Textiles in three dimensions: an investigation into processes employing laser technology to form design-led three-dimensional textiles

Textiles in Three Dimensions: An investigation into processes employing laser technology to form design-led three-dimensional textiles

by

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Abstract

This research details an investigation into processes employing laser technology to create design-led three-dimensional textiles. An analysis of historical and contemporary methods for making three-dimensional textiles categorises these as processes that construct a three-dimensional textile, processes that apply or remove material from an existing textile to generate three-dimensionality or processes that form an existing textile into a three-dimensional shape. Techniques used in these processes are a combination of joining, cutting, forming or embellishment.

Laser processing is embedded in textile manufacturing for cutting and marking. This research develops three novel processes:

- *laser-assisted template pleating which offers full design freedom and may be applied to both textile and non-textile materials. The language of origami is used to describe designs and inspire new design.*
- *laser pre-processing of cashmere cloth which facilitates surface patterning through laser interventions in the manufacturing cycle.*
- *laser sintering on textile substrates which applies additive manufacturing techniques to textiles for the generation of three-dimensional surface patterning and structures.*

A method is developed for determining optimum parameters for laser processing materials. It may be used by designers for parameter selection for processing new materials or parameter modification when working across systems.

Keywords

Three-dimensional textiles, laser processing, laser cutting, laser etching, pleating, cashmere, laser sintering, origami.

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Glossary of terms

chiffon	a very light sheer open mesh fabric made from silk or a manufactured fibre such as polyester
dupion	a woven silk textile with an uneven surface as the weft yarn varies in thickness.
hemp	fibre obtained from the hemp plant
LASER	Light Amplification of Stimulated Emission of Radiation
laser Sintering	fusing of particles by laser processing
linen	fabric woven from yarns made from flax
noil	a silk yarn produced from shorter fibres
organdie	a plain weave transparent cotton fabric, stiffened by a dressing
organza	a transparent fabric made from silk or a manufactured fibre such as polyester
paper nylon	a closely woven even weave fabric made from nylon

Papers published during the course of this work

Matthews J, Kavanagh TJ, Tyrer JR, *Laser Assisted Design for Three-dimensional Pleated Structures*, 28th ICALEO Laser Materials Processing Conference, 2-5 November 2009, Orlando, Florida, USA, Proceedings, pp 400-405

Matthews J, Walton K, *Three Dimensional Texturing and Patterning of Woven Textiles using Purpose Designed Fabric Structures*, 28th ICALEO Laser Materials Processing Conference, 2-5 November 2009, Orlando, Florida, USA, Proceedings, pp 745-750

Kavanagh TJ, J. Matthews, JR Tyrer, *An Inter-Disciplinary Search for Innovation in Textile Design*, Proc 86th Textile Institute World Conference, Vol. 2, 2008, 409-422.

1 Introduction

> "The combination of science and creativity, textiles and non-textiles, materials and processes is achieving fascinating developments in the early part of the 21 century in textiles". (Braddock and O'Mahony, 2005, 6)

Current developments in manufacture and engineering in all industries are impacting on all aspects of textile creation including fibre manufacture, yarn production, fabric construction, and finishing treatments achieving a variety of textile outcomes. Interventions, both hand and mechanical, may be made at all stages of the production process to enable new opportunities for the design and manufacture of new textiles. The drive towards ecologically sustainable uses of materials and production processes is resulting in the redesign of traditional modes of manufacture. Consumer demand for novelty in decoration and enhanced performance qualities in the textiles they use has created opportunities for both designers and manufacturers. Textiles are employed in several sectors. In the traditional textile segment of fashion and interiors, products are retailed across a broad marketplace from high-value, low-volume haute couture to high-volume, low-cost mass manufacture found on the high street. Textile materials are used extensively in other sectors – architecture, the automotive industry, for medical applications and in the defence and emergency service industries. Geotextiles are utilized in very high volumes by the agricultural and construction industries. Changes in manufacturing and the supply chain have led to global production and companies outsource many aspects of manufacturing activity. Textile technologies are informing developments even in non-textile applications. An example is the design and manufacture of high cost carbon fibre composites where weaving technologies are used to produce both two and three-dimensional cloths and structures used in aerospace applications. Designers in all these areas are in a unique position to innovate and differentiate textile products but not however, without informed collaboration with colleagues in other disciplines – engineers, materials scientists, chemists to name a few. This research will show that innovation and opportunity are to be found where traditional textile techniques and materials are revisited and reinvigorated with either new materials or new technical processes or both.

The research focuses on processes to create three-dimensional textiles with application in many sectors. Previous work by the author has developed an interest in this area and the contextual review confirmed that three-dimensional surface texture, patterning and structures are used extensively in all textile sectors with perhaps the exception of geotextiles. The analysis in the contextual review in chapter 2 will show that processes employed both historically and currently to create textiles with three-dimensional surfaces may be categorised as processes that fabricate textiles with a three-dimensional form, processes that achieve three-dimensionality by the addition of or removal of an existing two-dimensional material in some way or processes that reform or manipulate a two-dimensional surface to create one with three-dimensionality. It will be seen that these are not mutually exclusive and that techniques incorporated into these processes are joining, cutting, forming and embellishment with designers having the opportunity to use any or all of these to innovate at many levels.

Laser processing, an engineering technology established since the 1960s, is embedded in the textiles industry for cutting and marking. Used extensively for applications such as the surface decoration of denim and the cutting of synthetic fabrics for airbags, the process has not been universally adopted by all textile manufacturing sectors due to the processing difficulties of some materials. Designer-makers have not been able to fully engage with the technology due to the previous high cost of equipment and the lack of technical information in the public domain. This research investigates textile laser processing and outlines a method in Chapter 4 by which designers may successfully determine and optimise laser processing parameters for a variety of materials and systems. The research contributes to new knowledge by developing three novel processes incorporating laser processing for the design and manufacture of three-dimensional textile surfaces, namely laser assisted template pleating described in chapter 5, laser pre-processing of woven cashmere in chapter 6 and laser sintered textiles in chapter 7. At the time of writing, no evidence has been found of these or similar processes.

This research is the result of collaboration and has been supervised by the School of the Arts and the Wolfson School of Mechanical and Manufacturing Engineering. It was important that the outcomes of the research had the potential to be validated by both communities and chapter 3 describes the methodology that has been adopted and addresses issues concerning cross-disciplinary research involving design and engineering and the communication of ideas.

The focus of this research has been the development of processes for design-led three-dimensional textiles however the research has not concentrated on the design of these textiles. Samples have been included to illustrate the novel techniques but it was considered beyond the scope of this research to design collections, curate an exhibition or to evaluate the designs that were produced from an aesthetic viewpoint. It is envisaged however that further work would both validate processes and explore their commercialization. This is described in chapter 8.

It is appropriate to comment on why this research has been possible. The author has undergraduate degrees in both textile design and natural sciences together with City and Guilds qualifications (Part I and Part II) in Creative Embroidery. Experience gained though employment as a computer consultant (15 years) and as a textile designer in a freelance capacity selling through agents to both the fashion and interiors industry and exhibiting (10 years) has informed the practice aspects of this research. Skills gained from these various endeavours have enabled an 'intelligent' way of questioning and an insight into the benefits that may be obtained through research on the boundaries of disciplines.

> "It is the lone worker who makes the first advance in a subject; the details may be worked out by a team, but the prime idea is due to enterprise, thought and perception of an individual." (Sir Alexander Fleming)

There has been an intention throughout to capture the insights gained through 'happy accidents', reduce the wasted efforts of 're-inventing wheels' and publish the results of this research such that frustrations felt through knowledge not being accessible are not encountered by other designers working in this field. It is hoped that the new knowledge communicated through this research will contribute in some small way to the development of the domain of laser processing and textile design.

2 Contextual Review

2.1 Introduction

This research investigates processes to design or make three-dimensional textiles. It is cross-disciplinary research encompassing fields of historical and present-day textiles, textile design, textile manufacture and engineering. Problematic to this research is the accessibility of information. Publicly available literature on contemporary textiles and fashion is often of a superficial nature and not published through academic channels. Scientific journals are written using terms and knowledge that is not always comprehensible to designers. In industry, it is common for research teams to develop new processes and whilst products using these processes may be manufactured, specific details of method and materials are not placed in the public domain. As the research progressed, it became clear that it was necessary to establish a common understanding to be able to have a dialogue between the disciplines of art and design and engineering. This contextual review was conducted therefore to provide a framework in which to locate the research, to show where opportunity arises and to establish common ground.

As the research is concerned with the design and manufacture of design-led three-dimensional textiles, it is necessary to consider what constitutes a three- dimensional textile and what design and manufacture mean in this context. The chapter starts by formulating some working definitions. (Section 2.2)

Textile manufacturing will be described in terms of both products and processes. (Section 2.3) It will be shown that this is a very sophisticated industry with high levels of automation. However, as it is possible to interact at many stages of the varied processes, opportunities are created for the design of new products and for designers to innovate.

A review of three-dimensional textiles, both historical and contemporary is conducted. (Section 2.4) The main processes, both hand and machine, that are used to create or form three-dimensional textiles are categorised.

One development of this research is a new process for pleating. Existing pleating processes are discussed in detail demonstrating both limitations and opportunity. (Section 2.4.3.1)

Laser processing has developed as an industrial process fully embedded in the textile manufacturing and sampling for cutting and marking. The applications for which lasers are currently used in the textile industry are reviewed. (Section 2.5)

Finally, textile trends that may impact future developments are examined. (Section 2.6) The chapter concludes by highlighting opportunities for research. (Section 2.7)

2.2 Definitions

This research is concerned with the making of design-led three-dimensional textiles. In this section, definitions are derived for *three-dimensional textiles* and what the terms *design* and *making* encompass, is discussed.

From the definitions given below, it may be seen that words such as ‘textile’, ‘design’ and ‘manufacture’ have different meanings as a result of custom and usage and the context in which they are used. Dictionary definitions and terms defined by the *Textile Institute* that relate to this research are:

> ***textile*** *n* a woven fabric; any kind of cloth. Also a synthetic material suitable for weaving; any kind of various materials, as a bonded fabric, which do not require weaving. (Oxford English Dictionary)
>
> ***textile; textiles*** A **textile** was originally a woven fabric, but the terms **textile** and **textiles** are now also applied to fibres, filaments and yarns, natural and manufactured, and most products for which these are a principle raw material. (Textile Institute, 2002, 348)
>
> ***cloth*** *n* a name given in the most general sense, to every pliant fabric woven, felted or otherwise formed, of any animal or vegetable (or even mineral) filament, as of wool, hair silk, the fibres of hemp, flax, cotton, asbestos, spun glass, wire, etc. (Oxford English Dictionary, 9a)
>
> ***cloth*** A generic term embracing most textile fabrics. (Textile Institute, 2002, 67)
>
> ***fabric*** *n* a manufactured material; now only a ‘textile fabric’, a woven stuff (Oxford English Dictionary, 4)
>
> ***fabric (textile)*** A manufactured assembly of fibres and/or yarns that has substantial surface area in relation to its thickness and sufficient cohesion to give the assembly useful mechanical strength. (Textile Institute, 2002, 119)

dimension *n* 1 measure of length, width or height. 2 any directly measurable physical quantity e.g. mass, length, time, charge (Chambers Dictionary, 2010)

dimension *n* Measurable or spatial extent of any kind, as length, breadth, thickness, area, volume (Oxford English Dictionary)

three-dimensional *adj* 1 having or appearing to have three dimensions; i.e. height, width and depth (Chambers Dictionary, 1, 2010)

3D fabric (technical textiles) A three-dimensional structure used as a reinforcement in composite materials, consisting of three mutually orthogonal matrices of closely-spaces yarns (Textile Institute, 2002, 352)

tactile *adj* Perceptible to the touch (Oxford English Dictionary, 1)

A ***three-dimensional textile*** will be defined for this research as any fabric or cloth with length, breadth and thickness whose surface or surfaces vary in a way that may be discernable by touch. The scale of three-dimensionality may vary upwards from a few millimetres. The term will encompass both woven and non-woven materials, made from natural and manufactured fibres. It is not limited to technical textile fabrics. The textile need not be made in one piece so the term will refer to textile structures as well as textile surfaces.

