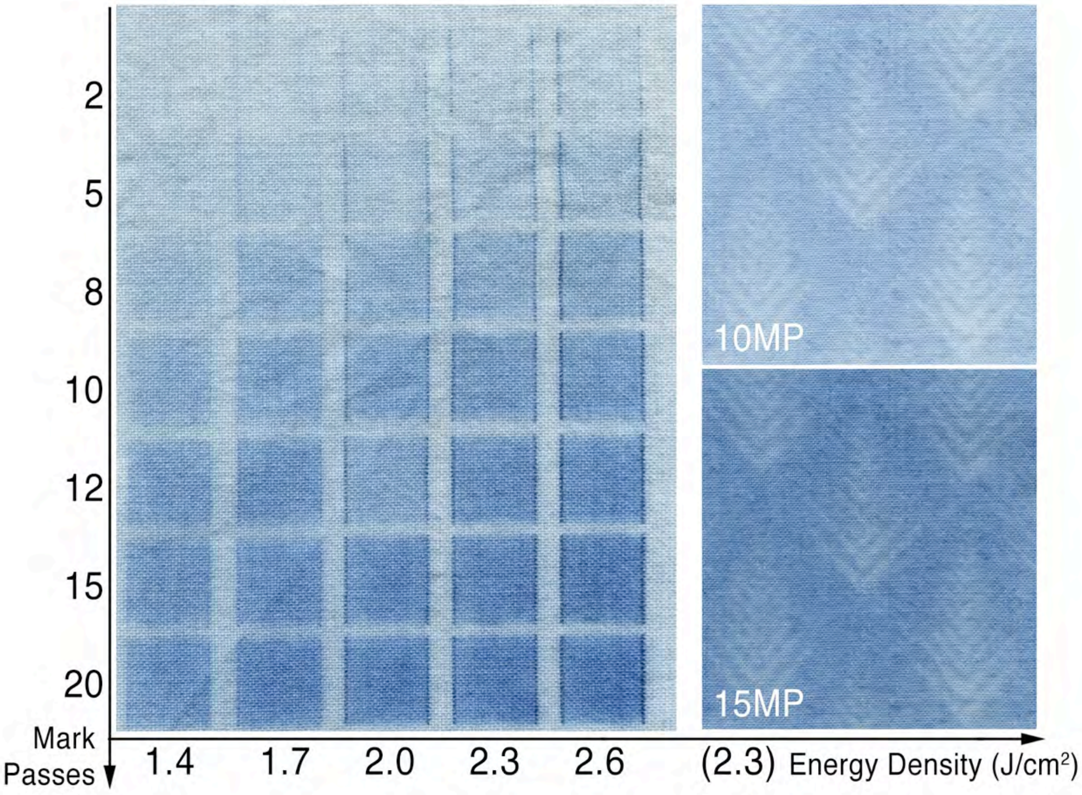


Figure 6.10 Peri-dyed Wool: Initial Sampling

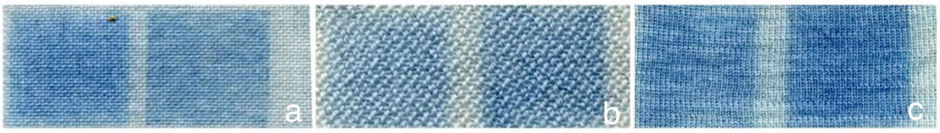


Figure 6.11 Peri-dyed Wool Initial Samples: a) Wool b) Oxygen c) Wool Jersey

6.9.1 Refining dye parameters for peri-dying wool

During the standard procedures for dyeing wool, auxiliaries are used as described in Chapter 4. Acetic acid provides the acidic conditions essential for dyeing wool. While dye uptake on wool using the peri-dyeing technique has been possible without the addition of auxiliaries as shown in Figure 6.10, acidic conditions may promote and improve the dye reaction by increasing the affinity of the dye to fibre. An experiment was carried out to examine the effects of applying auxiliaries for peri-dyeing wool. The auxiliaries for dyeing wool with reactive dye were made up in a solution with concentrations as described in recipe 1. Four, 4g samples were prepared. Dye liquor and auxiliaries applied to each sample before laser irradiation as follows;

a. Wool wetted out with water, 1% dye applied
b. Wool wetted out with auxiliary solution, 1% dye applied
c. Wool wetted out with water, 1% dye + auxiliary solution applied
d. 1% dye + auxiliary solution applied

Each sample was laser processed with a mark pass against energy density parameter grid with the results shown in Figure 6.12. Comparing sample *a* to samples *b, c* and *d*, it can be seen that the addition of auxiliaries have improved dye uptake allowing greater depth of shade after a lower number of mark passes. It was found that wetting out of the wool prior to dye application diluted the dye solution and was not necessary. Dye and auxiliaries can be successfully mixed together to provide a suitable dye solution as shown in samples *c* and *d*. Sample *d* provided the most successful uptake, with an even, level dyeing across each parameter and a clear definition and colour gradient between mark passes leading to a high depth of shade at the highest parameters.

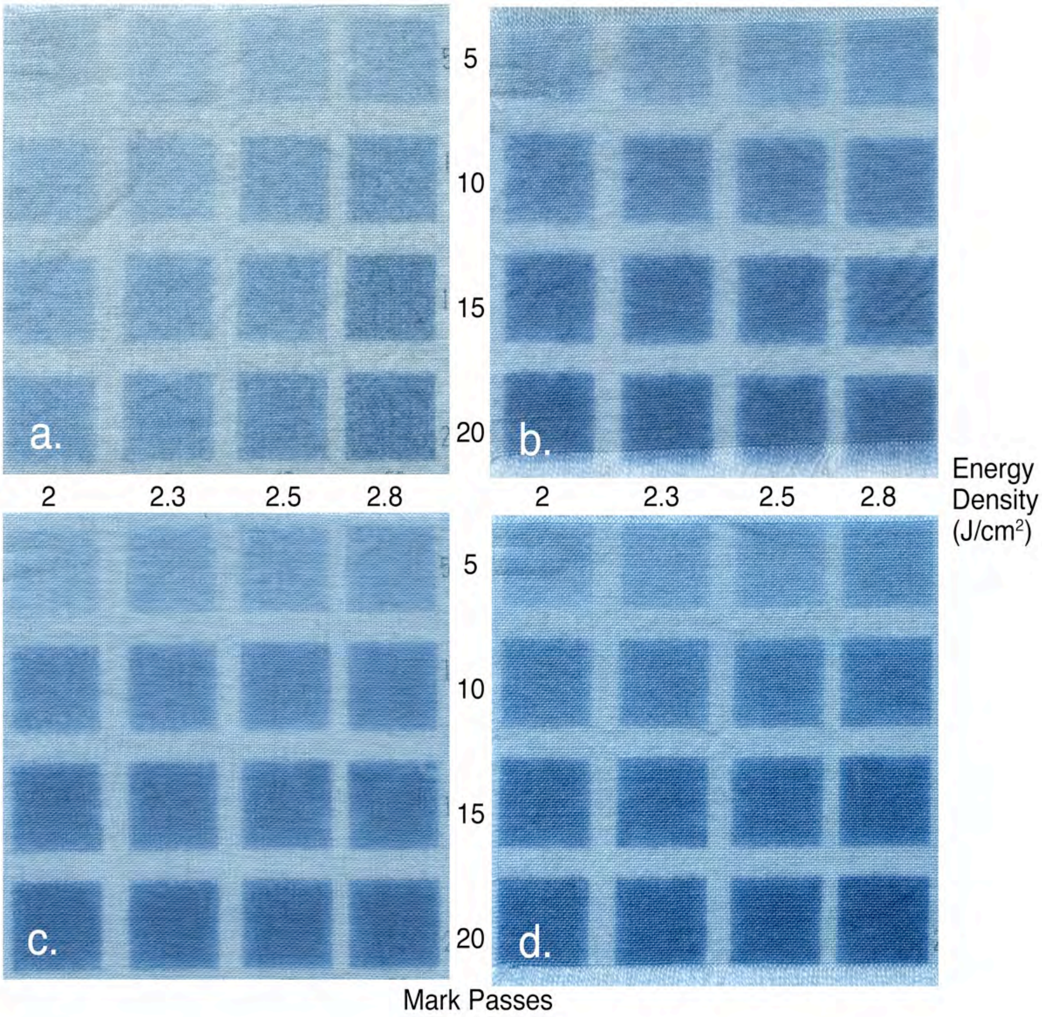


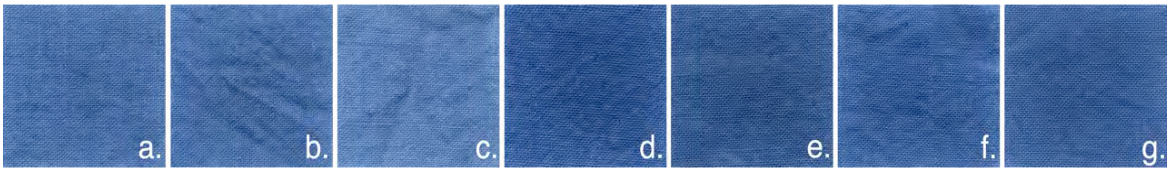
Figure 6.12 Auxiliary Tests for Peri-Dyed Wool

In order to further refine and examine the effect of auxiliaries in the peri-dyeing process, the proportion of auxiliaries used were tested. The concentration and combination of auxiliaries used in recipe 1 are specific for an optimised dye reaction within a dye bath, with expected temperature rate of 1.5°C/minute and overall dyeing time in excess of 90 minutes.

Glaubers salt at 5-10% owf is used to slow down the migration of dye into fibre to increase levelness (Huntsman, 2007). This provides obvious benefits for dyeing wool within a dye bath over an extended period of time. However, peri-dyeing provides consistent conditions through controlled laser irradiation that have been optimised for even and level uptake. For peri-dyeing, slowed migration of dye molecules may be counterproductive.

Albegal B is used in wool dyeing to improve dye exhaustion. For reactive dyeing of wool, the manufacturer's directions state higher liquor ratios of albegal B at 1-2% owf can be used depending on the depth of shade required (10). To optimise exhaustion and achieve a high depth of shade for peri-dyeing an increased amount of albegal B could be used. Suitable amounts of each auxiliary were confirmed experimentally.

7 vessels of dye liquor were prepared with reactive dye at a concentration of 2%. Varied amounts of acetic acid (AA), glaubers salt (GS) and albegal b (AB) were used for each solution. Water was used to keep overall dye liquor constant between each mixture. The solutions were used to dye equal sized squares of wool fabric. The resulting samples are shown in Table 6.1. Samples *a* and *b* contain only acetic acid. It can be seen that altering concentration of acid from 2% to 1% did not have any effect on the resulting dye colour, therefore acidic conditions of 1% were sufficient to promote uptake on wool by laser irradiation and used for subsequent samples. Samples *d* and *e* were processed with the addition of albegal b. It can be seen that increased depth of shade was obtained on both samples. Sample *c* was processed with the addition of glaubers salt, resulting in reduced uptake of dye onto wool. In samples *f* and *g*, glaubers salt has been used in combination with albegal b. It can be seen that reducing the amount of glaubers salt in the dye liquor results in improved uptake. This experiment has shown that glaubers salt can be vastly reduced from the amounts shown in recipe 1, or omitted as an auxiliary from the dye liquor solution for optimal peri-dyeing. Albegal B can be increased from the amount shown in recipe 1 to achieve an optimised depth of shade for peri-dyeing wool.



2% AA	1% AA	1% AA	1% AA	1% AA	1% AA	1% AA
0% AB	0% AB	0% AB	1% AB	2.5% AB	2.5% AB	2.5% AB
0% GS	0% GS	2.5% GS	0% GS	0% GS	2.5% GS	1% GS

Table 6.1 Refining Use of Auxiliaries for Peri-Dyeing Wool

6.10 Surface Observation

Microscopic surface observation of peri-dyed substrates was carried out throughout parameter testing to record the affordances and constraints of the process. It has been discussed in this chapter that peri-dyeing can provide a laser dyeing method, producing a deep depth of shade without causing fibre damage to the substrate. Figure 6.13 provides an example of peri-dyed wool at a laser energy density of 2.5J/cm^2 and 15 mark passes. Micrographs *a*, *b* and *c* show peri-dyed wool fibres at increasing levels of magnification, with no visible fibre damage on the sample. Figure 6.14 compares micrographs of polyester at varied parameter settings. Sample *a* and b have been laser irradiated at an energy density of 2J/cm^2, using increasing mark passes to achieve tonal variation without any visible fibre damage to the polyester fibres.

However, if laser energy density exceeds an acceptable level for the substrate, fibre damage will be observed under a microscope as shown on wool in Figure 6.15. On polyester that has been subject to increased energy density (Figure 6.14c) some fibre melting and damage is beginning to occur on the uppermost fibres, which can be observed as the dark, disrupted fibres in the micrograph.

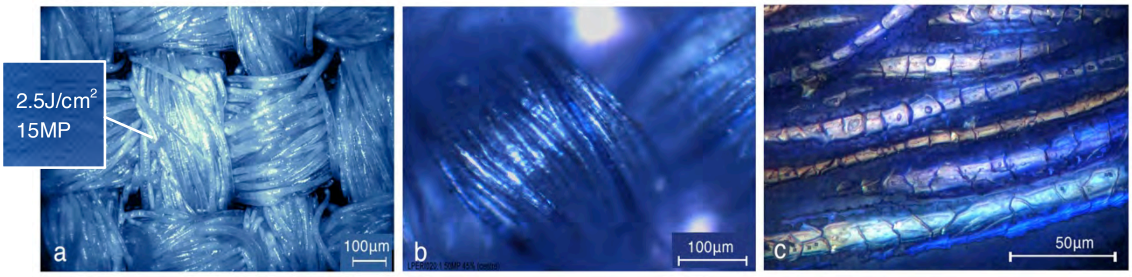


Figure 6.13 Micrographs of peri-dyed wool: no fibre damage

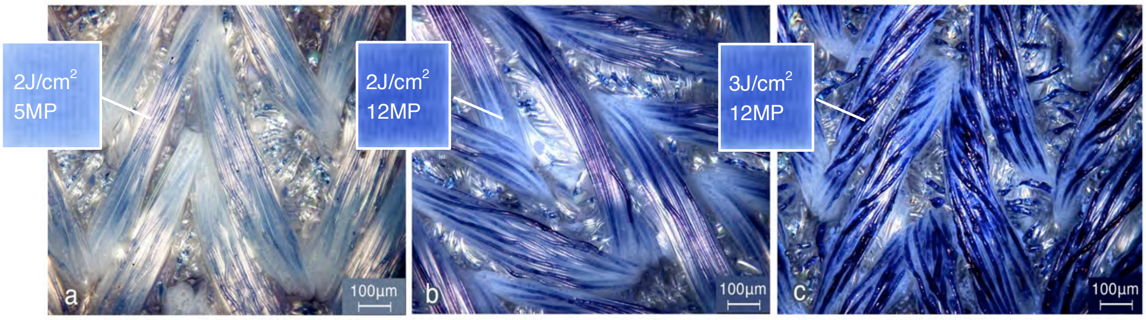


Figure 6.14 Micrographs of peri-dyed polyester at varied parameters

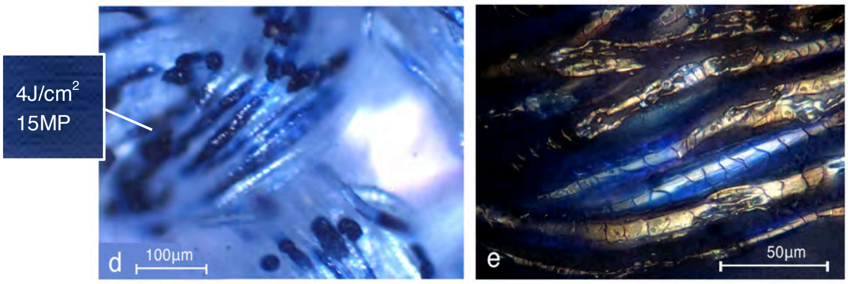


Figure 6.15 Micrographs of peri-dyed wool: fibre damage

This chapter has detailed systematic parameter testing that can be used to determine a suitable range of laser parameters that will provide a successful laser colouration method, without visible damage to the textile substrate. Microscopic examination was a useful method to ensure chosen parameters did not cause visible damage to the textile substrates. Further testing was performed to analyse the permanence of the peri-dyeing method and to determine the effect of peri-dyeing on strength and colourfastness properties of the substrates, ensuring the technique could meet international textile performance standards.

6.11 Dye Uptake and Fixation for Peri-Dyeing

After laser irradiation, each peri-dyed sample was rinsed in a solution of UPL to remove excess dye from the cloth. Figure 6.16a shows a peri-dyed textile with an all over pattern that has been rinsed in water. It can be seen that the non-laser treated areas of the pattern retain a light dye staining. Figure 6.16b shows a swatch from the same peri-dyed sample that has been rinsed with a solution of water and UPL, a non-ionic surfactant at a concentration of 2g/L. It can be seen that the UPL wash has been successful in removing excess dye staining from the sample, with the non-laser treated areas returning the textile's original undyed state.

Figure 6.16 Peri-dyed Sample a) Water rinse, b) UPL rinse.

A UPL wash proved to be an effective method of removing dye staining at lab scale to refine parameters of the process and to examine design and image processing possibilities. In the industrial dyeing of textiles however, a 'reduction clear' is routinely used to ensure unfixed dye is removed. This serves to improve fastness and provides a stable end colour (Burkinshaw & Kumar, 2008). In the dyeing of wool with reactive dye, ammonia is added to the exhausted dye bath at the end of the dye cycle to change the ph. of the dye liquor. This adjusts the acidic conditions to alkaline to prevent further uptake and remove unfixed dye molecules trapped within the substrate (Huntsmann, 2007). In recipe 1 (Section 4.4), a 15-minute ammonia wash at 80^{o}C is performed at the final stage of the dyeing process to clear excess dye.

An experiment to determine the suitability of an ammonia wash on peri-dyed wool was performed. Five wool samples were peri-dyed with reactive dye at a concentration of 2% at 0, 5, 10, 15 and 20 laser mark passes and a fixed energy density of 2.26J/cm^{2}. 2ml dye and auxiliary solution was used for each sample including the 0MP (untreated) control. After laser treatment, each sample was washed in a UPL solution prior to an ammonia treatment. Peri-dyed samples were treated in an infrared dye machine, with 200ml water and 1% owf ammonia at 80^{o}C for 15 minutes. Absorbance readings of the resulting liquor were recorded as shown in Figure 6.17. It was found that the concentration of dye in the liquor increased, as unfixed dye molecules detached from the test samples into the liquor. As the number of mark passes increased, the absorbance readings decreased, indicating a reduced amount of dye was present in the liquor. It can be concluded that a reduced amount of unfixed dye is present on the test samples with increasing laser mark passes, suggesting dye fixation improves with the number of mark passes.

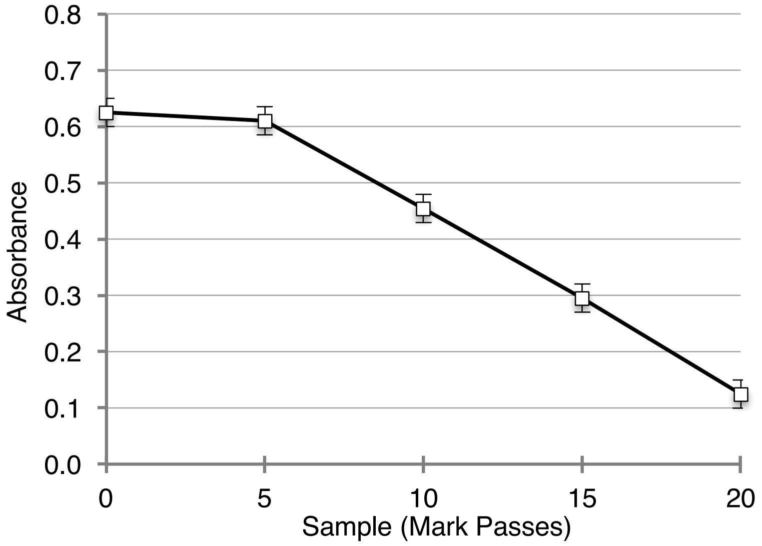


Figure 6.17 Absorbance of peri-dyed wool after a reduction clear

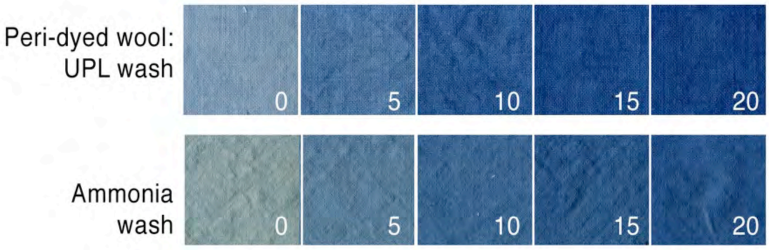


Figure 6.18 Peri-dyed Wool at increasing laser mark passes after UPL and Ammonia Wash

The samples in Figure 6.18 show a slight colour change when comparing ammonia treated samples to UPL only samples. The ammonia treated samples were lighter with some yellowing. Some fading may be expected due to removal of any unfixed dye from the sample. Yellowing is a reported issue on wool treated in high alkaline levels (Lewis & Rippon, 2013). The ammonia used was consistent with dye recipe 1, however this assumes acidic conditions to be present in the dye bath. After a UPL wash, the sample will no longer have an acidic ph. Therefore, to prevent yellowing, the amount of ammonia may need to be reduced, and the ph. monitored to ensure it would not rise beyond a ph. level of 8, to prevent fibre and colour degradation of peri-dyed wool.

Calculating the exhaustion and fixation for regular dyeing processes typically relies on measuring the absorbance of the dye liquor before and after the dye reaction and subsequent wash off has taken place. For the peri-dyeing process it has been possible to calculate the relative exhaustion compared to a non-treated control. The percent fixation was calculated after an ammonia wash off.

Five wool samples were peri-dyed with reactive dye at a concentration of 2% at 0, 5, 10, 15 and 20 laser mark passes and a fixed energy density of 2.26J/cm^2. 2ml dye and auxiliary solution was used for each sample including the 0MP (untreated) control. After laser treatment, each sample was sealed in a separate airtight container, containing the damp peri-dyed sample and any remaining dye liquor. The samples were then transported to the dye-lab and 200ml water and ammonia at 1% owf were added to each container. An ammonia wash was performed at a temperature of 80^{o}C for 15 minutes. Absorbance readings of the dye liquor for each sample were recorded using a spectrophotometer before and after the ammonia wash, with the results shown in Table 6.2. The absorbance figures have been used to calculate the exhaustion (%E), total fixation efficiency (%T) and fixation (%F) of the peri-dyed samples before and after the ammonia wash using Equations 5, 6 and 7 respectively (see Chapter 4.5.1.3).

Sample (Mark Passes)	**Absorbance**		**% Exhaustion**		**% Fixation**	
	After Peri-Dyeing (Abs$_1$)	After Ammonia Clear (Abs$_2$)	%E After Peri-Dyeing	After Ammonia Clear (%T)	%F	%F (Corrected by 16.9%)
20	0.35	0.51	90.10	85.81	95.23	78.33
15	0.58	0.71	83.75	80.02	95.54	78.64
10	0.92	1.03	74.23	71.24	95.97	79.07
5	1.33	1.34	62.84	62.56	99.55	82.65
0A	3.07	2.97	14.10	16.90	119.87	102.97
0B (Abs$_0$)	3.57					

Table 6.2 Absorbance, Exhaustion and Fixation Results for Peri-Dyed Wool

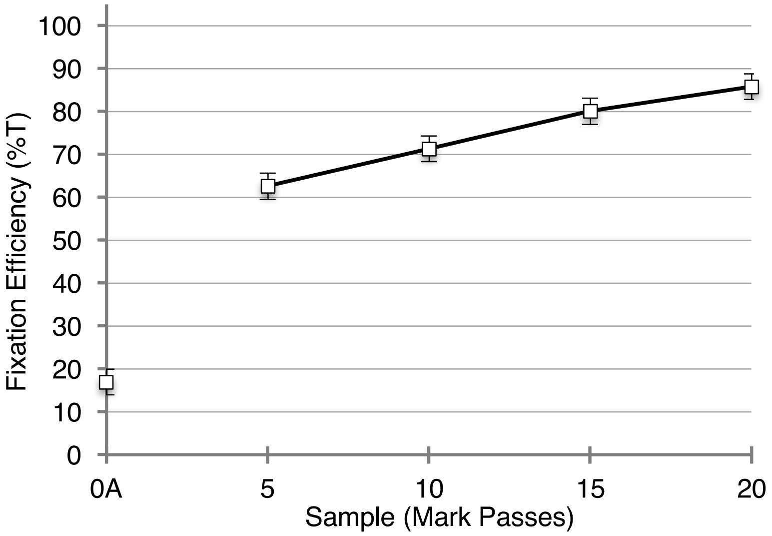


Figure 6.19 Fixation efficiency for peri-dyed wool after a reduction clear

The figures for the untreated control show an apparent uptake despite lack of laser treatment, which can be attributed to additional dye uptake that may have occurred in between processing stages. It can be approximated that a similar amount of additional uptake (around 16.9%) would have occurred on all samples. The figures shown therefore do not represent an accurate measurement for peri-dyeing in isolation. However, the figures are useful to show the relative levels of uptake that can be achieved with increasing number of laser mark passes, corroborated by visual observation.

Figure 6.19 shows a graph of the fixation efficiency for peri-dyed wool after a reduction clear, it can be seen that the fixation efficiency is high. This is particularly notable considering the laser dye reaction is only taking place on the surface of the textile. The efficiency improves as the number of laser mark passes increase. From this experiment, it can be concluded that increasing laser mark passes vastly improves dye exhaustion and fixation as shown, relative to the control sample.

A reduction clear for removal of excess or unfixed disperse dye on peri-dyed polyester was carried out using the following procedure: Peri-dyed samples were immersed in a 200ml solution containing 2g/l sodium diathionite, 2g/l caustic soda sodium hydroxide, 1g/l zetex and placed in an infrared dyeing machine for 15mins at 60°C. The resulting samples (Figure 6.20) showed a slight colour difference compared to the UPL only wash. It can be seen that the reduction clear removed dye staining from the untreated control. The results from these samples evidence the necessity to perform a reduction clear to remove unfixed dye from peri-dyed samples.

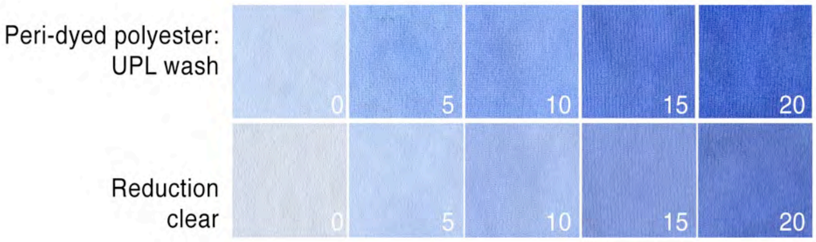


Figure 6.20 Peri-dyed Polyester at increasing mark passes after UPL and Reduction Clear

In order to perform subsequent performance testing on peri-dyed wool and polyester, it was necessary to first carry out a reduction clear to remove excess dye from each sample.

6.12 Colour Fastness

The samples described in the above experiments were further tested to determine the fastness properties of peri-dyed wool and polyester fabrics. The rubbing test *BS EN ISO 105-X12: 2002* was performed with a dry and a wet rubbing cloth on swatches of each peri-dyed sample. The staining and colour change values were recorded using the standard greyscale method (*BS EN ISO 105-A02: 1993* & *BS EN ISO 105-A03: 1993*). The samples are shown in Figure 6.21 and Figure 6.22, with the results recorded in Table 6.3.

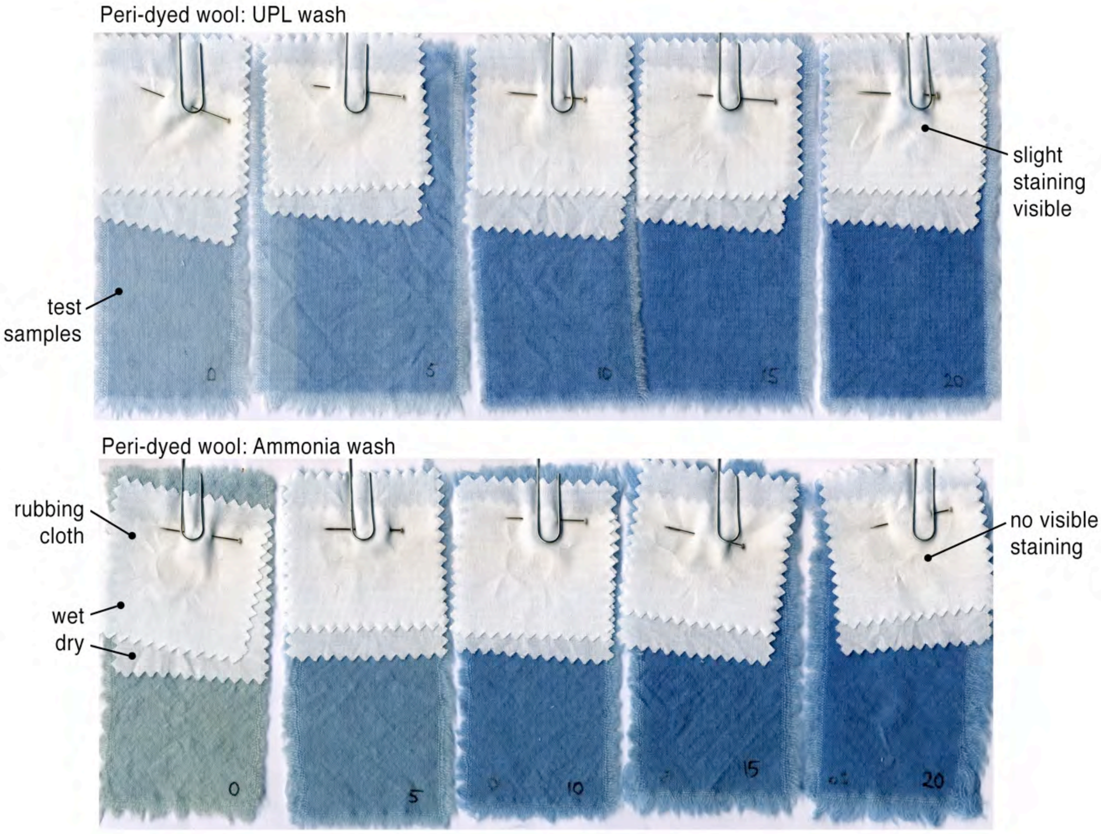


Figure 6.21 Fastness to Rubbing Test on Peri-dyed Wool at increasing laser mark passes

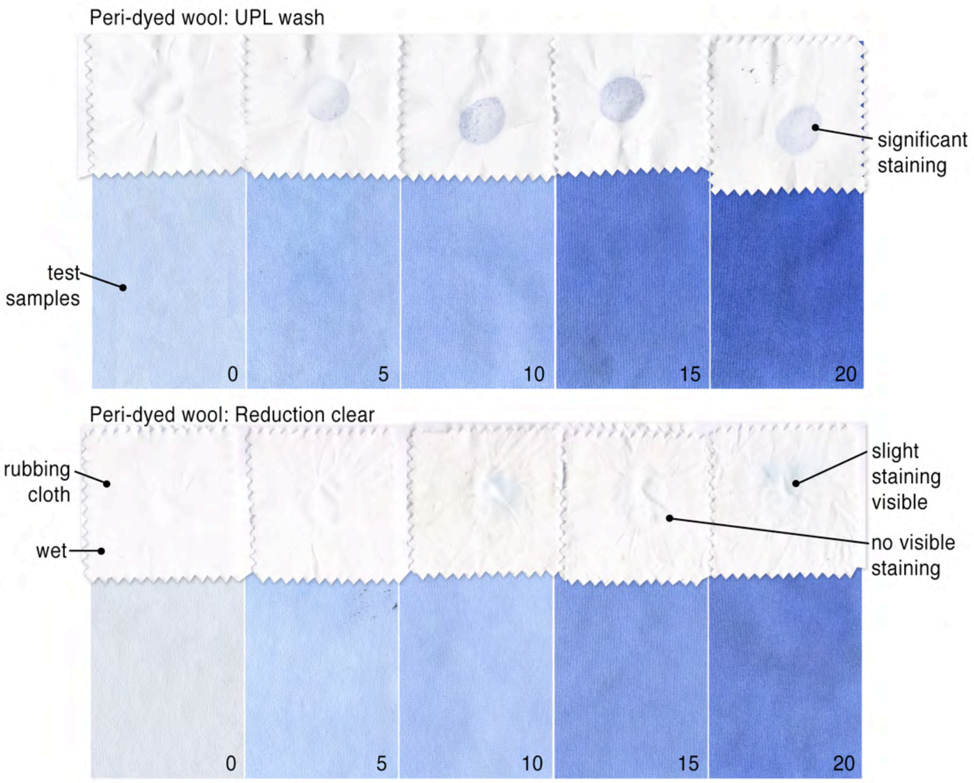


Figure 6.22 Fastness to Rubbing Test on Peri-dyed Polyester at increasing laser mark passes

Sample	Laser Mark Passes	Fastness to Rubbing (BS EN ISO 105-X12: 2002)											
		WOOL						POLYESTER					
		UPL Wash			Ammonia Wash			UPL Wash			Reduction Clear		
		Dry	Wet	Change	Dry	Wet	Change	Dry	Wet	Change	Dry	Wet	Change
a	0	5	5	5	5	5	5	5	4/5	5	5	5	5
b	5	5	5	5	5	5	5	4/5	4	5	5	5	5
c	10	4/5	4	4/5	5	5	5	3/4	2/3	4/5	5	4/5	5
d	15	5	4/5	5	5	5	5	3/4	3/4	4/5	5	5	5
e	20	4/5	4	4/5	5	5	5	4	3	4/5	5	4/5	5

Table 6.3 Fastness to Rubbing Results for Peri-Dyed Wool and Polyester

For wool it can be seen that fastness to rubbing results were high after the UPL wash, however the ammonia wash improved fastness to rubbing results at 10, 15 and 20 mark passes. The results for polyester show poor fastness to rubbing after a UPL wash only, however this improved significantly to provide commercially acceptable fastness to rubbing performance after a reduction clear. It was noted that the lowest scores were obtained at 10 mark passes, with scores improving as the number of mark passes increased. This corroborated the fixation results from the previous section; as the number of mark passes increased, dye fixation improved. These results show that a reduction clear is necessary after peri-dyeing to remove excess dye staining on the textile and improve fastness to rubbing performance. After the reduction clear, fastness to rubbing results were commercially acceptable, scoring highly on wool and polyester substrates.

The wash fastness test (*BS EN ISO 105-C10: 2007* (B)) was performed on peri-dyed wool and polyester samples after a reduction clear. No colour change or staining were observed on the tested samples or multifibre strips after the wash test for wool, with minimal staining at 20 mark passes for polyester. The results recorded based on the standard greyscale method and shown in Table 6.4, reveal high wash fastness performance for peri-dyed wool and polyester after the appropriate reduction clear to an acceptable commercial standard.

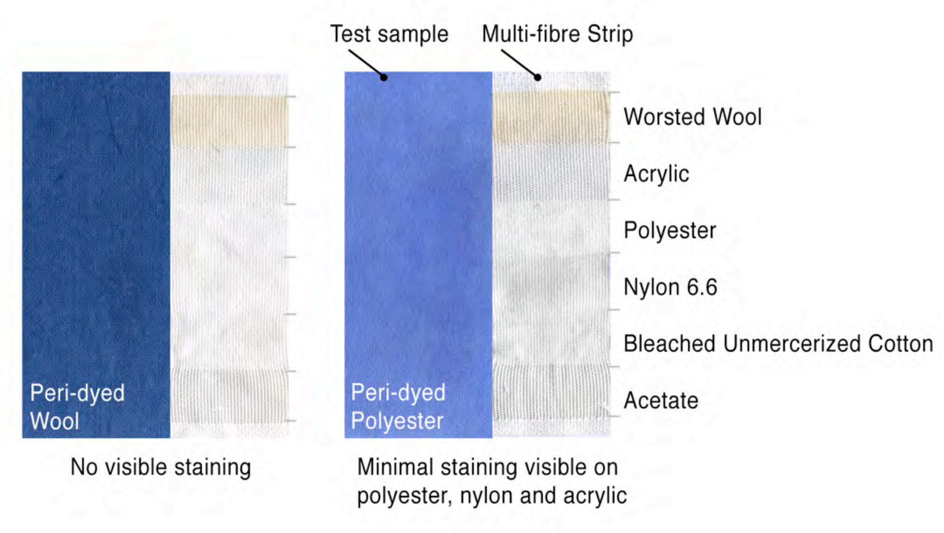


Figure 6.23 Fastness to Washing on Peri-dyed Wool and Polyester

Sample	Laser Mark Passes	Fastness to Washing BS EN ISO 105-C10: 2007 (B)							
		WOOL				POLYESTER			
		Cotton	Wool	Nylon	Change	Polyester	Nylon	Acrylic	Change
a	0	5	5	5	5	5	5	5	5
b	5	5	5	5	5	5	5	5	5
c	10	5	5	5	5	5	5	5	5
d	15	5	5	5	5	5	5	5	5
e	20	5	5	5	5	4/5	4/5	4/5	4/5

Table 6.4 Fastness to washing results for peri-dyed wool and polyester

6.13 Tensile Strength

International standard testing was carried out to examine the effect of peri-dyeing on the tensile strength of wool. Maximum force and elongation at maximum force were determined using the strip method (*BS EN ISO 13934-1: 1999*) as described in Chapter 4. Ten strips of peri-dyed and untreated wool were prepared and tested. The mean values are shown in the results Table 6.5. The results from tensile strength testing revealed that peri-dyed wool fractured after a load that was approximately equal to that of the control specimens. However tensile strain, or elongation, was reduced, suggesting that laser irradiation from peri-dyeing has produced a slight increase in the brittleness of wool fibres. Tensile strain of peri-dyed samples offered an improvement on that of the laser pre-treated wool.

Substrate	Tensile Strain BS EN ISO 13934-1: 1999			
	Load at Break (N)	Tensile Strain at Break (%)	Max Load (Kg)	Tensile Strain at Max Load (%)
Pretreated Wool	228.11	17.72	229.70	17.39
Peri-Dyed Wool	336.61	22.22	339.69	21.44
Control	339.03	30.96	342.11	29.48

Table 6.5 Maximum load and tensile strain results table

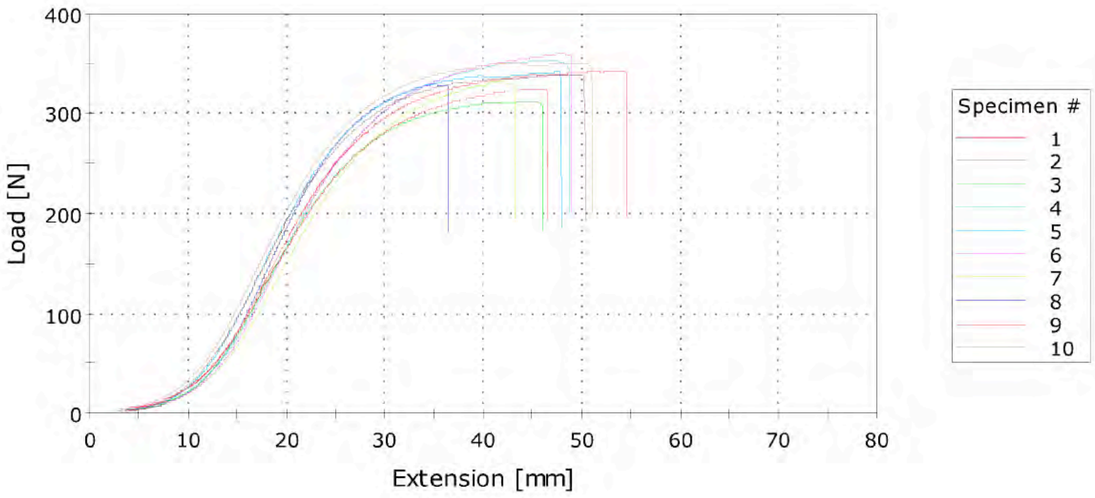


Figure 6.24 Load against extension graph for tensile testing of peri-dyed wool samples

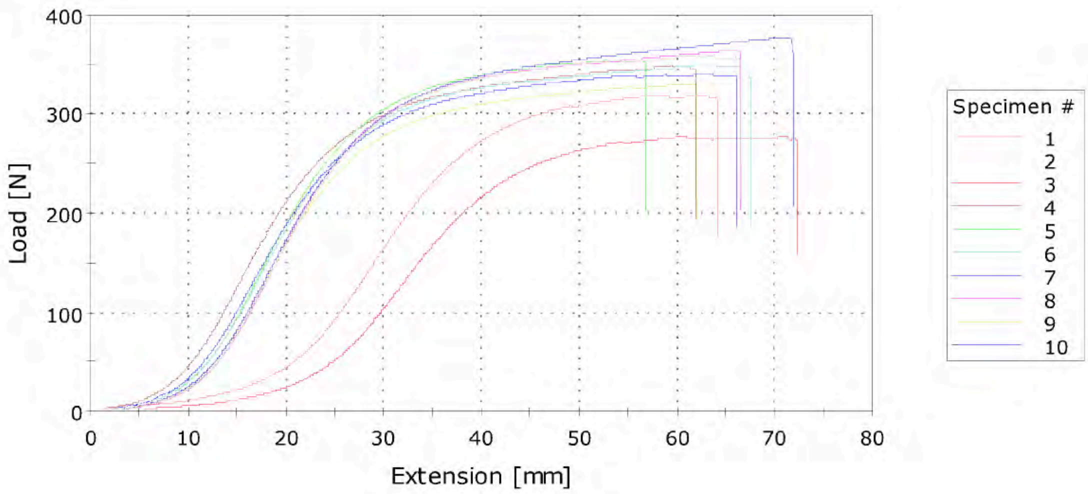


Figure 6.25 Load against extension graph for tensile testing of untreated wool control samples

The elastic limit can be described as the point at which permanent deformation of the substrate occurs. Within the elastic limit, a force can be applied to a substrate allowing it to stretch and return to its original size. On a graph of load against extension, the elastic region can be approximated as the linear portion of the curve. Comparison of the load against extension graphs for peri-dyed wool and untreated wool in Figure 6.24 and Figure 6.25 reveals the elastic limit of both sets of specimens to be approximately equal. When compared to the laser pre-treated wool specimens, peri-dyeing offers a significant improvement.