This research has a focus on the making of design-led three-dimensional textiles. Related definitions are:

design *n* A preliminary sketch for a picture or other work of art; the plan of a building or any part of it, or the outline of a piece of decorative work, after which the actual structure or texture is to be completed; a delineation, pattern. (Oxford English Dictionary, 6)

design, textile 1 The creative process leading to structures, patterns, and colours in textile materials, implemented to achieve aesthetic appeal, function and cost targets. 2 The developed specification for a textile material of product. (Textile Institute, 2002, 95)

designer *n* a person who provides designs or patterns; *adj* custom made, for specific purpose or effect (Chambers Dictionary, 2010)

Designer *n* One who makes an artistic design or plan of construction; a draughtsman; *spec* one whose business is to invent or prepare designs or patterns for the manufacturer or constructor (Oxford English Dictionary, 3a)

Manufacture *vt* to make *orig* by hand *usu* by machinery and on a large scale; to fabricate, concoct or invent; *n* the practice, act or process of manufacturing (Chambers Dictionary, 2010)

Make *vt* to produce (a material thing) by combination of parts, or by giving certain form to a portion of matter, to manufacture; to construct, assemble, frame fashion (Oxford English Dictionary, 1a)

Make *vt* to fashion, frame, construct, compose or form; to create; to bring into being; to produce (Chambers Dictionary, 2010)

This research will develop processes and techniques to be used by designers or manufacturers for the making of three-dimensional textiles either by hand or by machine. Textiles produced by these processes may be specifications, designs in themselves, textile products or artefacts. Consideration will be given to textiles that have application in any industry including, but not limited to fashion, interiors, automotive, medical, architecture and agriculture.

2.3 Textile manufacturing

Textile manufacturing has a long history developing from hand techniques through to the present day combination of very sophisticated automated processes. Consideration of textile manufacturing methods is relevant to this research as the way in which a given textile responds to laser processing and other processes to generate three-dimensionality depends on the composition and the fabrication processes employed during manufacture. The section starts with the manufacturing process and then examines the constituent parts in more detail.

The manufacturing cycle may have many stages as shown in Figure 1 starting with the production of a fibre and culminating with a textile end product, for example a garment. As can be seen from this diagram, not all steps are carried out for all textile production. The end use of a given textile will determine what properties the textile is required to have. These in turn will govern what fibres are chosen and which subsequent processes are required. As an example, the production of a blue 100% cotton tee-shirt with a printed design will require cultivation of the cotton crop, cotton fibre production, cotton yarn production, jersey fabric knitting, fabric finishing, fabric dyeing, fabric printing, garment construction, garment cleaning. A polyester geo-textile used to prevent soil erosion, will require the production of polypropylene fibre from oil as a raw material, and the construction of a non-woven fabric. The order of some processes may be varied depending on end use. Dyeing for example, a fabric colouring process, may take place on fibres, on yarns, on constructed fabrics or on garments. Consequently there is a range of options leading to a variety of outcomes. A strategy is required which is determined by what one wishes to achieve. For example in industry, decisions may be made to optimise design potential and to minimise cost. A designer may select a specific process route to achieve certain decorative effects.

Manual intervention may take place at each of the production stages depending on the equipment used. The level of automation may also vary. It is possible to find craft studios where the entire process is carried out by hand including dyeing, from hand-spinning wool to hand-weaving or knitting. At the other end of the spectrum are fully automated production lines where even looms are automatically operated. Often only some aspects of the process may be automated. For example, yarn production may be highly automated but it is common for weaving to take place on semi-automated looms. Speed, cost, consistency, and control of the supply chain are determining factors. In the developed world, textile manufacturing tends to have varying levels of vertical integration. Companies will outsource many processes in a global marketplace. As an example Heritage Ltd., who will be referred to later, source their fibres themselves but outsource their spinning, weaving and finishing to different companies mainly in China. Only the initial design of the product and the packaging for their customers is done in-house in the UK. This places a greater emphasis on communication between the various parties.

Motivation and opportunity for designers to innovate may be driven by customer requirements for textiles to have specific performance and appearance characteristics. An example is the use of sustainable products and manufacturing processes, which is being driven by a more ecologically aware consumer. Aspects of fibre, yarn and fabric production are now considered.

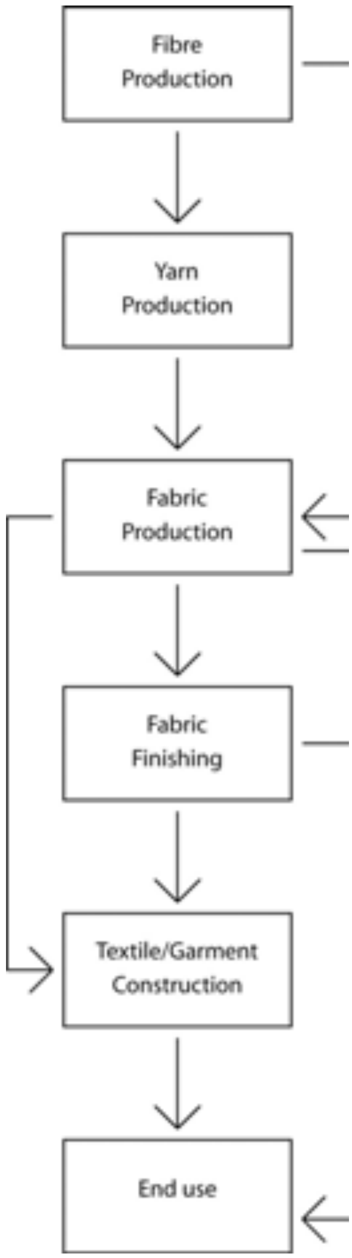

Figure 1: Production stages in the manufacture of textiles

2.3.1 Fibre production

Fibres used in textile production may be natural or manufactured. Figure 2 shows the classification of textile fibres, indicating which fibres have been used in this research.

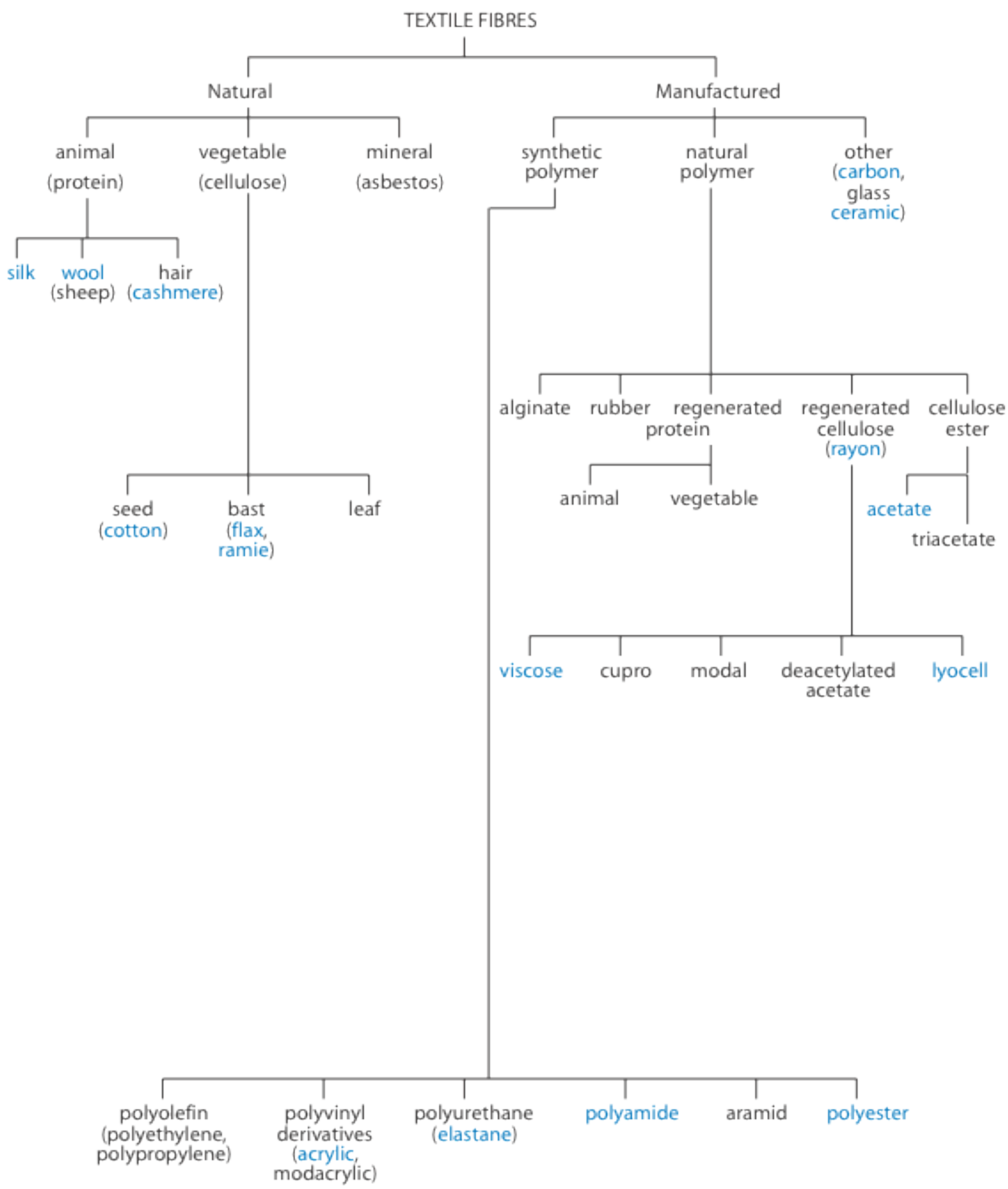

Figure 2: Textile fibre classifications. Fibres shown in blue are used in this research. (Adapted from Denton and Daniels, 2002, 407)

There are three groupings of natural fibres :

- Cellulosic – this includes all fibres from plants. The most common is cotton accounting for around 39.7% by volume of all fibres used. (Cotton Promotion Bulletin, 2010) Figure 3 shows that although the world use of fibre overall is increasing, the use of cotton is decreasing in relative terms. In the case of cotton, the seed hairs are harvested but fibres from other parts of plants such as stems (bast) and leaves are also used. Flax is used for linen and other common fibres are sisal, hemp and jute. Relatively new is the commercial development of bamboo fibres.

Figure 3: World fibre use increasing, use of cotton declining in relative terms. (Cotton Promotion Bulletin, 2010)

- Protein – these are the hair fibres from animals such as sheep, goats and camels and silkworms. Although much lower in volume, wool and to a lesser extent the noble fibres such as cashmere are high contributors by value. Relative to wool, silk is available on a small scale - less than 0.2% of the global textile fibre market in volume terms. However the unit price for silk is around 20 times the unit price for cotton. (International Trade Forum, 1999)
- Mineral – the only natural mineral fibre is asbestos, which has been replaced by manufactured fibres due to health risks.

Natural fibre production involves agriculture, fibre harvesting or gathering, cleaning and preparation.

Manufactured fibres fall into three categories :

- Natural polymers - Regenerated fibres are processed from natural polymers obtained by chemically extracting cellulose from wood pulp. Common examples are *viscose*, which is chemically identical to cotton, and *lyocell*. The by-products of this process pose environmental challenges.
- Modified regenerated fibres – the cellulose raw material is chemically modified so that a polymer may be processed into fibres. The polymer

remains in its modified form. These fibres are used for the manufacture of lining fabrics for garments and for cigarette filter tips.

- Synthetic –fibres are derived from oil. They are :
    - *Polyamide* (nylon) which was the first synthetic fibre
    - *Polyester*, the largest manufactured fibre in volume terms, around 40% of all fibres produced
    - *Acrylic*
    - *Polyolefin* fibres including polythene, *polypropylene, polyvinyl chloride* which is used as a replacement for asbestos
    - *Elastane* (*lycra* or *spandex)* which has high stretch characteristics
    - *Aramids* which are modified polyamides with either very high tensile strength (*Kevlar*) or flameproof characteristics (*Nomex*).
- Mineral – these fibres are being further developed for the technical textile market. They are:
    - *Glass* fibre used with plastics for re-enforcement in, for example, car body parts and thermal and electrical insulation
    - *Carbon* fibre produced from acrylics for performance fibres in the aerospace and automobile industries or for sports equipment. This is a high cost fibre.
    - Metal fibres for example steel and precious metals. Silver is used in medical textiles for its anti-microbial properties.
    - *Lurex* which is a combination of plastics and metals
    - *Alginates* extracted from sea weed and used for medical textiles
    - *Chitosan* produced from shells and extruded as an anti-microbial fibre

Manufactured fibre production involves extracting the polymer from the various sources described above. The solid polymer is reduced to liquid form and then converted to a fibre with one of the following three methods:

- *Melt extrusion* where the polymer is melted and fibres are extruded at high temperatures (250^0C-280^0C) and harden on cooling. Fibres made using this method such as polyester, polyamide and polypropylene are very suited to laser processing as they may be processed without discolouration. This will be discussed further in chapter 4.
- *Solvent dry extrusion* is used where the polymer is unable to be melted without discolouration and is dissolved in a volatile solvent and then extruded into heated gas which evaporates the solvent. The solvents are toxic, flammable, expensive and explosive in air. For both economic and

environmental reasons, the process depends on very efficient solvent recovery. *Lyocell* and some acrylics are produced by this method.

- *Wet extrusion* is used where the polymer dissolves in a non-volatile solvent. Acrylics and viscose are produced in this way. The dissolved polymer is extruded into a liquid bath containing a solvent in which it does not dissolve. The fibres are highly swollen and plastic. This process also depends on efficient solvent purification and recovery.

Extrusion in all these processes takes place through purpose designed spinneret's, which contain a varying number of very small holes and enable the fibres to be shaped. Drawing allows the crystal structures within the fibres to be orientated affecting the appearance and tensile strength of the fibre and consequent ability to be coloured through dyeing. Manufactured fibres may be modified through processes such as crimping, the application of finishes or additives such as pigments and delustrants. One important feature of manufactured fibres is repeatability from batch to batch. The fibre characteristics that are inherent or developed during manufacturing are described in section 2.3.2. Blends of fibres may be used to give desired performance.

2.3.2 Fibre characteristics

It has already been stated that the end use of a textile will determine the fibres that are selected. The main fibre characteristics are :

- ***Length and fineness*** – a high length to diameter ratio is required. Fibres may be produced as continuous filament or staple fibres. The only natural filament fibre is silk. Staple length varies according to fibre type and variety e.g. cotton (1cm-5cm) and wool (5cm-20cm) and determines both value and process route. Manufactured fibres are produced as continuous filament fibres. They are converted into staple fibres often so that they may be processed further down the manufacturing chain on staple fibre equipment.
- ***Strength*** or tenacity. The strength of a fibre will also affect its abrasion qualities. Fibres may change their strength characteristics when wet. Aramid fibres have very high strength to weight ratios.
- ***Elongation*** or elasticity. These qualities enable a fibre to be extended under stress and to return to their original form. *Elastane* is exceptionally elastic and is often used in small proportions in blends with fibres that are less flexible.

- ***Chemical, thermal and light resistance***. This determines how the fibre reacts to acids and alkali, heat and UV light.
- ***Capable of colouration***. Most fibres are naturally off-white. Not all fibres lend themselves to colouration. Polypropylene, for example, may only be dyed during the extrusion stage.
- ***Impurities.*** Manufactured fibres do not contain impurities. Those in natural fibres are removed to a greater or lesser extent though preparation and additional processes.
- ***Moisture content***. This affects comfort levels. Natural fibres tend to be hydrophilic and manufactured fibres hydrophobic.

Manufactured fibres may be engineered to have specific properties, for example to retain more or less moisture. Natural fibres may undergo processes to improve certain characteristics, for example *easy care* cotton which retains creases less or machine washable wool. Natural fibres may be used in blends with manufactured fibres to achieve a product with characteristics of both. In this case attempts are made to match the fibre length and strength. This research will show that it is desirable to engineer textiles to respond favourably to laser processing. Specific performance characteristics that are desirable will be discussed in Chapter 4.

Factors affecting fibre production are the cost, availability and sustainability of raw materials and the environmental effects of production processes both in terms of water and chemical usage and the treatment and use of by-products.

These aspects have not been a primary focus of this research. However it may be that laser processing offers an alternative to chemicals to achieve certain effects, for example *devoré*. Reference is made to this where relevant.

Both natural and manufactured fibres are used to make three-dimensional textiles. Both fibre types may be laser processed but, as will be shown in Chapter 4, respond in very different ways. Other qualities such as yarn characteristics, fabric construction and fabric finishing also play a role. These are discussed in sections 2.3.3, 2.3.4 and 2.3.5 respectively.

2.3.3 Yarn production

After fibre production, the next stage in the cycle is yarn production. In the case of non-woven textiles, the yarn stage is omitted as non-woven textiles are fabricated directly from fibres. This is described in section 2.4.1.3. The properties of a yarn are governed both by the fibres used in producing the yarn and the method of yarn production. These in turn will affect the properties of the fabric constructed from the yarn. Table 1 summarises relevant fibre characteristics some of which are relevant to this research, for example, thermal resistance, fineness, density and frictional properties.

Characteristic	Properties	
Physical characteristics	Length Fineness Cross-sectional shape	Crimp Density
Mechanical properties	Tenacity Extensibility Elasticity	Thermal resistance Torsional rigidity Flexural rigidity
General properties	Surface properties Frictional properties Resistance to abrasion Dimensional stability Moisture regain	Resistance to bacteria, fungi, mildew, moths etc Static properties Colour Properties when wet

Table 1 : Fibre characteristics

There are two main yarn types based on the type of fibres that are used:

- *Staple yarns* produced with staple fibres. Differentiation is made between short staple yarns such as cotton and long staple yarns such as wool.
- *Continuous filament* yarns manufactured from fibres, which run unbroken for the whole length of the yarn. Monofilament yarns are yarns that consist of a single continuous filament. Filaments yarns are also available as flat filament or textured filaments yarns, which have been treated to introduce deformed filaments.

Depending on the end use and the type of fibre being processed, factors that affect yarn manufacture are:

- The linear density of yarn
- The level of twist
- The state of the yarn - single, plied or cabled
- The method of yarn formation - ring spinning, rotor spinning, wrap spinning, core spinning, air jet spinning and friction spinning.

As an example, yarns for knitting require less twist to reduce spirality, which would cause tangling whereas yarns for woven textiles need to be strong with good abrasion resistance to enable them to withstand the weaving process.

Yarn manufacturing consists of the following stages:

- *Mix and blend*. Mixing combines similar raw materials e.g. cottons from different countries. Blending combines fibres of different origins e.g. polyester and cotton. Mixing and blending will be done for both cost and production reasons.
- *Open and clean*. Fibres are normally compressed for transportation and need to be separated into manageable quantities. The cleaning of impurities may take place e.g. dirt particles may be shaken out, however this is not necessary for manufactured fibres.
- *Separate the fibres*. Individual fibres need to be separated from one another. This is achieved by carding which also improves fibre alignment. Combing of natural fibres may be done to remove short fibres.
- *Align the fibres.* Fibres are arranged so that they all lie in the same direction.
- *Draft and twist*. The raw materials are drawn to the required fineness and the required amount of twist is inserted. A large number of options are available at this stage. Other options involve wrapping around a core, entangling untwisted fibres at intevals and adhesive bonding.

It became clear though the course of this research that yarn type and composition plays an important role and that where blends were used, that a difference in laser processing could be observed in between a blend in the yarn or a blend in the fabric construction. Fabric construction will now be discussed.

2.3.4 Fabric manufacture

Three main processes are used for the manufacture of textiles, namely weaving, knitting (both weft and warp) and non-woven construction. Hybrid methods are also used, for example lamination, which combines woven or knitted fabrics with adhesive bonding, a non-woven process.

These processes are described in more detail in subsequent sections, where relevant, for the making of three-dimensional textiles.

2.3.5 Colouring and Finishing

Fabric will undergo a number of processes after construction known as finishing. These are designed to remove substances that have been added as part of the manufacturing process and to add desired qualities to manufactured textiles. These aspects are important to this research. Some finishing treatments alter the three-dimensionality of a textile surface. Additives may assist or inhibit some subsequent processes such as colouration and some finishing processes may remove by-products. Relevant finishing processes are:

- *Singeing* – the removal of protruding fine fibres by flame creating a very smooth surface
- *Desizing* – removal of size which has been applied to warp thread to improve abrasion qualities
- *Scouring* – the removal of natural oils with detergents or solvents
- *Bleaching* – a process which improves the visual appearance of the fabric
- *Mercerisation* – a process which allows cotton fibres to swell and straighten under tension which increases lustre and dye substantivity
- *Heat-setting* – a process which stabilizes synthetics and synthetic blends to minimise fibre distortion such as creasing or shrinking at higher temperatures
- *Dyeing* – a variety of processes which enable fibres, yarns, fabrics or garments to be permanently coloured. Both the specific dyes that are used and the often sophisticated processes to apply them permanently are fibre dependant.
- *Printing* – the application of localised dye in a thickened form to generate pattern.

To reduce abrasion during weaving, yarns are sized with natural or synthetic starches. These may contain lubricants (wax or soluble oils) and anti-static agents. To increase the flexibility of yarns during knitting, yarns are lubricated with silicone. These additives are removed prior to colouration. It is possible that laser processing fabrics prior to the cleaning stage may offer advantage. It is also possible that the addition of materials that favour or inhibit the interaction of the laser beam with fibres may be of interest. This will be explained in more detail in chapter 4.

Section 2.3 has outlined the stages of textile construction from fibre selection and preparation through yarn manufacture and fabric construction. As has been explained there are many options. Some process routes are highly automated and others have hand process equivalents. Some stages are only necessary in an industrial context and many processes are required only as direct consequences of previous ones. An understanding of manufacturing processes was necessary to provide insight into why observed characteristics had effect and to identify where opportunity may be gained.

2.4 Three Dimensional Textiles

Previous sections examined the process of turning raw fibre into yarns and finished fabric. This section discusses how yarns and cloths may be used or modified in some way to create three-dimensional surfaces or be manipulated to form three-dimensional structures. It will review both historical and current textiles.

To explore a range of options, it is necessary to be able to categorise three-dimensional textiles. For this review, the following structure will be used:

- *Constructed* - Textiles that are fabricated with a three-dimensional surface or as a three-dimensional structure. Examples would be woven or knitted textiles discussed in Section 2.4.1.
- *Applied* - Textiles where three-dimensionality is achieved by adding to or subtracting from an existing two-dimensional textile surface in some way. Examples to achieve this would be embroidery where the surface is built up or *devoré* where chemicals are used to dissolve the surface of purpose designed fabric. See section 2.4.2.
- *Formed* - Textiles where a two-dimensional textile surface is manipulated to create a three-dimensional surface. Examples would be pleated or thermoformed textiles. See section 2.4.3.

These sections will be further subdivided to reflect processes that are used in either the initial creation or in one of several post-processes. It will be shown that there are not always clear boundaries and that the same techniques or combinations of techniques may be applied in many ways or different sequences to achieve very different three-dimensional surfaces. Similar effects may be achieved by very different techniques.