Peri-dyed, knitted polyester was tested for bursting strength using the standard test method (*BS EN ISO 13938-2: 1999*). Ten peri-dyed samples (at 2J/cm^2, 15MP) and ten untreated control samples were tested. The mean results from each set of samples are shown in Table 6.6, revealing peri-dyed polyester to have a reduced bursting strength, bursting at a slightly faster rate than the untreated control. However, the extension at which fracture occurred on the peri-dyed samples showed some improvement from the control sample, suggesting the peri-dyeing process did not have a negative effect on the stretching tolerance.

Substrate	Bursting Strength: BS EN ISO 13938-2: 1999			
	Pressure (kPa)	Extension (mm)	Time (s)	Bursting Strength (kPa)
Peri-Dyed Polyester	201.2	65.88	11.01	181.2
Untreated Polyester	286.30	60.27	15.7	266.3

Table 6.6 Bursting strength results table

6.14 Design Opportunities

6.14.1 Tonal Graphic Processing

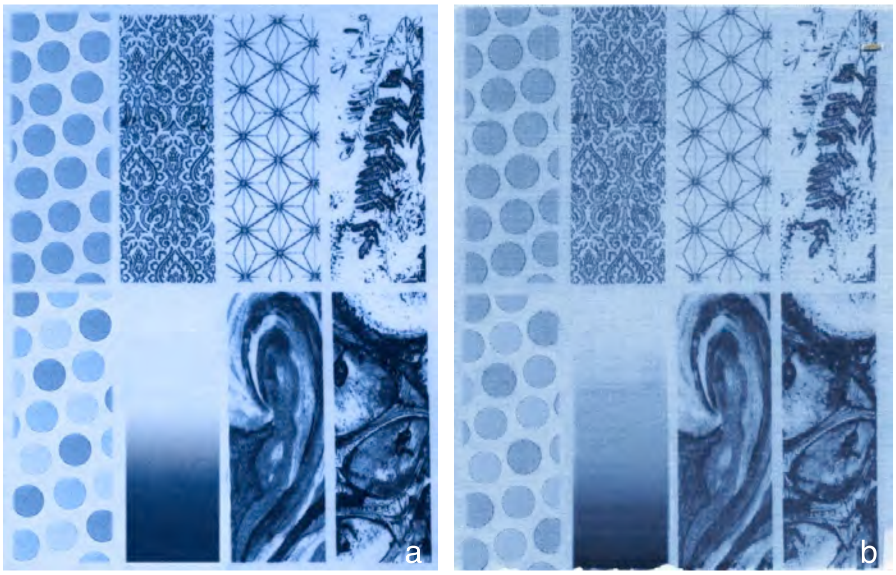


Figure 6.26 Mark making test sheet peri-dyed onto a) Polyester, b) Wool

The mark making test sheet was peri-dyed on polyester and wool textile samples using disperse and reactive dyes respectively. The resulting samples, shown in Figure 6.26, reveal that detailed linear graphics, tonal gradients, painterly and photographic imagery can be peri-dyed successfully, with high definition and multi-tonal precision. Further examples of design sampling on polyester are shown in Figure 6.27, showing accurate and clean image processing through precise fine linear detail patterns (a & b). Tonal gradients are processed smoothly (c) and photographic images can be processed as tonal graphics (d). Figure 6.28 further demonstrates the photographic capability achieved by peri-dyeing on polyester and wool substrates.

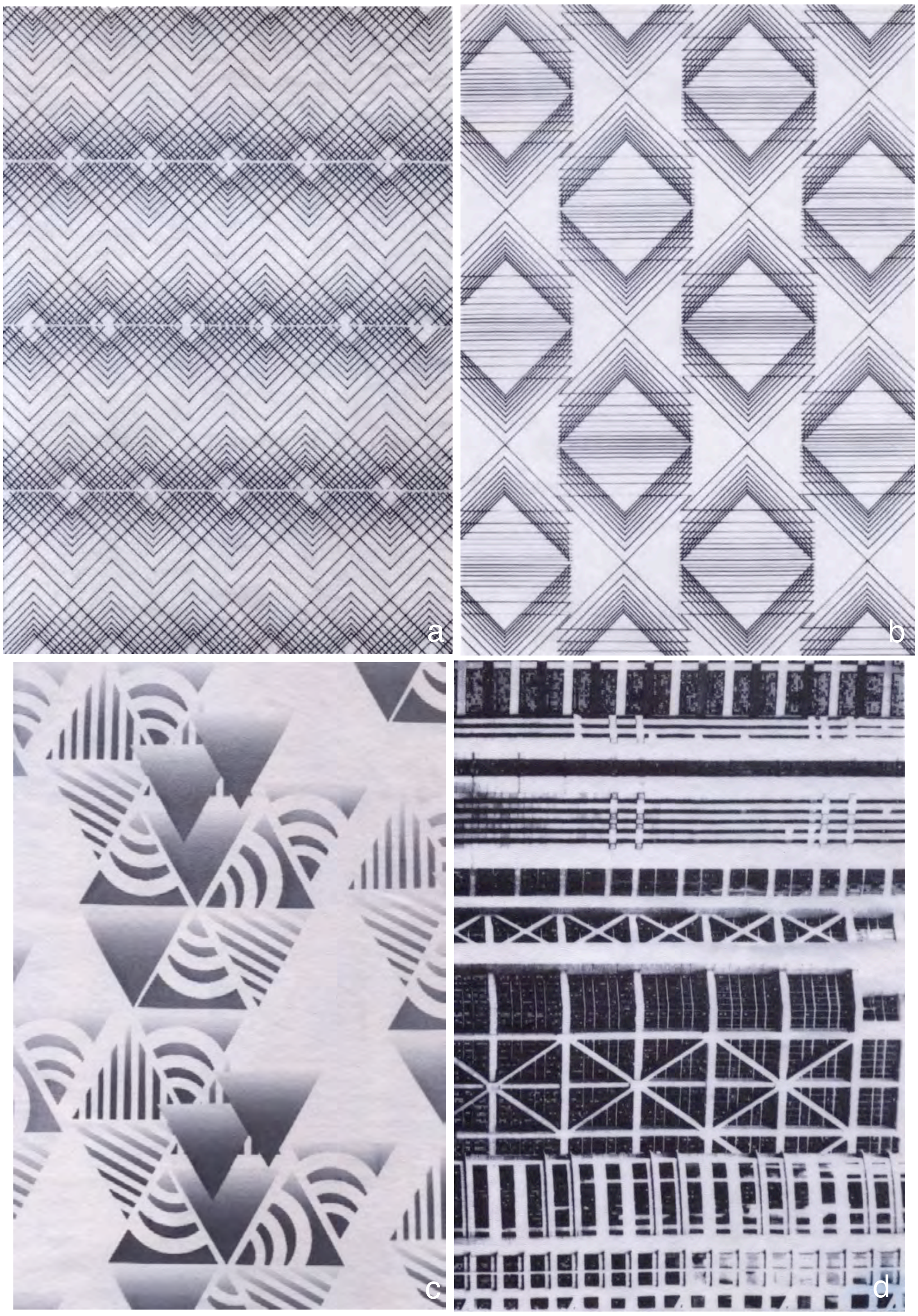


Figure 6.27 Peri-dyed Polyester a-b) Fine Linear detail, accurate image processing, c) Tonal gradients smoothly processed within AOP d) Photographic image processed as tonal graphic

Figure 6.28 Photographic Images Peri-Dyed on a) Polyester, b) Wool.

6.14.2 Multicoloured Peri-Dyeing Effects

Through creative sampling, multicoloured design effects were explored and a number of multicolour effects were achieved as discussed in this section.

With the laser processing only affecting surface layers of a textile substrate, it was found that double sided processing was possible, using two contrasting colours or patterns on each face of the textile as shown in Figure 6.29.

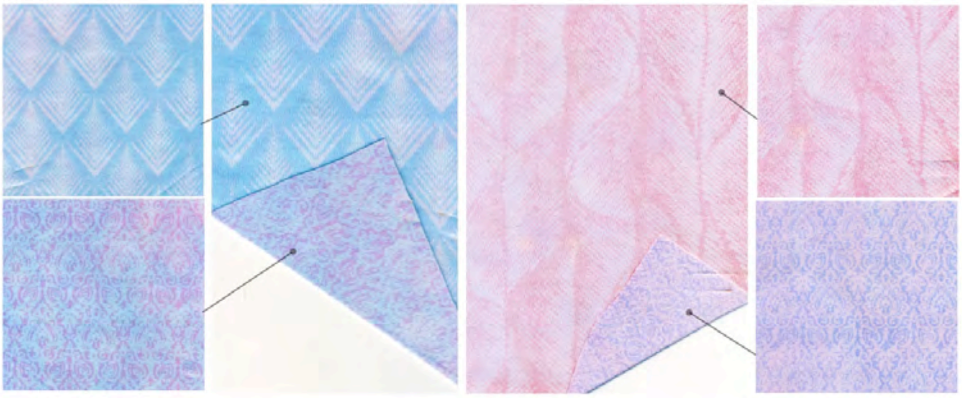


Figure 6.29 Peri-Dyed Polyester samples with processed with Double sided AOP

Peri-dyeing was shown to be effective on fabric that had been pre-coloured as shown in Figure 6.30. It was found that the peri-dyed colour merged with the original ground colour producing a mixed shade. It was necessary for the peri-dyed colour to be a darker shade than the coloured ground fabric for results to be effective.

Figure 6.30 Peri-Dyeing on a Pre-Coloured Ground

Application of dye by hand via pipette allowed multiple dye colours to be added and allowed to blend on the textile surface prior to laser fixation. An example is shown in Figure 6.31. 1ml blue dye was applied followed by 1ml each of red and purple. The dyes were allowed to bleed into one another and blend, as shown (*a*). After washing off the remaining dye from the sample, a blended colour result was obtained providing a subtle multicoloured gradient in the laser irradiated AOP (*b*).

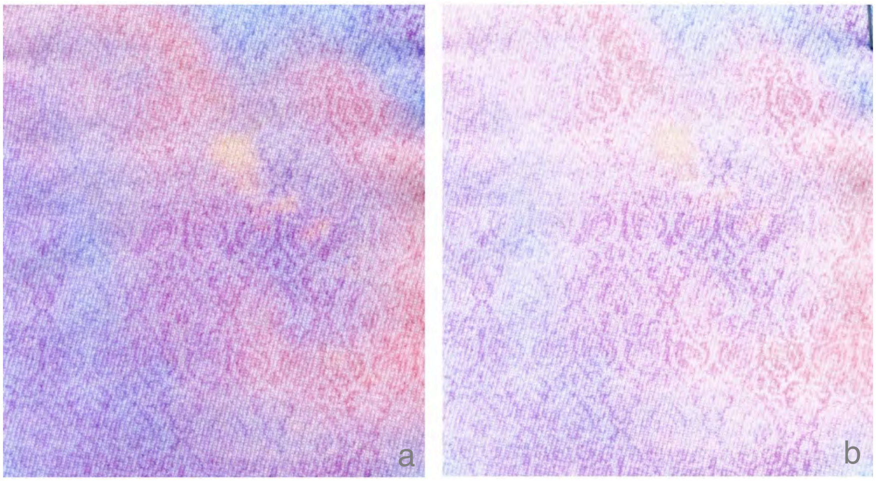


Figure 6.31 Blended dyeing for painterly effects a) before wash off shows areas of dye colour application, b) After wash off

Further sampling was conducted to experiment with this effect. Blue dye was applied to a polyester sample and orange ‘drops’ were added. Figure 6.32 shows the resulting peri-dyed sample. The orange colour drops add depth and a shadow effect the to the design. Figure 6.33 shows further sampling with colour blended dyes peri-dyed with a geometric design (*a*) and a photographic design (*b*). These samples have shown that a multicoloured design can be effectively achieved using a hand method, where each dye colour is applied by hand to an area of the textile. The process achieved partially controlled colour gradients, providing a blended dye effect within a CAD controlled graphic. Further experimentation was conducted to determine if multiple dye colours could be applied in a controlled manner, to achieve accurate placement of colour in targeted areas of a design.

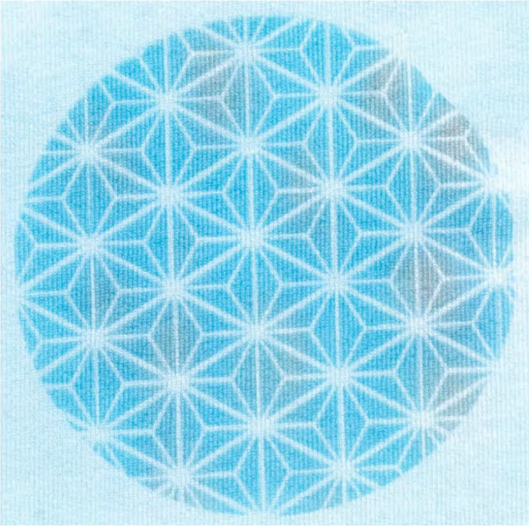


Figure 6.32 Two dye colours applied creating changes in colour across the design

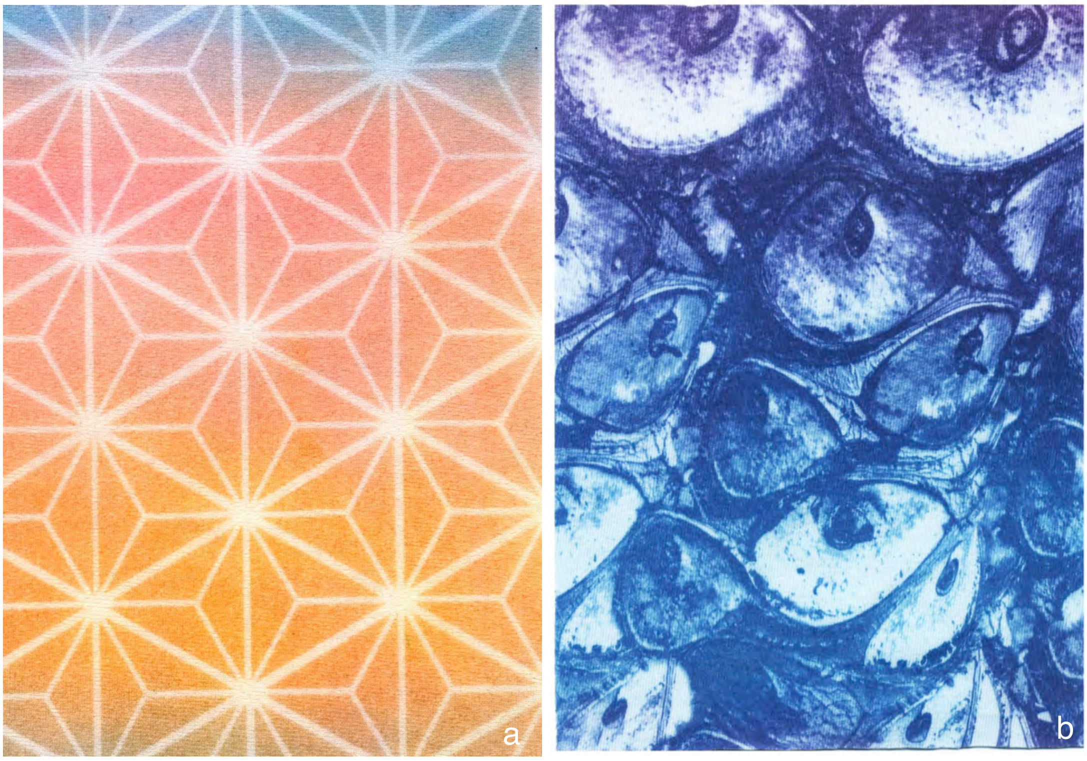


Figure 6.33 Peri-Dyed colour gradients on a) geometric design, b)Photographic design

The samples described above achieved multicoloured effects through blending dye colours. In order to further the design potential of the peri-dyeing technique, sampling was conducted to explore multi-layered colour processing. Digital files were prepared as colour separations, akin to a screen-printing process, with each colour assigned a separate design file. Dye colour 1 was applied to a polyester sample followed by laser irradiation of design file 1, a set of triangles. A second dye colour was then added to the same sample and a second design file, a second set of triangles, was laser irradiated. Finally a third dye colour was added and a third design file, consisting of a series of circles was laser irradiated to complete the pattern. After washing, the samples retained a three-colour pattern as shown in Figure 6.34. The colours were added in layers with laser irradiation in between each 'layer' of colour. However, the excess dye was not washed off between each layer, the dye was, 'used up' after each layer of laser processing, allowing a subsequent colour to be added without a wash off process between each dye colour.

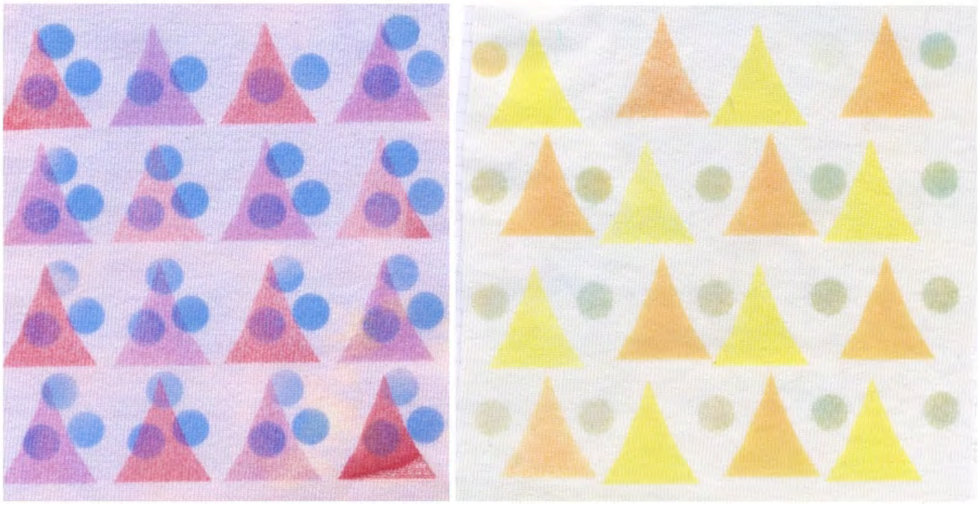


Figure 6.34 Peri-dyed polyester samples with layered processing

Further sampling explored the precision of this technique on alternate design imagery. Figure 6.36 show the two processing stages used to achieve a multicolored floral design. A blue dye was added to the sample followed by laser irradiation of the flower outline. Red and Yellow dyes were then added to the sample and allowed to blend. Laser irradiation inside the flower petals 'filled' the design with the blended dye colour. The same technique was used to create with a repeating version (AOP) shown in Figure 6.35.

Figure 6.35 Multicoloured AOP Peri-Dyed Sample

Figure 6.36 Peri-Dyed Sample: Layer 1) Blue dye applied followed by laser irradiation of linear flower outlines and background, Layer 2) Red and Yellow dye applied and allowed to mix followed by laser irradiation of inner flower, 3) Alternate design example

Colour separations were further examined with an aim to test a three colour print approach to achieve multi coloured designs. The traditional colours used for a multicoloured print process – cyan, magenta and yellow - were peri-dyed onto a polyester sample as shown in Figure 6.37. The colour diagram allows each colour to overlap to create a secondary colour range of red, green and blue in the overlapping areas. The results show potential to reproduce full colour imagery and indicate relevance to contemporary digital printing processes in terms of multi-colour dye application.

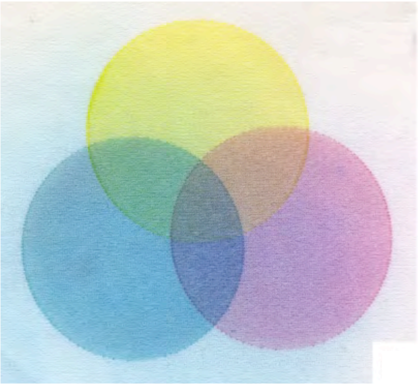


Figure 6.37 Peri-dyed CYM colour diagram

Figure 6.38 Peri-dyed photographic image: colour separations

A colour photograph was separated into its RGB (red, green, blue) channels on Photoshop, and each channel saved as a separate raster file. Dye was applied to a polyester textile relating to the corresponding colour channel, followed by laser irradiation. This was repeated for each of the channels. A combination of laser parameters and colour orders were tested, with the resulting samples shown in Figure 6.38. While the colour reproduction has not been fully resolved, the samples do show potential for reproduction of a colour photograph through the laser peri-dyeing technique. Further study into multicolour dye delivery would be required to optimise this process for peri-dyeing. The study of existing colour printing mechanisms may help to inform this process, which exists within digital reprographic fields. This line of enquiry was outwith the scope of this project, however it identifies an area of further work into full colour print production possibilities, drawing parallels with digital printing mechanisms.

6.15 Peri-Dyeing on Alternate Substrates

Figure 6.39 Peri-dyed felted and textured wool textiles

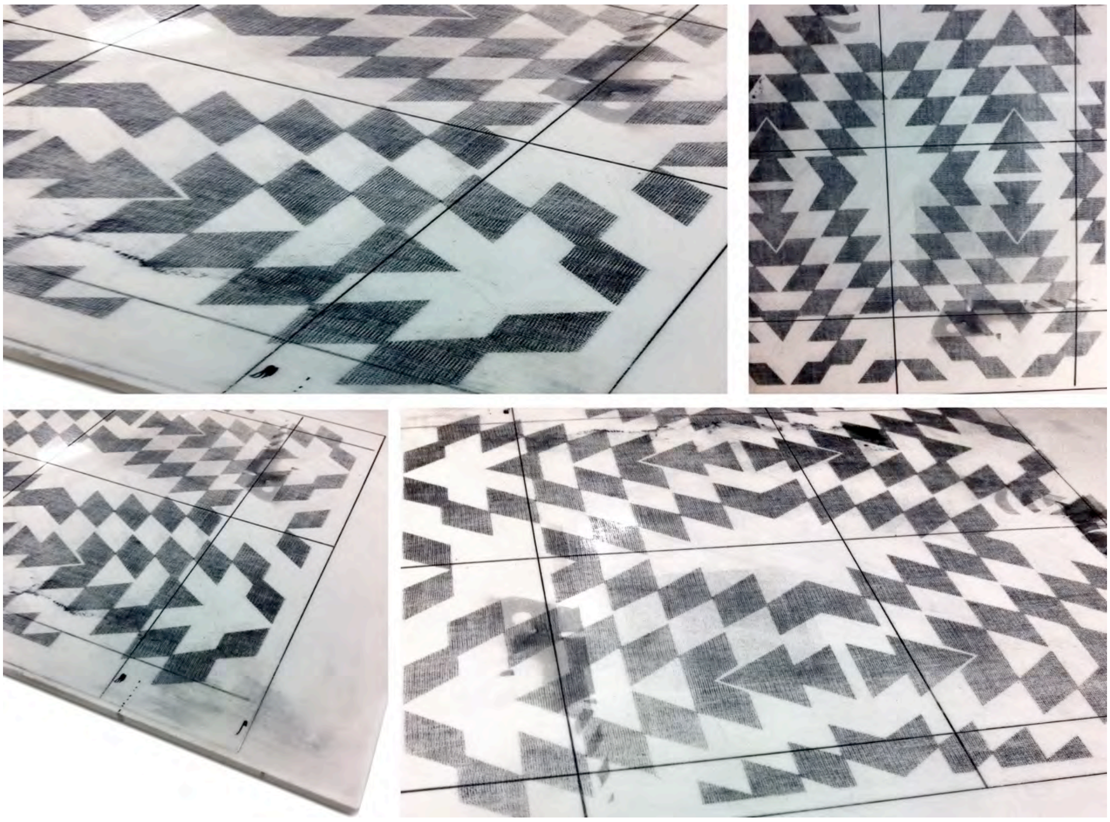


Figure 6.40 Peri-dyed 5mm acrylic board

Sampling explored the effect of peri-dyeing on a range of textile substrates and constructions including heavy weight, textured, felted and milled woven wool fabrics shown in Figure 6.39. The non-contact, precise processing advantages of the laser are significant in allowing fine detail designs to be peri-dyed onto textured substrates; a precision that is not achievable by digital printing or jacquard weaving on these surfaces.

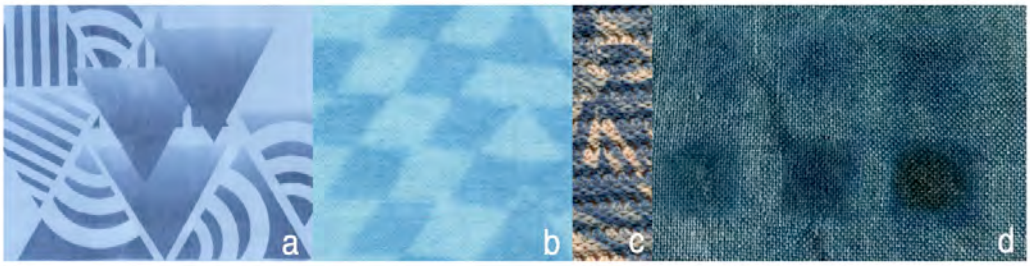


Figure 6.41 Peri-dyeing on a range of substrates: a) nylon, b) fine wool gauze, c) textured polyester knit d) linen

Figure 6.41 shows that woven or knitted structures, nylon, fine wools, heavily textured and relief surfaces can be peri-dyed effectively. Potential is also shown for the technique to be used for colouration and design of linen, revealing an area for further investigation. In addition, peri-dyeing was found to be suitable for surface patterning of solid substrates as shown on acrylic board in Figure 6.40. These samples widen the scope of the peri-dyeing process, showing it as a flexible technique for wide ranging substrate application.

6.16 Direct-to-Garment Peri-Dyeing

An opportunity to exploit the non-contact processing of the CO_2 laser was identified for the peri-dyeing process. This provides potential to utilise a direct-to-garment approach to textile design, whereby designs can be added to garment ‘blanks’ after their construction. Loughborough University’s links with bra manufacture was used as the motivator for processing an item of intimate apparel. In addition, the bra provides a shaped cup to test the potential for peri-dyeing across a three-dimensional garment shape. 1% reactive dye liquor was applied to the nylon garment, followed by laser irradiation of an AOP design. Figure 6.42 shows the resulting article after washing. The pattern appears distorted in the steep sloped sides of the bra cup. This requires editing of the CAD to compensate for the contour of the garment. However, the impact of this prototype clearly evidences three-dimensional non-contact processing, providing application advantages over existing print technology, which traditionally operates on flatbed surfaces only. The three-dimensional textile printing approach opens up direct-to-garment processing opportunities that could facilitate on-demand processing of finished garments.

Figure 6.42 Direct-to-Garment Peri-Dyeing

6.17 Laser Dyeing Discussion

This chapter has presented the development of a laser dye fixation method for textiles, referred to as peri-dyeing. In this technique, the dye reaction takes place at the point of laser material interaction.

The work in this chapter has shown control over the necessary parameters to impart graphic capability on a number of textile substrates and constructions, including knitted and woven wool, polyester and nylon. Appropriate tests were defined for the peri-dyeing process that worked across all tested substrates. These experiments also served to define an energy density range in which to work for appropriate graphics handling and dye fixation. Sampling has achieved multicoloured surface design effects with minimal or no damage seen under a microscope on polyester, wool and nylon substrates.

It was shown that laser energy density and repeated mark passes could be used to define colour and tonal gradients on textile substrates. Photographic quality graphics, and multicoloured surface design effects were achieved on both natural and synthetic fabrics. The remote, non-contact laser set up means that precision linear details could be achieved on highly textured fibre pile fabrics and three-dimensional surfaces as shown through sampling milled wool fabric and a garment prototype. This evidences a direct-to-garment processing capability with relevance to on-demand and customisation production contexts. Sampling demonstrated that the technique allows dye fixation on a range of substrates, both textile and solid plastics, widening the application opportunities. In addition, high fastness to washing and rubbing were evidenced, adhering to ISO international textile testing standards. This demonstrates the commercial viability of the techniques.

Chapter 5 showed that laser energy density could be used to specify colour values. Level dyeing is a key challenge for colouration in the textile industry. Chapter 5 has shown through CIE L*a*b* measurement that colour can be defined through laser energy density selection. After calibration, this could be used to define exact colour values or pantones with a level of control that ensures repeatability. This suggests clear advantages of laser pre-treatment as an enhanced colouration tool. However, as a pre-treatment, wet dye processes were still necessary, and fibre damage was possible with darker shades. This was addressed and progressed via the peri-dyeing technique, which provided targeted dyeing at the point of laser irradiation, further reducing dye and water waste. Peri-dyeing allowed laser controlled colour specification with clear potential shown for full colour reproduction of imagery. This is akin to digital printing, but has potential to advance digital printing processes through micro precision capabilities, non-contact and direct-to-garment processing.

The effects of laser irradiation on dye fixation for wool and synthetic substrates discussed in this chapter, and the surface and dyeing properties of wool discussed in Chapter 5 offer new design opportunities for textile design in line with the research aim. Results achieved from both laser dyeing techniques discussed in Chapters 5 and 6 have been summarised in Table 6.7 which presents a summary of the potential advantages and applications that have been identified.

The surface design effects that can be achieved have been categorised into five types based on the work carried out in this study. These are colour-coded in Table 6.7 and include; tonal colouration, multi-colouration, relief effects, non-contact surface design and precision graphics, as discussed below.

- **Tonal Colouration Effects (SE1)** and **Multi-Colouration Effects (SE2)** The digital laser dyeing techniques offer a range of tonal and multicolour colouration opportunities for textile design. Targeted application of laser irradiation can control colour values through selection of appropriate laser energy density. Clean tonal gradients, detailed surface patterning and photographic image capabilities have all been evidenced through sampling in Chapters 5 and 6. Laser pre-treatment of polywool facilitates differential dyeing resulting in multicolour design opportunites discussed in Chapter 5. The blending of dyes and layered processing in this chapter has shown that multicoloured imagery can be realised through peri-dyeing.

- **Non-contact surface design (SE3)** Non-contact laser processing provides unique surface design opportunities for 3D laser dyeing and patterning. Through the laser dyeing techniques, precise targeted graphics can be applied to textured, pile fabrics not achievable by traditional means (Figure 6.39). In addition, *Laser Textile Design* can be applied to three-dimensional products, finished garments and across seams as shown in this research in through the intimate apparel prototype in Figure 6.42. This opens up direct-to-garment processing opportunities that are difficult to achieve with conventional flatbed printing processes.

- **Relief effects (SE4)** Laser engraving of milled or felted wool was shown to create three-dimensional and relief textures with enhanced colouration in the laser treated areas after subsequent dyeing.

- **Precision Graphics (SE5)** With a beam size of 0.03cm the laser is capable of precision on a microscopic level. This facilitates precision graphic capabilities as shown through the design samples produced throughout this research. In addition utilising non-contact laser processing, the peri-dyeing technique allows fine linear colouration details to be applied to textured or pile fabrics. This reveals an advantage over alternate surface design procedures identified by contract interior manufacturer, Camira, as a unique feature that jacquard weaving or digital printing cannot achieve.

A number of further avenues for investigation were identified for the laser dyeing techniques. These have been categorised into three areas, which are colour coded in Table 6.7. They include; further investigation into colour reproduction and dye application methods, direct-to-garment processing, fixation of alternate dyes and finishes, and additional material exploration.

- **Colour reproduction and dye application (FW1)** Further work in developing full colour reproduction aspects of the peri-dyeing technique include optimising colour separation processes, that have been demonstrated in this chapter (Figure 6.37), with reference to reprographic techniques. In addition, alternate dye application methods could improve the accuracy of dye delivery. A pad mangle, flying print head, a nozzle or automated spraying device on a three-dimensional axis could be tested, similar to those used in automotive manufacture to maintain the non-contact processing benefits. Alternate dye carriers such as pastes, gels or solvents could also be investigated.

- **Direct-to-garment laser processing (FW2)** Peri-dyed samples on a three-dimensional garment shown in Figure 6.42 confirmed the capability of the laser textile techniques to be applied through a direct-to-garment approach. This mode of surface design application has potential to be developed into a digital *Laser Textile Design* service model relevant to on-demand, rapid prototyping or practitioner production contexts. Further testing could identify the necessary requirements for a digital interface and laser set up to process product blanks, on-demand and close to market. The techniques have the design flexibility relevant to mass customisation by suppliers or participatory design by customers at point of sale. Engineered design could be further explored for specific three-dimensional and shaped products.

- **Laser fixation of alternate dyes and finishes (FW3)** The technique also has potential to allow laser fixation of chemicals other than dye. Initial investigations have shown potential for fixing a hydrophobic compound (Aromatic Amide) on Polyester using the same peri-dyeing technique. This suggests hydrophobic coatings could be ‘peri-dyed’ onto textile substrates. Further investigation is necessary to determine the proficiency of peri-dyeing as a fixation device for alternate functional finishes including hydrophobic or hydrophilic coatings or compounds, flame retardant or antibacterial finishes. Laser dyeing processes could also explore potential for enhanced fixation or uptake of natural dyestuffs thus improving their potential for commercial application.

- **Additional materials (FW4)** Further testing of the peri-dyeing technique to examine laser dye fixation on a range of additional substrates and fabric constructions, for example proteineous fibres, linen, hemp and cotton, woollen carpets and non-woven materials. Initial tests in section 6.15 suggest the process would be effective on bast fibres such as hemp and linen. These fibre types may have local production capabilities and therefore an improved sustainability profile as discussed in Chapter 2.

Table 6.7 predominantly examines the merits of laser dyeing as a process for design, offering designers an overview of the effects that can be achieved and their advantages. Use of the technique in a professional design scenario is further explored in Chapter 9, during design development of a textile collection for contract interiors, and direct-to-garment processing on performance swimwear. The discussion on advantages of laser dyeing for sustainability and manufacture in Chapter 5.4 remain relevant to the peri-dyeing procedures, with increased design flexibility, improved dye, water and energy efficiency through targeted dye fixation and elimination of submersion dye processes. Further discussion relating to advantages of the techniques for manufacture, application and sustainability are discussed in Chapters 9 and 10.

Laser dyeing method	Surface Effect	Advantages Offered	Areas for Further Investigation
Laser pre-treatment of wool	Enhanced dyeing	• Controllable colour defined through laser energy density • Tonal pattern and colouration effects in one step • Reduced water, energy and dye consumption • High colour fastness to washing and rubbing	• Lifecycle Analysis Quantify energy, water, chemical savings (all methods)
	Tonal colouration and patterning		• Explore further dye, material, construction and composition combinations
Laser engraving and dyeing of wool	Relief Surface on milled fabric	Combines tonal dye and 3D textural design effects unachievable by other means	
Laser pretreatment of polywool	Multicoloured dye effects	Differential dyeing offers multicoloured designs from a single mixed dyebath	
Peri-dyeing laser dye fixation	Tonal dye colouration and patterning	• Controllable colour and dye fixation defined through laser energy density • Accurate graphic processing for clean colour gradients, fine linear detail and photographic imagery • Precise targeted microscopic control • Multicolored patterning • Reduced water, energy and dye consumption • High colour fastness to washing and rubbing	Alternate materials
	Precision graphics and fine linear details		• Dye fixation of alternate finishes: e.g.hydrophobic compounds, • UV laser and dyes • Natural dyes
Peri-dyeing dye blending	Multicoloured patterning		Engineered moulding for multi-coloured pattern
Peri-dyeing Layered processing	Colour reproduction		• Dye application methods- print head nozzle, pad mangle.
			• Full colour graphic reproduction CYMK colour separations
Peri-dyeing on three dimensional objects	Non contact, 3D laser dyeing for processing shaped or textured surfaces	• Direct-to-garment processing • Precise patterning on textured or high pile wools not achievable by traditional means	Engineered design for specific 3D products / shapes.
			On demand laser supply service with Digital interface and laser setup

Key:	Tonal effects (SE1)	Multicolour effects (SE2)	Non contact effects (SE3)	Relief effects (SE4)	Precision effects (SE5)
	Colour effects (FW1)	DTG (FW2)	Fixation (FW3)	Alternate materials (FW4)	

Table 6.7 Table of Advantages of Laser Dyeing Techniques and Further Work

6.18 Chapter Summary

This chapter has presented the development of the peri-dyeing technique; a laser dye fixation method for textiles. In this technique, the dye reaction takes place at the point of laser material interaction.

The chapter described experiments to optimise the technique through the systematic investigation and sampling of laser parameter and dye application variables. Appropriate tests were defined for the peri-dyeing process that worked across all tested substrates including knitted and woven wool, polyester and nylon. Testing evidenced high dye fixation efficiency on the surface of peri-dyed textile samples. This resulted in targeted dyeing and high definition graphic capabilities with minimal or no damage seen under a microscope, improving on previous laser dyeing techniques.

The commercial viability of the technique was demonstrated via testing conditions that adhered to ISO international performance testing standards. International standard testing revealed the permanence of the effects, showing high rub and wash fastness performance after a suitable wash off process in the form of a reduction clear. To fix dye at a high depth of shade, increased mark passes and energy density were required to be delivered to the substrate. Careful control of laser parameters is necessary to maintain an acceptable breaking strength for tensile properties of treated fabric substrates, although it was concluded that the elastic limit of peri-dyed materials remains consistent with that of the control. In addition, a significant improvement can be seen from existing fibre modification laser dye techniques discussed in Chapter 2 for synthetic fabrics and in Chapter 5 on wool.

Graphic capability was explored, evidencing a range of tonal, and multicoloured effects. From block filled shapes to fine linear details and photographic imagery, the technique was shown to be capable of processing any CAD files with precision. Multicolour processing, double sided textiles and colour separations have also been achieved. The technique allows remote, non-contact processing of finished textile products. Of note, the technique can function on three-dimensional and relief surfaces as shown on the highly textured wool and moulded bra garment. This evidences a direct-to-garment processing capability with relevance to on-demand and customisation production contexts.

Peri-dying has the potential to enable digital design innovation and customisation in the manufacture of finished textile goods contributing to environmental strategies through reduced energy, water and resource consumption. As well as agile processing opportunities that may facilitate responsive, less wasteful production systems, further discussed in Chapter 10.

CHAPTER 7 : LASER MOULDING FOR THREE-DIMENSIONAL TEXTILE SURFACE DESIGN

7.1 Introduction: Three Dimensional Textiles and Laser Processing of Synthetics

7.1.1 3D Textiles

As observed in the experiments in Chapter 4, and reviewed in Chapter 2 (Addrison, 2009) laser irradiation can be seen to affect the appearance and handle of the surface properties of polyester fabrics. During initial experiments, it was observed that the dimensional stability, that is the ability of a material to maintain its essential or original dimensions (Wolff, 2004) of knitted polyester and polyamide textile surfaces was affected during laser irradiation, causing a change in tension on the substrate. The author's background in woven textiles provided a familiarity with achievable design effects facilitated by altering tension in the production of constructed textiles. It was hypothesised that three-dimensional surface design effects may be achieved by laser irradiation of a fabric substrate under strain.

As discussed in Chapter 2, in the design and construction of commercial and industrial textiles, three-dimensional surfaces are often used to provide beneficial properties to the fabric. Some traditional constructed textile patterns exist for their enhanced properties. For example, honeycomb weave structures are traditionally used to provide increased absorption and insulation properties. Many functional finishes for textiles that were originally designed for high performance have become synonymous with high quality style, leading to their adoption in fashion and trend led textile products for their aesthetic appeal (Braddock & O'Mahony, 1999). Examples of traditional and contemporary three-dimensional finishes that show potential for aesthetic appeal and enhanced functionality are discussed with reference to specific laser moulding effects in section 7.8.

Traditionally, three-dimensional effects can be added during the construction of textiles such as weaving, or in the finishing phases through embroidery and stitching techniques. Some wet-techniques such as devoré, flocking, felting and shibori can also provide three-dimensional effects. Heat and heat-setting methods have long been used for creating three-dimensional forms on synthetic substrates. A number of textile practitioners have investigated heat or laser effects to produce three-dimensional textile outcomes. Nigel Marshal researched vacuumed formed textile structures, woven using plastic films (Braddock & O'Mahony, 1998) however these did not have the drape and handle normally associated with fabric. Like other forms of heat moulding, vacuum forming requires a new mould to be cast for each new design. Isobel Dodd created formed textiles by baking printed rubber fabric adhesive on rayon stretch velvet at high temperatures to alter tension across the surface of her textile based accessories (Dodd, 1999). This resulted in effective sculptural fabrics, however the method would contaminate the materials rendering them non-recyclable. Janette Matthews, used a CO_2 laser to aid creation of origami inspired three-dimensional textiles. The laser was used to make templates and to score or cut fabric for complex folded shapes (Matthews, 2011). Goldsworthy explored laser welding technology to bond synthetics producing layered outputs that provided three-dimensional and relief qualities (Goldsworthy, 2009).

The potential to use a CO_2 laser to heat set pre-determined shapes in a synthetic textile has not been previously explored. The use of laser technology to create three-dimensional textile forms may present processing advantages over traditional methods. The laser does not require moulds or complicated loom set up to produce three-dimensional forms and offers ease of pattern change through digital generation of designs. This in turn would allow targeted processing on textile 'blanks' or engineered garment pattern pieces. Laser technology offers dry processing, without requirement for additional materials, such as thread for stitching. The use of synthetic mono materials may provide additional sustainability benefits for ease of recycling at end of life.