Furthermore from examples that are shown, it is clear that materials are intrinsic to the success of a process. Not all processes will be successful on all textile materials.

Indeed new opportunities arise when a material from another industry undergoes a textile process. An example is woven carbon fibre in the production of composites or knitted and braided wire. The opposite may also be valid. Not all textile processes lend themselves to a high level of automation. Many techniques discussed here are only executed by hand and even where mechanised and/or industrial processes are used, a textile may be produced as a 'one-off' or in very limited quantities. Some techniques such as weaving have, through technical developments, a mechanised process which is analogous to that produced by hand. This is not valid in all cases. Although similar in result on some materials, laser processing is not equivalent to blade cutting.

The following sections review constructed, applied and formed three-dimensional textiles in turn.

2.4.1 Constructed three-dimensional textiles

This section describes textiles that are manufactured with a three-dimensional form. There are three main categories - woven on a loom, created from yarn with an interlocking process off-loom or manufactured using non-woven textile techniques. Processes discussed here are relevant to textiles covered in all other sections as the way in which an additional process may be applied, or the way in which a textile responds to these processes, depends on how the two-dimensional textile was constructed in the first place. For example the way in which certain textiles react to heat in for example a pleating process depends both on the weave structure and yarn composition. This research will show that it may be desirable to construct or engineer textiles with specific characteristics to facilitate the creation of a three-dimensional textile.

2.4.1.1 Loom woven textiles

Weaving is probably one of the oldest textile construction techniques and is thought to have developed before 6000BC (Harris, 1993, 16). A woven structure contains two sets of interlaced threads lying at right angles to each other and parallel to the fabric edges – known by the terms *warp* and *weft*. The warp lies parallel to the length of the fabric. During the weaving process, warp threads are held under tension on a *loom*. Some threads are lifted creating a space called the *shed*, through which the weft, which may be wound onto a shuttle, is passed. The woven weft is then compacted with a *comb*. A *plain weave* construction is created by lifting every alternate warp thread resulting in the weft passing over one warp thread and then under the next. Altering the order in which warp threads are lifted will result in woven surfaces that vary in pattern and texture.

The direction of the warp is known as the *lengthwise grain* and the direction of the weft, the *crosswise grain*. Diagonal to these is known as the *bias* and most woven fabrics may only be stretched along the bias.
Very complex woven structures, for example *multi-cloths* consisting of several layers woven together at intervals, may be produced on simple looms. Developments in loom design, dating from the Industrial Revolution onwards, have enabled the speed of weaving to be increased and made some aspects of the process easier. Shuttle-less looms with alternative systems using, for example, air pressure, water jets or rapier to insert weft threads have allowed for vast improvements in weave speed rates and reductions in noise levels. In spite of these developments, a constraint remains the setting up of a loom. Computerised digital looms with Jacquard attachments allow each warp thread to be electronically controlled separately for each weft insertion so that by using CAD, very intricate designs may be created. In spite of these technical developments, hand weaving is still used on a large scale for commercial purposes for example in India.

The surface texture and the three-dimensional quality of a woven structure are affected by several factors - tension, structure, type of yarn, and post processing. Figure 4 and Figure 5 show how surface texture may be achieved through the use of yarns with very different characteristics. When the fabric is removed from the loom, the yarns relax, as they are no longer under tension. Finishing treatments allow some yarn types to shrink more than others revealing a three dimensional surface.

Figure 5 shows what may be achieved through fabric structure. In this case, the fabric is made from three layers, woven together but interlocking only in places. Some material is cut away prior to finishing adding three-dimensionality.

Jacquard weaving techniques are being applied to carbon fibre reinforced composites to produce shaped preforms for use in the aerospace and automotive industries. (Soden and Hill, 1998)

Figure 4: Osamu Mita. MfrMitasho Co. (McCarty, C. and McQuaid, M., 1998, 69) Jacquard double weave, plain weave washi paper, mesh weave wool, felted. Same fabric, two views. Three-dimensionality created through different yarn types responding to the felting process in different ways.

Figure 5: Hideko Takahashi Circle Square II. Wool. Jacquard triple weave, cut, felted. Compound weave structure. Warps woven separately and together in places. Left reverse, right front.

2.4.1.2 Off loom woven textiles

Traditionally various methods have been used to create constructed textiles without the use of a loom. These all involve some method of interlocking one or more strands of yarn through loops.

2.4.1.2.1 Knitting

Knitting is used extensively in fabric manufacture. There are two construction methods in knitting. A *weft* knitted structure may be made by hand or machine on needles with a continuous length of yarn passing through intermeshing loops in rows along the weft of the fabric. Each row is known as a *course* and one row interlocks with the one above. Techniques exist to knit with several yarns throughout a piece so that colours and textures may be varied. It is also possible to decrease and increase stitches throughout the work creating either a lace effect or a raised structure. See Figure 6 (left).

A *warp* knitted structure consists of as many threads as there are loops, which are made along the warp of the fabric and interlock by intertwining. It is possible to engineer warp fabrics that consist of several layers knitted together and for each individual layer to be knitted from different yarns. Warp knitting is used extensively for technical textiles where performance characteristics are engineered into the fabric. Warp knitting is the fastest way of producing a fabric, whereas weft knitting is more versatile in terms of surface patterning and yarns that may be used.

Due to the loop construction, knitting may be stretched in several directions unlike a woven cloth, which will only stretch along the diagonal. Commercially, weft knitting is used for apparel, tights, imitation furs, household textiles and technical applications such as metallic scouring pads, aircraft nose cones and medical textiles whereas warp knitting is used for apparel, lace, geotextiles, medical and other technical textiles. Knitting techniques are used in an industrial context to knit wire into flat or tubular fine metal meshes for use in catalytic converters in the automotive industry.

Knitting machines, manual or powered, may produce flat or tubular knitted fabrics using either a flat or circular bed of fixed hooks. Pattern stitches can be controlled by manipulation of the needles, or with pattern reading devices and computers allowing for a variety of textural surfaces. Recent developments are circular knitting machines (Santoni, 2010) that create seamless garments for apparel and sportswear which when used in conjunction with elastomeric or stretch yarns, give close fit and reduce the need for garment construction and side seams as a whole garment including selvedge edges and logos may be knitted in one piece.

The three-dimensionality of a knitted surface is determined by yarn type and composition, stitch pattern, and stitch tension. Figure 6 shows the three-dimensionality that may be achieved through knitting. The hand knitted sculpture on the left has used stitch manipulation to alter the surface texture and form. It would have been knitted in sections that have been stitched together. The image on the right shows detail from a garment produced on a computerised knitting machine using very fine polyamide monofilament and polyester yarns. The garment is knitted in two pieces and stitched together only at the side seams and shoulders.

Figure 6: Left *Sheep in Wolf's Clothing*, Judith Duffy 1986. (Harris, 1993, 47) and right, *Snowball* Ulla Elison Bodin. (Braddock & Mahony, 2005, 181)

2.4.1.2.2 Crochet

Crochet, originating as a hand technique, uses a hook and a single strand of yarn to construct a textile in rows, locking the loops laterally and vertically. Crochet differs from knitting in that only one loop is active at any one time and stitches are supported only by adjacent loops unlike knitting where one entire row (*course* or *wale*) supports another. The Irish crochet lace shown Figure 7 (left) is an example of how fine yarn and crochet stitches may be used to create a fabric with a high level of three-dimensionality. The illustration on the right shows examples of crochet that has been formed to create three-dimensional structures of hyperbolic space. Yarn selection, tension and stitch pattern will determine the three dimensionality of a crocheted piece.

Figure 7: Left, late 19th century Irish crochet lace (La Couturière Parisienne, 2010) demonstrating how stitch pattern may produce relief and, right, how stitch pattern may create form, hyperbolic crochet kelp and coral shown at the Hyperbolic Crochet Coral Reef exhibition at the South Bank (June 2008 – August 2008)

2.4.1.2.3 Lace

Lace originated in the late 15th or early 16th centuries and is "an openwork fabric constructed not by weaving but by the looping, plaiting or twisting of threads either using a needle or a set of bobbins." (Harris,1993, 34). It may be classified into three main types - needle lace, bobbin lace and machine made lace. Needle lace is worked by hand by interweaving thread with a needle on previously laid down scaffolding of stitches. See Figure 8.

Figure 8: Needle lace. Each individual section is stitched separately and applied to create a three-dimensional image (Hirst, 1997, 29)

For bobbin lace, lengths of thread are wound onto a number of shuttles known as bobbins. Pins are used to hold stitches in place whilst threads are twisted together or knotted in a sequence. *Schiffli Lace* is achieved by machine embroidering a pattern on a purpose designed fabric, which is then chemically dissolved. Although expensive, a three-dimensional surface may be achieved.

Lace may also be made using other methods. For example in c*ut work* or *white work*, threads are removed from an open weave fabric and the created spaces are filled with embroidery. Knitting, knotting and crochet techniques may also be used to create lace, which is often similar in appearance to traditional methods of lace making.

Today, virtually all lace is machine made using warp knitting machines. This is less expensive than other methods but does not give much depth of design.

2.4.1.2.4 Braiding

Braiding has been made in many cultures since early times. Only one set of yarns are used which are interlaced diagonally from the edges towards the centre as in, for example, plaiting which is a form of braiding. Flat or tubular braids may be created. Cables, cords and ropes are created industrially using braiding techniques using natural and manufactured fibres as well as metals such as steel and copper.

2.4.1.2.5 Tufting

Tufting creates a pile fabric with a three-dimensional surface by inserting loops into a base fabric with needles. The base fabric may be woven or non-woven and is often coated or post-processed for example shrinking to hold the tufts in place. Chenille and candlewick used for bedspreads is an example of tufting. Hand tufting is used in traditional work. For example, a First-nation technique from the Yukon tufts dyed moose hair on caribou skin. Industrially tufting is used as a carpet manufacturing technique. Varying the height of the tuft or pile or alternatively tufting in only specific areas will result in a three-dimensional surface.

2.4.1.3 Non-woven textiles

This section discusses textiles that are not formed by weaving or constructed using the structured interlocking processes described above. They are manufactured from fibres, natural or manufactured, through the application of heat, solvents, chemicals or mechanical treatments. Non-woven textiles are used widely in high volumes in a variety of applications such as geotextiles, medical textiles, hygiene products, food packaging and carpets. Other than for interiors, the context of their use has not encouraged the development of three-dimensional surface design. Given the huge volumes, this could be considered a design opportunity and some research has been conducted in this area. (Kane, 2008)

There are three methods of manufacture. Initially a web of continuous filament or staple fibres is laid down. The fibres are then bonded by mechanical, chemical or thermal methods. Fibres may be laid parallel to one another, cross-laid, laid randomly or placed as a composite of several fibre types. The following are uses of non-woven techniques in the manufacture of three-dimensional textiles:

2.4.1.3.1 Felt

Felt is a fabric formed by the agitation of a mass of fibres containing at least 50% wool together with heat, moisture and pressure. Fibres are laid out in a *web*, which is *steamed* and *pounded.* During this process the wool fibres shrink, interlock and mat into a fabric known as felt. Although reduced in all three dimensions by the felting process, the thickness and evenness of the initial web relates to the surface qualities of the felted fabric. The amount of pounding determines the density of the felt. Other fibres may be included and techniques exist to felt directly onto fabrics. An example is *Nuno* felt developed by the Japanese Nuno Corporation, where wool fibres are felted onto silk organza. The silk distorts as the wool shrinks creating a three dimensional surface. Felt may also be steamed and blocked over forms to create three-dimensional shapes such as hats. Applications for felt include acoustic panels, clothing, rugs, gaskets, boot insoles and padding.

2.4.1.3.2 Needle felt

Needle felt is created by punching a dry fibre web or felted layer with very fine barbed needles, which allow the fibres to mat together. Needle felting is used as a hand technique to create three-dimensional objects. Synthetic suede and leather are manufactured using machine needle felting methods.

2.4.1.3.3 Bonding and lamination

Other methods of creating non-woven textiles are the bonding of fibres using heat or adhesives during fabrication or as a post process. These fabrics may be moulded or formed with three-dimensionality. An example is foam, which is often laminated to other materials and produced with three-dimensional surfaces in a variety of shaped forms. See Figure 9.

Both woven and nonwoven fabrics may be laminated together. These are often found in applications for performance textiles but would generally have two-dimensional surfaces.

Figure 9: *Stomatex* Heat treated, laminated foam laminate based on transpiration in nature. (Braddock & O'Mahony, 2005, 143)

2.4.1.4 Constructed three-dimensional textiles summary

A variety of methods, both machine and hand, exist for constructing fabrics from different materials. Some of these lend themselves to the creation of three-dimensional textile surfaces. Even where smooth or two-dimensional textiles are manufactured, the method of fabric construction and materials that are employed is relevant. The application of other processes that may be used to create three-dimensional surfaces, which will be discussed in sections 2.4.2 and 2.4.3. , is enhanced or limited by the fabric construction.

2.4.2 Applied three-dimensional textiles

This section will discuss textiles that are constructed using the techniques described in section 2.4.1. Their three-dimensionality is applied or enhanced by modifying an existing fabric through additive or subtractive processes. In some cases, traditional techniques such as stitch or cutting are used to apply or remove layers. Others are technologically advanced finishing treatments such as chemical pastes, which may be applied nonetheless by traditional printing processes. These versatile finishing techniques enable textiles to be transformed in appearance and texture using visual effects that make textile surfaces appear or feel very different. They may become ultra-smooth or textured, glossy or matt, fluorescent, phosphorescent or have light reflecting surfaces. In addition, these processes are able to imbue textiles with additional properties that make them for example both windproof and breathable, crush and wrinkle-proof, or able to react to heat or light. Great advances in this area known as *technical textiles*, where textiles are developed "primarily for their technical properties and performance rather than their appearance or other aesthetic characteristics" (TechniTex, 2010) have been made in recent years.

It has already been pointed out that it is important to understand the inherent properties of fibres, yarns and textile construction as these factors affect the way in which a textile will respond to the various process interventions discussed here.

2.4.2.1 Stitch and embroidery

Embroidery is a traditional technique whereby a two-dimensional surface is decorated with a needle and thread, by hand or machine in a variety of stitches. There is a strong worldwide embroidery tradition and demand for embellished textiles, which, even today, is passed down from generation to generation. Many of these traditional methods are being revisited and re-invigorated through the use of new materials.

Three-dimensional embroidered surfaces may be achieved by altering the scale and arrangement of stitches, using yarns in a variety of weights and textures and by incorporating other materials such as beads and wire or padding. Changes in surface qualities may also result from stitching in such a way that the ground is distorted by drawing and pulling threads to create holes or stitching folds in the fabric.

Stitches used in embroidery may also be used to join pieces or layers of fabric as in for example garment or soft furnishings manufacture. By the use of sophisticated pattern cutting techniques incorporating darts and gathering, three-dimensional forms may be created.

2.4.2.2 Machine sewing

The first patents for sewing machines were registered toward the end of the 18th century. Although fully electronic machines with computer controlled interfaces offering a variety of inbuilt stitches and accessories are manufactured today, the design of the sewing machine has not changed substantially with fabric being fed manually from the front through a needle. Advances have been made with machines offering vastly increased sewing speeds and automatic facilities such overlocker machines which simultaneously trim fabric, stitch a seam and have additions such as the automatic cutting of threads and vacuum systems for the collection of cloth waste and thread ends. Domestic embroiderers are able to achieve the appearance of commercial manufacturers and the contrary is also true. Commercial multi-head embroidery machines with multiple yarn feeds may be used to embellish textiles to achieve a handmade appearance.

Welding and bonding technologies are becoming more prevalent for specific garment and fabric types. Up to 95% of seams on outdoor garments are manufactured using these techniques. (Hayes et al, 2006). Seams of this type have increased flexibility, less bulk and as holes are not introduced by stitching, consequently better water repellence. The most common form of textile welding uses acoustic energy to cause vibrations within the fabric and generate heat due to friction. This process is known as ultrasonic welding. Bonding technologies apply heat under pressure. In both cases, fabrics must have thermoplastic qualities, which allow fibres to melt and flow forming a bonded seam. Sometimes coatings and additional films are added.

The first combined laser and ultrasonic sewing machine went into production in 2006 (Prolas, 2006). Both these technologies are used to fuse thermoplastic materials together with heat and pressure. There is however no evidence that a combined laser and ultrasonic machine is gaining market share over ultrasonic only machines. The ability to fuse fabrics together without stitch, which makes holes and weakens parent materials, is an interesting development, which warrants further research particularly in combination with natural fibres. Mention will be made of other processes that use laser technologies in section 2.5.

2.4.2.3 Quilting and appliqué

Quilting is technique, which creates a three-dimensional surface through stitching together two or more layers of fabric either by hand or machine. The relief surface is achieved either by stuffing the stitched shapes from behind with wadding or cord or, alternatively, including a layer of wadding between the layers to be stitched. Quilting techniques are often combined with patchwork. A recent exhibition at the V&A *Quilts1700-2010* explored British quilt making from the early 1700's to the present day including work by Tracey Emin. (V&A, 2010)

Three-dimensional textile surfaces may be created by the addition of layers of fabric, which may be applied by hand or by machine with or without decorative embroidered stitching. This technique is known as appliqué and may be executed by hand or machine. Appliquéd shapes may be raised using quilting techniques. Reverse appliqué is a technique where the negative shapes are applied. At ITMA 2007, combination multihead machine embroidery and laser cutting machines were seen which reversed the traditional appliqué process from two manufacturers one Italian, *Proel* (Proel, 2010) and one Chinese *Goldenlaser* (Goldenlaser, 2010). Instead of stitching previously cut out shapes onto a fabric ground, several layers were machine stitched together and then unwanted layers and areas were removed by selective laser cutting. (Figure 10)

Figure 10 : Example of reverse appliqué produced using a laser bridge system which combines machine embroidery with laser cutting. (Shirt Shack)

2.4.2.4 Cutting techniques

Cutting may be used to create three-dimensional surfaces both through creating cut-outs and distorting the fabric. Cutting may be achieved with blades, knives, punching, water-jet, laser cutting or by burning the fabric with a heated tool. Ultrasonic cutters are used on manufactured fibres as a method of fusing layers of fabric made from manufactured fibres together at the same time as creating decorative edges. Some interesting surface textures may be obtained through partially cutting fabric and allowing the attached cut fabric shapes to flow freely. Camilla Diedrich uses this technique with laser cutting for interior textiles. (Quinn, 2009, 184-191)

Post-processing may be required to change the surface quality of the cut edges. For example washing allows the edges of the cut areas of denim to fray resulting in a three-dimensional surface.

Several layers of cut fabric may be arranged on top of one another or stitched together in such as way that the underneath layers are revealed though the cut out areas. Jacob Schlaepfer has produced fabric in this way for Creation Bauman. (Braddock and O'Mahony, 81)

See section 2.5 for further detail on laser cutting and etching.

2.4.2.5 Printing techniques

Printing is “the production of a design or motif on a substrate by application of a colorant or other reagent usually in a paste or ink in a predetermined pattern”. (Denton and Daniels, 270) Whilst many of these techniques do not significantly alter the fabric to create three-dimensional surfaces, some may be adapted to change both the surface texture and appearance of a textile.

2.4.2.5.1 Heat transfer printing

Heat-transfer printing was developed by Ciba-Geigy (Braddock & Mahony, 2005, 86) and introduced in the 1960s. Fabric may be sandwiched between two sheets of heat-transfer paper, which has had varnishes and inks applied to it. It is then passed between heated rollers, transferring the chemicals to the fabric. Recent technological advances have enabled this process to be applied to a variety of new materials including ultra-micro fibres and a variety of three-dimensional surfaces may be achieved.

2.4.2.5.2 Discharge printing

Discharge printing is the removal or discolouration of previously applied dyes by the application of a printing paste containing suitable chemicals. Bleach would be an example. This process would not normally create a three-dimensional surface however the effects of laser etching of denim, which will be discussed in section 2.5.1 are similar.

2.4.2.5.3 High relief surfaces

Printing heat reactive chemicals on to textiles creates three-dimensional surfaces when heat is applied. An example is puff printing where the screen printing ink is mixed with *spandex*. Once dry, the fabric is heated and the spandex expands creating a raised surface, which is pliable. It has some stretch so this type of treatment may be applied to both knitted and woven textiles. Nigel Atkinson uses this technique with hand printing to create three-dimensional textiles for use in interiors. (Braddock & O’Mahony, 2005, 86)

2.4.2.5.4 Embossing

Embossing is a process used to give a three-dimensional surface to a textile by passing it through heated rollers known as calenders, which apply pressure and heat. If an engraved pattern is used on one side of the fabric and a soft layer on the other, embossing may be used to create surfaces with high relief.

2.4.2.5.5 Flocking

Another method to achieve a three-dimensional surface is flocking. This is where the fabric is printed with an adhesive. Minute textile particles are applied either by dusting, air blasting or electrostatic attraction. Once the adhesive is cured the loose particles are removed. Figure 11 shows the three-dimensionality that may be achieved with flocking.

Figure 11: *Pedocal.* 1996. Yoshihiro Kimura. Nylon, polyurethane, polyester and rayon. Flock printed. (McCarty and McQuaid, 1998, 63)

2.4.2.5.6 Resins

Silicone and resins may be printed in either structured patterns or applied by other methods in free flowing designs to obtain relief surfaces. Marcel Wanders has produces a table from stiffened lace which has been through dipped in resin to obtain a solid form. (Braddock and O'Mahony, 2005, 137)

The handle or feel of cloth will be changed to a lesser or greater extent by the application of resins. However, they are very successful in creating three-dimensional textile surfaces with interesting visual and tactile properties.

2.4.2.5.7 Burn out – chemical or heat

Dating from Victorian times *devoré*, also known as melt-out or burn-out, is a technique that has been used to create relief surfaces. A specially woven fabric is used, usually a silk/ synthetic blend with a pile. A chemical paste is applied by screen printing and when heat is applied, the paste reacts with some of the fibres, dissolving or destroying them. See Figure 12 which demonstrates effects of the process as used by Reiko Sudo. The paste may additionally contain dyes and pigments to colour the fabric.

Similar effects may be achieved in other ways. Isabel Dodd creates richly textured three dimensional surfaces from initially machine stitching silk and polyester and then passing the textile through caustic soda. (Braddock & O'Mahony, 2005, 95)

Figure 12: *Jellyfish*. Reiko Sudo. 1993. Polyester, screen printed and flash heated. (McCarty & McQuaid, 1998, 81)

2.4.2.5.8 Laminates

Most laminates are used to alter the surface properties of a textile through the application of membranes. Laminates may be visible or invisible and can create three-dimensional surfaces. Examples of laminates are holographic foils, glitter and metallic finishes, the application of jewels and sports logos.

2.4.2.5.9 Digital Printing

There are two digital printing techniques – UV printing and sublimation printing. In UV printing solvent-free inks are applied which are cured by ultraviolet light. The handle of the fabric becomes stiffer. More than one layer may be applied so that a three-dimensional surface may be built up as in Braille. In sublimation printing, the inks are cured by the application of heat through steam or heated rollers. The handle of the fabric is almost unchanged. Although digital printing offers a wide colour palette, screen printing is often used as a lower cost, faster process. Digital printing is increasingly employed due to design flexibility and the vast range of colours that may be employed within the same design. There are however issues with colour fastness for interiors fabrics

In summary, both screen and UV printing may be used as methods for applying three-dimensionality and surface texture to textiles. From the examples seen, the greatest variation is achieved through screen printing chemical pastes. As a consequence these processes are not all ecologically sustainable methods and seeking alternatives offers opportunity.