7.1.2 Effect of heat on synthetic polymers

To further understand the changes taking place on polyester and nylon substrates due to laser irradiation, it is useful to review the role that heat plays in the formation and processing of synthetic textiles.

When a synthetic fibre is formed, crystalline and non-crystalline (amorphous) regions are present. The fibres undergo further processing known as cold drawing, creating an ordered orientation and increased strength as shown in Figure 7.1. If the fibre were to be heated above the glass transition temperature, molecular movement in the amorphous regions would result in the fibre returning to the undrawn state, reversing the cold drawing process and resulting in shrinkage (Horrocks & Anand, 2000). To prevent shrinkage of synthetic textiles during use, a heat setting process is used to 'fix' fabric dimensions. The textile, with fibres in their drawn state, is held in place using stenter apparatus. When the textile is heated above glass transition temperature, molecular movement occurs as before, however shrinkage is not permitted due to the positioning on the tension frame. Instead, the relative orientation of molecules in the amorphous regions begin to crystallise in this position (ibid). The dimensions of the fabric on heat setting will be stable up to the heat setting temperature. That is, the fabric will not now shrink when heated above the glass transition temperature. However if the fabric is heated beyond the heat setting temperature shrinkage will occur.

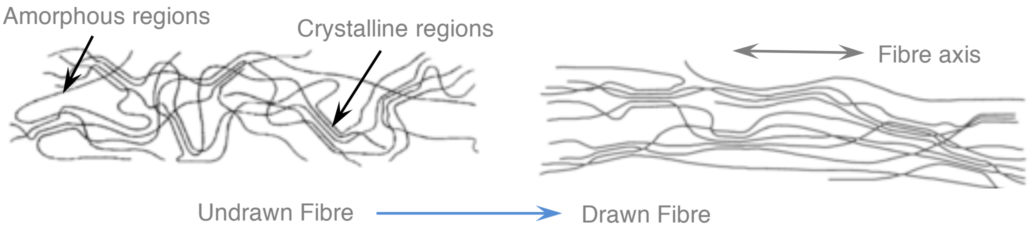


Figure 7.1 Effect of Drawing on a Polymer Fibre

Montazer and Bahtiyari have reported reduction in the crystallinity of polymers after laser irradiation for both polyester (Montazer, 2011) and polyamide fibres (Bahtiyari, 2011). It can be concluded that the reported change in crystallinity is related to change in temperature. When the thermal energy of the laser heats the synthetic fibres above their glass transition temperature, or indeed above their heat-setting temperature, some shrinkage may occur as the fibres return to a more amorphous state. If the power is further increased and the temperature of polymers is heated towards melting point, molecules in the crystalline regions are weakened by thermal energy and the polymer begins to melt further increasing the amorphous regions in the laser irradiated areas.

The following study examines the potential of using photothermal energy of a CO_2 laser to induce a heat setting effect on polyester and nylon substrates, investigating three-dimensional effects through controlled tension and targeted laser irradiation.

Knowledge of the effect of tension to induce three-dimensional surface effects in the weaving process as well as the use of hand controlled craft apparatus resulted in the development of the technique described in this chapter. As discussed in Chapter 3, this shows how an exploratory, craft-led approach in the initial stages of the research provided proof of concept and a hypothesis to be tested with further work. The development stages used a more systematic approach making use of technical and scientific processes to record and measure the effects. This provided rules, parameters, limitations and a best practice for the procedure. Polymer chemistry theory as discussed in this section facilitated explanation and understanding of the process. In the final stages, design practice was used to test the aesthetic and tactile qualities that could be achieved. A combination of the scientific and creative approaches were essential in creating this technique as a potential design tool for three dimensional laser moulding of synthetic stretch fabrics.

7.2 Tension equipment

Figure 7.2 Embroidery Hoop

Figure 7.3 Tapestry Frame

7.2.1 Embroidery Hoop

An embroidery hoop consists of two wooden circles as shown in Figure 7.2. It is traditionally used to hold fabric taught for hand and machine embroidery. Fabric is layered over the smaller inner circle to be trapped between the inner and outer hoops. The outer hoop has an adjustable circumference that can be used to hold the fabric securely in place. The tension of the fabric can be controlled by hand, by stretching the fabric over the hoop. A 25cm diameter embroidery hoop was used in the initial stages of this study and provided proof of concept of the laser moulding technique.

7.2.2 Tapestry Frame

An adjustable 20 x 20cm square tapestry frame was also tested, shown in Figure 7.3. Rotating bars on each side of the plastic frame could be used to tighten and release the fabric. This frame allowed horizontal and vertical directions to be stretched separately. The extension was measured by marking the internal area of the frame before and after tension was applied to the fabric. The extension was calculated by expressing the difference in length of these measurements as a percentage of the original dimensions as shown in the following equation.

$$E = (D_1 - D_2) / D1 \times 100$$

Equation 8 Extension

Where E is the Extension (%), D_1 is the original length of the fabric and D_2 is the extended length of the fabric in centimeters.

7.2.3 Stenter Frame

Stenter apparatus is used in the textile industry to stretch or secure fabric in uniform pre-determined dimensions as discussed in the previous section. In this study a laboratory-scale stenter frame was used to provide consistency and allowed a chosen level of tension on the textile samples for experimentation. The stenter frame used in this research can be seen in Figure 7.4. Steps for using the stenter to apply tension to fabric are listed below.

1. Fabric is attached to the frame by a series of small pins or *teeth* (a). When the fabric is first attached it should be held taught without stretching.
2. Horizontal tension can be altered by moving the vertical bars (b). The distance the bars have moved can be measured using the top ruler (c). Adjustable screws are used to loosen or hold the bars securely in place (d).
3. Vertical tension is altered by adjusting the lower horizontal bar (e). When force is applied to stretch the fabric vertically, the springs (f) on either side of the stenter show the force in deci-Newtons (dN) that has been applied to the fabric.

For each experiment, the horizontal tension, calculated using equation 8 is presented as a percent extension (change in width of the fabric) and the vertical tension, presented as a force in Newtons can be recorded and easily replicated.

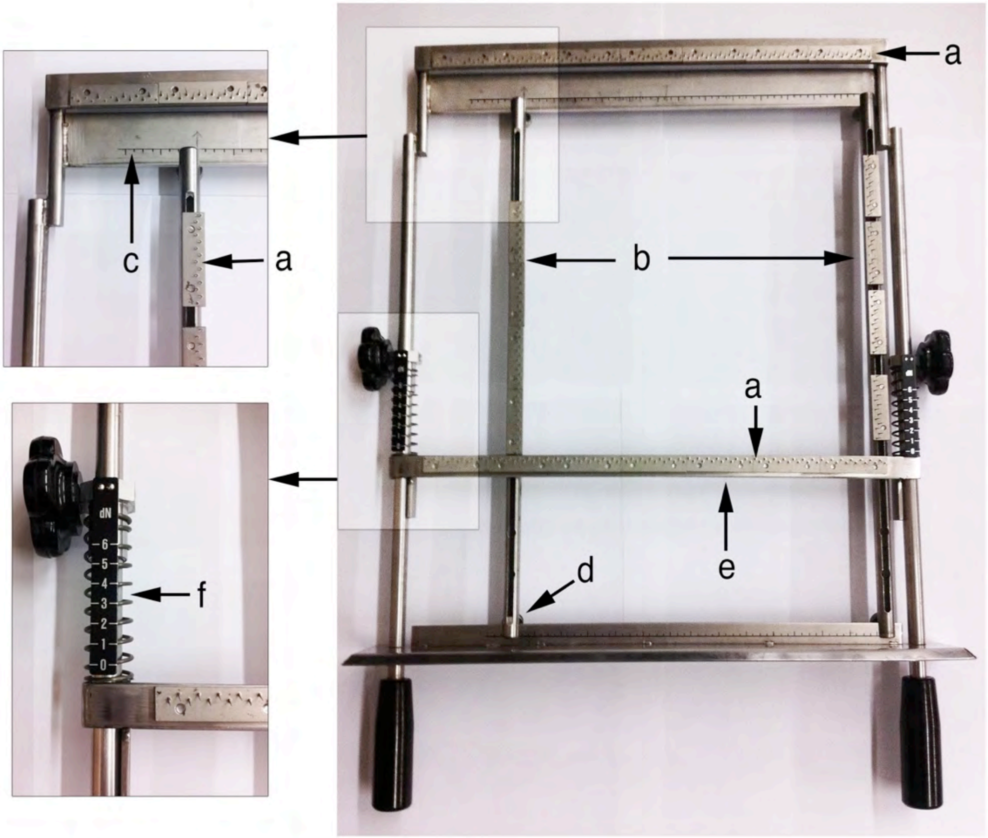


Figure 7.4 Stenter Frame

7.3 Establishing Tension Assisted Laser Moulding

A knitted polyester fabric held under tension on an embroidery hoop was laser marked with a series of test squares at an energy density of 3J/cm^2. The CAD file used for marking the squares is shown in Figure 7.5. When released from tension, the shapes appeared to retain their stretched proportions, resulting in a three-dimensional fabric surface in the laser treated areas (Figure 7.6). The embroidery hoop provided proof of concept of the laser moulding technique with initial tests showing that it could be used to create three-dimensional surface effects. However stretching the fabric over the embroidery hoop by hand did not allow consistent levels of extension across the fabric. It can be seen that the effects in Figure 7.5 have not been consistent across the sample due to an uneven fabric tension during laser irradiation. It was found that the extension could not be accurately measured using the embroidery hoop therefore the results were unpredictable.

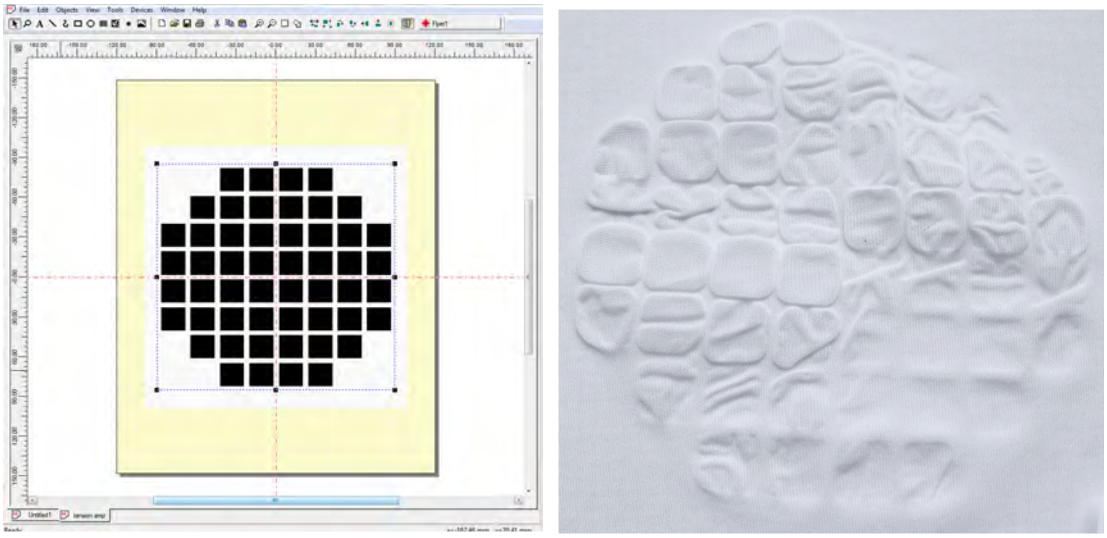


Figure 7.5 CAD file and resulting laser moulded polyester sample: squares irradiated under tension in embroidery hoop.

Figure 7.6 Laser Moulded Circles processed using Tapestry Frame

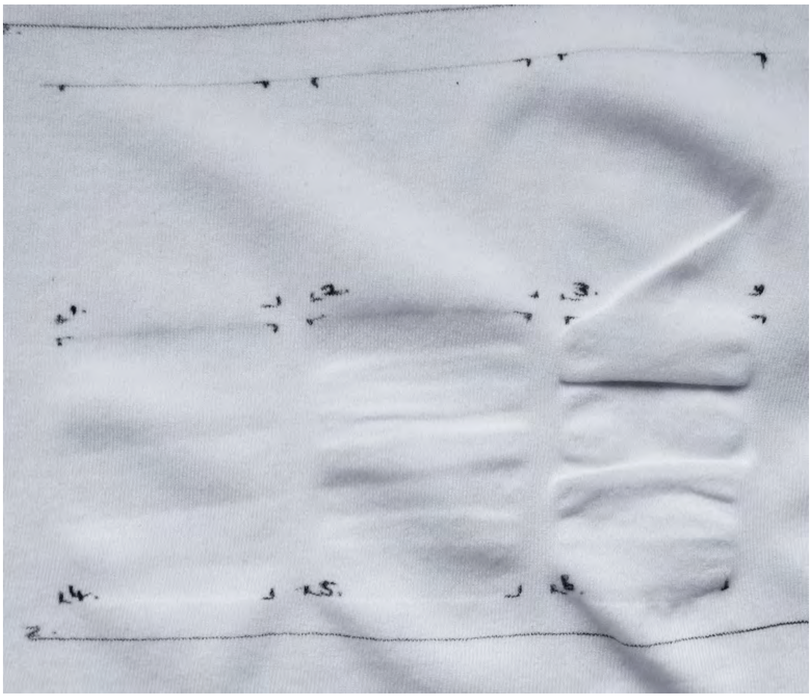


Figure 7.7 Laser Moulding Increasing Fabric Extension using Tapestry Frame

Initial tests using the tapestry frame demonstrated that even extension of the fabric under tension resulted in a more consistent three-dimensional effect across the surface of the cloth, see Figure 7.6. Measuring the extension for each experiment allowed comparison of the results and a greater level of control over three-dimensional effects. The tapestry frame was used to provide an initial insight into the effect of altering the fabric tension prior to laser irradiation.

The sample in Figure 7.7 was mounted on the tapestry frame and laser irradiated at an energy density of 3J/cm^2 with six rectangles, marked on the sample as 1-6. Rectangle 1 was irradiated without extending the fabric, each subsequent rectangle was laser marked after increasing the fabric extension. It was shown that increasing the tension of the fabric resulted in a more pronounced three-dimensional effect after laser processing However, it was found that the frame was unable to securely hold the fabric when stretched in excess of 25%. In order to further test the technique, equipment was required that could consistently provide a chosen level of tension on the textile samples for the effects to be controlled and replicated and accurately measured.

Figure 7.8 shows the process of laser moulding using a stenter frame. A CAD file consisting of a raster grid of squares was created using Winmark software (a). The fabric was held under tension and extended by % at a force of 0.4N. The fabric then was laser irradiated at an energy density of 3J/cm^2 under tension (b). Before the sample was removed from the frame, a change in the surface quality of the textile can be seen after irradiation (c) with the marked square showing increased transparency and stiffness. When the sample was released from tension (d), the marked areas created three-dimensional protrusions from the surface of the cloth (e).

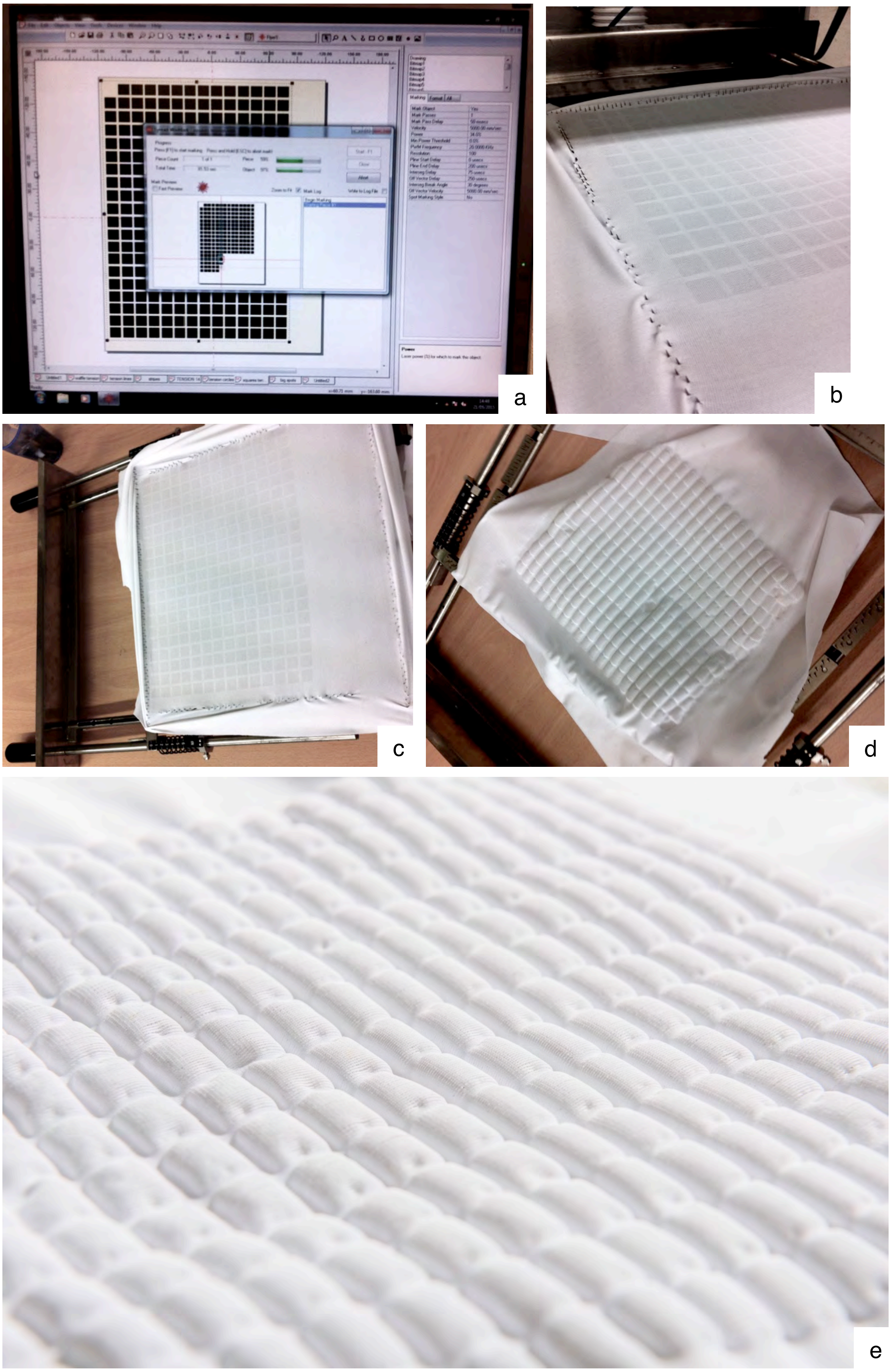


Figure 7.8 Laser Moulding using a Stenter Frame

7.4 Effect of Tension on Laser Moulding

In the initial experiments discussed in the previous section, it was noted that an even tension was essential for achieving a consistent three-dimensional moulding result. Despite being laser processed with the same shapes, an uneven tension during laser irradiation resulted in various sized moulds on release from tension. From this, it can be concluded that recovery after stretching in the laser irradiated area is affected by changes in tension. The effect of altering tension on the recovery of polyester fabric was investigated. The aim of this experiment was to discover the effect of altering tension on the intensity of the three-dimensional moulds, and secondly to determine if tension could be used as a means to control the effects for design purposes.

A set of shapes in fixed dimensions was laser marked with an energy density of 3J/cm^2 onto a polyester textile sample held taught but not extended. The sample was then extended at a force of 0.1N and the same three shapes were laser marked onto the extended textile sample. The process was repeated a further 3 times increasing the application of force by 0.1N each time and the extended length of the working area was recorded. Figure 7.9 shows the resulting sample revealing the evident effect of laser irradiation at increasing tensions from 0-0.4N. On release from tension, the new horizontal length of the laser irradiated area was recorded for each shape, A, B and C. The laser irradiated control shapes processed at 0N produced a barely visible result on the polyester textile sample. They have therefore been highlighted on the image in Figure 7.9 showing the original laser irradiated dimensions. The extension on the textile sample and the contraction of the laser irradiated shape were calculated using equation 8 with the results shown in Table 7.1.

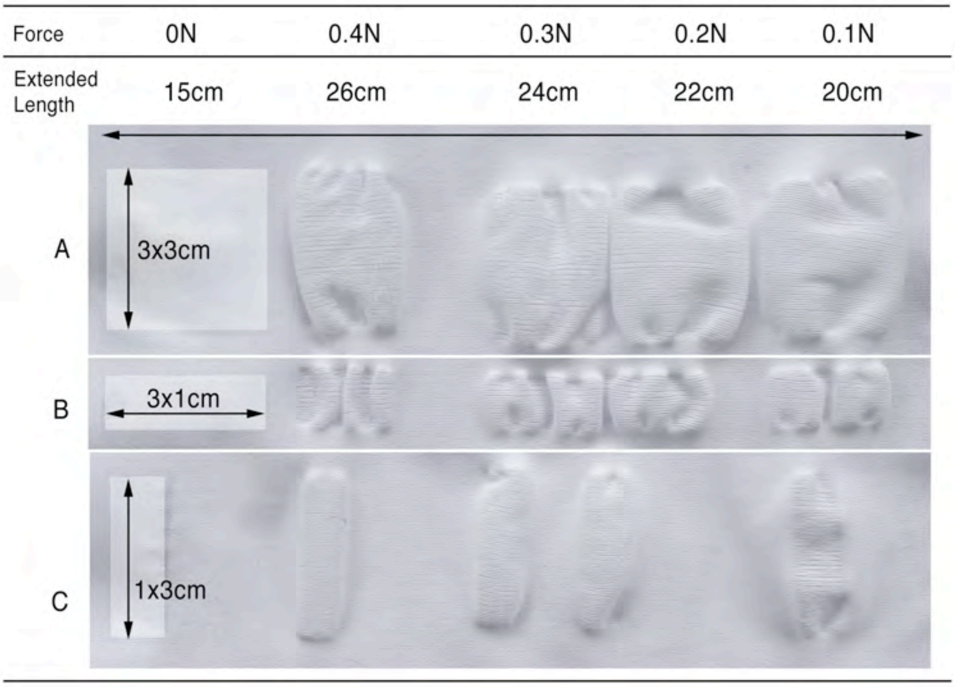


Figure 7.9 Laser Moulding at increasing tension with forces from 0-0.4N

Force (Newtons)	0.4N		0.3N		0.2N		0.1N		0N	
Extension (cm) on 15x15cm sample	11	73%	9	60%	7	47%	5	33%	0	0
Laser Processed Area	**Contraction after release from tension (cm)**									
A (3x3cm)	1.2	40%	1	33%	0.8	27%	0.6	20%	0	0
B (3x1cm)	1.2	40%	1	33%	0.9	30%	0.6	20%	0	0
C (1x3cm)	0.4	40%	0.35	35%	0.3	30%	0.2	20%	0	0

Table 7.1 Effect of tension on recovery of polyester fabric after laser irradiation

It can be observed from the sample and results in Table 7.1 that largest contraction provides the greatest 3D effect. The table shows consistent contraction across a variety of laser irradiated shapes.

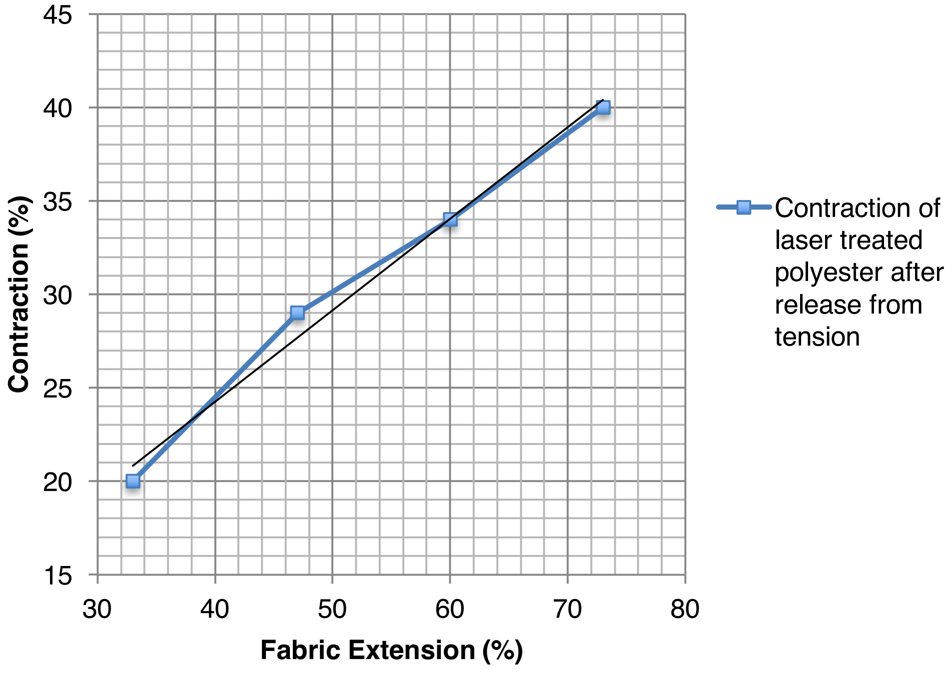


Figure 7.10 Effect of laser irradiation on recovery of polyester fabric

A graph of the fabric extension was plotted against the percentage contraction after release from tension in Figure 7.10. The straight line on the graph shows that the fabric extension is directly proportional to the contraction of the laser treated areas after release from tension. The graph can be used to predict the effects of using the laser moulding technique. An example is shown in the diagram (Figure 7.11): if a sample was extended by 50% of it’s original dimension and laser irradiated across 5cm, the graph can be used to determine a contraction in the laser irradiated area by 29% on release from tension. The diagram displays how the fabric retains it’s laser irradiated dimension, while the sample contracts resulting in a three-dimension protrusion from the surface of the cloth.

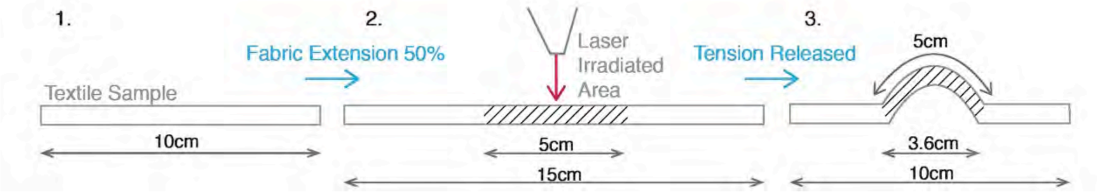


Figure 7.11 Diagram showing the effect of Tension on Laser Moulding

It was shown that altering fabric extension prior to laser irradiation can control the degree to which three dimensional properties can be achieved. After being released from tension, the dimension of the entire working area returned to equilibrium in its original relaxed position, confirming that laser treatment has not affected the bulk elastic properties of the sample, only that of the laser treated area. The scientific approach used in this experiment provided a measurable means to predict and control the laser moulding effects for the purpose of designing three-dimensional textile surfaces.

7.5 Effect of uniaxial and biaxial tension

Polyester was laser marked at an energy density of 3J/cm^2 with a pattern of squares with varied directional tension settings. The aim of this experiment was to determine the qualities that stretching the fabric in one or two directions would impart on the laser moulded shapes. Tension at a force of 0.3N was applied to the fabric resulting in a vertical extension of 60%. Increasing force in a horizontal direction was applied to samples b,c and d resulting in horizontal extensions of a) 0%, b) 30% c) 45% d) 60%. The parameters and observation of the results are as shown in Table 7.2. Figure 7.12 shows the resulting samples. It was revealed that uniaxial tension (extension in a single direction) results in significant distortion of the laser marked shape akin to a seersucker effect. As biaxial tension (extension in both horizontal and vertical directions) is applied, the gathering effect is reduced, eventually providing a full clear shape when tension becomes even in both directions.

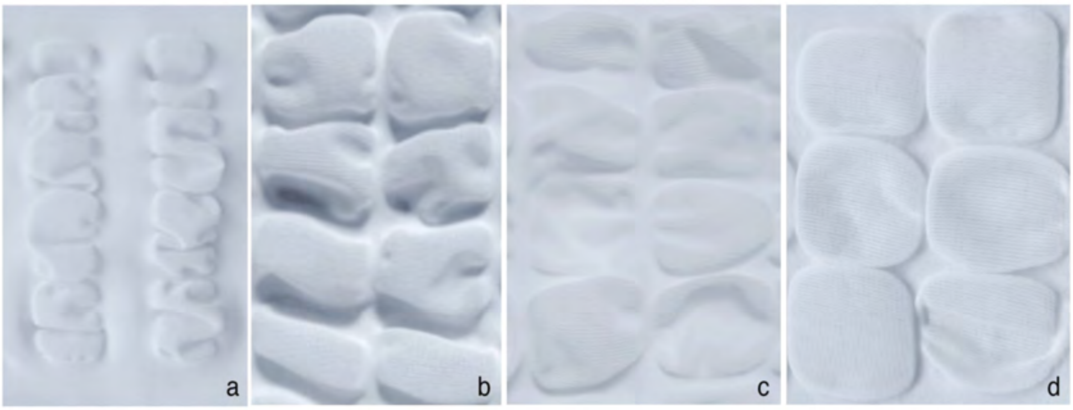


Figure 7.12 The effect of directional tension on laser marked squares

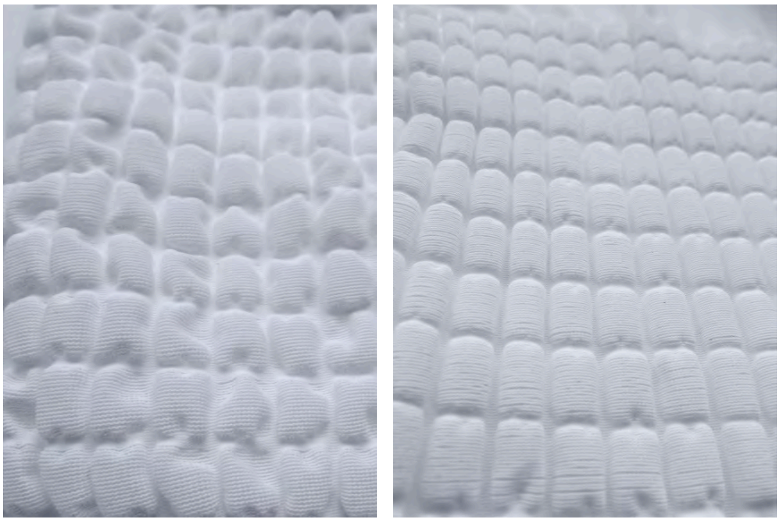
Extension	a		b		c		d	
Horizontal	0%		30%		45%		60%	
Vertical	0.3N	60%	0.3N	60%	0.3N	60%	0.3N	60%
Observation	Shape unclear Vertical Gathering		Shape Compressed in vertical direction		Shape outline clearer with some vertical compression		Full even shape, no directional compression	

Table 7.2 Observations on Effect of Increasing Biaxial Tension

Figure 7.13 Laser Moulded fabric design on nylon showing seer sucker effects

An example of uniaxial tension on a laser moulded textile design is shown in Figure 7.13. A uniaxial extension of 0.2N, 47% was applied in the vertical direction to a nylon fabric sample. Stripes of varying proportions were laser irradiated at an energy density of 3J/cm^2, resulting in a ruched striped ‘seersucker’ pattern on the fabric when released from tension.

Figure 7.14 shows another example of the effect of altering directional tension on laser moulded outcomes. An allover grid of squares was laser irradiated at an energy density of 3J/cm^2 on a knitted nylon textile. Sample a) was processed with an even tension in both vertical and horizontal directions, while sample b) had a higher horizontal extension. It can be seen that sample a) has resulted in an allover pattern of three-dimensional square lumps. The altered extension settings in sample b) have achieved a ribbed effect resulting in a drape and handle akin to pleating. Draping the sample on a curve provides an accordion effect that could provide potential ease of movement if used on a textile product. Possible applications are discussed further in section 7.8.



a) Vertical Extension 0.3N, 60% Horizontal Extension 60%

b) Vertical Extension 0.2N, 47% Horizontal Extension 60%

Figure 7.14 Altered Directional Tension on an Laser Moulded Nylon

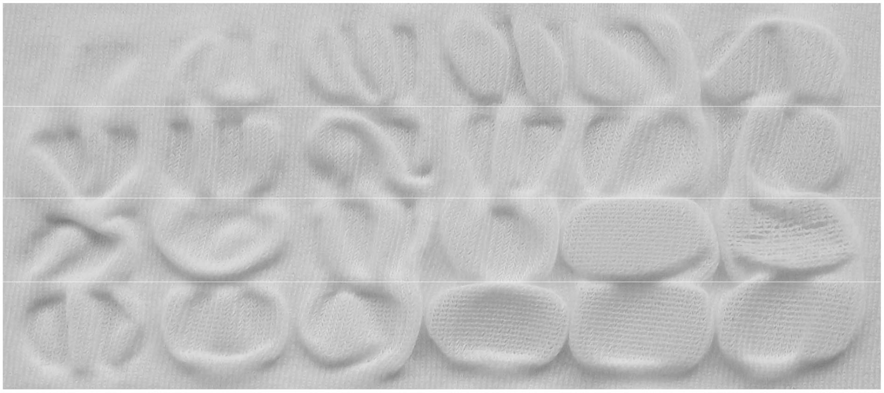
Power (W)	28	30	33	34	36	38
Energy Density (J/cm^2)	2.38	2.55	2.72	2.89	3.06	3.23
Resolution (dpi) 55						
70						
85						
100						

Figure 7.15 Laser Moulding with varied laser power and resolution

7.6 Altering Energy Density

In order to establish optimal laser settings and to examine the effect of altering energy density, a grid of variable parameters were laser marked on polyester fabric held under tension at a fixed extension of 60% at a force of 0.3N. Optimal parameters for the purposes of this study can be defined as those that provide three-dimensional design effects, whilst causing minimal thermal damage to the fabric to preserve functional properties.

The resulting sample (Figure 7.15) shows the effect of increasing energy density against resolution. While the size of the affected area remains the same after laser irradiation, the intensity of the three-dimensional effect increases with increasing laser energy density, up to the point of ablation. It can be seen that a resolution of 100dpi provides the greatest diversity in three-dimensional qualities by altering laser energy density, indicating this as the most appropriate parameter for design scope. The parameters shown can be used to achieve a scale of three-dimensional qualities from a slight undulation in the fabric surface at lower energy densities, to solid protruding shapes at higher energy density outputs. This is explained in the diagram shown in Figure 7.16. At higher laser energy densities increasing levels of melting and reforming result in a more solid, crystalline structure. Therefore the laser irradiated area is more likely to hold it's processed shape. At lesser laser energy densities, the effect is less solid, only partially holding the laser processed shape.

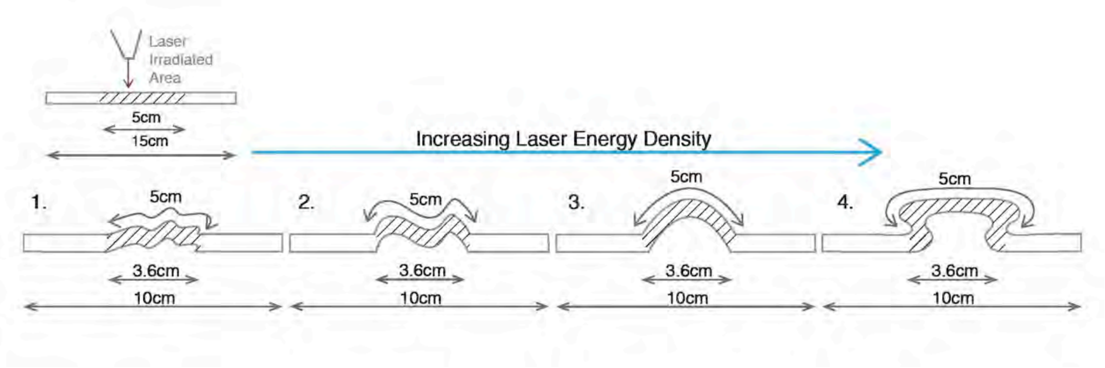


Figure 7.16 Diagram Showing the effect of Energy Density on Laser Moulding

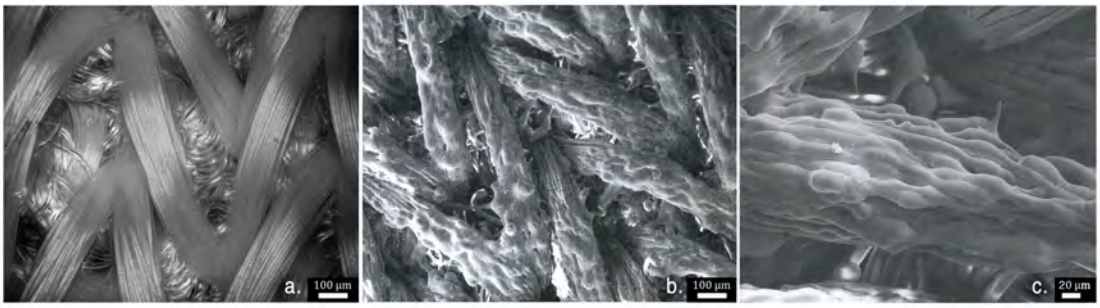


Figure 7.17 Micrographs of laser moulded polyester

The phenomenon can be explained through microscopic surface observation and with reference to the known effect of heat on polymer states as discussed in the introduction to this chapter. When the textile was held under tension, and irradiated by the laser so that temperatures above glass transition temperature are reached, crystallisation occurs where molecular movement is restricted by fixed tension. This acts to heat set the laser irradiated area in its extended dimension. When released from tension, the untreated cloth returns to it's original dimension while the laser irradiated area does not. This provides an excess of fabric in the laser irradiated areas leading to a rippled, undulating effect on the fabric surface. The drape and tactile properties of the laser treated area at lower energy densities have not been affected.

The micrograph in Figure 7.17a shows, no melting occurs up to 2.72J/cm^2. Higher energy densities (above 2.72J/cm^2) result in localised melting of the polymer fibres on the textile surface, as seen in the micrograph (Figure 7.17b-c). On cooling, the melted polymer solidifies, re-crystalising in it's new extended dimension. On release from tension the extended shape is permanently fixed on the fabric surface. The solidification and crystalising process has affected the drape and handle of the fabric, hardening the surface in the laser irradiated area subsequently holding the shape intact. In this instance, an excess of fabric also exists, however the fixed shape is forced upwards protruding from the surface of the fabric without undulation.

Below 2.38J/cm^2 it was noted that energy density was not sufficient to cause significant effect on the fabric surface. At energy densities above 3.06J/cm^2, the high thermal energy causes significant melting beyond surface level leading to fabric degradation as shown in micrograph Figure 7.17c. It was concluded that optimal parameters for laser moulding should use a resolution of 100dpi with energy densities between 2.38J/cm^2 and 3.06J/cm^2. Within this range, the use of lower energy densities for laser moulding have potential to create subtle relief effects while higher powers could be used to create dramatic three-dimensional surface qualities. The design of three-dimensional surface properties is further discussed in section 7.8.

7.7 Effect of Pattern Spacing

Two patterns consisting of repeated circles were processed using the laser moulding technique. Figure 7.19 shows the CAD file and resulting sample for pattern a). The laser moulding effect on the sample shown Figure 7.18 affected the dimensional stability of the entire working area, resulting in an undesirable warped surface in addition to the intentional 3D circles. It was observed that the space separating laser-irradiated areas was as important in the creation of a successful moulded sample. The non-irradiated areas of the textile must retain an adequate structure akin to a '*warp*' and '*weft*' for the structural integrity of the textile sample to remain intact. Figure 7.18 and Figure 7.19 display the difference between two types of pattern. Pattern a) consists of circles in a drop repeat pattern. There is no clear vertical or horizontal spacing to maintain the textile structure. The processed area is shown to distort the entire textile sample.

The diagram in Figure 7.20 shows how a laser irradiated pattern without clear vertical and horizontal spacing affects the textile sample to the same extent as laser processing of the whole working area. Pattern b) consists of squares in a block repeat pattern allowing clear vertical and horizontal lines of space to traverse the design. The textile sample remains intact and flat, with only the laser treated circles providing 3D protrusions from the cloth. This is shown diagrammatically in Figure 7.20.

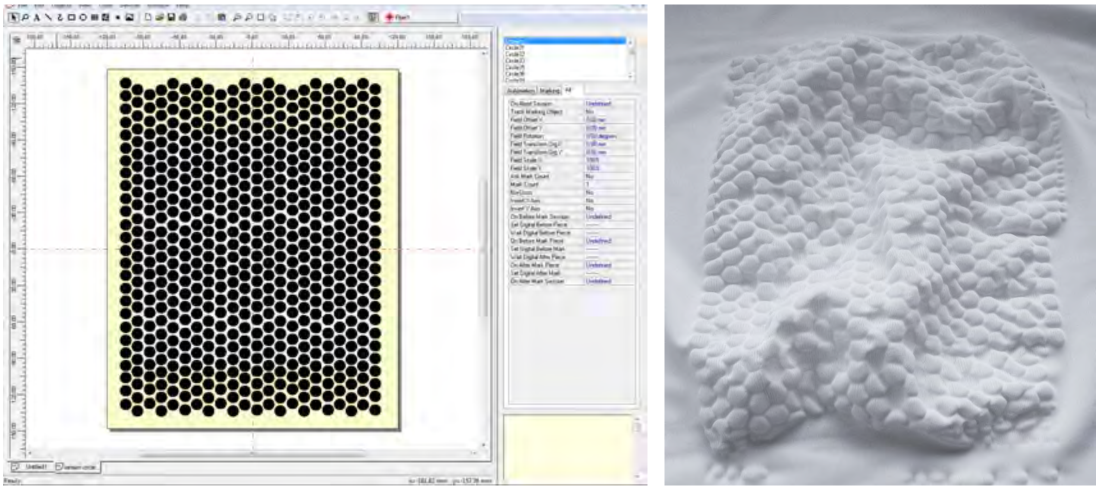


Figure 7.18 Drop Repeat Circle Pattern CAD and Resulting Sample

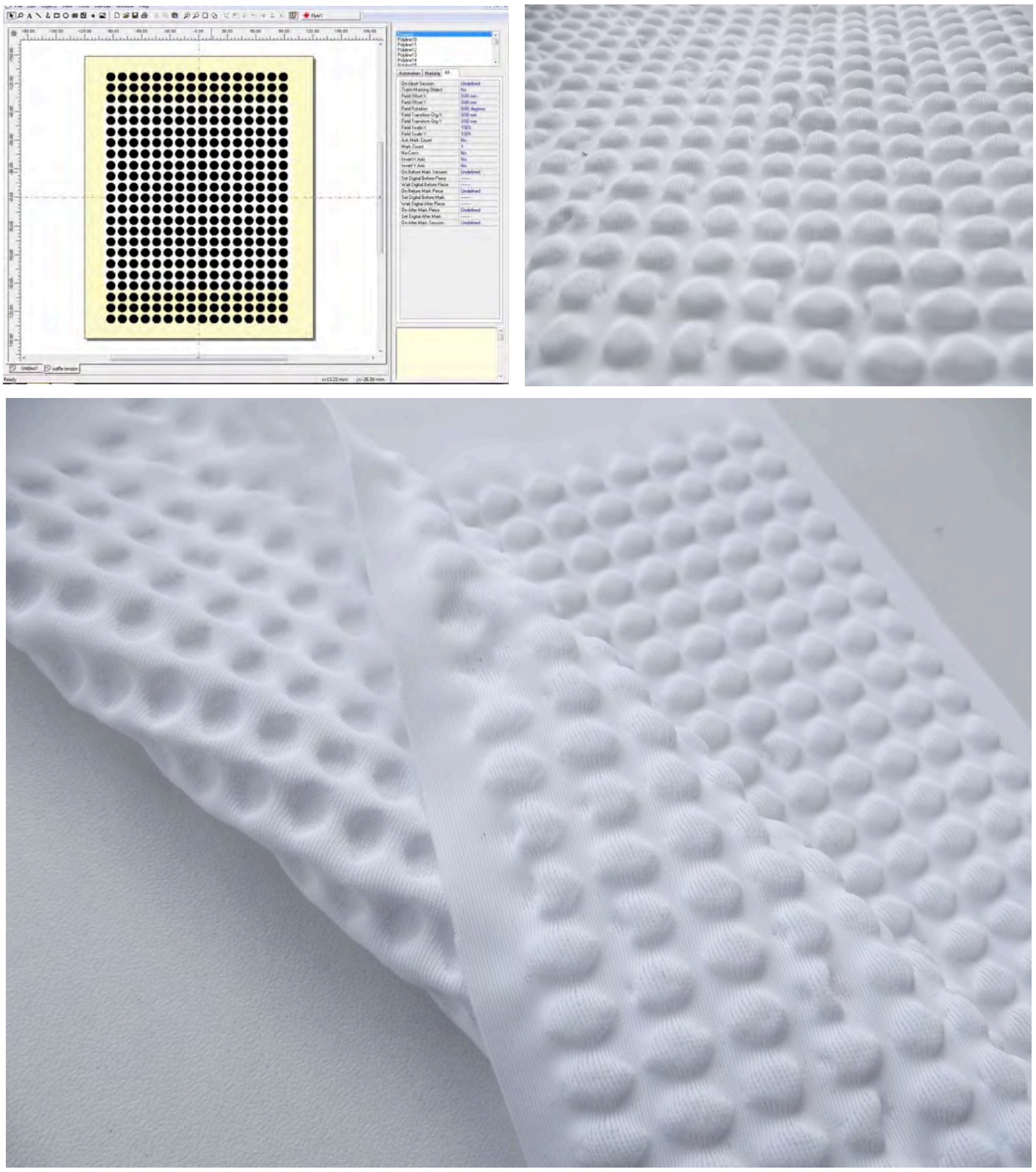


Figure 7.19 Laser Moulded Block Repeat Circle Pattern CAD and Resulting Sample

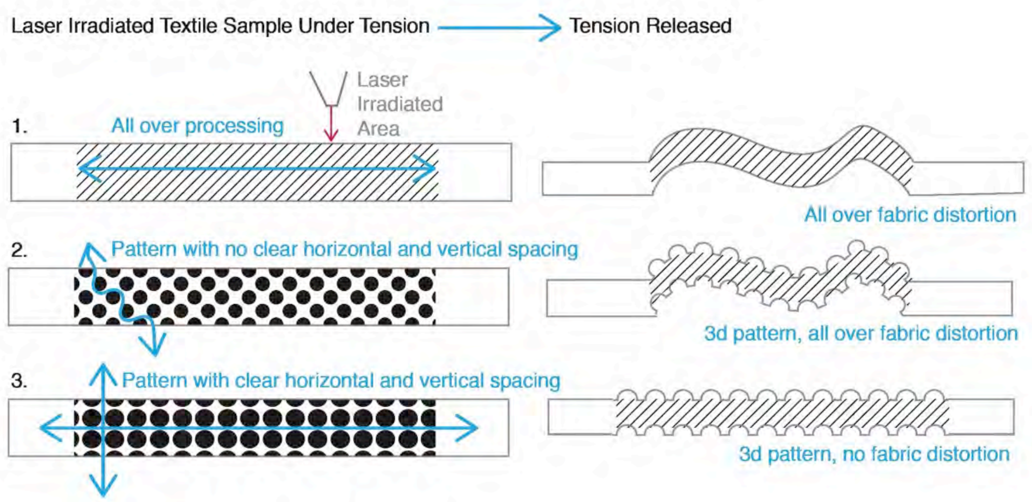


Figure 7.20 Diagram showing the effect of pattern spacing on Laser Moulding

7.8 Effect of Scale and Shape on Laser Moulding

As discussed in the introduction to this chapter, three-dimensional surfaces are often used to provide beneficial properties in the design and construction of commercial and industrial textiles. Many traditional constructed, woven and stitched textile patterns exist for the enhanced properties they can offer for textile end-use. For example, honeycomb weave structures are traditionally used to provide increased absorption and insulation properties in textiles. The effect achieved by altering scale and shape of three-dimensional textile surfaces was investigated. To do this, traditional constructed textile patterns including stripes, hopsack, basket weave, honeycomb and geometric shapes were used in this study to examine the aesthetic and functional effects that could be achieved by laser moulding. Parameters established in the previous sections were used to facilitate the desired effects. The following section analyses the resulting samples in relation to the design and application potential of the laser moulding technique.

The laser moulding technique was shown to enable embossed textures on polyester and nylon textiles. Lower powers were used to create subtle relief effects and embossed textures as shown in Figure 7.21. Weave pattern effects including hopsack and basket weave were laser moulded on nylon fabric. The resulting samples shown in Figure 7.22 and Figure 7.23 show that the traditional weave textures can be successfully emulated giving an optical illusion effect.

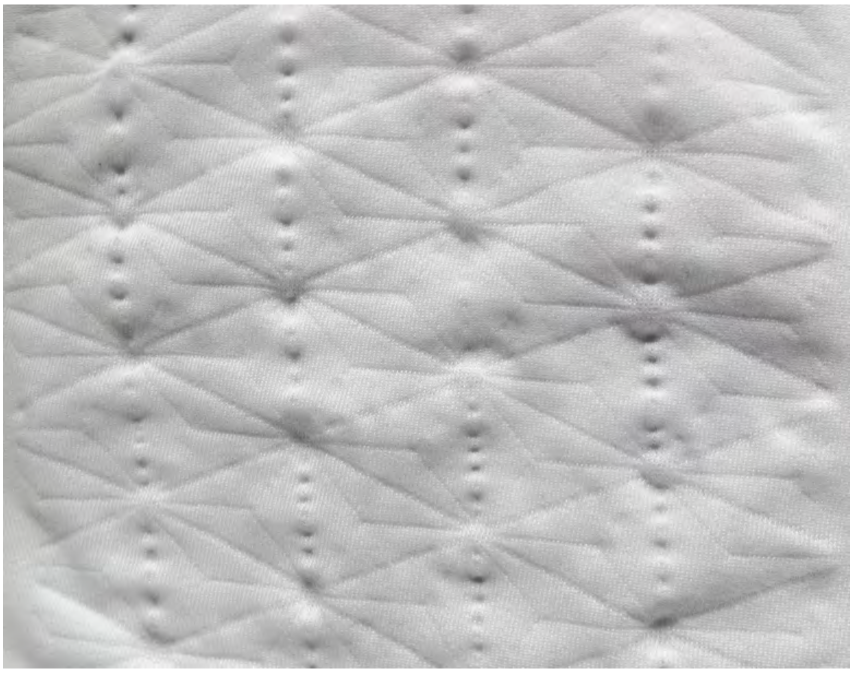


Figure 7.21 Laser Moulded Embossed Geometric Pattern

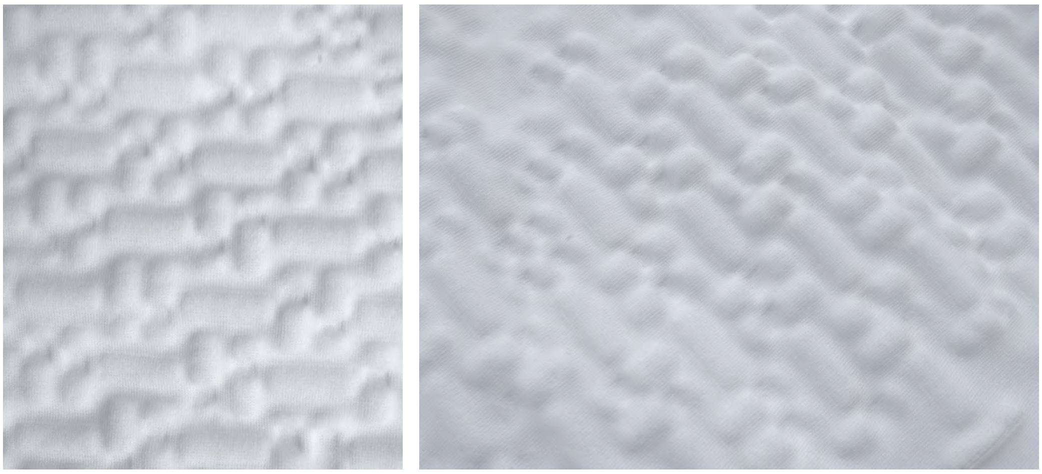


Figure 7.22 Laser Moulded Embossed Hopsack Pattern

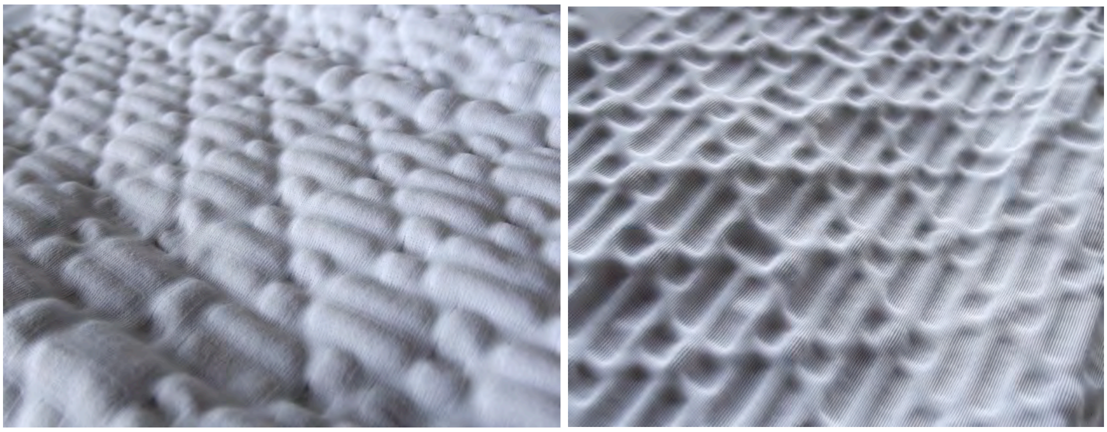


Figure 7.23 Laser Moulded basket Weave Pattern (front and back)

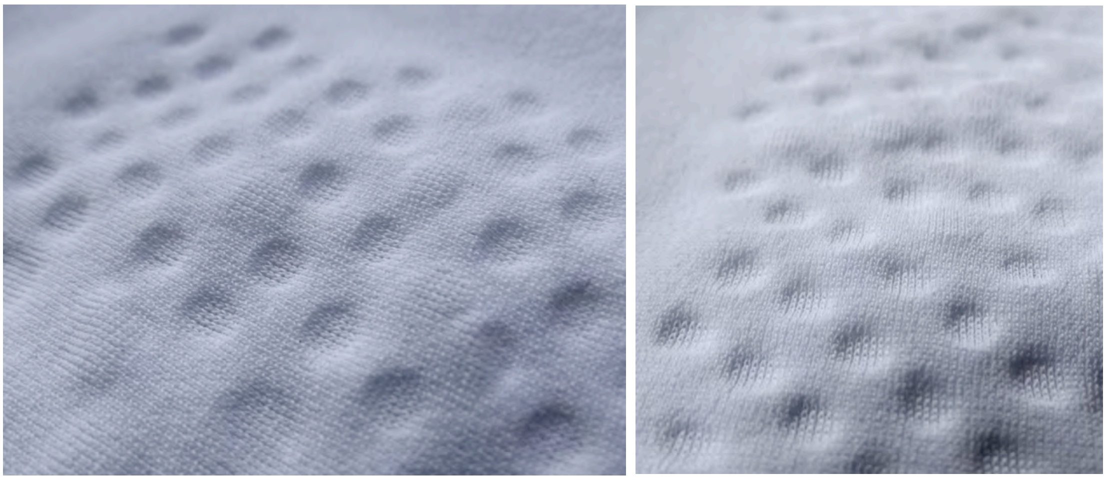


Figure 7.24 Laser Moulded Dimpled Fabric Texture

The sample in Figure 7.24 shows an example of small scale patterning with a circle diameter of 0.5cm, resulting in a dimpled fabric texture. Patterns of this nature have been used within performance wear to provide aerodynamic texturing. A similar surface is used in the design of Nike's TurboSpeed performance sportswear where textured surface patterns are placed on specific areas of the athlete's body. Nike claim the textured surface uses the same principle of dimples on a golf ball that reduce drag allowing it to travel further and faster (Nike, 2012).

With a beam size of 0.03cm there is the potential for laser moulding on a microscopic scale. Micro-patterning or micro-texturing has the potential to provide added or enhanced tactile properties. For example, adding a 'nap' to fabric can offer suede/peach skin textures. Emulating the tactile qualities of natural fibre fabrics such as cotton or wool is a desirable feature for manufacturers of synthetic textiles. If micro-texturing using the laser moulding technique can alter tactile properties of synthetic stretch fabrics, a potential valuable avenue for further investigation has been identified.

A honeycomb pattern was laser marked onto a polyester textile with the resulting sample shown in Figure 7.25. Honeycomb structures are traditionally used to provide increased absorption and insulation properties in textiles. They offer heightened absorption, making them common for towel fabrics. They also make strong insulators due to the pockets of air that can be trapped between the honeycomb areas of pattern. In a similar way, quilted surfaces trap air and padding between textile layers for insulating properties. Laser moulding on a large scale can be used to create dramatic three-dimensional moulds and surface qualities akin to quilting as shown in Figure 7.26, Figure 7.27 and Figure 7.28. The laser moulded samples could provide quilted textures for an aesthetic effect, or be layered to supply thermal insulation.

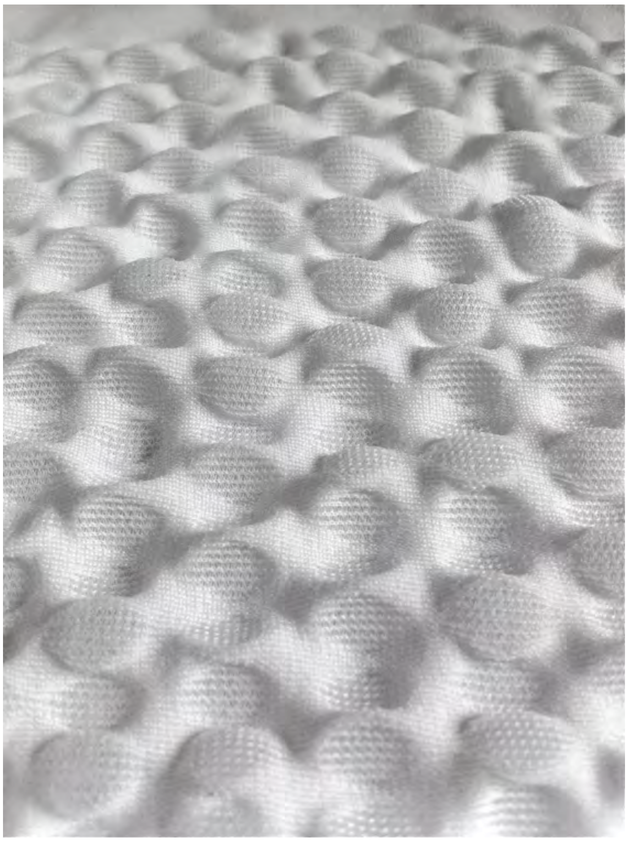


Figure 7.25 Laser Moulded Honeycomb Pattern

Figure 7.26 Laser Moulded Triangles, Quilted Effects

Figure 7.27 Laser Moulded Large Scale Three-Dimensional Moulding

Figure 7.28 Large Scale Laser Moulded Circles

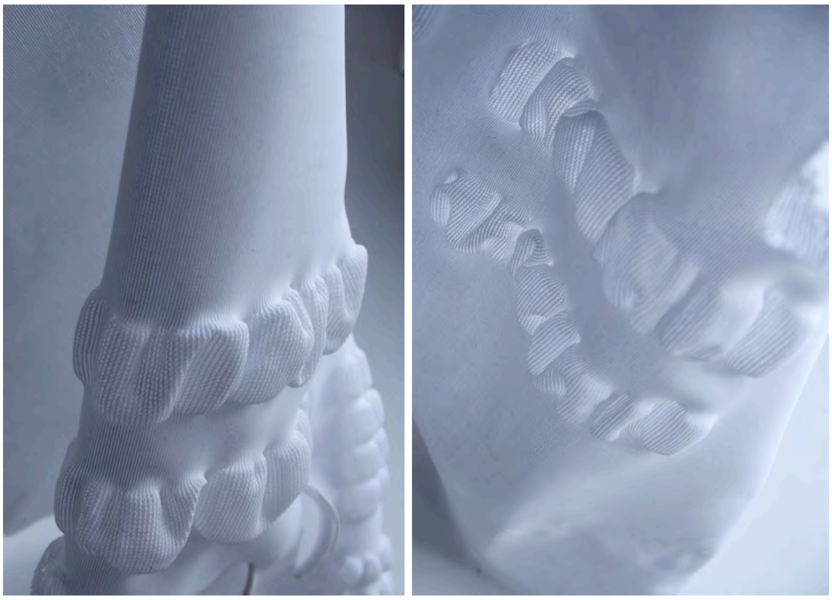


Figure 7.29 Laser Moulded Gathered Bands

Figure 7.28 shows an example of a laser moulded circle design. The circles have a diameter of 10cm resulting in large-scale moulds on a polyester textile. The substantial three-dimensional forms show potential for shaped product or garment applications. For example, laser moulded garment-pattern pieces could be engineered to fit the body. Circular shapes, such as those shown, could be used to laser mould bra cups onto a textile to be used in an article of clothing.

Laser moulding effects could offer additional decorative or functional effects in the design and tailoring of garments. For example gathered or ruched finishes as shown in Figure 7.29, Figure 7.30 and Figure 7.31 have been created through use of uniaxial tension as discussed in section 7.5. These effects have potential to add visual interest to a textile product, or add functionality such as ease of movement or ‘no sew’ darts. Figure 7.31 shows an example of a seersucker effect laser moulded onto a nylon fabric sample. This structure can also offer increased functionality in textile products. Seersucker is often used in clothing to offer heat dissipation in hot weather garments. The rippled areas of the textile remain loose, preventing fabric from touching the skin during wear, which in turn facilitates air circulation.

Figure 7.30 Laser Moulded ZigZag Pattern

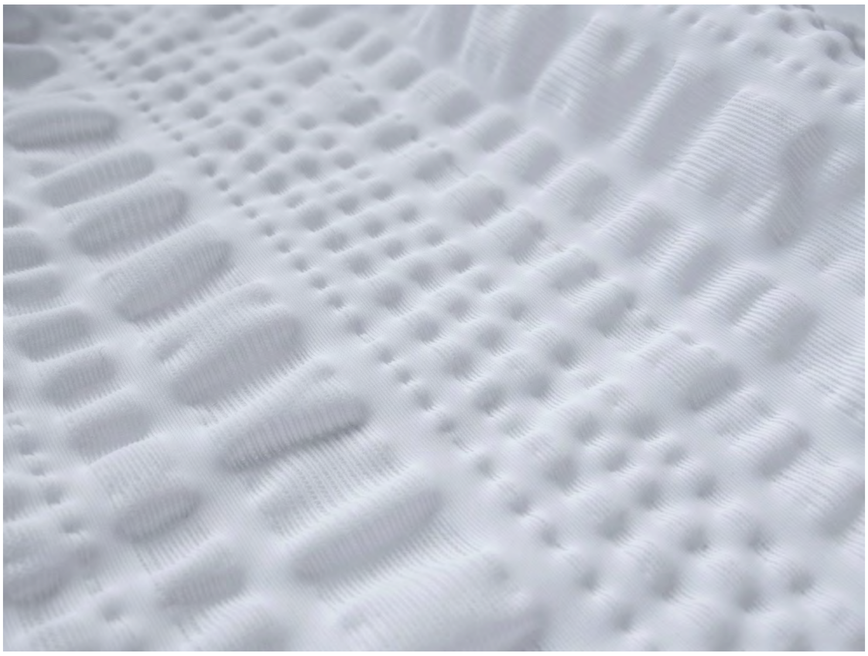


Figure 7.31 Laser Moulded Seersucker Effect

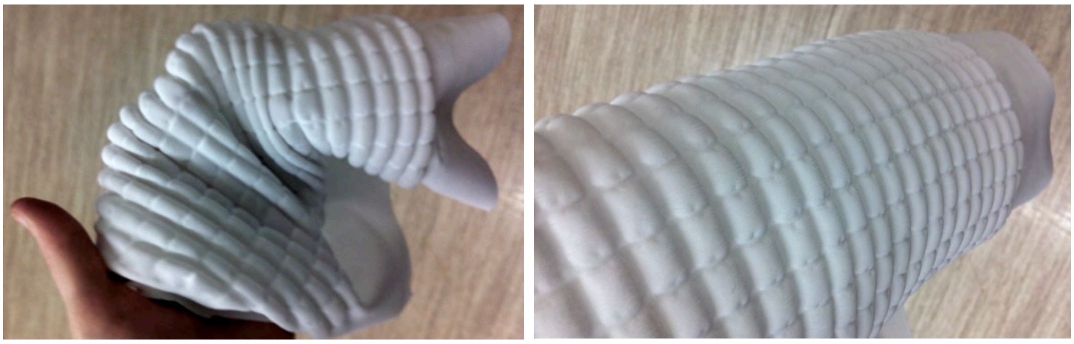


Figure 7.32 Laser Moulded Pleated Fabric

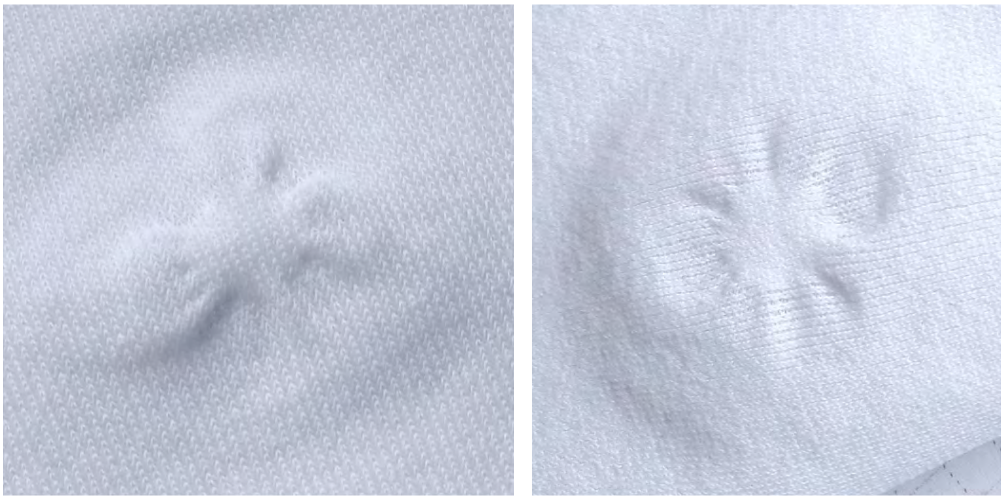


Figure 7.33 Gradiated Power Laser Moulding

Pleats are another form used in textile product applications to provide freedom of movement to the wearer. The sample shown in Figure 7.32 has been laser irradiated with the same design as shown in Figure 7.8 and Figure 7.14b with a higher horizontal than vertical extension. The resulting sample has an all over pleated, accordion effect. The images demonstrate the sample draped in a bent and a relaxed position exhibiting the properties of a soft spring which could have possible relevance for clothing, architectural or medical textile applications.

The sample shown in Figure 7.33 was laser irradiated using an organic floral shape producing a pinched effect with an irregular conical appearance on the textile surface. Pinched effects on fabric could be used for decoration or functional purposes on textiles. Could a gradiated moulding effect be achieved to produce conical effects by laser irradiating with a varied energy density? This has identified an area for further investigation.

Examining varied laser moulded shapes and their resulting forms on textile substrates has identified a library of potential decorative and functional design and application opportunities, summarised in Table 7.4, Section 7.10.

7.9 Laser Moulding and Colouration

Experiments were performed to test the potential to combine laser moulding and laser enhanced colouration techniques as described in the following sections.

7.9.1 Laser Moulding Synthetics as a Pretreatment to Dyeing

Laser moulded nylon samples were dyed using disperse dye. As discussed in section 7.1, heat moulding is known to remain effective up to the temperature at which the heat setting took place. Beyond that temperature fixed dimensions of the fabric are likely to become unstable, resulting in a loss of the heat-set properties (Horrocks & Anand, 2000). Therefore the temperature used to dye the laser moulded samples was kept below the glass transition temperature for each of the substrates to prevent any loss of structure. A maximum temperature of 100°C was used for each sample. However, it was found that the moulded effect diminished after dyeing at this temperature. The resulting samples are shown in Figure 7.34. An enhanced dye uptake on the laser marked areas resulted in a darker depth of shade, providing a multi-tonal colouration. However, it can be seen that the samples have not fully retained their three-dimensional form after the dyeing process, instead leaving a subtle relief surface. To improve on these results and to achieve colouration and moulding effects simultaneously, laser moulding and peri-dyeing processes were combined, discussed in the following section.

Figure 7.34 Laser Moulded Samples Before and After Dyeing

7.9.2 Peri-dyeing combined with Laser Moulding: *Laser Shibori*

The following experiment was performed using the peri-dyeing technique described in Chapter 6. Polyester fabric was attached to the tension frame and extended by 60% at a force of 3N. Blue Disperse dye at a concentration of 2% was applied to the fabric surface, immediately followed by laser irradiation. An all over pattern consisting of block repeated diamond shapes were laser irradiated onto the extended fabric surface. The fabric was then released from tension, rinsed in a solution of water and UPL and allowed to air dry.

The resulting fabric sample can be seen in Figure 7.35, showing a dyed three-dimensional relief surface pattern. The laser energy density delivered to the marked areas has provided a sufficient thermal reaction for dye diffusion and heat setting to take place simultaneously. The samples shown prove that peri-dyeing techniques can be successfully combined with laser moulding. The design opportunities provided by combining the two processes increase the design flexibility of CO_2 laser technology. For example, multicoloured imagery and pattern could be enhanced by three-dimensional elements in targeted areas of the design. The results could be compared to shibori dyeing, a resist dyeing process where dyeing and three-dimensional effects are combined, as discussed in Chapter 2. The *Laser Shibori* provides its own unique aesthetic effect, offering control, with a level of precision and repeatability that cannot be achieved with existing shibori processes or alternative textile production techniques.

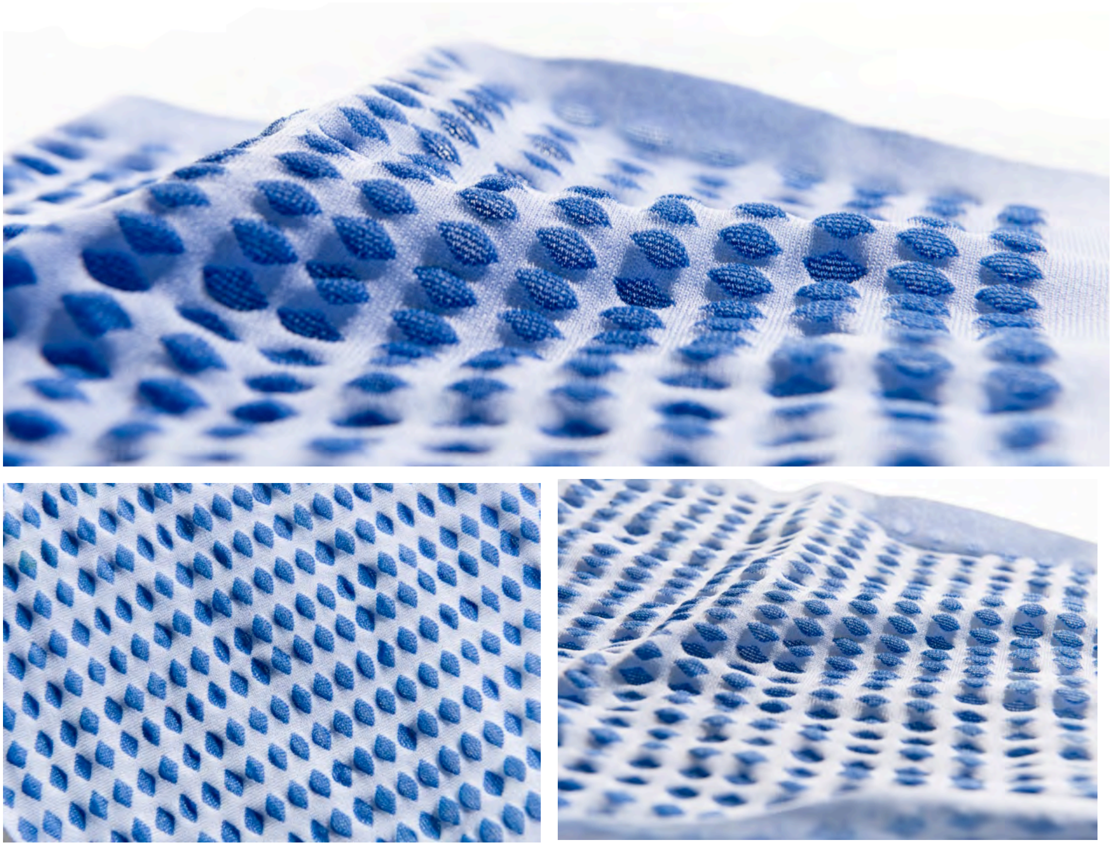


Figure 7.35 *Laser Shibori*: Laser Moulded, Peri-Dyed Sample.

7.10 Discussion

In this study, the laser moulding technique has been shown as an effective method for creating three-dimensional forms on polyester and nylon knitted textiles. The methodology used to develop and examine laser moulding made use of what has been referred to as ‘craft intervention’ (Woolley & Huddleston, 2016) as discussed in Chapter 3. The author’s knowledge of the effect of tension to induce three-dimensional surface effects in the weaving process as well as the use of hand controlled craft apparatus resulted in a craft-led approach in the initial stages of the research. As discussed in section 7.2, this provided proof of concept that was developed and tested with technical and scientific processes to measure and explain the process. Design practice was used to test the aesthetic and tactile qualities that could be achieved. The synthesis of the scientific and creative approaches proved essential in creating this technique as a design tool for three-dimensional laser moulding of synthetic stretch fabrics. Working in this way enabled innovation beyond creativity as discussed through potential application ideas.

Important parameters have been identified and explored through experimentation, leading to a system for predicting the three-dimensional effects to enable controlled design outcomes. These included;

1. Measuring extension to plan and control the resulting size of moulded forms.
2. Using uniaxial or biaxial tension to control gathered or uniform moulded effects.
3. Designing with consideration for pattern spacing to allow dimensional stability of the fabric to remain intact.
4. Altering laser energy density within a given range to control the intensity of the moulded forms.

This information has been summarised in Table 7.3. Altering the parameters shown offers a range of three-dimensional textile design features and opportunities.

Design Feature	Parameter	Method		
Size of Mould	Fabric Extension	Increase extension	To Achieve	Increased size of mould
Proportion of Mould	Uniaxial Tension	Increase uniaxial tension		Gathered appearance/ distortion of processed shape
	Biaxial Tension	Even horizontal and vertical tension		Uniform proportions of processed shape
Dimensional Stability of bulk Fabric	Design/ Pattern spacing	Allow vertical and horizontal spacing in design		All-over dimensional stability
Intensity/ Rigidity of Moulded Shape	Laser Energy Density	Reduce Energy Density (within range)		Undulating, subtle relief surface effects
		Increase Energy Density (within range)		Bold three-dimensional forms

Table 7.3 Laser Moulding Parameters for Design and Control of 3D effects

The effects achieved by altering scale and shape of three-dimensional textile surfaces has the potential to offer new or enhanced fabric properties as well as design features. Table 7.4 presents a summary of the potential advantages and applications of laser moulding that have been identified in this chapter.

The surface effects that can be achieved have been categorised into four types based on the work carried out in this study. These are colour-coded in Table 7.4 and include; Shaping effects, Texturing effects, Weave inspired effects and Stitch-inspired effects.

- **Shaping effects (SE6)** have the potential to offer benefits for finished textile product applications such as ease of movement at joints or engineered fitting opportunities.

- **Texturing effects (SE7)** add visual interest, changes in tactile qualities, and offer the potential for sweat wicking and aerodynamic properties.

- **Weave and Stitch inspired effects (SE8 & SE9)** The use of weave and stitch inspired effects present a rich library of aesthetic and tactile patterning opportunities borrowed from traditional textiles structures as well as the potential performance benefits they may offer, including thermal insulation, airflow, breathability and tailoring functionality.

A number of further avenues for investigation were identified for the laser moulding technique. These have been categorised into three areas, colour coded in Table 7.4. They include; further investigation into engineered design, additional three-dimensional design effects and potential for the micro-texturing of synthetics.

- **Additional 3D design effects (FW5)** Further work in developing three-dimensional aspects of the technique for additional moulding effects include investigating the use of gradiated energy density to provide gradiated moulding effects such as conical shapes. Alternate pleated forms could be investigated through laser processing of alternate shapes and tension combinations. Investigation into the effects that can be achieved through processing of organic shapes and free flowing patterns could be furthered. The *Laser Shibori* effect could be further investigated: targeted moulding could be explored in combination with colouration effects to enhance multi-coloured patterns and create three-dimensional imagery.

- **Engineered design (FW6)** Further investigation could explore the potential of applying the laser moulding technique for engineered functionality and fitting. This could be in the form of moulded garment pattern pieces for example shaped cups for womenswear.

- **Micro-texturing (FW7)** With a beam size of 0.03cm there is the potential for laser moulding on a microscopic scale. Micro-patterning or micro-texturing has the potential to provide added or enhanced tactile properties. For example, adding a ‘nap’ to fabric can offer suede/peach skin textures. Emulating the tactile qualities of natural fibre fabrics such as cotton or wool is a desirable feature for manufacturers of synthetic textiles. If micro-texturing using the laser moulding technique can alter tactile properties of synthetic stretch fabrics, a potential valuable avenue for further investigation has been identified.

Laser moulding method	3D Surface Effect	Known and Potential Advantages Offered	Areas for Further Investigation
Placement of moulding on product	Placement of pattern or function	Engineered design of textile product	Accuracy on garment shape
Large scale targeted moulding	Shaped forms	Moulded pattern pieces	Engineered fitting
			Gradiated effects
Higher horizontal tension moulding	Pleating	Soft spring Ease of movement	Alternate pleat structures/shapes
Microscopic scale moulding	Micro texturing/ micro patterning	Tactile properties/ emulate natural fibre textures?	Investigate potential of micro-texturing
Dimples small scale pattern moulds	Texturing	Streamlined aerodynamic for sports/ performance wear	Effect of shape and scale for best performance
Colouration combined with moulding	*Laser Shibori* Moulded print effects	Aesthetic and tactile	Engineered moulding for multi-coloured pattern
Altered scale, shape and pattern	Geometric patterning	Aesthetic and tactile, Optical illusion	Organic shapes and patterns
	Weave pattern effects (hopsack, basket weave)		Other traditional textile patterns/ structures, eg. Herringbone, hounds tooth
Diamond shaped repeat pattern moulds	Honeycomb	Insulation Increased absorption	Hexagonal and alternate tessellating shapes
Uniaxial tension moulds	Seersucker	Air flow	Undulating shapes
	Gathering	Ease of movement No sew darts/tucks	Tailoring functionality?
Repeat pattern shaped moulds	Quilting	Insulative	Alternate repeat pattern shaped moulds

Key:	Shaping effects (SE6)	Texturing effects (SE7)	Weave inspired effects (SE8)	Stitch-inspired effects (SE9)
	3D design effects (FW5)	Engineered design (FW6)	Micro-texturing (FW7)	

Table 7.4 Potential Advantages For Application Of Laser Moulding And Further Work

The use of laser technology to create three-dimensional textile forms may present additional processing advantages over traditional methods. Unlike regular textile embossing equipment, the laser does not require moulds or plates to be cast for each new design. Unlike the relief effects created through weaving, the laser does not require complicated loom set up to produce three-dimensional forms and offers ease of pattern change through digital generation of designs. This in turn would allow targeted processing on textile ‘blanks’ or engineered garment pattern pieces, adding additional properties to a textile, post-construction. Laser technology offers dry processing, without requirement for additional materials, such as thread for stitching. Using the technique for surface design effects could eliminate the need for additional embellishment for decorative textiles. The use of synthetic mono materials may provide additional sustainability benefits for ease of recycling at end of life.

7.11 Chapter Summary

A new method for moulding synthetic stretch textiles has been developed. The technique uses the photothermal properties of the CO_2 laser, allowing three-dimensional moulding of synthetic fabrics without the use of pattern moulds.

An explanation of the process on polymer properties has been provided. It has been discussed how the heating of synthetics can induce changes in crystallinity of synthetic polymers. Heat can therefore be used to alter properties of synthetic fabrics. Using the laser moulding technique, designs are set using the thermal energy of the laser on synthetic fabrics held under tension. The laser irradiation acts to heat set the marked areas so that when released from tension, they retain their marked shape, resulting in three-dimensional forms on the surface of the cloth. This chapter has presented systems for predicting the three-dimensional effects to enable controlled design outcomes as summarised in Table 7.3.

Potential applications and advantages have been discussed in relation to experimental laser moulded textile samples and summarised in Table 7.4. Avenues for potential further investigation have also been identified. The laser moulding technique can be used to design accurate surface architectures providing potential for engineered functionality and three-dimensional design features for textile product applications. Combining the technique with peri-dyeing processes resulted in an effect akin to shibori. Unlike the traditional craft practice, *Laser Shibori* offers precise control, repeatability and a unique aesthetic. Designs are created digitally and can be changed effortlessly. The method allows decoration to emerge from the structure of the cloth without contaminating the mono-material fibres. This in turn would allow the cloth to be recycled easily and adheres to a closed-loop system for a sustainable textile lifecycle.

CHAPTER 8 : LASER FADING LINEN

8.1 Introduction

This chapter describes a short study into the effects of laser irradiation on the properties of linen. This resulted in the development of a novel laser marking and fading technique using laser precision to apply subtle designs on natural linen. With identified resist dyeing opportunities.

Despite the apparent commercial research interest, the focus of laser fading remains within the realm of cotton denim fabrics. The potential for fading alternate natural fibre sources provided the basis for investigation in this study.

Linen can be grown in temperate climates; as such linen has a heritage of local production in the UK (Collier, 1980). Long fibres are extruded from the straw-like plant before being spun into yarns. Flax fibres show a higher strength than many alternate textile fibres and as such linen is often used for applications requiring repeated laundering and strength. Cellulose fibres show good resistance to thermal degradation compared to other fibre types (ibid), exemplified by the high temperatures needed for ironing and dyeing.

Exploratory sampling in Chapter 4 examined the effect of laser irradiation and its potential mark-making properties on a range of fabric substrates. Linen was identified as a suitable substrate to impart laser fading. A literature search on the effects of laser irradiation on linen or bast fibres revealed a lack of study in this area. The effects of laser irradiation on linen have been documented in relation to research into the Shroud of Turin. Degradation over time caused by UV irradiation has been offered as one possible explanation of the mysterious markings on the linen shroud. To explain possible darkening effects Baldacchini et al. (2008) exposed a linen textile to a UV laser beam until discolouration occurred. Further discussion on laser-bast fibre interaction has not been documented, providing a gap in knowledge on the effects of laser irradiation on linen and other bast fibres for textile finishing and surface design, addressed in this Chapter.

8.2 Surface observation and parameter selection

Winmark software was used to mark solid raster shapes for parameter testing on natural linen. Graphics were processed at a resolution of 85dpi. A series of parameter grids of laser energy density against velocity were processed and the resulting samples examined. Between 2.5J/cm^2 and 4.2J/cm^2 a fading effect on the linen surface was observed as shown in Figure 8.1. Beyond this parameter, the fading effect diminished and eventually at laser energy densities above 5.2J/cm^2, the linen surface darkened as a slight burning and carbonisation began to occur. The handle and integrity of the fabric samples was unaffected by the laser irradiation up to 5.5J/cm^2, after which tactile changes and thinning of the fabric could be identified as increased thermal fibre degradation occurred.