2.4.2.6 Multi-piece Construction

Three-dimensional textiles may be formed by constructing three-dimensional forms from two-dimensional textiles. Already mentioned is the use of stitching seams, darts and tucks.

2.4.2.6.1 Pattern generation

There are two methods or generating designs for garments namely the flat method, where pattern components are produced from a technical drawing or draft and the modelling method where a toile or sample garment is constructed. Once design and fit are completed on a model, individual components are copied onto pattern paper. As this is a very time consuming process and therefore relatively expensive, the toile is used extensively by the haute couture end of the market. In manufacturing, a high level of computerization is employed both to produce patterns from a draft and to visualize garments produced from patterns. These systems are becoming increasingly sophisticated with the ability to visualise 3D garments from 2D patterns including drape and texture properties of fabrics. (Gerber, 2010) Alterations may be made and the pattern components will be automatically generated in a variety of sizes. These elements are linked to fabric cutting systems, which optimize pattern layouts to minimise the cost of materials.

2.4.2.6.2 Fashion design

Fashion designers exploit construction methods to produce innovative three-dimensional forms for garments. Two designers who used repeating modular units were Pacco Rabanne who made dresses from interlinking plastic shapes (Braddock and O'Mahony, 1998, 106) and Galaya Rosenfeld who designed a system of interlocking modular textile segments, which may be rearranged and transformed into different garments and different surfaces without seams or stitching. (Quinn, 2002, 126) Others use construction methods for interchangeable forms such as Mandarina Duck who designed a jacket ,which transformed into a backpack. (Quinn, 2002, 122). In this area fashion almost approaches architecture. Several examples were seen at the *Skin + Bones* exhibition in London in 2008.

2.4.2.6.3 Rigid materials

Interlining, a non-woven textile may be used as a layer to stiffen other textiles and to give form in the making of garments and soft furnishings. The addition of rigid materials to textiles has the ability to transform the three-dimensionality of the surface and create structure. The insertion of bones into corsets has enabled the bodice to take a three-dimensional form. Wire is used in the construction of carnival costumes and hats to create garments with three-dimensional form. Designers have used solid materials to make three-dimensional textile forms. Hussein Chalayan created a round table, which became a skirt when worn. (Hodge, 2006, 12-13)

2.4.2.7 Applied three-dimensional textiles summary

The techniques discussed in this section enable an existing two-dimensional textile to be transformed by additive or subtractive processes into a three-dimensional form. Laser processing is used in this research for both additive and subtractive processing. These aspects will be discussed in more detail in chapters 6 and 7.

2.4.3 Formed three-dimensional textiles

This section examines textiles where a two-dimensional base fabric is transformed into a three-dimensional textile without the addition of applied materials. It will include processes like pleating or vacuum moulding. The inherent properties of a textile such as construction, fibre and finishing will determine how it responds to these processes. Although the processes may be applied to natural fabrics, many three-dimensional forms are permanent only when applied to manufactured materials. Thermoplastic materials may be transformed through heat into a new configuration, which is stable once the material is cooled. Some natural fibres such as wool and most synthetic materials show thermoplastic characteristics.

Pleating is reviewed here in detail, as the research in chapter 5 describes the development of new processes for pleating.

2.4.3.1 Pleating

Dating back to the ancient Egyptians, pleating or the structured folding of fabrics is one of the oldest finishing techniques. Pleating has been used over thousands of years by various cultures as a method of adding fullness to garments. Contemporary couture designers use pleating to add structure, movement and texture to clothing. Pleating is used for soft furnishings in interiors. Pleated structures are also used in architecture and in industrial applications such as filters. Since the invention of synthetic materials post World War II, permanent pleating has become possible but requires a minimum of 65% synthetic in the material composition.

A variety of pleating styles are found in use in fashion and interiors. Pleating types have the following characteristics:

- A pleat is formed by folding material back onto itself, for example, in a zigzag manner.
- Pleats may be folded in the same direction or may alternate as in boxed pleats
- The scale of the pleats may be even or vary
- Not all pleating is structured. An unstructured pleat will give a crushed effect.
- Pleats need not lie parallel to one another. Ray pleats are narrow at one end and wide at the other.
- Pleating may be stitched at one end to hold the folds in place. They may also be stitched such that they project from the fabric. This method is often seen in interiors on curtain headings.

The great variety of pleating styles that may be seen are shown in the following sections.

2.4.3.1.1 Egyptian Pleating

The earliest known examples of pleating are Egyptian. Fragments of pleated linen were seen at the British Museum (Figure 13) and examples from pleated tunics were seen at the Manchester Museum. (Figure 14) Due to the fragility of these samples, it was not possible to handle the textiles. All of the items viewed seem to have been pleated by hand in relatively even zigzag pleats. The Manchester examples seem to have been made from a length of linen folded into four, and pleated. From the seam construction, the garment appears to have been made after pleating. The most elaborate example of Egyptian pleating which is thought to date to the 6th Dynasty (Nicholson et al, 2000, 281) shows three types of pleating – simple pleating, closely set pleats and herringbone pleating. (Figure 15)

It is not clear what methods were used to achieve these complex and decorative pleats. Nicholson proposes three alternatives:-

- Hand pleating of wet linen, which would set the pleats in place as the linen dried. Folds may also have been fixed with a gelatinous sizing.

- The use of a pair of boards with a series of raised areas. An example of one of these boards was seen in the British Museum. (Figure 16) In the opinion of the author, this board was not used to create pleats in the examples seen. Further detail is described in chapter 5.
- The application of a weave structure exploiting the differences of spin direction of weft threads and changes in weave density to produce the effect of permanent pleating. Richards describes experimental techniques to investigate natural pleating as a result of weave structures in linen. (Richards, 2000) Whilst successful, this method produces a soft pleat more like a crepe.

Figure 13: Fragment of pleated linen kilt showing three layers, possibly pleated as one. British Museum 1889,1015.2

Figure 14: Part of a garment made from pleated linen. Pleats 5mm – 7mm apart. Manchester Museum 7071.A

Figure 15: Linen, pleated in one direction and then again at right angles, in bands . Cairo 51 513 (Staehelin, 1966; Plate XVI)

Figure 16: Wooden slat with 13 grooves. 25.4cm x 5.5cm x 1.7cm. Egyptian thought to be used for pleating textiles. British Museum 1881,0614.83

Figure 17: Left, Egyptian statue showing what appears to be a pleated kilt, British Museum, right Nefertiti, Louvre Museum (Vasseur, 2002, 35)

Although several examples of other pleating styles are seen on Egyptian statues, (Figure 17), no textile examples of these have been located. Trials based on Egyptian pleating are described in Chapter 5.

2.4.3.1.2 Miao Pleating

The second main cultural group to use pleating is found in China. The Miao people from the Guizhou province still make use of very full pleated skirts as part of their traditional dress. The skirts are made from several horizontal bands of pre-pleated fabrics. (Figure 18)

Figure 18: Left, Miao skirt made from several bands of pleated fabric. Waist 73.7cm, bottom diameter 4.872m. Whitworth Gallery T.1984.16, right, detail of indigo dyed Miao skirt showing gathering stitches. British Museum

Techniques vary from community to community and it is difficult to determine the exact process as the work is produced by women and interpreters are men. Balfour-Paul and O'Connor describe several methods to produce this pleating (Balfor-Paul, 1996, 66-99) and (O'Connor and Deryn, 1994, 65-68)

- Panels may be hand folded to produce very fine pleats, generally used when the cloth has an open weave or is very light cotton.
- Fabric may be pleated by neatly stitching two parallel rows, which are drawn and gathered tightly. Alternatively regularly spaced running stitches are placed at intervals of 2cm-3cm apart and then gathered up. This may be seen in Figure 18 right.
- Cloth is initially stretched on a mould, which may be bell shaped, barrels or poles. Pleats are teased into place with a sharp metal instrument. Alternatively, gathering lines, widely spaced apart may be stitched into the

fabric or the fabric may be loosely pleated by hand before it is bound onto a large cylinder.

- Previously gathered cloth, may be attached with stitched lengths of thread or string to a frame or to rods. These are repeatedly tensioned at intervals by wetting the string.

Balfour-Paul also refers to the cloth being starched. Cowhide glue is poured onto pleated cloth to stiffen it. O'Connor describes pleats being sprinkled with water containing gum or starch and being left to dry. This would both assist the pleating process by making the fabric easier to handle and would aid the retention of the pleats.

Yuchi and Shizhao describe a process whereby a piece of cloth is placed on a board, starched and then beaten. Vertical lines are drawn on both sides of the cloth along which folds are made. The folded cloth is sewn tightly, affixed to a circular piece of bamboo, which is inserted in a bamboo tube and steamed. It is then removed and air dried.

It would seem that an even fabric construction and the addition of substances to retain pleats also assist the pleating process itself.

2.4.3.1.3 Shibori

Shibori is a Japanese resist dye process by which a textile may be given a three-dimensional form. Prior to being dyed, fabric is manipulated by a variety of techniques such as folding, pleating, binding, twisting, crumpling, knotting or any other method which distorts the textile. During a subsequent process, shape is held in place by binding with string, stitch, knotting or clamps. This usually involves the application of heat and dye liquids. When unfolded, the textile will retain the "memory" of this process. Thermoplastic materials will permanently crease along the fold lines.

Wada described how pleats may be used in traditional shibori designs. (Wada, 1983, 103-122) *Arashi* is the name of one such shibori process where fabric is wrapped around a cylinder and secured. (Wada, 1983,125) Thread is then wound tightly onto the cloth or the cylinder is rotated while the thread is held under tension. Periodically, the thread wound cloth is pushed up the cylinder compressing the fabric into folds. Variations may be achieved by placing the fabric on the cylinder on the bias. The fabric may also be twisted while being compressed. Sparks describes this process as a way of creating pleated fabric similar to that made by Fortuny referred to later in this section. (Sparks, D., 2005, 38-43)

Mura Kumo shibori is a clamped method of creating finely pleated fabrics. (Wada, 1983, 137) A tube of fabric is inserted over a pole, compressed and clamped. It would then be placed in a dye bath or could be steamed.

A contemporary shibori pleating method has been devised by Hiroyuki Shindo. This was demonstrated in the Indigo exhibition (Whitworth Gallery, 2007). A long length of fabric is tensioned between two large cylinders. The fabric on one cylinder is flat and unfolded and that on the other, pleated along the length of the fabric. To introduce pleating, the fabric between the two cylinders, is pleated or crimped by hand and then wound on. The next section of fabric is pleated and the process is repeated until the whole length is hand crimped. Shibori dyeing methods are used to colour and permanently crimp the material. The vertical pleats obtained by this method are not even along the length of the fabric.

Resist dye techniques historically form part of the textile cultures of many parts of the world. Tie-dye, a technique similar to shibori, was assimilated into western culture in the 1960s stimulated by eastern travel. A general interest in new processes and surface design developed in the United States and Europe from the 1970s onwards, which encouraged a western interest in shibori. This interest was further stimulated by publications on techniques and exhibitions. (Wada, 2002, 45) In post-war Japan, the change to western dress resulted in a decline in shibori produced textiles. To survive, artisans looked at developing new methods and to reintroducing old techniques resulting in the first International Shibori Symposium (ISS) being held in 1992. (Wada, 2002, 71) Examples of contemporary three-dimensional shibori textiles may be seen in Figure 19. These are excellent examples of how a traditional craft technique has been adapted and enhanced by the use of new technology and new materials, resulting in a change of emphasis from colour to form. A US patent (5356055,18 October 1994) describes the process for producing the garment on the right. It is fully constructed, folded and wrapped and then placed in a cylinder to steamed to retain the pleats.