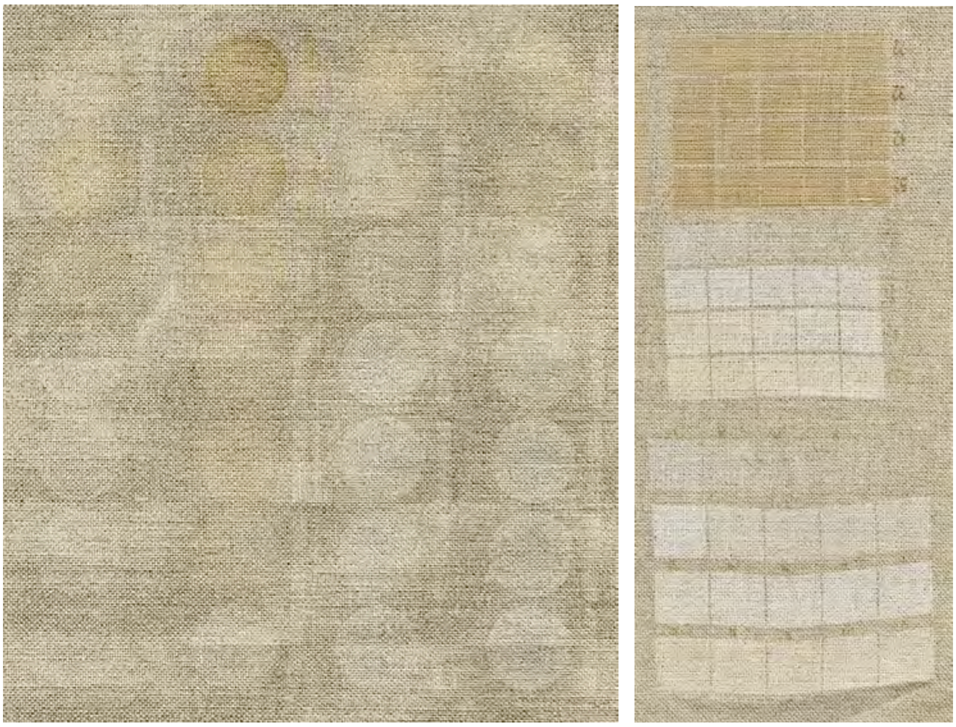


Figure 8.1 Laser Irradiated Linen: Parameter Testing

The energy densities for fibre damage on dry linen are considerably higher than that of the previously tested substrates, wool and polyester. The natural properties of linen can withstand high temperatures, corroborating the effect shown on the test samples. Only after the high temperature of increased energy density, does linen fibre damage begin to occur. However, this does not explain the fading effect observed across a lower range of energy densities. Microscopic observation of laser irradiated linen at an energy density of 3.4J/cm^2 was inconclusive. Further work is required in examining the linen fibres to fully understand the fading mechanism that occurs on linen fibres at certain energy densities. Scanning electron microscopy may facilitate this during further investigation.

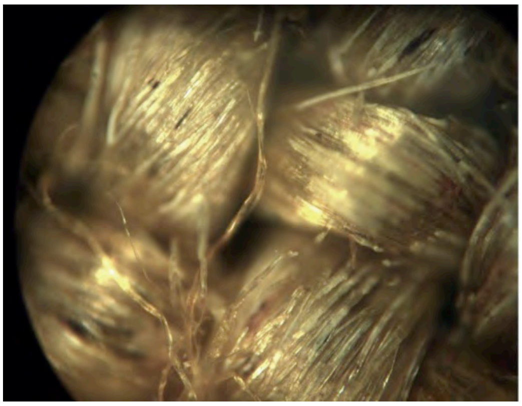


Figure 8.2 Laser faded linen micrograph

8.3 Alternate linen substrates

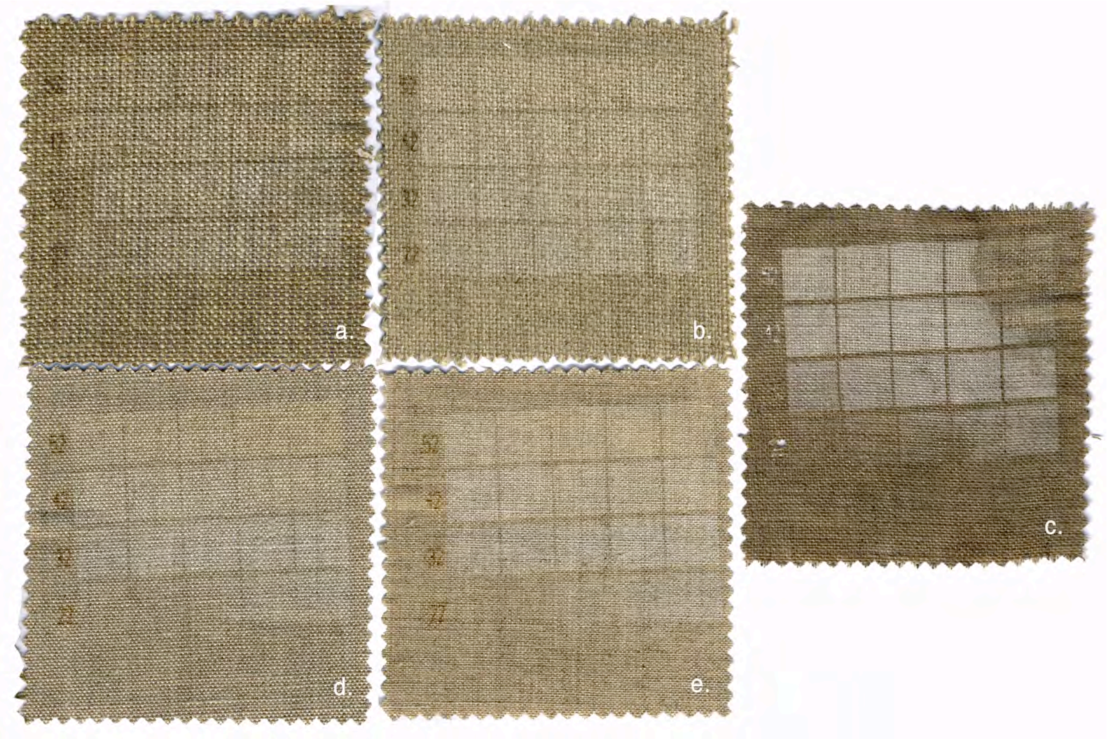


Figure 8.3 Laser fading linen: substrate testing

Five alternate linen test specimens were laser processed to identify if the laser fading phenomenon was a function of all linen substrates. Laser irradiation was found to effectively fade five alternate substrates across a range of weights, yarn counts and finishes as shown in Figure 8.3.

8.4 Colour measurement

Two linen substrates were chosen for further testing. Ten samples of each linen *1* and *2* were laser treated with energy densities between 2.5 and 4.9J/cm^2, a range determined previously to cause effect on the substrate. The laser irradiated samples were measured under a reflectance spectrophotometer and the CIE Whiteness Index Values recorded. The results are displayed in the graph in Figure 8.4. Increasing values in the whiteness index indicate 'whiter' results. The graph shows that energy densities between 3 and 4J/cm^2 consistently provide the most effective colour fading effect on different linen substrates. The highest whiteness difference values for linen 1 and linen 2 were 27 and 36.21 respectively, providing a significant fading result. A recurring curve can be observed for both substrates, with a distinct plateau of high whiteness values either side of a peak, after this, the level of whiteness rescinds, consistent with the visual results. The optimal parameter for linen fading was identified from the graph as 3.4J/cm^2.

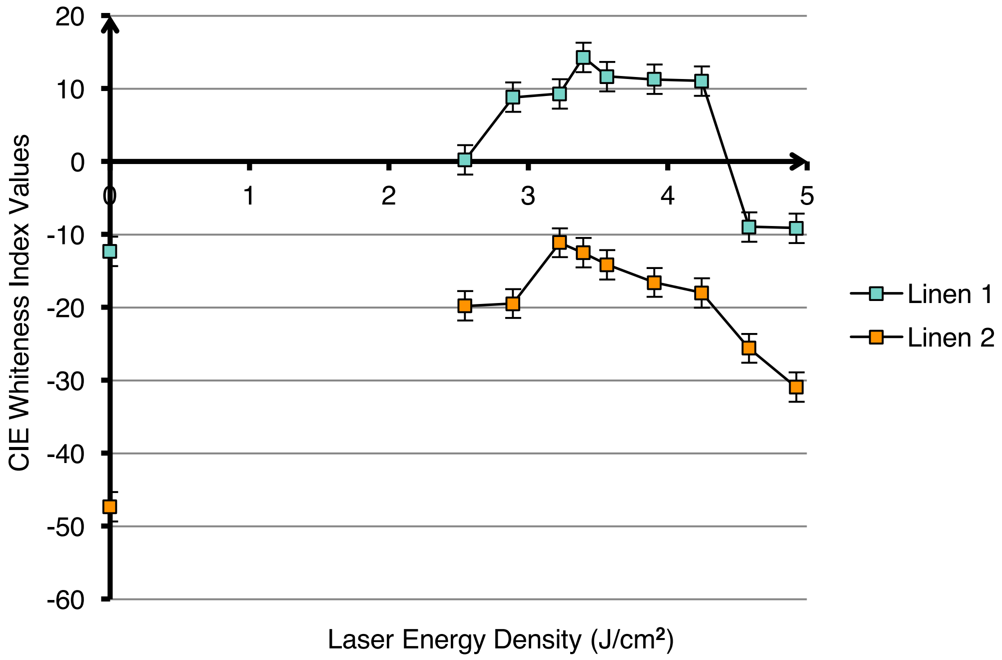


Figure 8.4 CIE Whiteness Index of Natural Linens

8.5 Colour fastness to Washing

Sample	Energy Density [J/cm^2]	Colour Measurement	Fastness to Washing BS EN ISO 105-C10: 2007 Test B		Fastness to Rubbing BS EN ISO 105-X12: 2002		
		CIE W*	Cotton	Colour Change	Dry	Wet	Colour Removal
a	0	0	5	5	4/5	4	4
b	2.9	8.84	5	4	4/5	3	3
c	3.4	14.30	5	4/5	4/5	3	3
d	3.9	11.31	5	4/5	4/5	3	3

Table 8.1 Testing Results Table for Laser Faded Linen

To examine the permanence of the laser fading effect on linen, laser irradiated samples at increasing energy densities were tested to determine the fastness of the effect to washing and rubbing. The results are shown in Table 8.1.

The international standard test method, *BS EN ISO 105-C10: 2007*, was used to determine the effect of washing on fastness of the laser irradiated and dyed samples. A multi fibre strip was attached to each sample, which was then agitated under controlled conditions of time and temperature in a soap solution. After rinsing and drying, colour change of the fabric sample and staining on the adjacent fabric were assessed by comparison to the original fabric. A value from 1 to 5 was awarded using the appropriate grey scales (see Chapter 4), where a score of 1 is a poor colour fastness result and a score of 5 equates to no loss of colour or no staining.

The washed samples shown in Figure 8.5 showed high fastness to washing, with only minimal loss of fading on the tested specimens. The test showed the laser fading effect is retained after washing procedures, suggesting relevance for application on commercial textile goods.

Figure 8.5 Colour fastness to washing: Laser faded linen at energy densities of a) 0J/cm^2, b) 2.9J/cm^2, c) 3.4J/cm^2

8.6 Colour fastness to rubbing

Colourfastness to rubbing under both wet and dry conditions was determined by the *BS EN ISO 105-X12: 2002* standard test method. Test samples were rubbed with a dry cloth and a wet cloth using a crockmeter, which provides a constant rubbing pressure of 9N. The staining of the rubbing cloths and the colour change on the fabric sample were then assessed using the same grey scale scoring system as above. The results are recorded in Table 8.1 and the samples shown in Figure 8.6.

It can be observed that fastness to wet rubbing achieved poor results that may not meet commercial standards, however, it is notable that the untreated control also showed poor rub fastness results, despite the fabric having a known commercial value. A poor fastness to rubbing may limit the commercial application of the technique to textile goods that are not subject to regular abrasion. The technique may not be suitable for upholstery and clothing for example, but could be applied to decorative textile goods. Further work may demonstrate the fastness properties of alternate linen substrates to have improved rubbing performance.

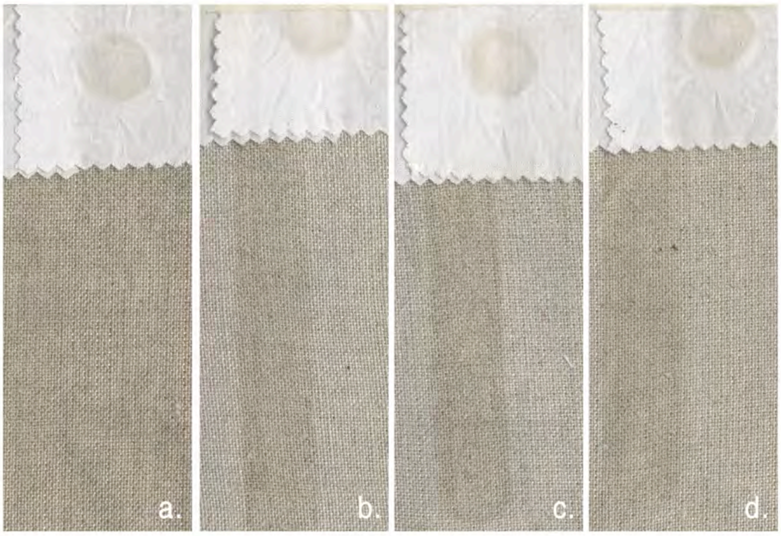


Figure 8.6 Colourfastness to Rubbing: Laser faded Linen at energy densities of a) 0J/cm^2, b) 2.9J/cm^2, c) 3.4J/cm^2, d) 3.9J/cm^2

8.7 Laser Fading for Linen Textile Design

Using the optimal parameter for linen fading of 3.4J/cm^2, as identified in Figure 8.4 and a parameter of 5.3J/cm^2 that was found to induce a dark effect on linen without significant fibre damage, a series of three-colour designs were processed. The resulting samples are shown in Figure 8.10 - Figure 8.9. A range of block filled shapes and decorative patterns shown that the technique could impart effective three-colour design effects. The subtle tonal results are appropriate for the rustic, minimal, natural trend profile that is regularly associated with linen fabrics. Laser precision allowed fine linear details to be highlighted by the fading technique.

Figure 8.7 Laser faded linen textile designs

Figure 8.8 Laser Fading Linen for Decorative Surface Design

Figure 8.9 Laser patterned linen

8.8 Effect of Laser Fading on Dye Properties of Linen

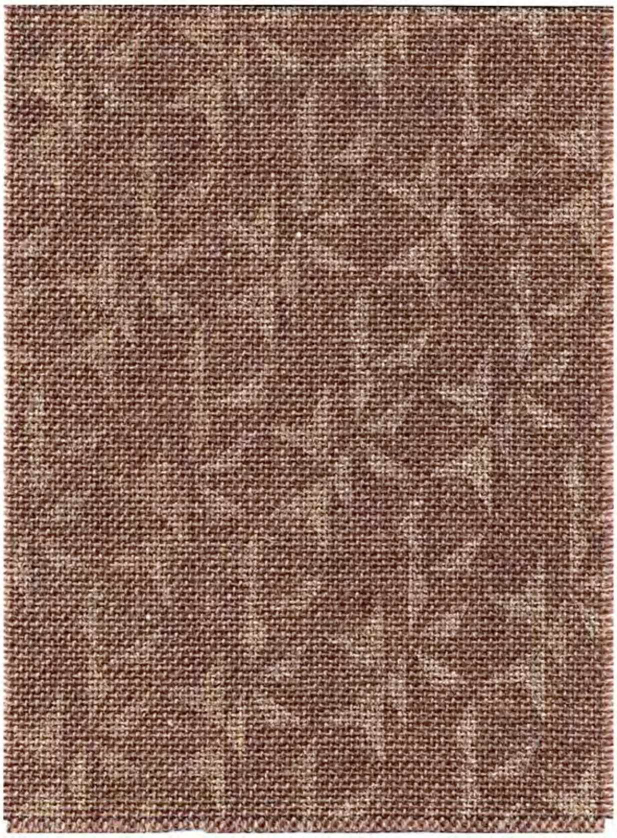


Figure 8.10 Laser Fading linen on a pre-coloured linen ground

Contract interior manufacturer, Camira, provided a previously dyed linen sample. An all over pattern was laser irradiated on to the fabric using the optimal energy density for laser fading. The resulting sample, shown in Figure 8.10, shows the whitening effect has been effective on a pre-dyed ground. This could increase the colour opportunities for designing with the laser fading technique. This suggests that laser processing could be used in place of a wet-printing process for linen goods.

Further sampling was conducted in order to determine the effect of laser irradiation, particularly the laser fading effect, on the dyeing properties of linen substrates. The sample shown in Figure 8.1 was dyed using a yellow direct dye and the dyeing procedure described in Recipe 3 (Chapter 4). After dyeing the laser faded areas of the substrate retained a white appearance, while the non laser treated areas of the cloth were dyed yellow by the direct dye procedure. It can be observed in Figure 8.11 that the laser fading technique acted as an effective resist to dyeing linen. This has clear design opportunities with targeted laser processing used to determine accurate areas to resist dye uptake. This is noted as a reverse of the laser pre-treatment for wool technique described in Chapter 5. Using the technique as a dye resist method has potential to address poor fastness to rubbing observed in section 8.6. After dyeing the fading effect had served its purpose as a resist, and therefore, no longer be essential to the design effect. The integrity of the design would be retained even if the fading effect was diminished by abrasion.

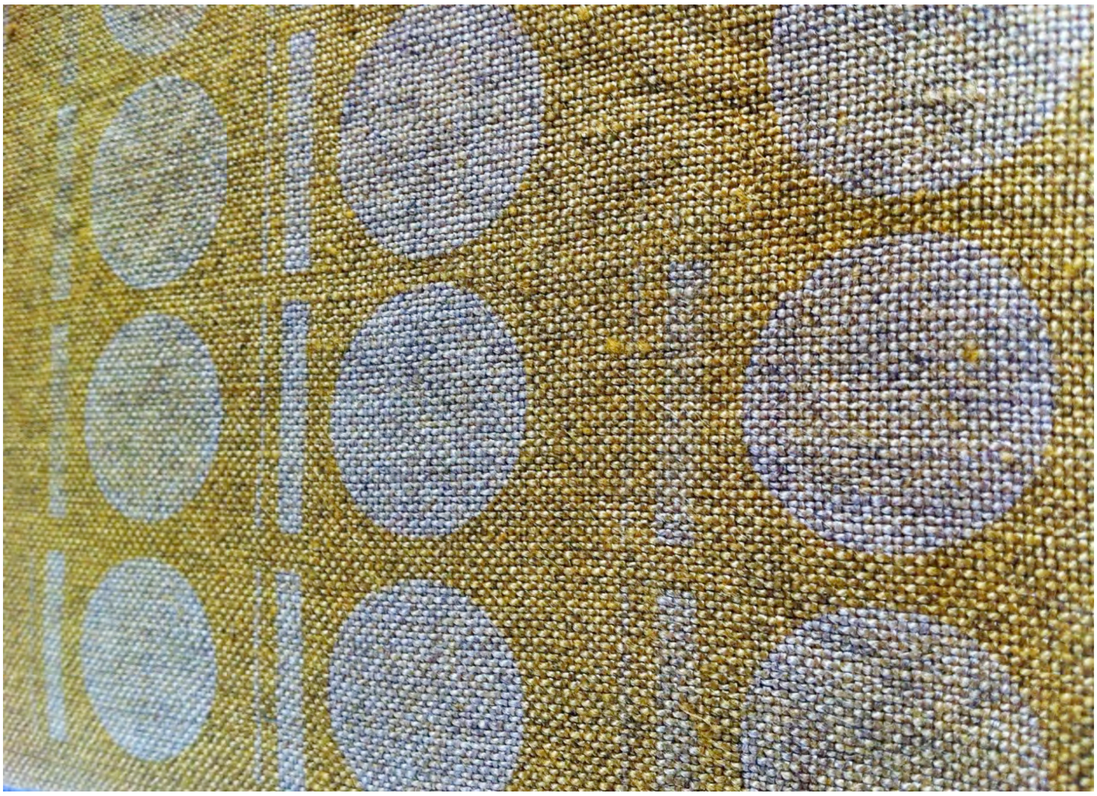


Figure 8.11 Laser faded linen as a dyeing resist method

8.9 Discussion

The technique developed in this chapter provided fading and darkening effects on natural linen fabrics using a CO_2 laser. The CIE Whiteness Index was used to determine whiteness values of laser faded linen, to determine the optimal processing parameters for optimal fading effect. In addition the study identified a laser induced dark effect as a result of intense laser thermal energy on the substrate. Suitable parameters were identified that induced carbonisation without significant fibre degradation or damage to the bulk properties of the textile. These effects combined provided a tonal range with which to create subtle tonal, CAD controlled imagery for linen surface design. As a completely dry process, this provides an alternative to wet or chemical processing to achieve decorative effects on linen goods or an all-over lighter shade. The technique could be used as an alternative to printing methods for patterning linen without the need for water, printing pastes or chemicals.

Due to the naturally mid-brown colour of linen, bleaching is common for commercial linen textile goods. However, bleaching of linen presents difficulty due to the linen lignen content, traditionally overcome by strong chlorination processes or multiple bleaching treatments (Hickman, 1994; Abou-Okeil et al., 2010). Legislation restricting the use of environmentally unsound chemicals, chlorine included, means that alternate methods are required (Hickman, 1994). This research has identified a method by which laser processing can fade natural linen, presenting opportunities as an alternate dry finishing technique to pattern and improve linen material properties.

In addition, the fading technique was established as an effective dyeing resist method, expanding the design opportunities of the technique. Targeted laser processing can be used to determine accurate areas to resist dye uptake. Resist dyeing methods often rely on the addition of chemical pastes by screen-printing or by compression methods, such as Shibori. The laser offers an alternate aesthetic to traditional resist techniques through precision graphic capability and advantages over screen-printing methods as a non-additive, dry process.

Laser faded linen was shown to have high fastness to washing using ISO international textile testing standard methods. While the rubbing fastness performance did not meet desired standards for the commercial focus of the research, the laser fading technique has nonetheless provided a novel decorative design opportunity for textiles. The technique may not be suitable for textiles requiring high abrasion resistance such as upholstery and clothing; however, this chapter has identified appropriate application for decorative textile goods. Using the technique as a dye resist method has potential to address poor fastness to rubbing as the integrity of the design would be retained even if the fading effect was diminished by abrasion as discussed in section 8.8.

Further work for laser fading linen could explore resist design effects from a creative perspective. Further ISO performance testing may demonstrate the fastness properties of alternate linen substrates to have improved rubbing performance. Additional microscopic investigation and SEM analysis is necessary to determine the mechanism of the laser fading effect on linen fibres.

8.10 Chapter Summary

This chapter described the development of a technique allowing fading and darkening effects on natural linen fabrics using a CO_2 laser. These effects combined were shown to provide a tonal range with which to create subtle tonal, CAD controlled imagery for linen surface design. As a completely dry process, this provided an alternative to wet or chemical processing to achieve decorative effects on linen goods or an all-over lighter shade. Traditional linen processing often makes use of extensive bleaching processes to whiten the natural linen tone. Therefore environmentally friendly alternatives are an attractive prospect for the linen processing industry to reduce water, energy and chemical effluent. Limitations of, and appropriate contexts for the techniques were reported

The short study reported in this chapter demonstrated laser fading of linen to be an effective surface design tool as a dry process, or combined with dyeing as a resist technique resulting in a selection of showcase samples and suggestions for further investigation to improve the performance of the technique for a wider range of commercial applications.

CHAPTER 9 : LASER TEXTILE DESIGN COLLECTION AND INDUSTRY FEEDBACK

9.1 Introduction

The purpose of this chapter is to provide analysis of *Laser Textile Design* techniques developed in this research, as potential tools for manufacture and design through development of a design collection and industry feedback using focus group methods.

Previous chapters have shown the laser to be a dexterous tool for textile design with the newly developed techniques providing a variety of aesthetic and tactile outcomes for design purposes. In order to analyse and showcase the abilities of the techniques, a design collection was developed. The purpose of the collection was to validate and analyse the practical use and effectiveness of the laser techniques within the context of professional design practice. This was carried out using the author's background as a professional designer, which provided the appropriate skills and 'know-how' to carry out and answer a design brief. This chapter considers the merits and perceived value of the techniques, the collection and significant development samples through discussions with industry. Focus group methods were used, which served to provide detailed feedback in four key areas. The four areas have been running themes of focus throughout the study relevant to the analytical framework discussed in Chapter 3.

- Considerations and advantages for manufacture
- Considerations and advantages for design
- Considerations and advantages for sustainability
- Considerations and advantages for application

Discussions were held with two groups formed by the project's industry partners, who operate within two distinct sectors of the textile industry: the first, a company specialising in the design and manufacture of contract interior fabrics; the second, a leading performance swimwear brand. These companies were chosen to provide feedback from the context of two different industry perspectives.

9.2 Design Collection

9.2.1 Design Brief

In professional design scenarios, design briefs are given to provide designers with the necessary background information and instructions required to complete the piece of work. Design Briefs may be specific, detailing the scope, aims and objectives of a project (Phillips, 2004) or they may provide a broad outline and direction allowing a greater freedom of interpretation for the designer (Brown, 2009). In the case of this research, the design brief provided a broad overview.

The industry design brief was complied for this research project in collaboration with Camira fabrics. Information provided by Camira was used to develop the brief including the trend direction information for Autumn Winter 2015 / 2016 compiled by their design team under the theme, '*Perspective*' and a colour palette with pantone references from UKft (2014). A visit to Camira's head office in Huddersfield, U.K.

provided insight into the company's previous interior fabric collections, including their applications, performance standard requirements, best selling fabric styles and trend related imagery. The resulting brief, shown in Figure 9.1, detailed relevant company trend directions including guidance on aesthetic themes, colour palettes, materials, intended market and delivery deadlines. The brief enabled an appropriate industry focused response to be delivered in the form of a final design collection.

Contract Interior Design Brief

TREND/CONCEPT DIRECTION | 'PERSPECTIVE' combines dimension, construction, composition and structure with a mathematical and engineered approach to design and colour. Perspective looks at simple individual shapes that interlock and are stronger as a collective. Synergy is important '*the interaction of elements that when combined produce a total effect that is greater than the sum of the individual elements*'. Inspiration can be drawn from honeycomb and parallels drawn with how the modern office operates. Inspiration also can be taken from 'tile' designs, which are featured heavily in recent trade journals such as simple geometric designs, which become quite different when placed next to one another.

Key Words: Construction & Composition, Mathematical, Engineered, Cloth Architecture, Considered, Collective, Simple, Neat.

Pattern: Taking simple geometric shapes and investigating how they change when multiplied. Consider a plain base with co-ordinates created by adding colour in simple ways. Imagery may look to 3D images, structure on top of structure, layer on layer, origami, frameworks, skeletons of shapes, 3D mapping.

COLOUR DIRECTION | Pantones: please follow UKft for Pantone references for A/W 15/16.

BRIEF | Develop a collection of designs drawing on the theme of 'Perspective'. The collection will focus on woven natural fibre fabrics considering a variety of fabric weights. Designs are to consider imagery construction and composition with a particular focus on; distressed non-repeating dye effects and graphic and structural effects. The designs should sit within the evolving Camira portfolio of contract interior fabrics.

FUNCTIONAL CONSIDERATIONS | colour fastness to light, colour fastness to rubbing, tensile strength and abrasion relevant for the contract interior market.

DELIVERY | Review of the collection will be November 2014.

Figure 9.1 Design Brief

9.2.2 Design Development

From the design brief shown in the previous section, a refined colour palette was selected, inspirational contextual ‘found’ imagery was gathered, and first hand visual research was generated in the form of original photography and sketchbook drawings (Figure 9.2). This information was used to create mood boards as shown in Figure 9.3. A colour palette was developed and dye mixtures were tested for colour matching using the peri-dyeing technique. The mood board and visual research were used to inspire further design development using Adobe Illustrator and Photoshop to produce CAD patterns and placement imagery. A combination of this work was used to create inspiration boards to show the pattern and textural qualities to be used in the final design samples (Figure 9.4).

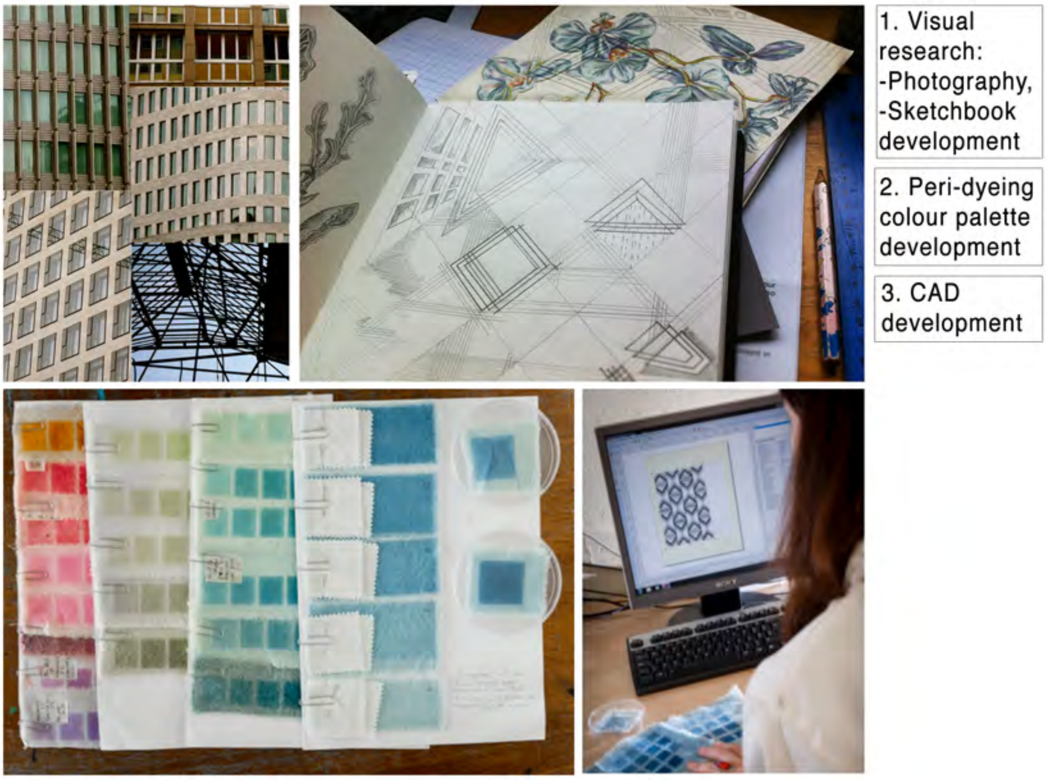


Figure 9.2 Design Development

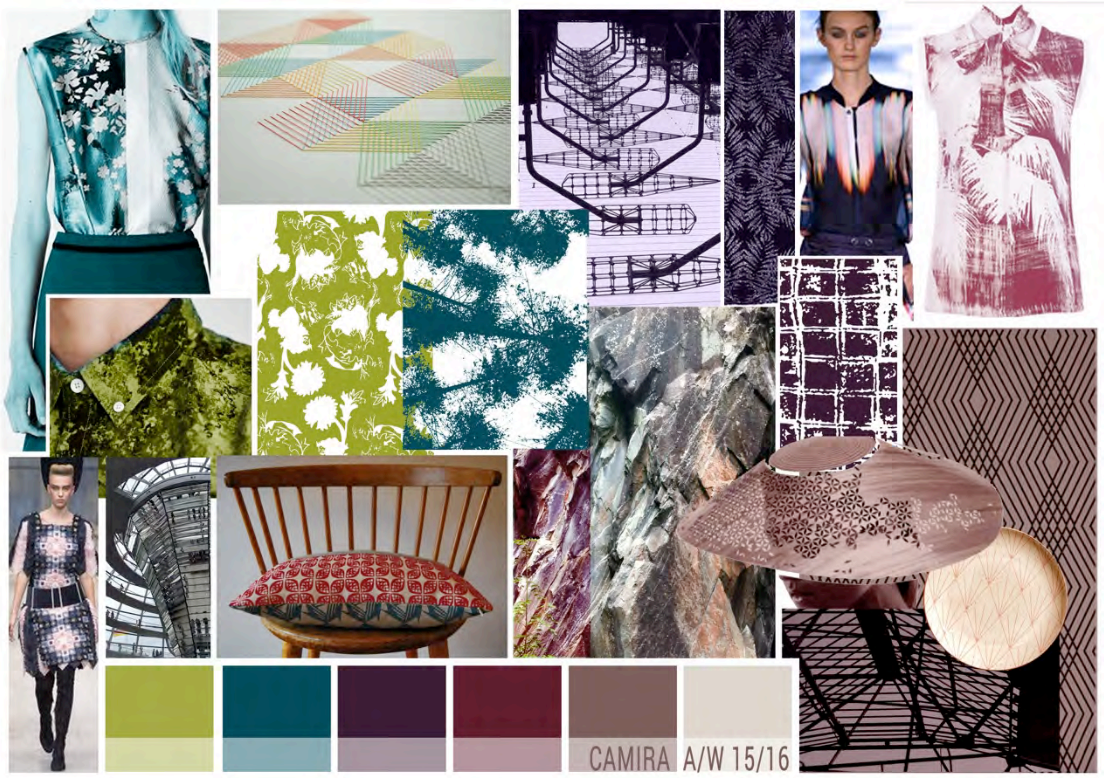


Figure 9.3 Mood Board

Figure 9.4 Pattern and Texture inspiration boards

9.2.3 Laser Textile Design Collection

The information, mood boards and visual research gathered in the design development stage were used to produce a final collection of *Laser Textile Design* samples shown in Figure 9.6. Laser techniques developed in this research were used to create the sample collection. Peri-dyeing was used to achieve laser precision on fine linear details (*1-5*), multi-coloured processing (*5*) and photographic imagery (*12, 22*). Laser enhanced dyeing of wool was combined with laser engraving for differential milling resulting in relief tonal pattern effects (*15, 24*). The laser fading linen effect was used on a pre-coloured linen fabric (*21*). The materials used included a variety of woollen fabrics including plain and textured weaves, milled finishes and a coloured linen, provided by Camira. The patterns and textures created took inspiration from architectural structures combined with natural silhouettes and textures. The architectural structures inspired detailed linear geometric patterns (e.g. samples *1-5*). The natural imagery inspired textured less repetitive patterns for example the tree silhouettes, rock and moss textures (e.g. samples *6,9,12,18,22*).

The *Laser Textile Design* collection served multiple functions within this research. Creation of the collection acted to validate the laser techniques as appropriate textile design tools. In addition, the collection provided qualitative data in the form of samples to be analysed through industry feedback.

Figure 9.5 Samples from the *Laser Textile Design* collection

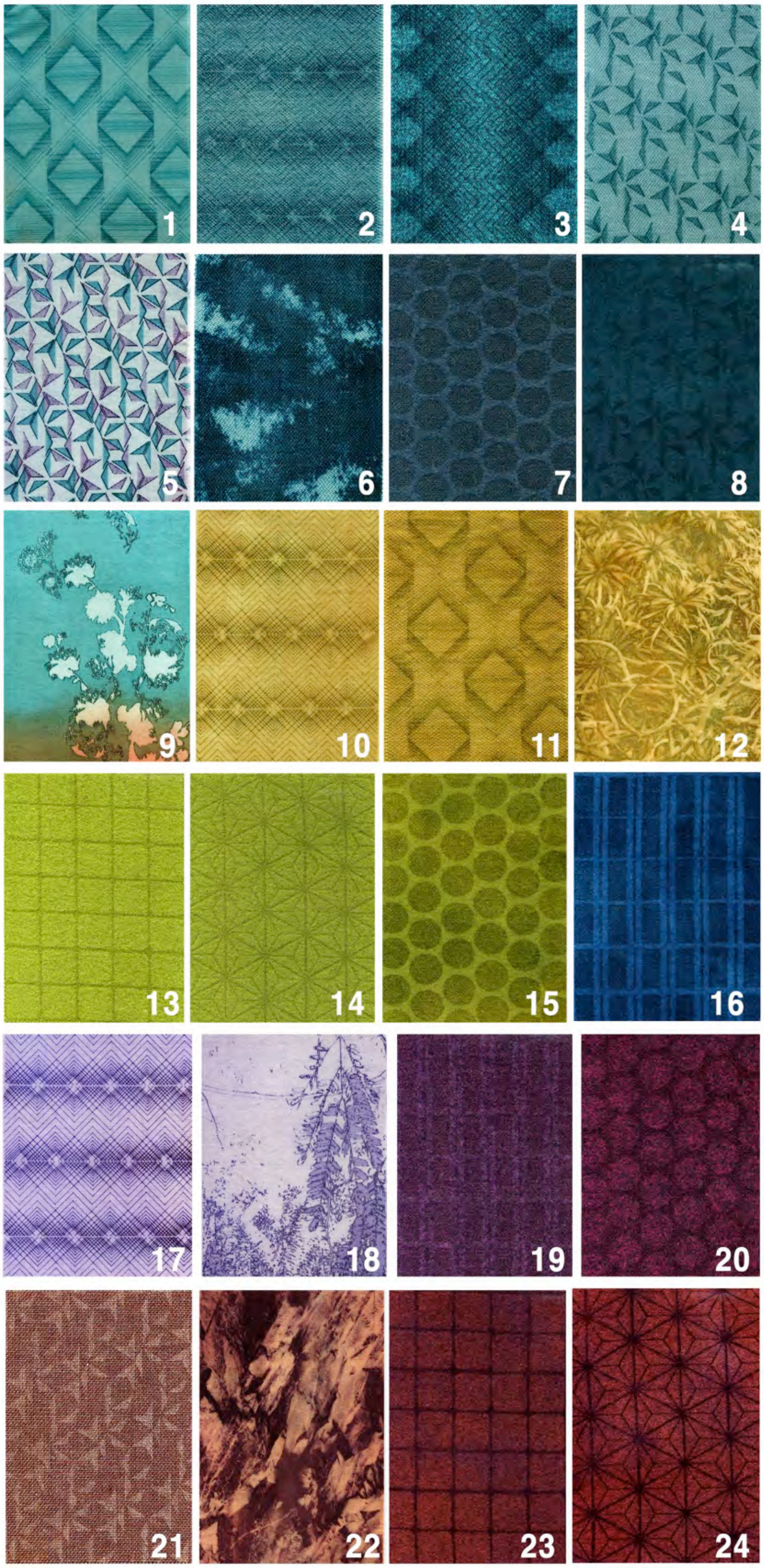


Figure 9.6 *Laser Textile Design* Collection for Contract Interiors

9.3 Focus Group Methods for Collecting Industry Feedback

As described in Chapter 4, focus groups are a useful method of collecting qualitative data on a wide range of topics. They usually take the form of a group discussion on a specific subject (Liamputtong, 2011) that is led by the aims of the research (Morgan, 1997). For design and product development, they can be particularly helpful in gaining insight and opinions from a specific audience or end-user (Langford & McDonagh, 2003). In this study, discussions with two groups were conducted. The 'audience' or participants consisted of team members working within the design, research and development departments of two companies in different categories of the textile industry. Individual participants roles are noted in sections 9.4 and 9.5. The participants were chosen to contribute focused feedback and relevant industry perspective on the *Laser Textile Design* techniques and design collection in line with the research question (Chapter 1).

Each group served a slightly different function in the research. Industry feedback from group 1 provided design feedback and evaluation of the *Laser Textile Design* collection, while in industry feedback from group 2 emphasis was placed on design propositions and product development regarding the laser techniques. Combined, the qualitative data gathered from the industry feedback was used to analyse the design, function, commercial fit and potential future directions of the laser textile techniques and their resulting sample collection.

9.3.1 Data collection and analysis of focus group data

Langford and McDonagh (2003) suggest multiple techniques can be employed within a focus group study to examine recurring themes and to triangulate data. In this research, focus group methods were employed to collect data from more than one source, including recording transcripts, written, brainstorming and ranking activities. A moderators guide, structured discussion and group activities were used to carry out, record and capture industry feedback.

Moderators guides were used to plan a schedule of tasks and questions to steer and structure the group discussion into the required topics. The guides used in this research (see Appendix 3) were based on a template adapted from Langford and McDonagh (2003). Group activities were carried out, including written and ranking exercises, to distinguish the importance of topics raised (Morgan 1997) and to capture individual as well as collective voices (Barbour, 2007).

In order to analyse the group discussions, summaries of various levels were used to '*narrow down the richness of the data'* (Langford and McDonagh, 2003: 45). The data, which included a transcript of the discussion, ranked samples or ideas, and written key points, were coded thematically in three stages according to the list below. The main themes were categorised into topics (1). Initial coding was used to determine the type of response (2) and used as headings to sort the transcripts into tables (Appendix 3). The four topics distinguished in the analysis framework for this research, were used for further thematic analysis of the transcript (3). The number of occurrences or mentions of topics was also recorded to help determine the importance of each idea.

1) Coded into topic headings: e.g. laser technique, sustainability

2) Coded by type of response:

- Reponses to design collection
- Concerns
- Suggestions
- Technique advantages
- Company insights

3) Coded thematically:

- Considerations and advantages for manufacture (economic/ practical / alternatives to tradition)
- Considerations and advantages for design (aesthetic / tactile/ emotional response)
- Considerations and advantages for sustainability (materials/processing/ systems))
- Considerations and advantages for application (function/performance/product)

Findings from the data are discussed in the following sections.

9.4 Group 1: Laser Textile Design for Contract Interiors

A structured industry discussion was conducted at a contract interior manufacturer. (Figure 9.7). The aim was to analyse the effectiveness of the laser techniques and design collection, relative to design and manufacture in an interior textiles market. Particular focus was placed on discussion of the design collection, created in answer to the company's brief. Participants' roles included: Director of technical projects; director of design; creative design and development manager; designer; technical developer; with the researcher acting as moderator. The moderator's guide and coded transcript for this group can be found in Appendix 3.

Figure 9.7 Participants Examine *Laser Textile Design* Collection

The group discussion was recorded, transcribed and coded with topic headings identified as:

- Laser engraved/ enhanced dyed milled wool
- Peri-dyeing
- General Comments
- Sustainability
- Linen

Responses based on each topic were coded thematically based on the four themes important to this research, consisting of considerations and advantages for: manufacture; design; sustainability; and application. The frequency of responses for each topic and theme are presented in Figure 9.8. Additional recurring themes were identified within each of the topics (sub-themes).

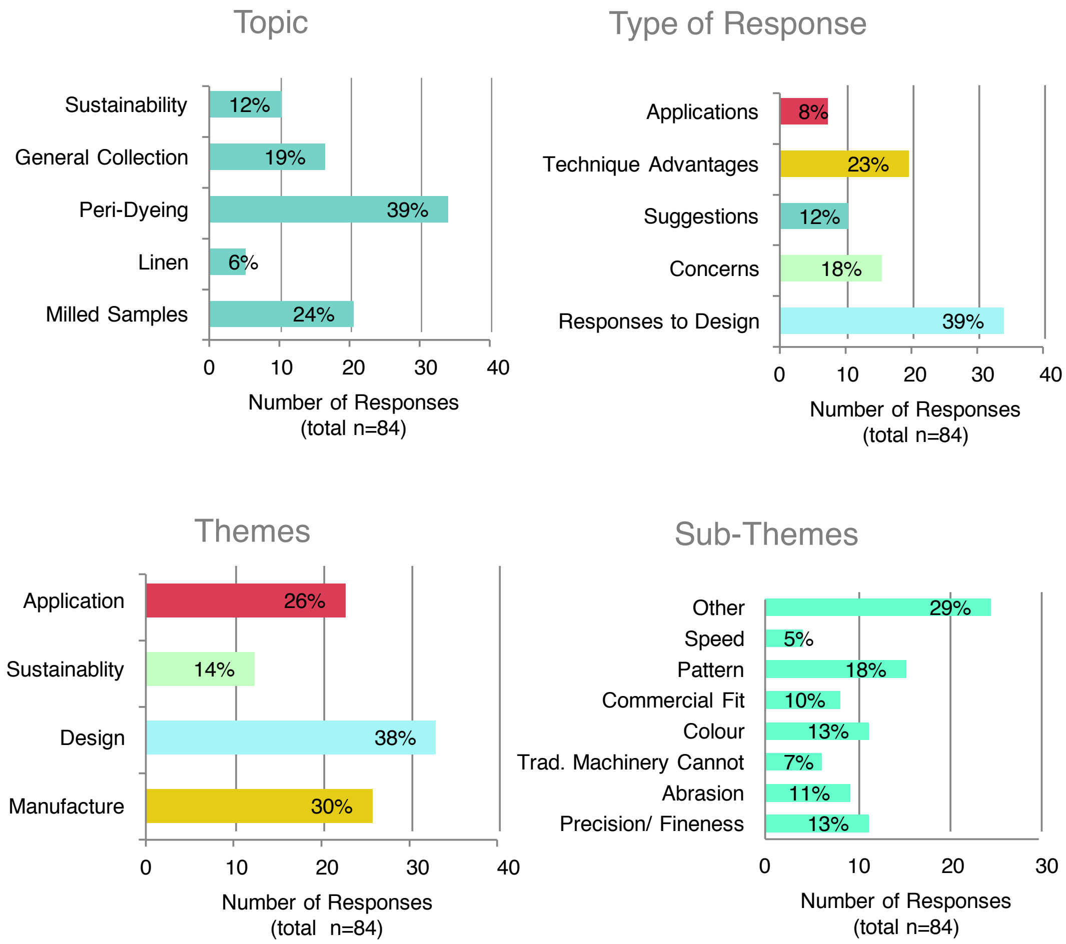


Figure 9.8 Themes identified within industry discussion data: Contract Interiors

The charts in Figure 9.8 show participants were most engaged in discussion themes relating to design, aesthetic and pattern. This was expected due to the area of expertise within the group, three out of five were employed in design-based roles, and participants were asked for their responses to a design collection. During the discussion, participants were asked, '*Consider what is most important for a successful design collection?*' with an aim to establish qualities that made designs suitable for the context of their company and customers. The properties of a successful design collection, compiled by the participants are presented in Table 9.1.

Participants were then shown the *Laser Textile Design* collection (Figure 9.6) and asked to identify the aforementioned attributes that were present in or absent from the collection. Within the samples of the design collection, participants identified beauty, visual and tactile texture, non-directional pattern, appropriate colour, and the suitability for use within sets as coordinates. The laser textile techniques were developed systematically with conditions optimised to ensure repeatability. Technical testing, completed to ISO standards (discussed in Chapters 5-8), suggested the samples would meet with safety regulations. The contract interior manufacturer provided the textiles used for the sample collection, it is known therefore, that the fabrics were suitable for upholstery purposes. The features and responses discussed above suggest the samples meet the functional and aesthetic attributes of a successful design collection, according to the group, as based on their collective industry expertise.

Properties of a Successful Design Collection	
Functional Properties	
Fitness for purpose	Safe
Performance	Meets regulations
Cost Effective	Repeatability and continuity
Upholsterability (easy to apply to all product styles)	
Aesthetic / Tactile Properties	
Beauty	
Colour	
Sets, collections that work well together, co-ordinates (patterns to go with plains etc.)	
Demand for visual texture and texture in handle.	
Importance of Pattern/ Imagery	- Increased demand - Restrictions: Small and non-directional to avoid line up issues. - Only small volume of directional patterns made

Table 9.1 Properties of a Successful Design Collection: Compiled by Contract Interiors Participants

A ranking activity (Figure 9.9) at the end of the session required participants to identify their top seven samples, relative to the attributes and contexts for a successful design collection discussed above. The top ranking samples are shown in Figure 9.10 with the results presented in Table 9.2.

Figure 9.9 Ranking Activity: Contract Interiors

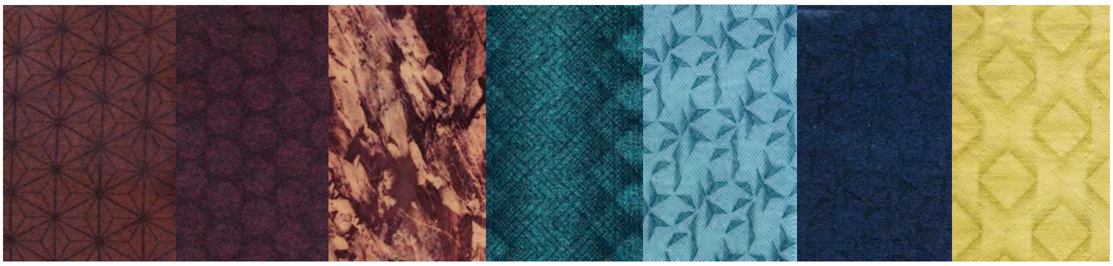


Figure 9.10 Top 7 Samples: Ranked by Contract Interiors Group

Sample	Number of Votes	Rank							Score
		1st	2nd	3rd	4th	5th	6th	7th	
24	4	••			••				22
20	4	•	••				•		21
22	3		•	••					16
3	2	••							14
4	4		•	•			•	•	14
8	2				•	•			7
11	1		•						6

Table 9.2 Top Ranking Sample Scores: Contract Interiors

Reflecting on the discussion, attributes of a successful design collection and the top ranking samples, it was concluded that laser engraving of milled wool was most interesting to the group. Samples using this effect were voted in the top two, with a third in position 6. In addition, discussion around the milled samples accounted for 24% of the conversation, where it was identified that the relief texture achieved was not achievable by other means available to the company. It was discussed how differential dyeing on the laser engraved, milled samples would allow pattern to remain on the textile after the effects of repeated abrasion in use, lead to wearing away of the relief surface fibres, thereby diminishing the three dimensional effect. Rather than a negative aspect, this was seen as way to increase durability, as the textile pattern and texture would evolve and change during use, providing novelty. Applications for the milled wool samples were identified: these included, upholstery and soft seating considering the aforementioned effects, or for wall panels, dividers and screens, where the issue of abrasion would be less significant.

Discussion relating to peri-dyeing of samples accounted for the highest proportion, 39% of responses from the group and four out of the top seven samples. The intricate, detailed patterning achievable by peri-dyeing on heavyweight or textured wool was identified as important (13%); a precision that cannot be replicated by jacquard weaving for upholstery weight fabric: '*if it's finer than weaving it brings in a new appearance, so fine lines and photographs would be interesting*'; '*To get a fine looking jacquard fine yarns are needed, not suitable for upholstery*'; '*If we could still use coarse yarns and get fine looking patterns and effects then that would be something that we can't do with our looms*'.

Colour and pattern were sub-themes that accounted for a significant proportion of the responses (totaling 31%). It was discussed that the colours used within the collection were accurate and appropriate for Camira's current trend direction, in particular the darker colours, which yield higher sales for the company. This indicates effective colour matching is possible using the laser dye techniques. Non-directional, small repeat patterns and abstract, textural patterns were considered as the most desirable forms of patterning for interior textiles as both avoid line up issues at seams and pattern cutting waste.

The contract interior manufacturer currently use a variety of dyeing techniques for colouration and patterning of their textiles, including overdyeing and cross dyeing on fabric blends. The laser dyeing techniques could allow construction of single fibre weave structures, that could be laser treated to provide defined patterning, colour, tonal and textural variation, that their current modes of manufacture could not achieve. 7% of the responses referred to interest in techniques that traditional machinery could not replicate: '*Anything that you can't weave, we are interested in*'. It was noted that the laser techniques: '*increase the desirability of wool and natural fibre fabrics*'.

9.5 Group 2: Laser Textile Design for Performance Swimwear

Unlike the previous contract interior group, the aim was not to analyse the merits of the techniques in relation to the design collection, but instead, to identify avenues of interest and opportunity that the techniques may provide for manufacture and design. Particular focus was placed on uses for 3D textiles within performance swimwear and scope for the laser moulding technique to facilitate this. Participants' roles included: Materials innovation manager; Materials technician; Industrial designer; Research Manager; Innovation Manager with the researcher acting as moderator. The moderator's guide and coded transcript for this discussion can be found in Appendix 3 with topic headings identified as:

- Laser Moulding,
- Peri-dyeing,
- Hydrophobia,
- Direct to Garment Printing,
- *Laser Textile Design*

Responses based on each topic were coded thematically based on the four themes, important to this research consisting of considerations and advantages for: manufacture; design; sustainability; and application. The number of responses for each topic and theme are presented in Figure 9.12. Additional recurring themes were identified within each of the topics (sub-themes). During the discussion, ideas were mapped on a spider diagram (Figure 9.13). A ranking activity (Figure 9.14) at the end of the session required participants to identify their top suggestion from the diagram. The top ranking suggestions are presented in Table 9.3.

Figure 9.11 Group Discussion: Performance Swimwear

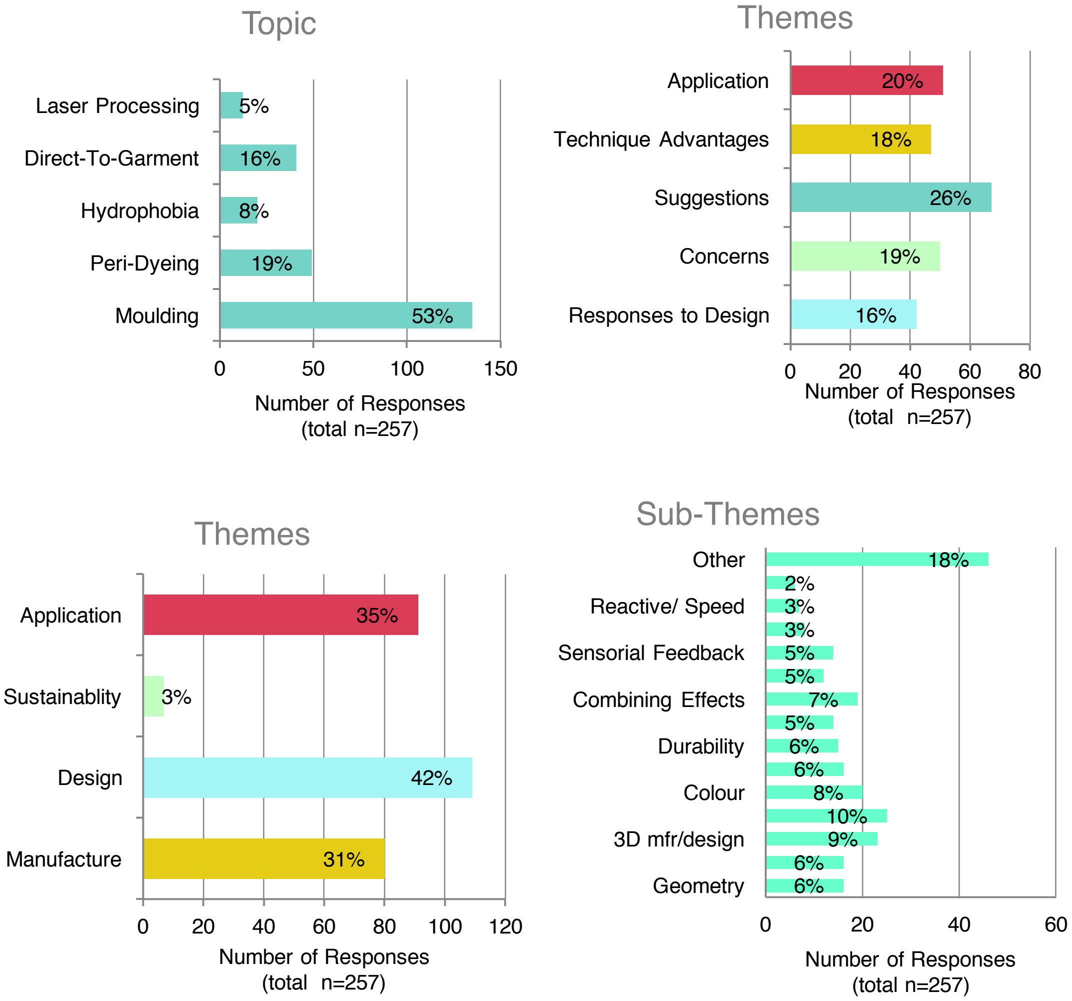


Figure 9.12 Themes identified within discussion data: Performance Swimwear

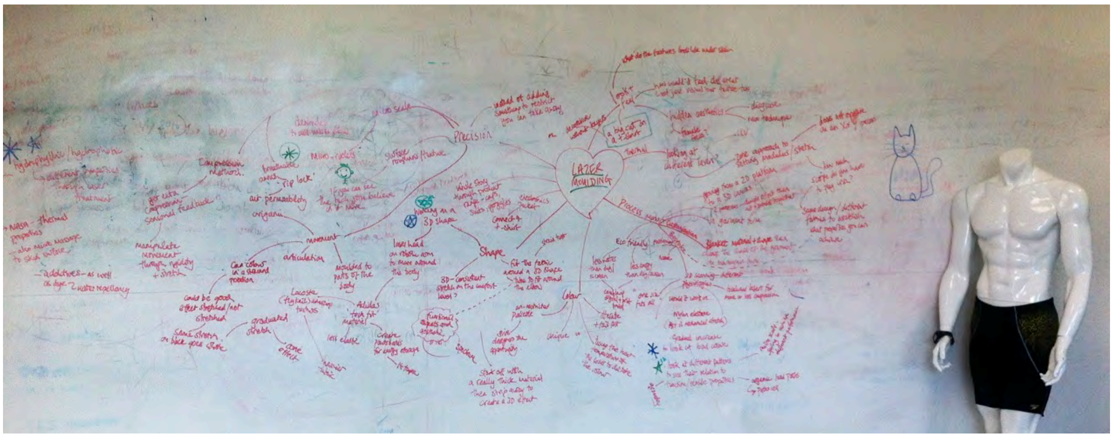


Figure 9.13 Spider Diagram of ideas and suggestions for *Laser Textile Design* by performance swimwear group based on samples shown

Top ranking suggestions reflect participants' ideas that would be most beneficial for performance swimwear. However, participants agreed that working with what can be done best is better than trying to fit the process to their needs: '*this exists- what can we do with it'*. The discussion that follows focuses on the recurring themes identified within the industry feedback. It is important to note, that the team within a performance swimwear brand are likely to have bias, seeking technical and functional properties of materials that may induce competitive performance gains. The discussion was dominated by 'blue sky' ideas. This identified valuable directions for further work beyond this research project. Suggestions leaned towards customisation services and direct-to-garment processing with an emphasis on function while recognising that the laser techniques would allow aesthetic to be controlled simultaneously. The potential to combine functional and aesthetic properties was of interest to the group, accounting for 6% of the overall responses.

Figure 9.14 Ranking Activity: Performance Swimwear

Top Ranking Suggestions
• Adding customised pattern, tension or compression to a 3D shape, Direct-to-Garment
• Engineering functional material properties in a targeted manner: controlled hydrophobic and hydrophilic areas; controlled areas of texture for air permeability
• Tensile or compressive properties gained by different geometric patterns.

Table 9.3 Top Ranking Suggestions from performance swimwear group

‘Suggestions’ accounted for the highest type of response at 26% of overall responses. This reflected the aim of the discussion, to consider potential and identify opportunities for the laser textile techniques within design and material development of performance swimwear.

Responses to the design and aesthetics of the *Laser Textile Design* techniques was positive and highlighted the ‘*story around precision*’ relating to 5% of the overall responses. Precision was mentioned when referring to the advantages of the aesthetic, function and application of the techniques. Participants were interested in the idea that aesthetics or tactility and function could integrate: ‘*showing the technical’*, allowing customers to feel or see performance benefits that also serve to provide a unique aesthetic to the product. Potential functional application of the laser moulding technique identified included: creating insulative pockets for recovery and heating post-swim or pre-swim; creating texture providing sensorial feedback that could stimulate the surface of the skin; altered compression, elasticity or gathering for fit and comfort; and using variations in texture, air permeability and three-dimensional relief effects for streamlining.

Streamlining was identified as a significant theme during the discussion, accounting for 5% of the overall responses. Three-dimensional protrusions and altered surface texture have been previously used in performance swimwear with claims to aid streamlining and flow, enhancing the performance of swimmers in the water. An example was shown to the moderator (Figure 9.15) where a sharkskin textural effect was used on the body of the suit to provide streamlining, and a panel of three-dimensional plastic dots was used as a ‘*turbulence management system*’. Regulation has since banned the addition of secondary materials to swimwear in competitive swimming; therefore the non-additive laser moulding technique was identified as a way to replicate three-dimensional effects while remaining compliant with regulations. However it was noted that actual performance benefits were difficult to measure, with features often used for marketing purposes providing a point of difference between market competitors.

Figure 9.15 Altered texture and three-dimensional features on swimwear to aid streamlining

Most textile surface designing within fashion occurs on a two-dimensional plane, despite application to a three-dimensional garment. Participants agreed that the concept of designing for a three-dimensional shape from the outset could allow design advantages.

The dialogue suggested enthusiasm around direct-to-garment capabilities, ranking as the top suggestion and with 16% of the overall responses focused on the subject. Direct-to-garment processing was highlighted by the moderator as a potential advantage of non-contact laser processing. However, conversation was not directed by steering questions to focus particularly on this topic, further signifying it's importance to the participants. Participants highlighted the advantages that a direct-to-garment approach would offer their company, suggesting possibilities to: '*test the market and iterate and fail fast, I think that's the key', and:*

> *You could be very reactive to how the trends in fashion are. As long as you can get the whole spectrum and consistency, that would be really exciting, actually give designers the flair to find inspiration quickly and turn it into a product or a prototype*.

Recognising the rapid prototyping opportunity laser technology may provide within this topic, comments around ideas of mass customisation, personalisation and bespoke design made up 10% of the overall responses from participants. The participants responded that customisation was: '*on our roadmap*', that it was a '*niche*' and '*exciting opportunity*'. One participant suggested that moving to personalisation, through either personalised design or fit was one step further than customising goods with one participant exclaiming: '*that's it for me, that's what our ambition is*'. Participants suggested that blank panels could be added within swimwear, and peri-dyed designs could later be added, providing bespoke customisation for teams.

Considering the possible benefits and uses of laser moulding, the effect of pattern and geometry on fabric properties was of interest. It was noted that the laser moulded samples provided differences in elasticity and compression depending on the design. It was suggested that further exploring geometric shape and pattern combinations may determine a relationship with tensile properties: '*would certain shapes correlation be more prone to different stretch and compression properties'*. Compression was identified as an important attribute to add performance benefits within swimwear.

The laser moulded effects have the potential to be applied in a targeted manner, allowing engineered properties to be designed into finished textile products. The possibility of engineered fitting, including the ability to apply targeted compression, or relaxation into a standard material via laser processing was identified as an exciting opportunity that would require further work. Using a similar concept to the laser moulding technique, but beginning with a densely knit fabric structure or garment, the laser may offer potential to be used to alter textile properties in targeted areas, offering a personalised fit to the wearer. Engineered materials were discussed, suggesting that use of a fabric purposely constructed to undergo laser moulding could achieve different levels of compression or areas of air permeability: '*So you are getting a bespoke fabric, starting with a standard fabric base and using the laser to manipulate tensile properties to whatever you want: that would be really interesting to us*'.

Concerns included durability and performance issues particularly, the effect of laser on the stretching modulus and tensile strength of materials, the degradation of elastane and the colourfastness within chlorine conditions. Colour accuracy was also flagged, with customer preference towards bright colours. However, participants agreed that while their customers may show preference to bright or neon colours when choosing swimwear '*off the shelf*', if provided with the choice for personalized choice of colour and pattern, this would be more advantageous to the brand than achieving a neon palette. With one participant dismissing this concern entirely: '*it* (peri-dyeing) *has a certain handwriting of it's own that is absolutely gorgeous*'.

In response to the industry feedback, designs for swimming shorts were created to demonstrate the potential for direct-to-garment peri-dyeing as shown in Figure 9.16. A pair of swimming shorts would be constructed with a blank side panel. The garment would then be peri-dyed in three-dimensional form.

Figure 9.16 CAD: Garment print designs for swimwear

9.6 Summary of Industrial Feedback

The *Laser Textile Design* collection facilitated discussion of the laser techniques and their potential advantages for design, manufacture, application and sustainability. Each discussion group served a different function, seeking comment and suggestions at different stages of the design development process. Group 1 provided design evaluation, while group 2 discussed potential development and design propositions. This summary discusses findings from both groups noting relevant group-to-group validation and their distinctions. Combined, the qualitative data gathered from the groups was used to analyse the perceived value of design, function, commercial fit and potential future directions of the laser textile techniques and their resulting sample collection.

The *Laser Textile Design* collection received positive responses from both groups in relation to aesthetic, tactile and three-dimensional effects. Colour accuracy was important to both companies. Concerns regarding colour were addressed during the group conversations. Participants from the swimwear brand felt that vibrant, neon colours would be more appropriate for their customer base. However, participants believed that the ability to provide customer customisation with choice of colour and pattern would be desired over a specific level of vibrancy. Additional sampling with use of appropriate dye colours has since shown that vibrant neon colours are achievable by peri-dyeing, as shown in Figure 9.17. In addition, participants from the interior manufacturer commented on the high level of colour accuracy achieved in the design collection compared to the colour direction provided in the design brief, showing that colour matching and repetition is achievable with the laser dyeing techniques. Alternate ways to alter the final colour result were also suggested. In group 1, it was discussed that peri-dyeing could apply pattern to a pre-coloured ground (as shown in Figure 6.30). While in group 2, it was suggested that the garment could be constructed predominantly in black, with blank panels to allow for targeted pattern and colour customisation.

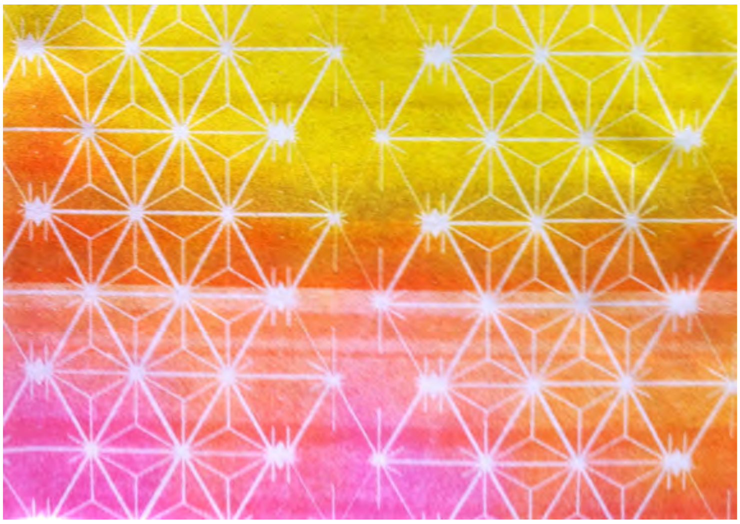


Figure 9.17 Neon Peri-dyed Polyester

Both groups expressed concern with speed and durability or damage caused by laser processing. Both groups were interested in ways to enhance material properties by application of design or functional features. Novel approaches were important to both companies, neither expressing an interest in replacing conventional manufacturing processes, but implementation of techniques that could provide new textile techniques or application methods that cannot be replicated by traditional means. For example, in reference to the peri-dyeing technique, both groups identified non-contact processing as advantageous for their companies: Group 1, as a means to pattern fine or photographic detail on upholstery weight fabric, while participants from the swimwear brand recognised the potential customisation opportunities that peri-dyeing could offer as a rapid prototyping, direct-to-garment tool. Group 1 identified pattern-cutting waste as an issue when using textiles that contained directional patterns. A direct-to-product approach could help to negate this problem.

Both groups identified commercial application of the techniques for their company. Group 1 was presented with a collection aimed for their company’s market, created using the company's own materials; a set of professional sales samples that could be showcased to clients in the appropriate format. Through the design collection, the commercial potential in the techniques was apparent. Appropriate applications were identified as upholstery for soft seating, wall panels, dividers and screens.

Group 2 was approached from a more conceptual standpoint, presented with design samples and information about the laser techniques. The discussion identified future directions that laser techniques could offer that would be of interest to their company including using the peri-process to apply hydrophobic properties to textiles, as well as 3D or direct-to-garment processing.

Sustainability was an issue on the agenda for both companies. The production of sustainable materials was particularly important to Group 2, as a fabric manufacturer. Eco-efficiency was important to both groups: it was viewed as a way to benefit environmental and economic issues. When asked about importance of sustainability to the company, Group 2 participants agreed that it was at the forefront of their company strategy: ‘*We know sustainability is good business, for us it’s not a practice for legal or charitable reasons, it’s a growth strategy*’ (Camira, 2015). However, when the designers were asked specifically how it affects their design decisions, they noted that sustainability issues were not considered during everyday design decisions for aesthetics or construction. This reflects the authors experience working in industry, as discussed in Chapter 1. Decisions that consider sustainability are regularly made during product development and manufacture, often outside of the designers’ influence. It is hoped that providing designers with digital techniques that are less harmful to the environment, such as techniques developed within this research, may offer designers the tools to make design decisions that consider sustainability from the outset.

9.7 Chapter Summary

This chapter presented the development of a design collection from an industry design brief. Samples were created using the *Laser Textile Design* techniques discussed in Chapters 5-8. Industry feedback was collected from contract interior and performance swimwear companies using focus group methods. These were conducted using the design collection to facilitate discussion, evaluation and potential future directions for the laser textile techniques. The data collected included discussion transcripts, written and ranked samples. Data was coded into themes that have been presented and discussed. It was concluded that the *Laser Textile Design* collection provided novelty, innovation and potential for further work and development within two distinct sectors of the textile industry. Instances of appropriate commercial fit were also identified.

CHAPTER 10

LASER TEXTILE DESIGN: TOWARDS A SUSTAINABLE TOOL FOR DESIGN AND MANUFACTURE

10.1 Introduction

> *To what extent can laser technology be used to modify textile substrates for the creation of novel, sustainable surface design techniques?*

This chapter discusses *Laser Textile Design* as a tool to support textile manufacture and design. The aim of the discussion is to bring together and reflect on the different aspects of the research study including the experimental results and findings from industry feedback, relative to their effectiveness in answering the research question. As well as examining the individual *Laser Textile Design* techniques developed throughout the research, this discussion considers the use of laser technology more broadly as a tool for textile design and manufacture measured against the analytical framework (as discussed in Chapter 3.6.4).

The aim of the research was to develop new sustainable creative opportunities for textile design by investigating laser processing technology to achieve surface design and three-dimensional effects. The three research objectives (discussed in Chapter 1.4) were met during the research in order to effectively address the research aim.

Workshop conditions were established (Objective 1) and laser parameters were explored, in Chapter 4. Troubleshooting included ensuring level and even processing by identifying the optimal settings for effective graphic processing. Exploratory creative sampling tested a range of fabric substrates resulting in technical and tacit knowledge of laser textile interaction. Through the exploratory experiments, design opportunities for laser colouration and three-dimensional effects were identified as four avenues for focused investigation.

Four distinct *Laser Textile Design* techniques were developed (Objective 2), including a laser enhanced dyeing technique for wool and wool blends, peri-dyeing: a laser dye fixation technique, a laser moulding technique and a laser fading linen technique. Together these techniques offer tonal, multicolour, precise graphic processing and three-dimensional or relief surface design capabilities for wool, linen and synthetic substrates as proved through the creation of a textile design sample collection. The commercial viability was affirmed through formal industry feedback and technical testing that adhered to ISO international textile performance standards.

Discussion in the following section evaluates the *Laser Textile Design* techniques against the analytic framework relevant to their suitability for manufacture, design, application and sustainability (Objective 3).

10.2 Towards a sustainable tool for manufacture and design

This section considers the potential for digital laser technology to facilitate sustainable innovation in the field of textile design and manufacture. As well as supporting cleaner and more efficient textile processing, the potential will be considered for digital *Laser Textile Design* to offer alternate procedural modes across multiple stages of the textile and garment lifecycle. As discussed in Chapter 2, previous design research studies have acknowledged the potential sustainability and production benefits that laser technology may offer as an alternate manufacturing opportunity including Stoyel (2003), Ondogan (2004), Goldsworthy (2014) and Akiwowo (2015). This section builds on the aforementioned discussion of potential advantages and application opportunities with particular relevance to the findings of this research study, backed up by experimental evidence from Chapters 4 to 8 and first hand industry specialist feedback from Chapter 9.

To evaluate the effectiveness of the *Laser Textile Design* techniques, an analysis framework was employed listing the key themes for consideration. Evaluating the perceived value and significance of the research to the textile industry: for manufacturing (A1); for textile design (A2); for textile product application (A3); and for sustainability (A4) within the textile lifecycle.

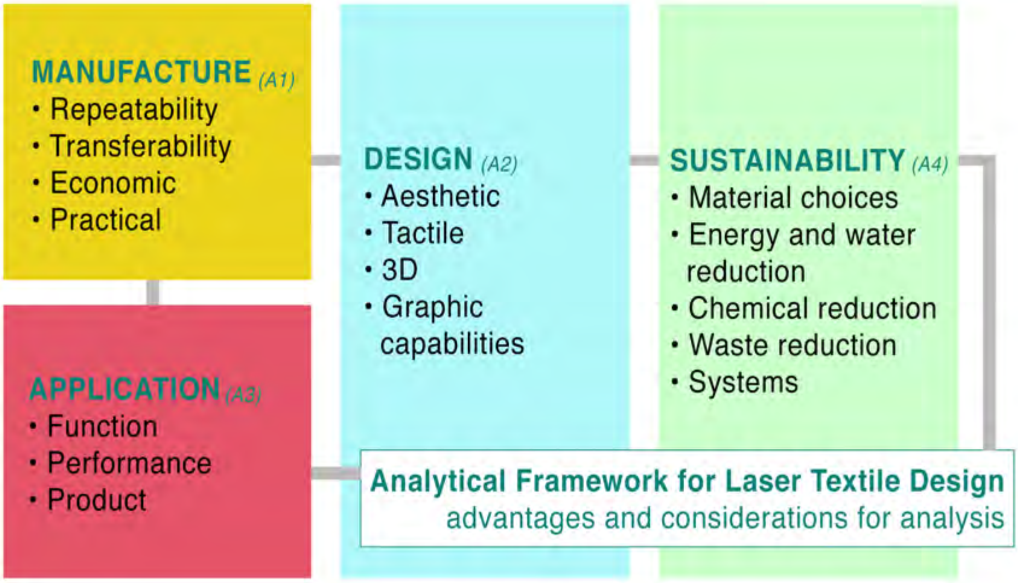


Figure 10.1 Analytical Framework Summary for *Laser Textile Design*

10.2.1 Considerations and Advantages For Manufacture

CO_2 lasers are established digital manufacturing tools within the textile industry. They provide an energy efficient, dry process and offer environmental as well as economical efficiency. Lasers are CAD controlled therefore, designs can be changed easily without the complicated set up associated with many analogue processes; for example, screens for screen printing. They are non-contact, which means processing can be done on textured, pile fabrics, as shown in this research in the design collection for contract interiors (figure 9.6). Surface design can be applied to three-dimensional products, finished garments and across seams as shown in this research in through intimate apparel and swimwear prototypes (figures 6.42 & 9.16).

Direct-to-garment laser processing equipment exists within textile manufacturing, used in the denim industry. The factors listed in this paragraph and discussed in the literature review combined with the techniques developed within this research revealed laser technology as a diverse and efficient processing tool. However, current uptake of CO_2 laser techniques for design in the textile industry, beyond cutting and fading denim is limited. This research has developed new opportunities for CO_2 lasers to be used in textile design and manufacture through the four distinct *Laser Textile Design* techniques.

Usually, high temperatures and long processing times are required to achieve maximum dye uptake on wool, In Chapter 5 this study showed that dyeing laser pretreated wool at a reduced temperature of 80^oC can achieve an elevated level of dye uptake. In Chapter 6 peri-dyeing was shown to achieve colourfast dye fixation at the point of laser interaction. As well as an apparent visual effect, dye exhaustion results for both techniques indicated an increasing amount of dye uptake was achieved as the laser energy density delivered to the fabric was increased, corroborated by colour data testing. It was shown that the laser enhanced dyeing for wool technique provided clear eco-efficiency benefits for manufacture with a reduced overall dyeing time and temperature from standard practice, displaying potential for an estimated 54% reduction of energy during dye production. The eco-efficiency benefits of laser enhanced dyeing for wool are also relevant to peri-dyeing procedures. With its increased design flexibility, the peri-dyeing technique improves dye, water and energy efficiency through targeted dye fixation and elimination of immersion dye procedures.

The use and thorough documentation of standardised measurements such as energy density for quantifying the energy delivered to test substrates and CIE L*a*b* colour data for quantifying colour levels has ensured that the *Laser Textile Design* techniques have high levels of control and transferability for industry and practice beyond this research. Repeatable results have been shown through extensive testing and design sampling; a feature rated of key importance for manufacture, according to feedback from contract interior manufacturers.

The laser techniques developed in this research provide design flexibility from a single machine. This increases when considering each CO_2 laser process discussed in the literature review. The reduction of processing stages may improve production rate for manufacture. For example, combining the functionality of the laser to perform multiple production tasks at once, such as combining colouration, surface design and laser cutting, or the elimination of a wet processing stage through laser pretreatment for wool or linen, would allow additional economic and environmental benefits when compared to outsourcing each individual stage of the production process, for example, fabric manufacture, screen printing and garment production in addition to storage and transport between these phases.

In Chapter 2, it was discussed that *Laser Textile Design* can be positioned across the surface design and finishing stages of textile production (Figure 10.2). The opportunity for digital processes to move the design stage further down the production cycle allows for late stage decisions, providing a more responsive approach to design. For independent designers working in the designer maker mode of production, this could facilitate bespoke production. For manufacture and supply chains responsive or *nimble* manufacturing can offer reduced lead times and minimum orders to reduce surplus stock. Digital techniques, production systems and software can lead to adoption of ‘on-demand’ production.

The majority of textile manufacture is directed towards volume production, with Far East manufacture dominating the industry. However, within the shifting landscape of fashion and retail, where bricks and mortar stores compete with online shopping, the requirement for supply chains to adapt to keep up with consumer and retail behavior is paramount. The ability to offer responsive, close to market production is a desirable attribute that would allow brands to react quickly to market changes and trends. The design and processing flexibility offered by digital *Laser Textile Design* techniques coupled with rapid, post-processing capabilities suggests a nimble local production opportunity for *Laser Textile Design*.

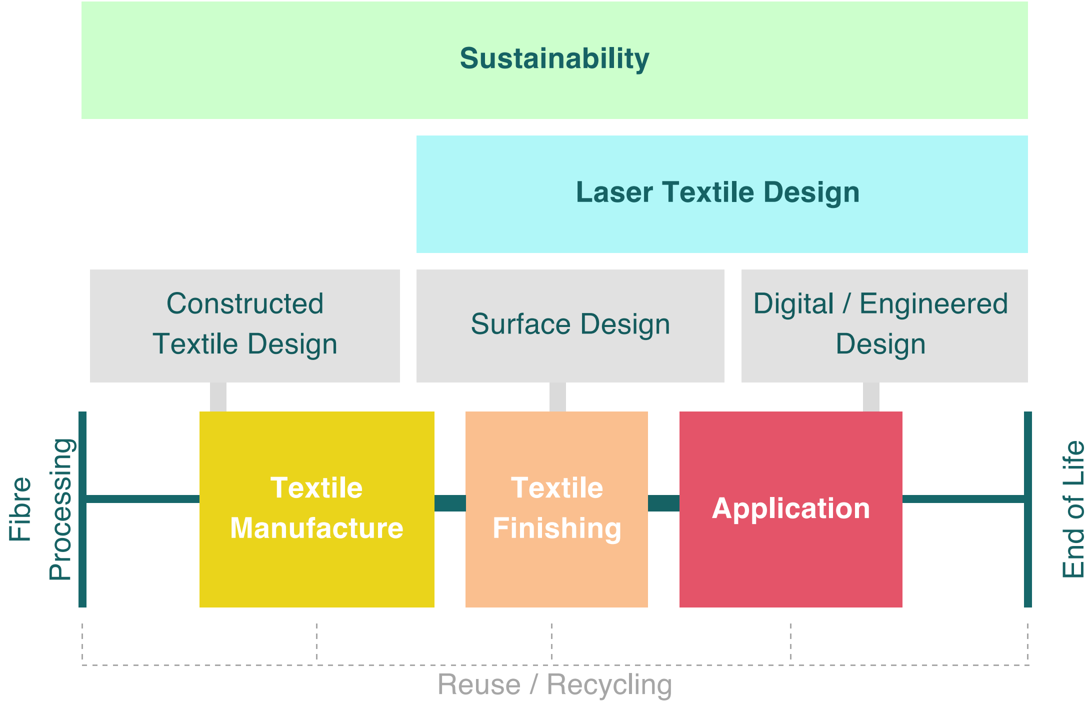


Figure 10.2 The opportunity for digital *Laser Textile Design* to move the design stage further down the production cycle allows for responsive manufacture

This section describes clear advantages of the developed *Laser Textile Design* techniques for manufacture, supported by the research data and confirmed by discussions with industry. As such, interest from industry has been established that led to a successful funding bid for research into technology transfer of the peri-dyeing technique with an aim to optimise the laser beam characteristics with specific heat distribution profiles for textile processing.

Further work relative to using the *Laser Textile Design* techniques for manufacturing, lie in providing a full commercial picture, including production time, exact amounts of water and energy consumed and unit costs for product processing on different applications.

10.2.2 Considerations and Advantages For Design

The development of four *Laser Textile Design* techniques has shown laser technology to be a diverse surface design processing tool for designers. The four techniques can offer design flexibility for: tonal colouration; multicolored design; fading; three-dimensional, textural and relief effects. This research has documented strategies to optimise processing parameters, colour, 3D and mark making to achieve high definition tonal graphic capabilities, improving on previous laser studies. Double-sided, colour blended and photographic surface design effects have been demonstrated using the techniques. Full colour reproduction was identified as an area for further investigation using the peri-dyeing process.

Figure 10.3 Multicoloured peri-dyeing: Designs on wool

Digital design and CAD control of the techniques have relevance for designers as a familiar working strategy to digital printing processes. As with digital printing, CAD control offers relative design freedom and ease of pattern change. Short run production capabilities allow late stage design decisions in industry, negating the requirement for early forecasting to predict colours ahead of season. For fashion and textile practitioners working in the designer/maker mode of production, these benefits can facilitate bespoke design, adding to the market offering for digital and rapid prototyping of goods.

While parallels can be drawn to digital printing as discussed above, the *Laser Textile Design* techniques can be used as surface design tools, not only for colour patterning, but also textural effects and dye fixation capabilities. Accurate duplication of designs from the design studio across the supply chain can be a challenge in the fashion and textiles industry. Designs for laser processing saved as digital files can be stored, changed and duplicated easily.

The non-contact digital laser effects have the potential to be applied in a targeted manner, allowing engineered surface design to be delivered directly onto finished textile products as evidenced in the swimwear and intimate apparel garments, laser patterned in this research. Textile designers typically design on a two-dimensional plane. Integrating digital design software with the three-dimensional processing capabilities of the laser may challenge textile designers to work with engineered design approaches that relate specifically to product or garment shape.

Alteration of energy density during the laser colouration techniques allows controlled targeted dyeing as shown in Chapters 5 and 6. Level dyeing is a key challenge for colouration in the textile industry. Chapter 5 has shown through CIE L*a*b* measurement that colour can be defined through laser energy density selection. After calibration, this could be used to define exact colour values or pantones with a level of control that ensures repeatability. This suggests clear advantages of laser pre-treatment as an enhanced colouration tool. However, as a pre-treatment, wet dye processes were still necessary and fibre damage was possible with darker shades. These issues were progressed and addressed via the peri-dyeing technique, which allowed targeted dyeing at the point of laser irradiation, further reducing dye and water waste. Peri-dyeing allowed laser controlled colour specification with clear potential shown for full colour reproduction of imagery, akin to digital printing, advancing digital printing processes by remote, micro precision capabilities.