Figure 19: Left, detail of costume for *The Lion King*. Joan Morris (Wada, 2002, 71) and right, Issey Miyake. Autumn/Winter 1993/4. Partial crushed and tied polyester. (Wada, 2002, 78)

2.4.3.1.4 Fortuny

Mariano Fortuny, inspired by an ancient Egyptian torso of an Armenian princess (de Osma,Guillermo, 1994, 84), created the ‘Delphos robe’ which first appeared in 1907, from very finely pleated silk. See Figure 20. He patented a pleating process in 1909, which describes a system for vertically pleating and horizontally undulating silk with heated ceramic tubes. (Fortuny patent 414.119, 10 June 1909) It is not clear how the silk was pleated but according to de Osma, it is likely to have been applied manually. Dresses were best stored rolled and twisted tightly into a ball.

Figure 20: Left, Fortuny patent 414.119, 10 June 1909 for a machine to pleat and undulate silk used in the *Delphos* dresses, shown right. (Desveaux, 1998, 75-76)

2.4.3.1.5 Pleating Patents

A number of patents for the pleating of fabric have been issued. Some of these relate to pleating machines, others to manual methods of pleating fabric and methods for retailing pleats. The patents of Fortuny and Miyake have already been mentioned. An innovative example making use of technological developments in textile materials is a method for stitching thermo-shrinking fabric with water-soluble threads in rows. (US patent 6423165, 23 Jul 2002) When heated, the surface texture of the garment becomes three-dimensional. The patent makes provision for using fabrics of different weights and construction, which respond in different ways to temperature. No evidence was found of patents that relate to the structured pleating on previously cut or printed fabric.

2.4.3.1.6 Issey Miyake

Issey Miyake, the Japanese fashion designer, experimented with pleating prior to launching his *Pleats Please* collection in 1993. Miyake developed an innovative process using predominantly synthetic fabrics or blends of fibres that he developed. He utilized two techniques, firstly pleating prior to construction and secondly fully constructing the garment much larger than required and then pleating. This may be seen in Figure 21.

Figure 21: Left, Miyake grey skirt. Panels pleated while folded then seamed. 65% polyester, 35% silk. Victoria & Albert Museum T.266-1994, right, Miyake grey/black top with hooked sleeves constructed prior to pleating. Polyester. Victoria & Albert Museum T264-1994

The industrial pleating process involves garments being hand fed into a heat press sandwiched between sheets of paper. This process permanently pleats the fabric in very narrow pleats with a hard sharp pressed edge. Depending on the type of fabric used, the garments may be machine washed and dried without ironing. He also developed designs, which contained printed images that contracted after pleating. Examples were contained in his Pleats Please collection (Braddock and O'Mahony, 2005, 172)

In 2010, Miyake launched a new concept in pleated garments which has been called "132 5". Research was undertaken by Miyake's Reality Lab and was based on mathematical folding of paper. (Dezeen, 2010) This collection consists of folded two-dimensional forms, which become three-dimensional garments when unfolded. An example may be seen in Figure 22. Materials used for the production of these are 100% recycled polyester fibres using a process developed by Teijin Ltd.

Figure 22: Miyake "132 5" collection launched in 2010 using the concept of two-dimensional folding that becomes a three-dimensional garment. The shape on the left unfolds into the dress on the right

2.4.3.1.7 Template Pleating

This method, seen at F. Ciment Ltd, a company dating from the 1920s based in Potters Bar, and also carried out by a few companies in France such as M Serge, Paris (Vasseur, 2002, 76) and Gérard Lognon, Paris. (Vasseur, 2002, 81) It is used for high-end fashion and in the entertainment industry. Apparently dating from the end of the 19th century, the method uses two identical brown paper patterns as a mould to pleat panels of fabric. (Ciment, 2007) The maximum size of a panel is determined by the size of pattern. Paper patterns are made from a very thick paper, which can withstand being steamed repeatedly. They are scored by hand and manually folded to produce a surface texture, taking up to 40 hours to produce a single pattern depending on complexity. Paper patterns are lightly waxed with a candle to allow the fabric to move easily. Designs vary from very simple to complex using folding techniques reminiscent of origami and may be applied to different fabric types as long as the fabric may be steamed.

To pleat a panel, a pre-folded pattern, one half of a pair, is spread out flat on a large table, clamped on one end and weighted on the other. Ironed fabric is placed smoothly on top. The second pattern is placed on top of this with corresponding folds matching the underneath pattern. The three layers are clamped, weighted and gradually encouraged to concertina by hand until the whole set of patterns and fabric is compressed into the predetermined folds. Depending on the design, this is rolled inside another piece of paper and tied or just fixed at each end.

Figure 23: Templates used for template pleating. Atelier Gérard Lognon (Trebbi, 2008, 68)

Fabric is steamed for between 12-20 minutes depending on the type of fabric and allowed to cool. Patterns from manually pleated fabrics are unrolled and the fabric removed. Patterns are used several times over until they tear or are damaged. Synthetic fabric, wool and silk retain the pleats when washing. Shrinkage is determined by the fabric composition and construction, and contraction by the design chosen. Some designs are heat fused onto a backing fabric to stabilise the folded fabric. This is done machine or by hand with an iron. Some designs are pleated twice – once in one direction and then again in another. This creates an effect similar to the Egyptian design shown in Figure 15. Figure 24 and Figure 25 show fabric folded by template pleating.

Figure 24: Left traditional origami design, right, basket weave. Polyester. (F Ciment Ltd)

Figure 25: Origami design. Both the manufactured suede (left and polyester chiffon (right) have been pleated using the same template (F Ciment Ltd)

2.4.3.1.8 Nuno and Reiko Sudo

The Japanese company Nuno together with designer Reiko Sudo has experimented with a combination of craft techniques and modern technologies to reinvigorate textile production. An example of this is the origami pleated scarf shown in Figure 26. Fine polyester is folded by hand according to an origami design, which is similar to that in Figure 24 (left) albeit at a different scale. The folded fabric is transfer printed in a heat press, which allows the folds to be set and dyes to permeate the fabric.

Figure 26: Nuno, origami pleated scarf. Victoria and Albert Museum T.124:1-1998

2.4.3.1.9 Inoue Pleats Company

The Inoue Pleats Company was established in Fukui, Japan in 1943 (Moma, 1998) and was the first company to produce pleating in Japan on a large scale. (McCarty, McQuaid et al. 1998) They use and have developed several methods including crushed pleating which results from placing thermosetting polyester fabric inside a small container, machine pleating and a variety of designs achieved with manual pleating and heat setting. See Figure 27.

Figure 27: Left, Square L, 1996, centre, Wrinkle P, 1992, right, Blizzard, 1996 all Inoue (McCarthy & McQuaid, 1998, pp. 76-78)

2.4.3.1.10 Princess Pleater

The Princess Pleater is a manual machine with rollers designed to enable narrow widths of up to 9 inches fabric to be evenly pleated for use with smocking where stitches are applied to a pleated surface. During the pleating process, a set of three interlocking rollers are turned by hand and gathering stitches are inserted by forcing the fabric on to a pre-arranged set of up to 24 gathering needles. Whilst it is possible to change the spacing of the threads by removing needles, it is not possible to alter the length of the stitches. The machine therefore is only able to pleat to one design. There is also a limitation of the thickness of fabric that may be pleated. (Princess Pleater, 2007)

2.4.3.1.11 Fluting irons

Other manual methods have been used to pleat fabrics. Towards the end of the 19th century, there was a fashion for pleated collars and cuffs. Fluting irons and crimping machines were devised. Jewell describes some of these patents and shows examples from England, Europe and the United States. (Jewell,1977). These devices were limited in that they pleated only narrow widths of fabrics and only one specific design.

2.4.3.1.12 Machine pleating

Industrial pleating machines have been developed to allow continuous lengths of fabric from narrow width ribbons to full width apparel textiles to be pleated.

Fabric may be passed between one or two sheets of thin crepe type paper. Depending on the machine and the type of fabric being pleated, the paper may vary in weight between 22g and 80g. (Vasseur, 2002, 78) Rollers lightly heat the fabric so that it temporarily adheres to the paper. Fabric and paper together then pass through shaped rollers, which mould the fabric into pleats. Depending on the fabric composition, this heating may be sufficient to permanently set the pleats. In other cases, the pleated paper and fabric are then steamed to set the pleats. Various designs are possible by altering the rollers that are used resulting in pleats of different sizes and different spacing between them. This method is able to produce very precise pleats. An example may be seen in Figure 28 (right).

Figure 28: Machine pleating. Left semi structured pleating, right, even machine pleating. (F. Ciment Ltd)

Another machine design produced semi structured pleats. (Figure 28 left) The machine contains a number of grippers which are positioned across the width of the fabric. These may be individually controlled by software to pinch pleat the fabric in a forwards or backward folds as it is passed through heated rollers. Combinations of these determine the pattern that is produced. A limitation of this method is the lack of precision of individual pleats and the types of fabric for which this method is suitable. Knife pleats used in filters are pleated using a machine where a horizontal blade pushes the fabric downwards. It is then compacted forming the pleat. Controlling how far the blade moves down, determines the size of the pleat. A fourth machine type produces completely unstructured pleats. It uses a methods based on a shibori technique where fabric is compressed into a cylinder and streamed to set the folds. An example may be seen in Figure 27 (centre).

2.4.3.1.13 Janette Matthews

The previous work of the author uses pleating in conjunction with cuts on predominantly natural fabrics to create three-dimensional surfaces. Examples may be seen below. A design made up of structured cuts is designed using Adobe Illustrator and laser cut onto fabric. Using hand manipulation and the application of heat from a domestic iron, pleats are set in place usually at right angles to the cuts. Millinery irons are used for small pleats. Starch may be required depending on the fabric type to set the design. The process is very timeconsuming as each pleat needs to be folded and set by hand. The structured pleating is varied by pleat size, spacing, fold direction and cut angle.

See examples in Figure 29 and Figure 30.

Figure 29: Laser cut and hand manipulated cotton. Janette Matthews 2006

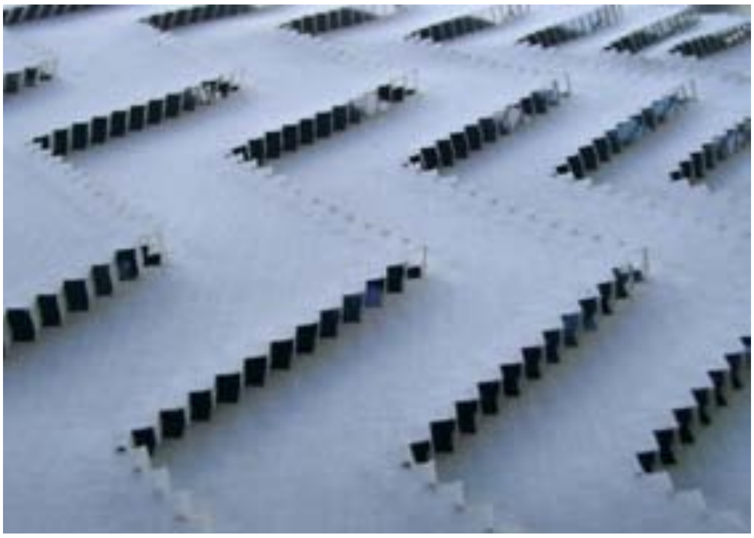

Figure 30: Laser cut and hand manipulated linen. Janette Matthews 2006

2.4.3.1.14 Pleating summary

This section considers the issues related to the pleating of textiles. The review of historical and contemporary processes and the author's own practice has enabled the following conclusions to be made:

In order to form pleats in a length of fabric, folds need to be formed. Folds may be formed by hand, manually with the assistance of tools such as moulds or metal tools to score lines or by machine. The composition and structure of the fabric, the grain, the weight of the fibres and the finishing of the fabric all influence the ease of folding. In addition the position of pleats, and the quantity and scale of pleats make folding more or less difficult. These factors all inter-relate. As an example, it is easier to pleat an even, close weave, stiff fabric, along the grain.