With a beam size of 0.03cm the laser is capable of precision on a microscopic level. This facilitates precision graphic capabilities as shown through the design samples produced throughout this research. In addition utilizing non-contact laser processing, the peri-dyeing technique allows fine linear colouration details to be applied to textured or pile fabrics. Revealing an advantage over alternate surface design procedures identified by contract interior textile manufacturer, Camira, as a unique feature that jacquard weaving or digital printing cannot achieve.

Figure 10.4 Laser peri-dyeing technique allows intricate targeted surface design of textile substrates.

Potential improvements to the technique and equipment may include alternative dye delivery systems. For example, using a pad mangle or an automated ‘flying head’ process could improve the accuracy of dye delivery. However, the hand controlled dye application by pipette offered design opportunities through craft intervention that may not be easily achieved through automated methods. For example hand controlled dye mixing resulted in blended colour effects as shown in Figure 6.33.

The laser moulding technique developed in this research can be used to design accurate surface architectures, using the procedures articulated in Chapter 7. The technique can provide three-dimensional design features for textiles. It allows decoration to emerge from the structure of the cloth without additional materials.

Sampling showed the effect of changing processing patterns on the shaping and texturing effects that add visual interest through changes in the dimensional, tactile, drape and handle qualities of textiles. The use of weave and stitch inspired effects in test samples presented a rich library of aesthetic and tactile patterning opportunities borrowed from traditional textiles structures as well as the potential performance benefits they may offer, identified as thermal insulation, airflow, breathability and tailoring functionality. Using the technique for surface design effects could eliminate the need for additional, additive embellishment for decorative textiles.

A technique has been developed allowing fading and darkening effects on natural linen fabrics using a CO_2 laser. These effects combined can provide a tonal range with which to create subtle tonal, CAD controlled imagery for linen surface design. As a completely dry process, this provides an alternative to wet or chemical processing to achieve decorative effects on linen goods or an all-over lighter shade. The work could be furthered by additional exploration of laser irradiation as a resist dyeing method for linen, evidenced in Figure 8.6.

The *Laser Textile Design* techniques were sampled on a number of fibre types predominantly wool, polyester, nylon and linen. Cloth constructions from fine weight weave to thick milled upholstery weight wool have been tested, showing the laser techniques to have a diverse processing ability. The study can be defined as heavily material-led, with material properties imperative to the surface design effects achieved. For example, milled or felted wool provided the conditions necessary for relief laser devoré effects combined with enhanced dyeing. The stretch properties of polyester and nylon jersey were necessary to carry out the tension heat-moulding processes for the laser moulding technique. Dye effects achieved on wool blend textiles were also fibre-specific.

Combining techniques within the research further increases the design opportunities for laser processing. In this research combining laser engraving devoré effects with enhanced dyeing resulted in a new aesthetic. The relief textured wool effects achieved were of particular interest to the contract interior industry partner.

Peri-dyeing was combined with laser moulding as discussed in Chapter 7, again providing textural and aesthetic surface design outcomes. Combining three-dimensional laser moulding with laser dyeing processes resulted in an effect akin to shibori. The *Laser Shibori* provided a unique aesthetic effect, offering control, with a level of precision and repeatability that cannot be achieved with existing shibori processes or alternative textile production techniques.

The *Laser Textile Design* techniques provide methods for surface design with a new aesthetic, and new processing capabilities. Attributes that are not possible with existing methods have been discussed. The design opportunities afforded by the *Laser Textile Design* techniques offer benefits for design practitioners, students and educational facilities as well as industry through documented novel ways to employ laser technology and digital practice for textiles. The thesis has documented clear procedures and technical information to optimise the techniques and allow control and transfer to alterative laser systems and from designer to designer.

10.2.3 Considerations and Advantages For Application

During this research, the production of commercial samples and prototype products validated the commercial suitability of the *Laser Textile Design* techniques. A design collection for contract interiors was produced and presented as a set of commercial sales samples to industry professionals in the sector. The collection was created using materials provided by the interior fabric manufacturer, showcasing the ability of the techniques on a wide range of fabric weights, textures, constructions and finishes. Feedback from industry suggested particular interest in the three-dimensional relief qualities of laser engraved and dyed milled wool samples, and the precision graphic capabilities of the peri-dyeing technique on textured or thick woolen upholstery weight fabrics. These were identified as features that could not be produced or applied to interior fabrics by conventional means.

As previously discussed, ISO international standard textile testing procedures were used to ensure the tested substrates met with commercial regulations. Techniques were optimised and tests showed high colourfastness to washing and rubbing. Laser pre-treated wool showed a reduced tensile strength compared to untreated samples, however suitable applications were articulated including light garments and soft furnishing accessories. Suggestions to limit thermal damage were offered in Chapter 5, including the selection of a lighter colour palette, which requires less energy density. Acceptable levels of tensile strength were determined for peri-dyeing, providing wide-ranging application opportunities.

The research outcomes identified 3D garment dyeing and surface design opportunities. The direct-to-garment approach to manufacture, mentioned in previous sections, was of particular commercial interest to participants of the performance swimwear focus group. By applying peri-dyed colour and pattern onto finished three-dimensional products, prototypes including swimwear and intimate apparel were produced. This validated the capabilities of the *Laser Textile Design* techniques to be applied in a direct-to-garment approach relevant to on-demand, rapid prototyping production contexts.

This mode of surface design application has potential to be developed into a digital *Laser Textile Design* supply service, following commercial models in existence such as: online custom clothing brand, Print All Over Me (2015) who provide 'design your own' product blanks to consumers; or digital printing bureaus, such as Spoonflower (2015), who provide digital fabric printing and sampling services for professional and amateur textile designers. The agile nature of non-contact digital laser technology combined with the proven variety of surface design, colouration and three-dimensional effects developed in this research would be suitable for an on-demand service of this manner.

Combined with an on demand service proposal, the techniques have the design flexibility relevant to bespoke production contexts but also for mass customisation by suppliers or participatory design by customers at point of sale.

Transferability to an on-demand production systems would require reliable repeatability and control over the laser as a design and surfacing tool, addressed within the research via testing that meets international standard regulations as discussed in Chapters 4 to 8.

The research has suggested functional applications for the *Laser Textile Design* techniques including enhancement of performance properties of materials. Chapter 7 identified insulation, texturing and potential for sweat wicking and aerodynamic properties provided by three-dimensional laser moulding. Chapters 5 and 8 identified ways that laser irradiation enhanced the material properties for wool, wool blends and linen. They included: increasing the affinity for dye in wool; targeting irradiation to intensify the polyester properties in polywool; and by lightening linen fabric, a process that usually requires extensive bleaching processes. Discussion with a performance swimwear brand, indicated an interest in applying targeted hydrophobic and hydrophilic properties to textiles, that the peri-dyeing technique has potential to facilitate, providing an avenue for further work.

10.2.4 Considerations and Advantages For Sustainability

How do the novel *Laser Textile Design* techniques developed in this research support sustainable innovation? As discussed in Chapter 2, the diagram in Figure 10.2 shows where *Laser Textile Design* intervenes within a textile lifecycle, thus revealing where it can play a role in improving sustainability. Reviewing the benefits provided by the *Laser Textile Design* techniques across the textile finishing and application stages reveals sustainability benefits across all four levels of Stevels scale, as summarised in Table 10.1 and discussed below.

Sustainability Principle	***Laser Textile Design* Technique Advantages**	**Stevels Level**
Material Choices	• Improved processing for more sustainable material choices • Effective processing on Mono Materials	Level 1
Energy and Water reduction	• Dry Processing • Low temperature post-processing • Energy Efficient • Combining production stages	
Chemical reduction	• Improved dye performance- minimise dye chemicals • Alternative finishing requires no chemicals	
Waste Reduction	• Targeted, digitally engineered design • Non-contact, Direct-to-garment or product • No moulds, screens, mechanical parts to replace. • Agile manufacture, Responsive supply, less surplus stock	
Sustainable Systems	• Customisation/ personalisation • Local production • On demand systems	Level 4

Table 10.1 Advantages of *Laser Textile Design* for sustainability

10.2.4.1 Material Choices

At it’s most simple; lasers offer improved processing with options for designers and manufactures to choose more sustainable materials to manufacture goods. The research has shown that the developed techniques improved material properties for wool and linen. Both fabrics can be locally sourced. The textiles remain as mono-materials with no additives, stitching or coatings, leaving the materials uncontaminated for ease of recycling.

Blended wool is non-recyclable, therefore presents a contradiction to the pure materials used throughout the rest of the research. A better laundering profile and enhanced durability may present some environmental and longevity advantages for polyester/wool blend fabrics, nonetheless the problem of non-recyclable or non-biodegradable textile waste is an issue that should be considered by designers and product developers when choosing to use a blended textile. The laser technique could help address the issue by adding value to re-use, re-design or upcycle existing polywool products, increasing the duration of their useful life.

10.2.4.2 Energy, water and chemical reduction

The laser techniques provide economic and sustainability benefits via efficient manufacture. Tests carried out within the research have shown that water, energy and chemicals were reduced. Laser pre-treated wool was shown to reduce energy by 54% by reducing time and temperature of the dyeing process. Enhanced dye uptake was also proven, meaning that less dye is necessary for achieving the same shade on the same material compared to standard procedures.

Peri-dyeing facilitated targeted dye uptake using low dye concentrations of 1-2%. Sampling showed high levels of dye uptake were achievable at optimised laser settings ensuring reduction in dye waste. Elimination of dye baths used in conventional exhaust dyeing procedures signifies a substantially lower water consumption of the technique.

Laser fading of linen provides a completely dry surface design method for adding tonal graphics or pattern to linen. The laser's capability to cut, dye, pattern and mould substrates would allow the combining of production stages, an opportunity that does not exist in conventional textile manufacture.

The benefits discussed in this section may be classed as 'incremental' improvements at levels 1 and 2 according to the Stevels (1997) scale of sustainable innovation. With an industry so large, even small improvements in water, energy and chemical efficiency can equate to vast economic and environmental savings. As previously mentioned, life cycle analysis of the *Laser Textile Design* techniques was not within the scope of this study. More quantifiable definitive sustainability data such as comparative consumption levels of water, energy and chemicals should be pursued. This would ensure the information was available if the techniques were to be adopted by industry.

10.2.4.3 Waste reduction

Targeted, engineered placement of designs can reduce waste from lining up patterns when pattern-cutting. For example, construction of a standard bra consists of fifteen separate components. Each of the components including fabric, trims, straps, must be dyed and patterned separately in bulk. Consideration of the wasted energy, water and dye used to colour and pattern remnants that are typically disposed of after pattern cutting, reveals an opportunity for significant improvement. With direct-to-garment *Laser Textile Design*, design colour and pattern can be added as required, specifically engineered to the garment shape.

The laser operates a remote, non-contact set-up, which provides the ability to place designs on finished products and across garment seams. This offers potential for manufacturers to customise finished, three-dimensional blank garments to meet the requirements of brands and retailers. As discussed previously, if suppliers can be responsive to their customers needs, there is an opportunity for reduced stock holding and surplus stock reduction. For example H&M (2015) published a sustainability report that states their intention to reward business to suppliers who can help to offer more responsive supply to them as part the company's sustainability strategy. If more brands follow suit the demand for responsive systems is only likely to increase.

10.2.4.4 Sustainable Systems

Finally, examining the proposal of an on-demand laser design service, begins to consider re-design of the systems of production, where emphasis is given, not only to more efficient manufacture, but also to new systems, for a more responsive supply chain and on-demand, personalisation capabilities for retail. 'Fashion on demand' has been cited as one of the key ways to achieve a more sustainable fashion industry by changing the mode of supply and production, moving into the higher levels of sustainable innovation that may further facilitate environmental strategies in the industry.

During this research, industry partner and performance swimwear brand, Speedo provided swimming shorts with blank side panels, in which colour and pattern were added using the laser peri-dyeing technique. This provided a working prototype evidencing the direct-to-garment processing capability of the technique. For manufacture, garment suppliers and retail, the direct-to-product production approach offers 'mass customisation' and responsive supply, as previously discussed.

Benefits include producing smaller product runs, reducing surplus stock and even offering customer customisation. For example, the proposal for an on-demand *Laser Textile Design* service would support an online business model, envisioned where customers can examine virtual designs that are made to order on payment. This negates the problem of stockholding designs that may not sell or become obsolete through changes in trend. For independent designers, access to such technologies could allow their designs to compete with big name brands on a similar platform. In addition, an on-demand or customisation laser service could provide customers with participatory design opportunities, which may lead to greater aesthetic sustainability and psychological attachment to garments, increasing longevity of use.

10.3 Laser Textile Design: Reflections on Methodology

Similarities across previous textile design research studies were identified and coupled with Action Research principles to articulate an *Interdisciplinary Textile Design Research Methodology*. Imperative to the approach was the synthesis of scientific and designerly research methods encompassing both qualitative and quantitative analysis and a set analysis framework against which to measure the effectiveness of the research. The methodology presents a robust strategy relevant for future textile design researchers, allowing practice based, design-led research backed up by robust technical knowledge from interdisciplinary fields to enable a platform for innovation beyond creativity as articulated in the previous section through industry feedback, suggestions and prototypes for application, sustainability and manufacturing.

Design specific skills were key to advancing the research from a design perspective, while systematic rigor of controlled experimentation and international industry standard textile testing ensured commercial relevance and transferability for manufacture. Dialogue with engineers, textile chemists, fabric manufacturers, product and material developers within performance swimwear and contract interiors, as well as fellow textile designers including the author's professional experience in commercial design and product development within fashion, textiles and accessories, helped to maintain a commercial focus to the research and broadened the research application potential. This has led to outcomes in the form of prototypes for interior and performance swimwear markets.

A craft-led approach in the initial stages of the research provided proof of concept and a hypothesis to be tested with further work. The development stages used a more systematic approach making use of technical and scientific processes to record and measure results. This provided rules, parameters, limitations and a best practice for the laser procedures resulting in four new documented techniques. Fibre and dye chemistry theory facilitated explanation and understanding of the processes.

In the final stages, design practice was used to test the aesthetic and tactile qualities and applications that could be achieved. The combination of tacit knowledge gained from creative experimentation together with the technical knowledge gained from quantitative testing and analysis was imperative to achieving the research goal of evolving techniques, which have opened new creative opportunities for textile design whilst being viable and communicable for industrial and commercial application.

10.4 Chapter Summary

The techniques, textile design collection and garment prototypes developed in this research have shown that laser processing offers new and unique creative opportunities for textile design, colouration and three-dimensional effects. The digital *Laser Textile Design* techniques developed in this research allow patterning of fabrics in ways that have not before been possible. Enhanced colouration techniques provided a documented 54% reduction in energy, with further reductions suggested by the elimination of immersion dyeing through the peri-dyeing process. Linen and laser moulding techniques provided complete elimination of wet processing.

In addition to supporting cleaner and more efficient textile processing, digital *Laser Textile Design* has the potential to contribute towards a sustainable tool for production and supply across the sector. With potential to add to the market offering of digital on-demand, rapid prototyping, and customisation services. Therefore, contributing to a move towards a more sustainable, agile textile design industry.

Peri-dyeing shows potential for a non-contact laser based printing system, which could more closely meet the needs for future manufacturing systems. As 3D printing and fully-fashioned garment technology become the norm, the demand for systems that can meet the changing needs of the supply chain and consumer behaviour is likely to increase. Improved sustainability; rapid prototyping; on demand; and customisation moving towards personalisation services, are some of the key themes that future systems must consider, all of which have been discussed in the context of laser processing and the *Laser Textile Design* techniques.

Of note, the technique advantages discussed in this chapter have also been observed as advantages for manufacture, design, application and sustainability, revealing sustainable innovation to have value beyond the environmental benefits and towards an improved textile design industry, from production to design, commerce to practitioner.

CHAPTER 11 : CONCLUSION AND FURTHER WORK

11.1 Thesis Conclusion

The research presented in this thesis described the development and optimisation of four *Laser Textile Design* techniques, effectively fulfilling the research aim. The interdisciplinary textile design approach used practice as a site for research. In doing so, the research synthesised design and science with industrial collaboration, facilitating innovation in textile design that is relevant to designers, engineers, and industry. This has been reflected on throughout the work. The techniques detailed in this thesis and summarised in the following section (Contributions to Knowledge) provided a range of surface design effects. Laser precision and parameter control was used to define colouration and three-dimensional results on natural and synthetic textiles.

The discussion in Chapter 10 answered the research question by detailing the extent to which the *Laser Textile Design* techniques could support manufacture, design, application potential and sustainable innovation for the field of textiles, notably by evidencing a 54% reduction in energy during dyeing procedures from laser enhanced dyeing of wool. The peri-dyeing technique added additional benefits, further reducing the water and dye required for colouration of wool and synthetic substrates by eliminating the need for immersion dyeing procedures, while retaining high colour fastness properties. Eco-efficient processing modes were proposed, stemming from the direct-to garment sampling achieved through the research; these included, on-demand, agile manufacturing systems and customisation services.

11.2 Contributions to Knowledge

This research has offered advancement for textile design and finishing, dyeing and printing procedures, CAD and laser processing, further developing digital laser dyeing processes and three-dimensional finishing. It adds new knowledge to the field of textile design in the following ways.

1. Development of a laser enhanced dyeing technique, as a pre-treatment to dyeing that is specific to colouration and surface patterning of wool and wool blend textiles. This included explaining and investigating the enhanced dye uptake mechanism distinctive to wool. A CO_2 laser enhanced dyeing technique has not before been developed for wool. The work provided colour and performance analysis and opportunities for low temperature dyeing of wool-based textiles, resulting in a laser dyeing technique that can define exact tonal colour values with a level of control that ensures repeatability. This research also describes the combination of laser engraving and enhanced dyeing to create relief surface design and colouration effects on milled, or felted wool. Multicoloured surface design effects were achieved on wool blend textiles, cross-dyed in a single dye bath. In addition the increased affinity for dye after laser treatment allowed a reduction in time and temperature of the dyeing process, equating to a 54% reduction in energy

compared to standard wool dyeing procedures; a saving that demonstrates clear economic and environmental advantages for textile design.

2. Development of laser peri-dyeing, a dye fixation technique, that allows the dye reaction to take place at the point of laser material interaction. The work provided laser and dye parameter optimisation and performance analysis through ISO international standard testing. The peri-dyeing technique further reduced the water and dye required for colouration of wool and synthetic substrates by eliminating the need for immersion dyeing procedures, with high colour fastness properties. This technique vastly reduced thermal damage induced by laser irradiation on textile surfaces, and provided multicolour surface design opportunities drawing parallels with digital printing capabilities. Advancements of conventional textile processing were evidenced and included micro precision capabilities, double sided, non-contact and direct-to-garment processing on three-dimensional shapes and finished garments. The commercial potential of the technique was demonstrated through industry validation and development of a *Laser Textile Design* sample collection. In addition, the technique showed potential for the application of additional coatings other than dye.

3. Development of *Digital Laser Shibori*, a technique that combines colouration from the peri-dyeing process with three-dimensional laser moulding. A laser moulding technique was developed that processes three-dimensional forms through tension assisted heat moulding together with defined strategies to control and predict the three-dimensional effects for design. Uniaxial and biaxial tension, pattern spacing and laser energy density were identified as parameters for controlling three-dimensional surface design effects, including the height, shape and dimensional stability of 3D fabric designs. A collection of design samples replicated a variety of geometric and traditional textile structures, demonstrating the functional and aesthetic application potential of the techniques.

4. Development of a linen fading technique that uses the laser to fade natural linen for decorative surface design effects. The technique allows dry processing of linen textiles and results are discussed in relation to ISO international textile testing standards. Evidence of a laser resist dyeing effect was demonstrated and a collection of design samples was produced.

5. Demonstration of a design-led *interdisciplinary textile design research methodology*. The methodology used a combination of design and scientific approaches to research, with commercial validation through collaboration with industrial partners (articulated in Table 3.1 and Figure 3.2). The combination of hand and digital textile design practice, quantitative scientific experimentation, international standard textile testing and qualitative industry feedback facilitated material and process innovation for textile design with documented design, sustainability, manufacturing and application benefits.

The methodology has relevance for future design researchers, offering a clear approach to negotiate cross-disciplinary fields with an aim to foster responsible innovation.

The research also contributes to the field of textile design in the followings ways:

- A *Laser Textile Design* sample collection and prototype garments demonstrating 3D garment dyeing and surface design opportunities for textiles. These samples showed the techniques were suitable to generate results in a commercially relevant format at the leading professional edge.

- Presents a refined approach to process and parameter selection, improving on existing studies, by honing and refining laser processing methods in a way that is relevant to alternate fibre types.

- An articulation of the laser as a sustainable digital tool for agile manufacture and design and suggestion of adoption opportunities of the *Laser Textile Design* techniques. Industry and commercial relevance were evidenced through structured discussion and feedback from a contract interior manufacturer and a performance swimwear brand.

11.3 Further Work

Opportunities for further work and investigation to advance the research that were identified during this study are presented in this section.

11.3.1 Further Work for Laser Textile Design

Furthering the design opportunities for the developed techniques include investigation into full colour reproduction aspects of the peri-dyeing technique. This would include optimising colour separation and dye processes that have been demonstrated in the work, with reference to reprographic techniques.

Further testing of the peri-dyeing technique to examine laser dye fixation on a range of additional substrates and fabric constructions could broaden the application potential of the techniques. For example proteineous fibres, linen, hemp and cotton, woollen carpets and non-woven materials. Initial tests in section 6.15 suggest the process would be effective on bast fibres such as hemp and linen. These fibre types may have local production capabilities and therefore an improved sustainability profile as discussed in Chapter 2. In addition, using the peri-dyeing technique on 3D-printed ‘textiles’ could facilitate colour and design as part of the rapid prototyping process. Peri-dyed samples on acrylic board would suggest potential for this application.

The technique also has potential to allow laser fixation of chemicals other than dye. Initial investigations have shown potential for fixing a hydrophobic compound (Aromatic Amide) on Polyester using the same peri technique. This suggests hydrophobic coatings could be ‘peri-dyed’ onto textile substrates. Further investigation is necessary to determine the proficiency of peri-dyeing as a fixation device for alternate functional finishes including hydrophobic or hydrophilic coatings or compounds, flame retardant or antibacterial finishes. Laser dyeing processes could also explore potential for enhanced fixation or uptake of natural dyestuffs thus improving their potential for commercial application.

Further work to develop and improve the laser moulding technique lies in expanding the three-dimensional design effects that can be achieved, examining engineered design opportunities and the potential for micro-patterning or micro-texturing as discussed in the following paragraphs.

Additional three-dimensional design effects, specifically furthering the *Laser Shibori* effects could enhance multi-coloured patterns and create three-dimensional imagery. Developing three-dimensional design aspects of the technique for additional effects include examining functional geometrics, processing of organic shapes and free flowing patterns, and investigating the use of gradiated energy density to provide gradiated moulding effects such as conical shapes. Alternate pleated forms could provide an expanded range of achievable shapes.

Placement of moulding could be furthered through engineered fitting or shaping for moulded garment pattern pieces, for example, shaped cups for womenswear. This could offer an exciting opportunity to develop custom fitting with the goal of starting from a blank standard fabric and adding targeted properties or shaping based on requirement.

The work examined macro-scale moulding, however with a laser beam size of 0.03cm, there is the potential for laser texturing on a microscopic scale. Micro-patterning has the potential to provide added or enhanced textile properties. For example, adding a ‘nap’ to fabric can offer suede or peach skin textures. Technical textile testing could be used to quantify changes or enhancements to fabric comfort properties such as air permeability and thermal conductivity after laser treatment. Emulating the tactile qualities of natural fibre fabrics such as cotton or wool is a desirable feature for manufacturers of synthetic textiles. If micro-patterning using the laser moulding technique can alter tactile or functional properties of synthetic stretch fabrics, a potential valuable avenue for further investigation has been identified. In addition, this would have potential to reduce the need for blended fabrics, improving the material’s recyclability profile.

Further work in the laser fading of linen could more thoroughly investigate the fading mechanism to determine if the lighter shade is in fact the result of a residue from laser irradiation of the linen fibres. The technique could be further investigated as a laser dye resist method incorporating further testing, such as dye exhaustion, colour data and ISO colour fastness testing to determine the effect of laser irradiation on the surface and dyeing properties of linen.

11.3.2 Further Work for Issues of Sustainability

For further articulation of the sustainability profile of the *Laser Textile Design* techniques, further work lies in examining Life Cycle Assessment of laser textile processing as a proposed tool for textile production. Efficiency savings offered by the laser processes could be further quantified in comparison to a range of equivalent processing techniques, including dyeing procedures and digital and analogue printing processes, in relation to water, dye, chemical and energy savings.

In addition, the impacts outside of the manufacture, finishing and application phases of textile processing could be examined. For example, the benefits that digital *Laser Textile Design* may offer for the use, re-use, recycling and end of life phases could be investigated, with specific relevance to circularity within a textile lifecycle. Work in this area could further the discussion on advantages for mono-material processing, upcycling and customer customisation.

11.3.3 Laser Equipment and Technology Transfer

Further work towards commercialisation of the laser techniques developed in this research would require the provision of a full commercial picture, including production time, exact amounts of energy consumed and unit costs for product processing on different applications. This commercial market opportunity could be tested though further collaboration with industry, to produce prototype garments and make quantitative comparisons to their existing modes of manufacture.

Research in an optical engineering context could optimise the laser beam characteristics with specific heat distribution profiles for textile processing. The work produced as part of this research has already led to a successful further funding bid for this aim. In addition, alternate laser wavelengths could be investigated to determine the capability to replicate the infrared laser irradiation techniques described in this research. The potential for irradiation in the ultra violet spectrum to reduce thermal fibre damage may present advantages over the CO_2 laser.

Investigation into alternate dye application methods could enhance the accuracy of dye delivery for peri-dyeing. A flying head, a nozzle or automated spraying device on a three-dimensional axis could be tested, similar to those used in automotive manufacture, to maintain the non-contact processing benefits. This would further boost the efficiency of dye and water consumption, delivering only the amounts required for effective dye fixation, and may eliminate requirement of a reduction clear process. Alternate dye carriers such as pastes, gels or solvents could also be investigated.

This research has proposed on-demand laser processing opportunities. Peri-dyeing on three-dimensional garments confirmed the capability of the laser textile techniques to be applied through a direct-to-garment approach. This mode of surface design application has potential to be developed into a digital *Laser Textile Design* service model relevant to on-demand, rapid prototyping or practitioner production contexts. This provides an avenue for further work into the development of an on demand laser processing service with possible co-creation and customisation opportunities. Further testing could identify the necessary requirements for a digital interface. Collaboration with service design specialists and software developers may facilitate development of an accessible, user friendly, non-specialist interface that would be relevant for textile designers and practitioners from amateur to professional.

11.4 Afterword

Integrating digital practice within the textile design discipline, combined with increased knowledge of the specialist scientific and technical aspects of emerging technologies, may allow designers to engage fully with new processes, and develop new approaches to textile design to drive innovation in the field.

In the view of the author, the *Laser Textile Design* techniques developed in this research can make a valuable contribution to the design and manufacture of textiles. The research has shown that creative engagement with digital laser processes has produced brand new aesthetic possibilities, grown out of a craft textile practice. But more than the aesthetic value, feedback from industry and discussion in this thesis has articulated advantages for: manufacture; designers; appropriate contexts for application of the techniques; and proposals for efficient, on demand garment processing systems to support improvements in the sustainability of textile design.

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APPENDICIES

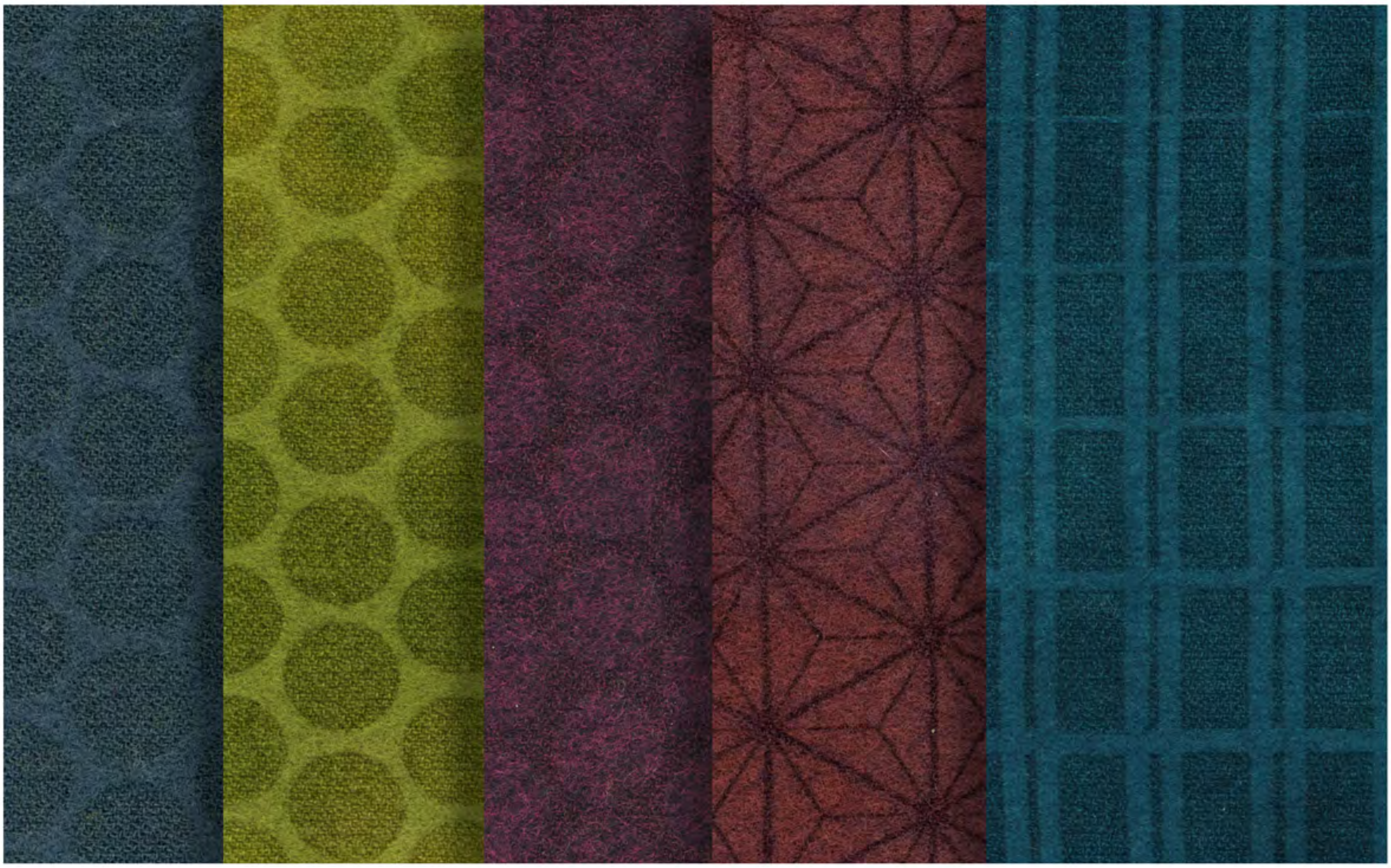
Appendix 1 Design Samples

The following pages present a portfolio of the design samples created as part of this research. All samples were creating using the *Laser Textile Design* techniques developed in this research.

LASER ENHANCED DYEING OF WOOL AND WOOL BLEND TEXTILES

A novel laser technique developed from the current research uses the laser to modify the surface of woollen textiles, increasing dye affinity. The process removes microscopic scales from the wool fibre surface, resulting in an enhanced dye performance in the laser-treated areas. Targeted designs can be laser marked on the surface of the cloth making use of differential dye uptake to achieve multi-tonal surface design on wool and multicolour surface design on wool blends.

It was demonstrated that the laser pre-treated wool can be dyed at a reduced temperature and time, saving water and energy as well as combining coloration and patterning in one process. During coloration, the potential for an estimated 54% reduction of energy was displayed. Textile performance tests show that high fastness to washing and rubbing was achieved to meet current industry and consumer standards. Laser engraving can also remove the felted or brushed surface fibres of milled wool, to reveal the underlying woven structure. This can provide three-dimensional relief surfaces in parallel with the multi-tonal design effects.

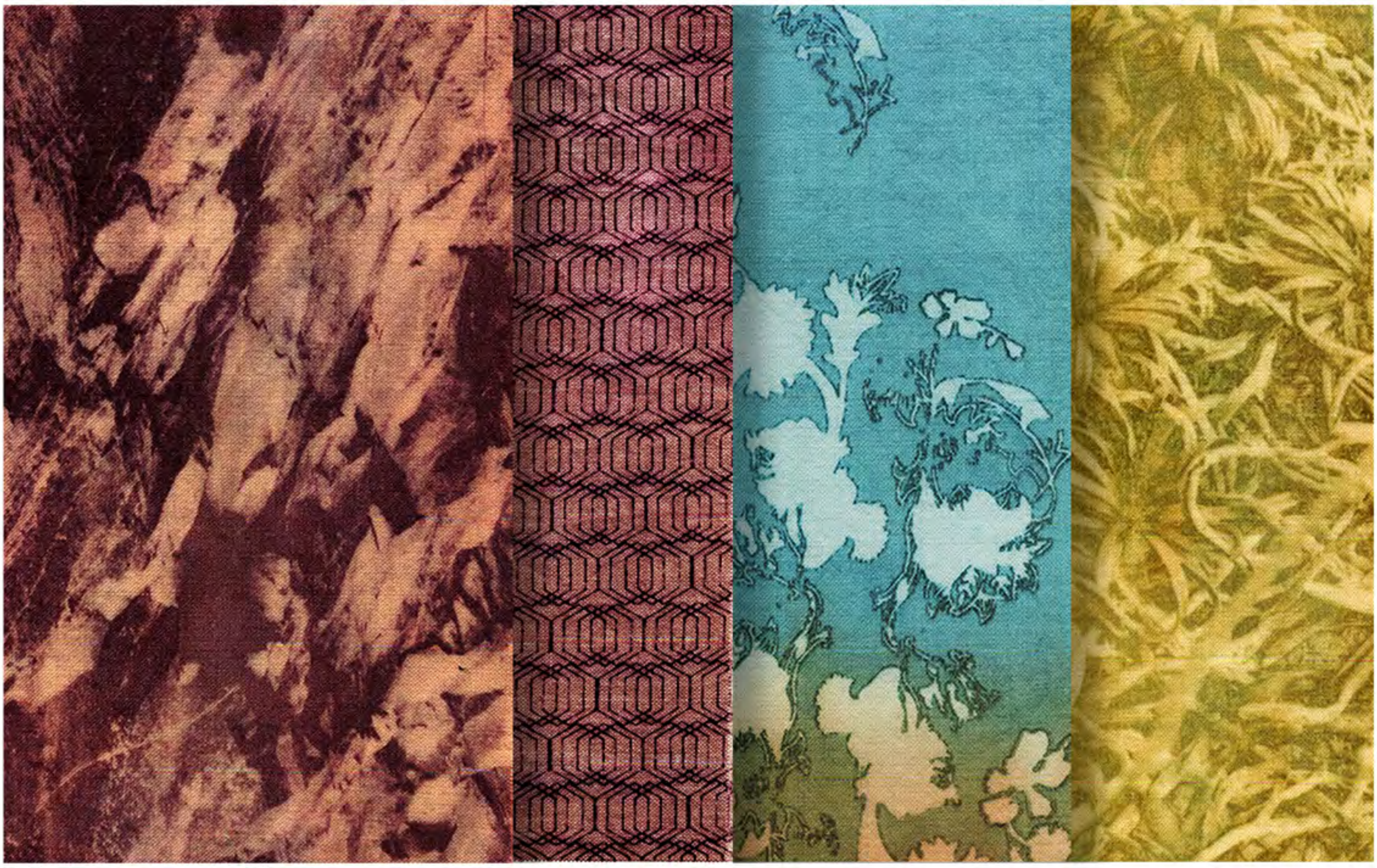


LASER ENHANCED, DYED AND ENGRAVED WOOL SAMPLES

PERI DYEING

This laser based dyeing technique allows intricate targeted surface design of textile substrates. In this technique, the dye diffusion and reaction takes place at the point of interaction between the laser and textile material. Photographic quality graphics, and multicoloured surface design effects can be achieved on both natural and synthetic fabrics. The non-contact laser set up allows precision detail to be achieved on high-texture fabrics. Peri-dying enables digital design innovation, direct to garment processing and customisation in the manufacture of finished textile goods with sustainability benefits through reduced energy, water and chemical consumption.

PERI-DYED SAMPLES

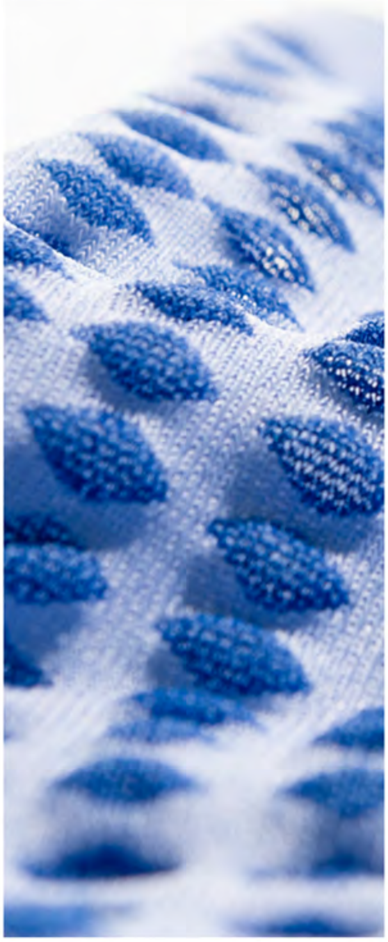


PERI-DYED SAMPLES

LASER MOULDING

A technique using the photothermal properties of the CO_2 laser has been developed, allowing three-dimensional moulding of synthetic textiles. This technique allows designs to be ‘set’ on synthetic fabrics using the laser, resulting in three-dimensional forms on the surface of the cloth. The moulding technique can be used to design accurate surface architectures providing potential for engineered functionality and three-dimensional design features for textile product applications.

The laser does not require moulds or complicated loom set up to produce three-dimensional forms and offers ease of pattern change through digital generation of designs. Laser technology offers dry processing, without requirement for additional materials. The method allows decoration and functionality to emerge from the structure of the cloth without contaminating the mono-material fibres. The use of synthetic mono materials may provide additional sustainability benefits for ease of recycling at end of life.



LASER MOULDED SAMPLES

LASER FADING LINEN

A novel laser marking and fading technique uses laser precision to apply subtle designs on natural linen. As a completely dry process, this technique can be used as an alternative to printing methods for patterning linen without the need for water, printing pastes or chemicals.

LASER FADED LINEN SAMPLES

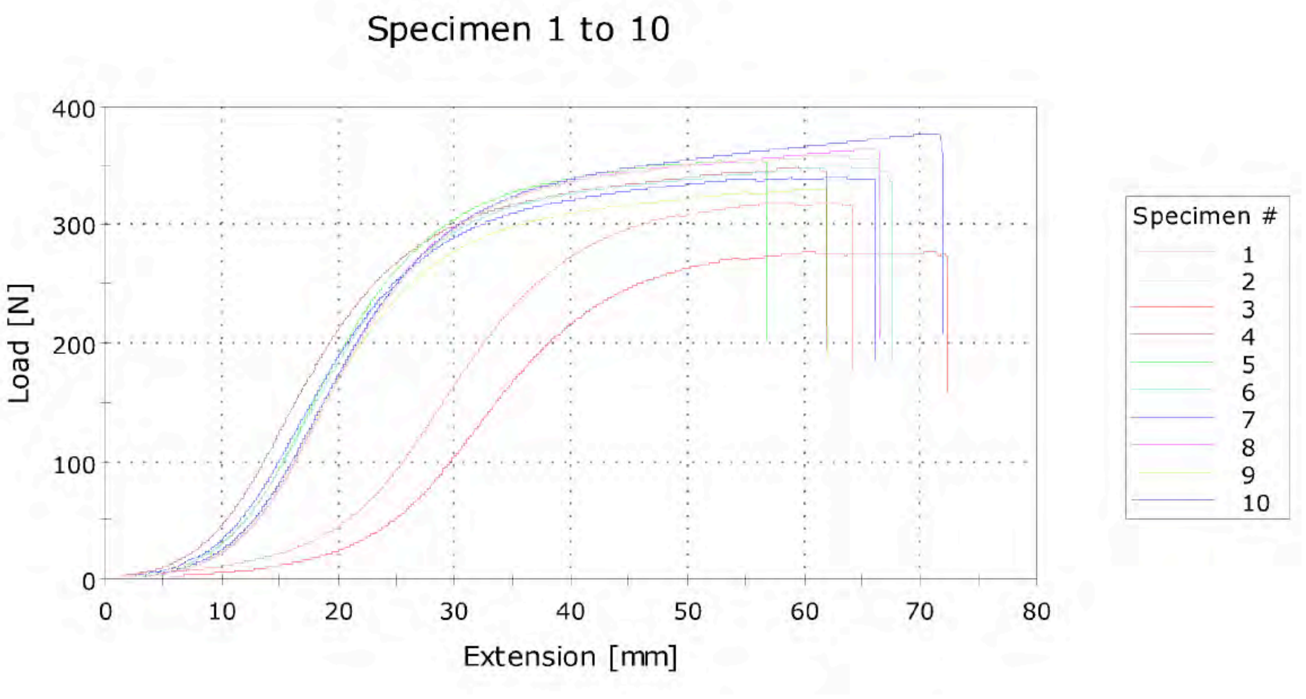
Appendix 2 Experimental Data: Technical Testing

Wool: Untreated/ control

ISO 13934-1:1999(E) DETERMINATION OF MAXIMUM FORCE AND ELONGATION AT MAXIMUM FORCE USING THE STRIP METHOD

Gauge Length	200. mm
Rate 1	100.00000 mm/min
Preload	True
Rate	10.00000 mm/min
Number of specimens in sample	10
State of Test Specimens	ex. conditioned or wet
Width	50.00000 mm
Any deviations from the procedure?	No

Tested specimens: 10



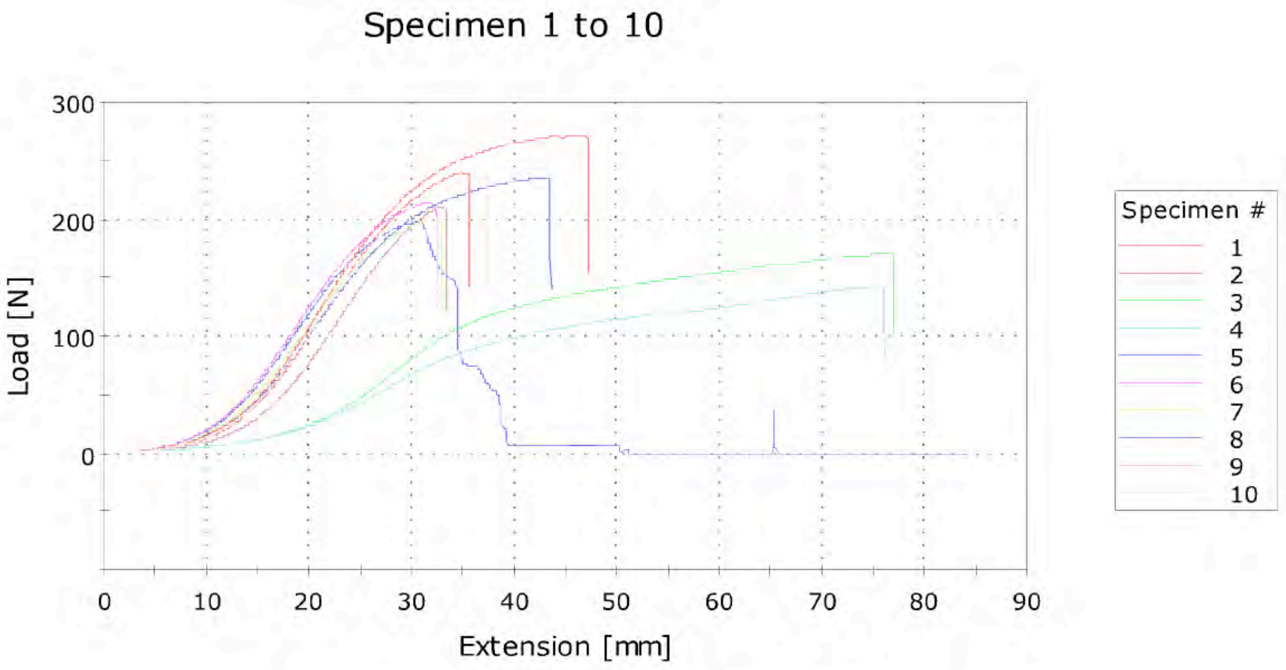
	Load at Break (Standard) [N]	Tensile strain (Extension) at Break (Standard) [%]	Maximum Load [N]	Tensile strain (Extension) at Maximum Load [%]
1	316.09	31.16	318.00	28.32
2	356.54	31.25	359.22	29.28
3	274.38	32.43	277.73	26.98
4	345.69	30.10	348.72	28.94
5	353.52	26.85	354.76	26.80
6	337.24	32.21	350.30	30.50
7	339.62	31.54	340.54	30.40
8	362.94	31.04	364.28	30.99
9	329.81	29.00	330.49	28.97
10	374.47	33.99	377.09	33.63
Mean	339.03	30.96	342.11	29.48
Standard deviation	28.25	1.97	28.17	2.02
Coefficient of variation	8.33	6.36	8.23	6.86

Wool: Pre-treated/washed

ISO 13934-1:1999(E) DETERMINATION OF MAXIMUM FORCE AND ELONGATION AT MAXIMUM FORCE USING THE STRIP METHOD

Gauge Length	200. mm
Rate 1	100.00000 mm/min
Preload	True
Rate	10.00000 mm/min
Number of specimens in sample	10
State of Test Specimens	ex. conditioned or wet
Width	50.00000 mm
Any deviations from the procedure?	Samples 3, 4 and 5 failed to cease elongation after the break point, providing anomalous results. Therefore, Samples 3, 4 and 5 have been omitted from the results table.

Tested specimens: 10



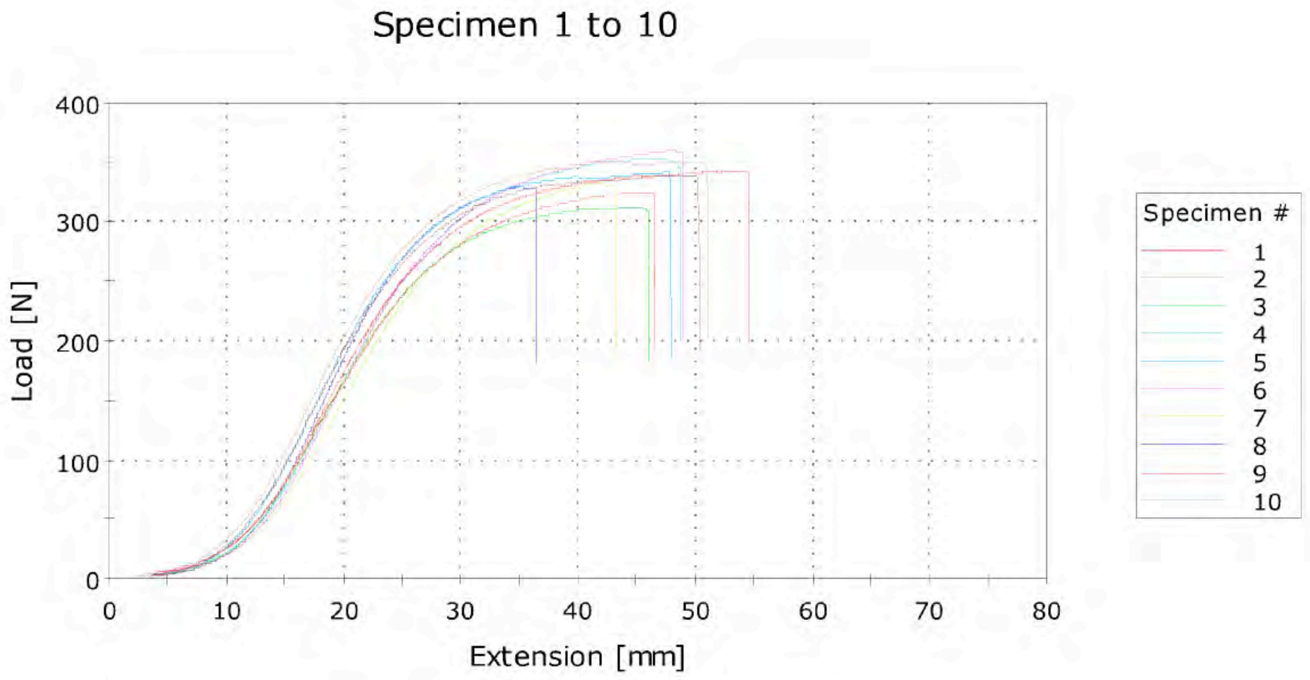
	Load at Break (Standard) [N]	Tensile strain (Extension) at Break (Standard) [%]	Maximum Load [N]	Tensile strain (Extension) at Maximum Load [%]
1	239.29	17.95	240.28	17.68
2	207.72	14.56	210.11	14.46
6	211.09	16.02	213.69	15.82
7	197.70	16.1	199.10	15.84
8	234.29	19.76	235.78	19.55
9	269.94	20.87	271.41	19.75
10	236.74	18.77	237.52	18.64
Mean	228.11	17.72	229.70	17.39
Standard deviation	24.55	2.26	24.24	2.05
Coefficient of variation	10.76	12.77	10.55	11.82

Wool: Peri

ISO 13934-1:1999(E) DETERMINATION OF MAXIMUM FORCE AND ELONGATION AT MAXIMUM FORCE USING THE STRIP METHOD

Gauge Length	200. mm
Rate 1	100.00000 mm/min
Preload	True
Rate	10.00000 mm/min
Number of specimens in sample	10
State of Test Specimens	ex. conditioned or wet
Width	50.00000 mm
Any deviations from the procedure?	No

Tested specimens: 10



	Load at Break (Standard) [N]	Tensile strain (Extension) at Break (Standard) [%]	Maximum Load [N]	Tensile strain (Extension) at Maximum Load [%]
1	321.69	21.85	323.57	21.29
2	339.09	23.19	340.04	22.99
3	316.89	20.99	321.34	20.78
4	346.01	22.47	353.92	21.13
5	337.64	21.87	340.42	21.31
6	359.16	22.23	360.29	21.94
7	329.27	21.63	333.04	21.16
8	328.44	18.58	330.11	17.99
9	341.99	25.34	342.83	25.29
10	345.9	24.08	351.37	20.52
Mean	336.61	22.22	339.69	21.44
Standard deviation	12.70	1.81	12.94	1.85
Coefficient of variation	3.77	8.16	3.81	8.64

Appendix 3 Focus Group Data

Moderator's Guide				
Date: 11/03/15	Moderator: Laura Morgan, LEBIOTEX Focus Group: Contract Interior Manufacturer	Total: 2 hrs 0 minutes		
Topic	Description	Aids	Duration	Start
Pre-Meeting Drinks	Refreshments, Greet participants.		10	13.30
Introduction	- Objectives of the project, structure of session, practicalities. - Explain mood boards and layout samples	Mood Boards	5	13.40
Visual Evaluation of Samples	Please take a moment to have a look at the samples and feel free to chat about them, I would like to hear your initial reactions, then I will ask you some more specific questions.	Sample Collection	10	13.45
Warm Up Discussion	- Consider what is most important for a successful design collection? - Assign scribe to write key words on chart - Which attributes are present in this collection? Missing? - If not already covered: What has been successful in terms of the following: Range, Aesthetic, Colour, Emotional Response.	Flip chart and pens	15	13.55
Discussion of contexts for fabric use	- Consider the commercial context, how and where these samples could be used? - From the individual qualities mentioned earlier; what is the appropriate context for the Colour, Pattern, Texture, Weight?		15	14.10
Ranking Activity	Keeping these attributes and contexts in mind, please can you use each of the coloured stickers to rank the most successful samples in the collection.	Coloured Stickers	5	14.25
Discussion of Design Techniques	- What methods/ processes do you currently use to achieve colour, surface effects and pattern? - What restrictions? What up and downsides? - Are there any effects here that you cannot produce currently? - Customer demand for techniques/effects? - Volume of dyed goods /patterned jacquards/ print/ other techniques per year?	Flip Chart and pens	15	14.30
Explanation of techniques	- Discuss laser techniques: linen fading, laser engraving, peri-dyeing. - Advantages: Combines dye, patterning, digital, non contact.	Laser treated samples	5	14.45
Discussion of laser techniques	- If you had access to techniques, how would you use them? - What desirable attributes you would like to gain? - Seek comment on: Fine linear detail/ photographic detail/ differential milling - Relevance of the techniques used: is there a demand for the design qualities achievable?		15	14.50
Sustain -ability	Advantages: water and dye reduction, low energy, digital.		5	15.05
Discussion of Sustain -ability	- Importance of sustainability to the company? - Comment on sustainability of the techniques/ importance in your role as a designer/ would it effect your design decisions? - Importance of saving energy, dye stuff, effluent and process?		15	15.10
Feedback discussion	Encourage final comments, conclusion and close.	Consent form	5	15.25
Key:	• Moderator presentation • Steering question	• General discussion point • Group activity	• Topic key question	

Focus Group 1: Contract Interiors. Coded Themed Transcript

Participants:
GB: director of technical projects
CC: creative design and development manager
FK: director of design
S: technical development
R: designer
LM: Researcher (Moderator)

1st themed into topic headings: Laser enhanced dyed and engraved wool; Peri-dyeing; General comments on the design collection; Sustainability
2nd coded into type of response: Aesthetic, Application, Suggestions, Concerns, Advantages, Company insights
3rd coded thematically: based on what key areas of analysis for this research:
Considerations and advantages for manufacture (economic/ practical / alternatives to tradition)
Considerations and advantages for design (aesthetic / tactile/ emotional response)
Considerations and advantages for sustainability (materials/processing/ systems)
Considerations and advantages for application (function/performance)

Discussion Topic	Responses to Design Samples/ Collection	Concerns	Suggestions	Technique Advantages	Applications
Dyed and Laser engraved milled wool samples	Colour: Unlevel dyeing: lovely quality both interesting in different ways, some people like a more subtle effect 3D milled wool- fantastic effect beauty Gorgeous, looks fantastic on milled fabric Abstract Feather pattern: looks so soft and distressed and looks like, is it just like a line coming and going. I like, that you can't really see what it is, a distressed pattern.	controllable? can be repeated? It's going to wear that surface away and the design will disappear, We'd just have to worry technically whether the surface fibre would wear away and therefore the design would wear away.	Could be abrasion tested Feather pattern engraved Blazer: my number one if it was dyed.	Offers 2 tone interest, or more subtle effect Dyed afterwards: pattern will remain due to enhanced dye colour. A more blurred pattern would show less obvious wear. Feather engraved pattern on Blazer) Going to fade more gracefully than some of the geometrics Couldn't achieve that 3D effect on any of our machines through weaving or anything really	Definitely soft seating with some of these on the Blazer effects ones. These would be good wall coverings - wouldn't have to worry about the pile wearing away Range of applications depending on abrasion performance.

Linen	interesting More interesting with the effects than the plain cloth		It would be lovely to see effect on Camira's wool warp/ flax weft fabric (flax). Could fade flax and enhance dyeing on the wool. Would be interesting to have both effects going on within one fabric.	Fading pattern has changed it from original I can't tell what fabric it was originally	
Peri	Fine lines Fine quality of image on the finer fabrics. Fractured Triangle on aquarius: has all the factors that make a successful collection. Non-directional small pattern. Colour would be easily used in most places. The fabric is a suitable upholstery weight (peri-dyed on their upholstery fabrics). This sort of thing (successful) in terms of trends, I've seen a lot of this (picks up abstract tree canopy photographic peri-dyed sample) you know almost faded, aged, worn, distressed. Patterns that are a little more abstract? Yeah, like this one (points to rock and moss photographic) you could have a more faded out colour on the panel, and a darker more	We don't do fabrics as fine as that, but we could do Multi colour: Is that a two stage process? And does that take twice as long as the one colour? Is the dye stuff fixed? Do you have to steam it or something to finish it?	Currently take twice as long on a lab scale. Developing the technique to target dye colour with a printing nozzle would allow colour to be applied in a targeted manner. (oh yeah, that would be clever.) ammonia wash on wool- a form of reduction clear. Technical testing techniques prior to design collection, dye uptake, dye fixation, wash and rub fastness and tensile strength, tear testing. so the process is	based on jpeg or flat images so could use a photograph or anything fine lines and quality of the image we are incapable of creating anything as sophisticated as that anyway, whether by jacquard or anything LM: and what about the more detailed effects like the fine linear patterns and perhaps the more photographic imagery. Do you see that having a commercial application? GB: Interested in anything that you can't weave, because if it's finer than weaving it brings in a new appearance, so photographs would be interesting. Photographic effects and very fine linear or detailed patterns can't be achieved as easily using trad techniques-customers might be interested in. So obviously with the jacquard we are limited generally by the width. The repeating width kind of repeats three times generally across a 144cm wide piece of fabric. So to have something similar to that print there, where it is a full width	Upholstery on upholstery weight fabrics. Any sort of pods or panels. Would be a nice panel design. Fine linear pattern onto Oxygen: Something like that would work well, because you could have a more faded out colour on the panel, and a darker more saturated colour, you know the same

	saturated colour, you know the same kind of colour but with more depth on the upholstery. Opportunities for multicoloured effects: Two colour design: (Turquoise colour first then the purple colour)- That's really nice that. Yeah it is. fineness.		optimised to meet testing standards and to ensure the peri-dyeing process is not a damaging to fabric. Even though it is a thermal process, the heat is absorbed by the water based dye liquor and therefore is not burning the wool fibres. GB: It'll not get passed the boil will it? and you can boil wool for a long time.	repeat, something where you would not be limited in that way would be interesting. Fineness: We couldn't weave that fine. To get a fine looking jacquard fine yarns are needed, not suitable for upholstery. If we could still use coarse yarns and get fine looking patterns and effects then that would be something that we can't do with our looms . non-contact, can process very textured or relief surfaces over three dimensional shapes or seams, unlike normal printing methods that require flat surfaces. The possibility of printing in a specific pattern piece shape is there, reducing the problem of waste in pattern cutting.	kind of colour but with more depth on the upholstery.
General Collection	very impressed Gorgeous They are all good in different ways , 3 different sectors. very elegant colours. aren't all the exact colours that we would normally sell, but they are colours that would sell. In terms of volume it's the darker colours which would sell the most. That greeny colour, the lilac's there isn't it, that duck egg's there, certainly they are	how long does it take to do one sample? how fast did you say it went Is it using the same laser or do you have to change? Wouldn't the laser degrade the yarn? As digital print becomes cheaper it's going to become more popular, so that's the driver of it for us- at £10 a meter		Anything that you can't weave, we are interested in,	

	all there in fact. It's covering a lot of (the same colours as they have chosen). So that's really good. Considering that we've worked on these independently and they are coming together so well. actually they sit really nicely together (My collection & their fabric moodboard)	minimum to digitally print, it's hard to sell a lot of that. Non directional pattern- reduce pattern cutting waste			
Sustainab- ility	Yes interested- core to company- starting point Product development- yes important Daily design decisions not so much	Saving water energy on agenda for sustainability and company growth. How much saving/ cost for set up?	Effects on other bast/ hemp fabrics? LCA	Reduced waste pattern cutting (with non-directional ptns) Longevity- if wear results in interesting desirable 'new' pattern. Increasing desirability of wool/ natural fabrics.	

Contract Interior Manufacturer Coded Transcript Table

Type of Response	Responses to Design Collection 33	Concerns 15	Suggestions 10	Technique Advantages 19	Applications 7
Topic	Milled Samples 20	Linen 5	Peri 33	General Collection 16	Sustainability 10
Themes: Considerations/ advantages for:	Manufacture 25	Design 32	Sustainability 12	Application 22	
Additional recurring themes (sub-themes)	Precision / Fineness				11
	Abrasion				9
	Can't achieve on conventional textile machinery				6
	Colour				11
	Commercial fit				8
	Pattern				15
	Speed				4
	Other				24
Total responses 84					

Number of Occurrances of each Theme

Moderator's Guide				
Date: 28/04/15	Moderator: Laura Morgan Focus Group: Performance Swimwear Brand	Total Max : 2 hrs 0 minutes		
Topic	Description	Aids	Duration	Start
Pre-Meeting	Refreshments, Greet participants.		5	13.00
Introduction	- Objectives of the project, structure of session, practicalities. - Explain new process and layout samples.	Technical Samples	5	13.05
Visual Evaluation of Samples, and warm up Discussion	Please take a moment to have a look at the samples and chat about them, I would like to hear your initial reactions, or any ideas on the application of three-dimensional textiles. This can be as broad, blue sky as you wish. Then as we go along, I will ask some more specific questions.	Laser Moulded Sample Collection	15	13.10
Discussion of contexts for fabric use	- Still considering the uses of 3D textiles: - Assign scribe to write key words on chart - How could 3D/ relief properties be used? - How could this technique be useful in your design process? - If not already covered: What shapes and patterns do you think might lend interesting properties? - Shapes/ patterns to aid swimmers path through water; - Moulding that allows for body shape, e.g. areas of differing tension/rigidity; - Placement on body of moulded channels/ texture. - Any other requirements for 3D/relief effects in swimwear?	Flip chart and pens Any books/ info from company library	20	13.25
Discussion of contexts for fabric use	Looking at the list we have made, I would like to discuss how I might take this further and discuss specifically: - What shapes, patterns and placements should be used to achieve the ideas we have discussed? - What are the most important attributes?		20	13.45
Discussion of Texture	Group to display any 3D/ relief/ differing texture examples. - Discuss desired benefits and functional advantages.	Company Samples	5	14.05
Discussion of Relief / Tension/ Texture Techniques	- What methods/ processes do you currently use to achieve textured pattern? Tension, rigidity etc? - What restrictions? What up and downsides? - Are there any effects that you cannot produce currently? - Customer/ technical demand for techniques/effects? - Volume of these techniques per year? - Note sustainability of dry process. Seek comment?		10	14.10
Introduction of Peri-Dyeing technique.	- Discuss peri-dyeing laser technique: - Advantages: Combines dyeing and patterning, digital, non-contact. Potential for combination of techniques. - Sustainability: Water, dye and energy reduction.	Laser treated samples	5	14.20
Discussion of laser techniques	- If you had access to techniques, how would they be useful? - What desirable attributes you would like to gain? - Seek comment on: linear /photographic/ 3D detail - Relevance of the techniques used: is there a demand for the design qualities achievable?		15	14.25
Feedback discussion	Encourage final comments, conclusion and close.	Consent form	5 End	14.40 14.45
Key:	• Moderator presentation • Steering question	• General discussion point • Group activity	• Topic key question	

Focus Group 2: Performance Swimwear. Coded Themed Transcript

Participants:			
	DR: Materials innovation manager	MA: Materials technician	AB: Industrial designer (Applied Innovation Designer)
	RB: Research Manager	RW: Innovation Manager	LM: Researcher (Moderator)

1st **themed into topic headings**: Moulding, Peri Dyeing, Hydrophobia, Direct to Garment Printing, Laser Processing
2nd **coded into type of response**: Aesthetic, Application, Suggestions, Concerns, Advantages, Company insights
3rd **coded thematically:** based on key areas of analysis for this research:
Considerations and advantages for manufacture (economic/ practical / alternatives to tradition)
Considerations and advantages for design (aesthetic / tactile/ emotional response)
Considerations and advantages for sustainability (materials/processing/ systems)
Considerations and advantages for application (function/performance)

Discussion Topic	Responses to Design Samples/ Collection	Concerns	Suggestions	Technique Advantages	Applications
Moulding	Changing/ opening the knit a little bit slightly more transparent any sort of visible surface roughness has a lust factor I like some of the textures - can't really replicate them. Especially (hex). unique, 3D features; raised in all	durability tests? If you stretch the fabric 100 times would it retain 3D shape? Can you do it on a Nano scale this? (yes) interesting when you strain it becomes flatter. So bearing in mind when you put the swimsuit on it stretches you might loose 3d features. How to ensure the effect when you are wearing, stretching round the body, Would be really good. my biggest issue with garments is that they are	how the moulding affects the durability of the fabrics, repeated stretching It might be that thicker, stronger fabrics need to be used to increase tensile strength, to make sure that stability is retained even after stretching. reconfigure the properties of the yarn down to the Nano scale. micro scale is enough. They use it in other industries like micro-riblets to help streamline flow. if people can see the technology they almost believe it a lot more instead of adding something, you can take something away, etching or changing the surface properties/ physical properties of localised area. Complex graduated compression across different points. pleating or gathering effects	not restricted unlike other types of printing techniques, Like flocking, adding flocking or something for extra compression Reductive technique: Which you just can't do with other techniques. That's quite difficult to replicate. Jacquard? A bit like a devoré. It's lighter, reverse of a jacquard. I can't see how you would do that otherwise. From aesthetic point of view, imagine	Utilising the three dimensional aspect & relief aspects on a garment or suit. Like the sharkskin dentiricals or targeted areas of compression. Micro-riblets to help streamline flow. Change properties for surface roughness to it, but has to be non-random roughness: streamlined, put technology on the inside to give them perception feeling something. Like dimple effect it doesn't have to be visual on the outside, it's about tactile feedback that they get. More commercial than technical end of the scale. Add rouching to hide, areas for people who are self conscious about their body in a swimsuit. I've heard that mentioned before: ruffles to hide spare

	dimensions. also about the internal bit of it. The feel, of a raised profile, does it feel different to consumer when they put it on so they almost have that control? It's like flocking more flattering and appealing -gives more confidence, when working out -not on show. with swimming, you are really exposed? Something off the body could appeal in one way, but when it is on it has a different feel. 3D form, looks great as a visual thing aesthetic and functional can be both/ or be implicitly linked. Just aesthetic is	2D and that there is no shape so when on there are different residual stresses depending on the shape of the body would you need to make sure that when it is straight that the fabric is not all crinkly, unless that's the effect you want. Aesthetic and function: holds more weight; more powerful if reason for it. Kind of belittling the effect if it is just another aesthetic. 1st principle to prove that it's not bunching here, and not baggy there, that articulation is a massive issue in comfort for most close fitting garments I should think in some degree, so that could be really exciting. a guidance system: could we do this on a material that is more elastic, or more rigid? on a larger scale you are setting the chosen physical properties as a whole, how much do physical properties change with different designs	it could possibly open up a new design feature Designing what you want it to look like on the person interesting concept to have dual identity origami techniques, folding, layering, complex configurations so when stretched it unfolds and unpacks. That could be a great dimension to consider with laser precision. How could you combine shrinking certain aspects and enlarging others to make self packaged aspects garment- shaping or movement or articulation. try to fit something around a 3D shape. Simple shape: a sphere, something that would almost replicate a shoulder make a tube and fit it over an elbow, so you could do a technique that would measure the strain dynamically, show how the material is straining, or with elbow bent and straight and the benefit of that for fit and comfort. making a full garment 3D formed, that starts really, basic amending it to suit the movement, rather than it just being aesthetic, it's functional. making the functional aspects aesthetic as well. more or less elastic to create structures like power bands, or energy storage, maybe you can start to influence or support movement. kinesiology tape pulls when you are aligned properly, compression: two different ways. In some of our elite stuff – a higher tighter construction add more elastane to give stretch and recovery and snap back, or similar to the Thera bands, where you are almost locking something out. This laser moulding is more like that; could you get extra compression or sensorial feedback. A technical suit, that when you don't feel the resistance you have got the right technique. Starting high compression material and use laser to relax or take	sculpturing where you can add visual features without adding more material. It's got to be aesthetic, it got to be pleasing, not just functional, it looks good and I feel good in it. Interesting concept to have dual identity you've got the control to have both aesthetic and function at once traditional fabrics operate very much on an x and y. It's horizontal or it's vertical. It's hard to get so much of a distinguished difference on a set curve around a body, so it offers a whole dimension of engineering. Finished in a garment Breatability/ insulation would give a massive commercial potential. More customisable… customisable, instead of sewing airtex,	tyres. So anything that could give you that confidence would definitely be of interest. Garment- shaping or movement or articulation. 3D form absolutely awesome. Addidas tech fit stuff, where they have those bands stretch and recovery and snap back sensorial feedback Thera bands power bands kinesiology tape manipulate movement, so it is easier to do that (moves arm in one direction) than do that (moves arm in opposite direction) to help in training. Shoes and gloves like fly knit on shoes, this could be a really amazing texture for Lacoste or something like that. Or potentially thermal properties for Berghaus? Looking at these little bubbles of air. Well even if it's under strain if you look at that there's going to be able to be more air able to flow through here where it has been laser treated, than were it has not.

	fine. functional does not always look great, depending where on the product. Better to have both. That'd be cool, really cool. (gradient moulding) localised decorative element would like to see that. excited about these affect fabric drape. Almost like an origami fold, because of the shape, different property on the laser treated pattern than where there is a lot more room to give. Geometry a really interesting	different compression zones, but it is very complicated it's very expensive What's the thickest Material that you could do? It works on synthetic fabrics, on cotton you would not be able to heat set it to retain or hold the shapes. You can knit those kinds of structures into fabrics. is this quicker or cheaper interesting from a performance point of view because we are so restricted on placing or printing anything onto that fabric. in order to get more compression they've just added a PU panel, which has affected the air permeability of the fabric, but is there a way around that? looses stretch when set? probably too far away from commercial at this point.	some of the compression away in areas Enough compression your arm would snap back with a force when stretched, techfit bands that are very rigid versus areas that are elastic, can you replicate that with this technique maybe? materials layered: laser only interested in top layer won't affect underneath Have you looked at different levels of stretching? do get a gradual effect. on a 2D fabric aiming to get it uniform. But on this you could actually dictate different stretch modulus zones. use a fabric that was more withstanding, designed to be heat set realise what application is then change the fabric accordingly. Keep system the same but get different response by changing fabric. Different performance/ reponse from same design, on different fabrics- That could also help us differentiate: generate properties as you wish, using laser manipulate it down to whatever you want. Bespoke fabrics would be really interesting. two processes? change the fabric properties. on shorts, on panel you could have a dimple effect on the fabric then mould if you started with a really thick material and got it back to a material thickness that we use now. take two real short-term scenarios, like the fit around the elbow, that would be one with an aesthetic and a functional benefit. **2D to 3D** add some 3D qualities of a print, so it starts to come out. Instead of just doing a print in 2D parts could become three dimensional in areas. **GEOMETRY** using different patterns to get change stretch properties interesting: might be a relationship between the shapes used to the tensile property. On any scale. One area hexagonal, to give	mesh underarm modify one pattern piece to have breathable properties in a targeted area. From a decorative point of view: embellishment coming from the fabric, rather than sewn on top of it. Sustainability benefit from sticking to one material for recyclability. Exactly, you are not adding layers on, it's all on the same fabric using the cutting and moulding together in the garment If you can sandwich air then you are going to get insulative properties potential to mix the aesthetic with the technical. Or to gain a specific aesthetic out of the technical. If you could take what was five components and make them one component, that's massively beneficial.	Panels of breathable material when istretched. Make breathable properties, on the other hand almost string vest effect, for insulating pockets of air. Could laser be used for shaping aspects or engineering functionality? You know you can't have anything that closes the holes up. With the laser process you are not doing that, even though you might be restricting the stretch, you are not adding or restricting the openness or breathability of the fabric. A rip lock, where they lock air out, stick electronics in here. If you have a board, at the minute, how do you create a pocket –you end up with a fold or something, but if you had a whole pattern of bulges, it could hide it completely. It's almost the perfect height for that. You could laminate two together assemble components, laminate then when stretched it would be perfectly formed so it holds itself in place fabric bubble wrap. User interface interesting Buttons Tactile button all sort of build in; it's quite nice. Insulative: for recovery and heating post-swim or pre-swim

	aspect feels like lace translucent quality almost a seersucker effect. Which is quite difficult to control in manufacture llike disguise/ camouflage	Do the effect on any non-woven, non-knit stretchy membrane need to be careful with the elastane. Look at how that is affected. direct comparison between the polyester PBT, and nylon elastane. Will it melt/ negatively affect the elastane, mechanical stretch properties?. Nano, or micro, it's always a compromise of whether you want to show the technology or not?	property X, and oval shape is going to give Y, adding function Nano; achieve performance gain on micro scale where you can't see it, eg. squiggles might make it springy, because the shape influences properties. It could still stretch how does scale-ability and geometry or design influence output performance? By the geometry of the design you could actually influence the physical parameters. Computational analysis to work out lots of mechanical shapes that give you stretch properties based on the geometry. A spring. Different properties based on the shape. Geometry looking at the shapes and patterns to see their relationship between tensile properties- would certain shapes correlation be more prone to different amounts of stretch like a 1A, 1B.		elite fabric: map out the ligament in a body and map them to change the tensile properties and change the properties in different ways. If a pattern like the yellow squiggle on the shorts, was found to be good for aiding stretch, then that could almost determine where about you are going to put pattern on the body. Also if those kinds of textures stimulate the surface of the skin, when applied and aids the flow of blood to the skin surface, all those things that you don't even consider. Some of those micro-textures might have benefits. And then big cat on a t-shirt. Don't forget the Connect 4 t-shirt.

Discussion Topic	Responses to Design Collection	Concerns	Suggestions	Technique Advantages	Applications
Peri Dyeing	It is pretty impressive isn't it? To be able to get this print without? It's amazing, incredible. The ability with the laser to control where you are putting colour. It's quite	Have you been able to achieve brighter colours, as these are duller colours does it retain same physical material properties? Does it cause damage? If you put elastane is there a temperature limit? Would it degrade elastane. Start niche with customisation: something others can't do, you start to have gain. And then scale it up. Trying to keep a commercial head on it, but not let that be a limiting factor. Grinning, with the white coming through get that on the PBT. What it looks like on, is most important thing. Maybe	how about really bright or fluorescent colours? In an ideal situation we could apply the dye directly from a nozzle, or soak the fabric with a pad and mangle technique we tend to set a tolerance for our testing, a sort of upper and lower modulus of elongation & hope our fabric would sit within a midpoint, we can provide tech sheets, and specification for this fabric as a reference point. You could also print when it's in a strained position obviously the print changes when	Really interesting not printed/ dyed conventionally usually digitally printed, flat bed, digital printer, direct inkjet. Bespoke or the customisable. Imagine you could just put your suit on, and put whatever you want on there, that's going to be the benefit of this. Commodity item, millions of metres getting produced- hard to change the momentum of that kind of huge	that's only one tonal colour, but if you could pick your own colour and do that in your club colours, in your favourite colour…

	interesting that you can do kind of photographic, that precise level of detail. I think the printing is really great, that seems like to kind of short term quick win. I think that it has a certain handwriting of it's own that is absolutely gorgeous. Interesting. Cool different shades nice. We'll have it! Definition.	at point of sale that would be an issue, but actually when wearing it, is when it has to look good. Do we have to consider strain/ stretch when designing print. We don't design it based on its stretch. An issue with the grinning in current digitial printing with certain suppliers, Is there anything in this from an eco point of view? Fit and compression. What's the right amount, how do you design that? How do you grade and modelling it,? If we give you a picture of Alex can you process that? What benefit compared to digital printing? Multicolour: to apply the dye, would you have to remove it, or just put another on top If you had a darker colour, say black, could you put a lighter colour on top? Colours not exactly right application for our us, tend to use brights, lights darks, bright neon might be preferable in a race suit, but picking from a palette and designs and they can have their face etched on to it… But you can get bright colours colourfastness to chlorine tests? Idoes it change colour slightly	you are stretching. Can you get coloured dye that changes colour depending how much heat is applied to it? It's almost like that global hyper colour from the 80's. That would be a great combination of using the heat from the laser to dictate the colour. One dyestuff that goes on but the laser determines because it reacts to the different heat. another dimension, depending how small you could go: print it on the side of a yarn so that when stretched you could almost get another colour or pattern. You could achieve iridescence in that way. If the temperature changed the colours can't process on darker colours: Well that's fine, not a problem. You could just put white panels in it. use brighter dyes, nylon produces very vibrant results. wool samples performed an ammonia wash off, and wash fastness is excellent after that. Combine mould and dye would be interesting.	organisation- wet screen tables set up all 100m long automated, so may have to start niche with this do customisation a lot less water, less energy. Another advantage is combine the dyeing/ printing process in 1 step, instead of bulk dyeing reams of fabric, you can apply targeted colour and pattern to a garment blank, reducing waste. And the advantage is to use less water? Less water, non-contact processing and extremely fine detail that would otherwise not be achievable on this kind of textured woollen surface from conventional methods. Environmental benefits, of water and energy reductions processed remotely, over seams and on finished, blank products Can Create design in 2d or 3d	

Discussion Topic	Responses to Design Collection	Concerns	Suggestions	Technique Advantages	Applications
Hydrophobia	targeted areas of hydrophobia/	under SEM, damaging the	instead of a surface feature can you increase touch or moisture.	control/ limit damage.	turbulent management system: could you

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	hydrophillia on same cloth as required that would be really interesting really interesting with the hydrophobic, hydrophilic extreme polar opposites would be amazing. Brilliant.	fibres, that's how you are opening them It needs to stretch as well. on micro scale if within tolerance would be fine.	You could laser treat all of it. from a performance point of view, a combination between hydrophobic and hydrophilic is better than 1. Different parts that would be extremely hydrophobic, In racing you want areas to be slightly attractive to create a layer. micro or on a Nano scale that would be really interesting. Especially the going from hydrophilic to, hydrophobic, once in an assembly it performs differently from when its in separated parts. test hydrophobic & hydrophilic separately, then combine in different assemblies & get a different response than predicted from individual results. You change the surface qualities with that, because water molecules are quite big, so it would work on micro-scale: you could influence flow properties at that level.	So you've got printing, but now you've got waterproofing and you've got three-dimensional features as well.	achieve an essentially similar effect from having hydrophobic and hydrophilic areas. Its like a gutter, water running down and into channels. Channelling It's a riblet- It's a true riblet! Not just a marketing riblet.

Discussion Topic	Responses to Design Collection	Concerns	Suggestions	Technique Advantages	Applications
Direct to Garment Printing	it's really impressive, lovely if we are looking at moulding combined with dye. interesting to think about. I think this holds a real exciting opportunity about precision. laser combining shaping and colouring, I think those three maybe top level ideas are quite	For customised fit- How do you make that rule to calculate the effect for individual people? Personalised fit: sounds great but would be a massive piece of work. how to move from 2D to 3D. At the	same process changing substrate to give it a shape or a different feature to it. Blanket finish on fabric, then make the garment then secondary production process can quickly programme and change shape of the garment on a mannequin or add surface feature in, or trim the plastisol print separately,	a non-contact set up. As opposed to having to print on a flat bed machine, or worrying about pattern moulds or anything like that. You can work on an already 3D garment. You can work across seams. you can work on finished garments as well, ok. So can you work in garment form as well opportunity about precision customisation when it's on them, they know it will be perfect. Garments usually created using seaming into 3D object. This gives opportunity to actually start using 3D canvas I think that is the key for me; 3D is where I get excited that it can be done. When 3D shapes created from 2D platform you have to hold 3D shape in mind. With Laser you can do it directly onto 3D form -really exciting. Prescision: you could apply someone's name. Bespoke patterning. Whereas you are not going to set up a knitting machine to knit a bespoke image.	you could almost finish it in its useable form, then, when relaxed it doesn't really matter how it looks. you mentioned point of sale, but you will always sell it like that (points to mannequin). Retail is going away from rags on a hanger anyway, and when it's on them, they know it will be perfect. Just imagine you could just walk into a store. If you could go to a stand at an event and say you want that, then watch it being put on, that simplest form at an event or in retail, people could just come in and see it being made right in front of their eyes. a bespoke order that came in & they had all 3D scanned themselves & needed the

	exciting from a material repurposing point of view. Bespoke: would be really exciting Desirable That would be amazing. That's it! That's it for me- on demand/ direct to garment	moment the way that we engineer prints is very 2D and printed flat Is there a maximum size that this can be? Is there a limit?	or do something to make your production line really efficient and standard, and then you add your design flair features as a customisation aspect. customisation If you could make the garment standard and adjust it. The laser could be moved around a garment. mass customisation at the point of sale.	We position customisation on our roadmap. Everyone is looking at customisation; one step further: personalisation straight away. Laser may be simple to adapt to rollers & flatbed, but why not shoot for the 3D automated. That's what your ambition is. If you say Levi's are already doing something with 3D processing we know it exists. you can process over seams and on finished, blank products Instead of being 2D it's 3D… But it's that idea that it's already blank, it's done, it's ready to go. You have your fabric, you add the colour and pattern and then you can cut it out, all in the same process on the same machine. Bespoke one of the main advantages for the peri-dyeing having ability for customisation, e.g bringing in garment blanks rather that pre-ordering dyed or patterned fabrics Wouldn't have palettes that you are restricted to. You can be very reactive to how the trends in fashion are. As long as you can get the whole spectrum and consistency, that would be really exciting, actually give designers the flair to find inspiration quickly turn it into a product or a prototype	size. I may be a medium (don't laugh) and Rob may be a medium but we have different physiologies, different shapes, so could you tailor that performance so that in certain areas localised to give high /lower stretch properties whether you wanted more/ less compression One size fits all but manipulate the size using the laser. that would change things. If you could have one size fits all and then you can manipulate that and you can add that design flair -definitely worth looking at could literally have somewhere to design & do it all in store, w/out having to construct fabric. customisation would be amazing. you need a white blank space that you can then dye bespoke colour test the market & iterate & fail fast, I think that's the key.

Discussion Topic	Responses to Design Samples/ Collection	Concerns	Suggestions	Technique Advantages	Applications
Laser Processing	Sounds good. I think that's an exciting thing. hard this to pick just one, there's so many.	What time frame making these? How quick does the laser scan Any size restrict? How to work on 3D shape? a lot it could do, important to focus on what it does well, not what we need. Ultimately the process has to	adapted to work with rollers or around a 3D shape. With a flying head, moveable head. engineered specific to requirement. technology to work on a 3D garment. Rapid prototyping 3D printing approach.		You can almost see a whole story around laser because you could laser etch onto goggles, caps and you could process the fabric. You could almost have a story that runs through the whole lot.

		have own goals, gold standard achievement has to be quick to use on a larger scale.	bigger laser beam spreads out. process can be done faster		

Performance Swimwear Brand: Coded Transcript Table

Type of Response	Responses to Design Collection 42	Concerns 50	Suggestions 67	Technique Advantages 47	Applications 51
Topic	Moulding 135	Peri 49	Hydrophobia 20	Direct to Garment 41	Laser Processing 12
Themes: Considerations & advantages	Manufacture 80	Design 109	Sustainability 7	Application 91	
Additional recurring Ideas identified	Effect of design/ geometry on moulding properties				16
	Standard material, engineering in properties: for fit/ compression				16
	Designing, manufacturing in 3D form				23
	Customisation, bespoke and personalization opportunities				25
	Colour accuracy				20
	Aesthetic plus function				16
	Insulation/ breathability				8
	Nano/ microscale processing				6
	Durability				15
	Precision/ targeting				14
	Reactive, prototyping, speed				7
	Combining processing effects				19
	Streamlining				12
	Sensorial feedback				14

(total entries: 257)

Number of Occurrences of Each Theme