The issue of placing pleats is a further complication if a printed or woven design is taken into account or, as in the author's work, pleats are required to be placed precisely adjacent to cuts.

A second issue is pleat retention. This usually involves setting the folds either with heat or some form of glue-like substance e.g. starch. In addition, the folds need to be held in place while the setting takes place. Often stitches or some form of clamping or binding are used. The ease of achieving this again depends on the fabric type and construction and the pleating design. The setting of pleats is not necessarily permanent. A development of the pleating process will be described in depth in chapter 5.

2.4.3.2 Moulding

Textiles may also be formed into three-dimensional surfaces through the use of moulds. Various techniques have been developed to enable materials to take on the form of the mould. Some are:

- Vacuum moulding where fabrics coated in liquid resins are laid in moulds and set under pressure and heat. This process is used with textile carbon fibre composites for the manufacture of body parts for the automotive industry.
- Soaking a fabric in various liquids which when dried naturally or baked allow the fabric to retain the shape of the mould
- Applying heat to thermoplastic materials clamped between positive and negative mould forms

In her PhD thesis, Baurley (1997) researched various aspects of moulding fabrics and methods for creating moulds including fabric formed from the mould of a hand. Figure 31 demonstrates moulding techniques to create garments from fine organza. The mould to create this bodice is made from wood. A limitation of this process is the shearing ability of a fabric. Densely woven, thick fabrics are less successful.

Figure 31: Yoshiki Hishinuma. *Fish Dress*. Spring 1997. Heat transfer on moulded polyester. (Braddock & O'Mahony, 1998, 128)

2.4.3.3 Formed three-dimensional textiles summary

This section has reviewed processes that are used to form existing two-dimensional textiles into three-dimensional textiles. Although *shibori* techniques are able to produce very interesting three-dimensional textiles forms, much work has already been done in this area. With the development of thermoplastic fibres and finishes, pleating techniques however, are of interest for investigations into techniques to produce three-dimensional solid forms and textured surfaces. Research into pleating techniques is detailed in chapter 5.

2.4.4 Techniques

The techniques to create three-dimensional textiles, may be summarised as joining, cutting, forming or embellishment techniques. Table 2 shows an analysis of the techniques used to create the three-dimensional textiles that have been discussed. In many cases several techniques are used. Traditionally, the technique most commonly used for joining is stitching. The interface or joint where two or more pieces of material are joined by stitch is known as a seam. Factors that determine the type of seam to be used are aesthetic appeal, strength, durability, comfort, ease of assembly, equipment and cost. Synthetic materials and the demand for performance textiles have driven alternative joining methods to be considered. Stitch may weaken a material at the seam joint, the place where extra strength is required, and the extra layers of material make a seam less flexible and consequently affect comfort and performance.

Other joining techniques are in use, namely fusing, welding and adhesive bonding. Fusing uses thermoplastic resins, which are initially applied to a material. The application of pressure and heat or steam enables the layers to be fused together. Welding is a thermal process, which melts fabric fibres, a thermoplastic coating or a film at the join surfaces. Heat in welding processes is applied by different methods – heat sealing, ultrasonic welding, laser welding and dielectric welding. Adhesive bonding uses an additional material at the interface between the fabrics to be seamed, which reacts either chemically or mechanically causing joining. The above methods have varying amount of success in terms of production speed, ease of application, strength, appearance and materials that may be used.

	Joining	Cutting	Forming	Embellishment
Constructed				
Loom woven	x		x	x
Off loom				
Knitted	x		x	x
Crochet	x			x
Lace	x	x		x
Braiding	x			
Tufting	x			x
Non-woven				
Felt	x		x	
Needle felt	x		x	x
Bonding	x		x	
Lamination	x		x	
Applied				
Stitch	x	x		x
Embroidery	x		x	x
Welding	x			
Machine sewing	x		x	x
Quilting	x		x	x
Appliqué	x	x	x	x
Cutting		x		x
Printing				
High relief			x	x
Embossing			x	x
Flocking			x	x
Resins			x	x
Burn out		x	x	x
Laminates	x			x
Digital printing				x
Formed				
Pleating			x	
Shibori			x	
Moulding			x	

Table 2 : Three dimensional textiles and the techniques that are used to produce them indicated by 'x' in the corresponding row/column

Cutting is used extensively in textile production, both as is demonstrated here for embellishment, but also for garment construction. Cutting is either done by hand using scissors or knives, or by machine using powered scissors, a round knife, a straight knife, a band knife, servo assisted cutting, press cutting and computer controlled laser cutting systems.

Opportunity arises through the innovative use of materials and techniques. This research will describe a new process for pleating textiles and two new processes for embellishing textiles, one that uses additive techniques and one that uses subtractive techniques. These new developments all make use of laser processing. The next section reviews the current use of laser processing with textiles.

2.5 Laser Processing of textiles

Laser processing of textiles is embedded in the industry as a textile manufacturing tool for cutting and marking or engraving. The first demonstration of a laser took place in a research laboratory in California in May 1960 and systems began to be manufactured commercially during the late 1960s. (Ion, 2005,1) The CO_2 laser, commonly used in industry today for the processing of textiles, was developed in 1964 at Bell laboratories, New Jersey and first commercialised by Coherent two years later. (Steen, 2003, 3) Adopted first by the automotive industry, laser-fabricated products came into wide use during the 1980s. This section will describe the laser equipment currently in use for processing textiles, consider applications and review new trends to identify opportunity.

2.5.1 Laser cutting and engraving

Textile manufacturing uses predominantly CO_2 lasers at the lower end of available power ranges namely 10W – 200W. The laser beam interacts with the fabric thermally creating a cut or a mark depending on how much energy is provided. This will be explained in more detail in chapter 4.

Two systems are manufactured to enable textile processing, namely laser cutters and laser engravers. Flatbed laser cutters allow fabric to be laid across a flat surface and the laser beam is delivered via a nozzle which moves just above and over the fabric area. These systems are available in varying sizes depending on the textile application. As an example, the entry model from *Eurolaser* has a working area of

327mm x 635mm and the largest system they manufacture has a working area of 3240mm x 3000mm. (Eurolaser, 2010) Companies that process large applications such as yacht sails use lasers with beds of up to eight metres in length. (Automated Cutting Services, 2010)

Laser engravers allow the beam to be directed via galvanometer mirror systems onto the fabric. Working areas are much smaller but processing speeds are very fast. A system from *CadCam Technology* has a working area of 1,800mm x 1,500mm and a maximum processing speed of 24,000mm/s. (CadCam Technology Ltd, 2010) In contrast, the *Eurolaser* systems mentioned above have processing speeds of 3,810mm/s and 1,000mm/s respectively.

Depending on the application and fabric type being processed, systems allow single or multiple sheets of fabric to be processed, roll-to-roll lengths or whole garments. Laser systems are controlled by specialist software and both vector and raster images may be processed. This will be discussed further in chapter 4. Optical recognition systems enable for example automatic cutting of pre-printed designs.

Recent developments include the integration of laser cutting and other textile manufacturing systems. An example is the laser bridge system from *Seit,* which combines a laser cutting system with multi-head embroidery systems for appliqué applications. (Seit, 2010) Advantage is also gained by using manufactured fibre fabrics as the edges are simultaneously sealed by the laser beam, which prevents fraying.

2.5.2 Laser textiles applications

Laser cutting and marking may be achieved by both cutting and engraving systems. Laser cutting offers several advantages to the textile industry as it enables intricate patterns to be cut with accuracy without tooling coming into contact with material in contrast to blade cutting, for example. The cutting operation is under software control. Consequently there is a lack of tool wear and the process allows for repeatable designs and the ability to change designs easily without retooling.

Applications include the cutting of sail cloth, parachute and kite material, embroidered emblems, drapery, fashion fabrics and lace. Laser processing is used in the automotive industry for the cutting of airbags, seat belts, seat covers and carpets.

Integrated badge making and labelling systems are available which enable the embroidery or printing of labels and motifs followed by cutting out of shapes by laser. (Steen, 2003,142)

Laser engraving is used extensively in the finishing of denim where it may be used to selectively remove synthetic indigo dye from the fabric surface, often on fully constructed garments. *Technolines* who own a number of US patents offer systems for the patterning of denim, leather and other fabrics. Their process offers an alternative to sand blasting, significantly reducing the loss of fabric strength and environmental issues associated with the traditional process. (Technolines, 2009)

Limitations of the process relate to the materials that may be processed. As will be explained in chapter 4, charring which results from the processing of natural fibres is usually not aesthetically acceptable to the apparel market. It is also generally not possible to cut fabric stacks making the process is more suited to single layers.

2.5.3 Laser welding

As an alternative to the stitching of seams, TWI has developed a laser welding process, *Clearweld* which may be used with thermoplastic textiles. A purpose developed film is applied to the joint interface. (Clearweld, 2006) This assists the absorption of laser energy causing localised melting and fusing forming a stitch-less, water-resistant seam. The method retains the flexibility of the seam and does not materially affect appearance. Applications have included airbag construction, bed assembly, medical furniture, protective clothing and inflatables. There are however manufacturing issues concerning the tensioning of fabrics during welding, welding curved surfaces, multiple layers and complex shapes.

2.5.4 Laser sintering

Selective laser sintering was invented by Ross Holder in 1979 and commercialised in the late 80s. (Hopkinson et al, 2006, 64) The concept of laser sintered textiles was originated by Jiri Evenhuis in 1999. (Freedom of Creation) The process uses an additive manufacturing technique, the building of three-dimensional forms layer by layer with laser sintered polyamide powders, to produce three-dimensional garments and accessories with a construction similar to chainmail. The first commercial products of this type were marketed by *Freedom of Creation* in 2005. (Freedom of Creation, 2006) Figure 32 shows an example from the current product range.

Figure 32: Laser sintered bag (Freedom of Creation, 2010)

Research was conducted in this area by the Additive Manufacturing Research Group at Loughborough University in collaboration with Freedom of Creation and the Rapid and Bio Manufacturing Research Group from the University of Liverpool. Bingham's PhD thesis examined modelling and the generation of data for three-dimensional textiles produced by these methods (Bingham, 2007) The current AHRC and EPSRC funded *Considerate Design* - *Evolving Textiles* project led by Dellamore at the London College of Fashion aims to create body conformable seamless and flexible textile structures using rapid manufacturing. (Considerate Design, 2010)

2.5.5 Designers using laser techniques

Increasingly designers are using laser techniques for achieving both cutting and surface patterning. Examples are Daniel Herman, a Swiss fashion designer who graduated from Central St. Martins College of Art and Design, produced a collection, which exploited the concept of light using laser-cut latex.

Janet Stoyel founded *The Cloth Clinic* in 1994 was short listed for the *Jerwood Prize for Applied Art* (1997). She has experimented with laser cutting and laser marking of both natural and synthetic fabrics and leathers as well as the use of ultrasound techniques for sealing layers, seams and trapping fabrics between layers. Stoyel has worked with several leading fashion designers such as Paloma Picasso, Paul Smith, Helen Storey, Donna Karan, Joe Casely-Hayford, Philip Treacy and Gucci. (Cloth Clinic, 2006)

While conducting doctoral research at Loughborough University School of Art and Design, (2006) Bartlett experimented with lasers for etching and cutting in fashion applications. She collaborated with *Boudicca* on several collections.

Eugène van Veldhoven is a Dutch textile designer specialising in print and surface techniques. Laser cutting, ultrasonic welding and pleating are among the techniques that he uses. (dutchtextiledesign, 2010)

In 1998, the Swiss textile manufacturer Jakob Schlaepfer adopted laser cutting technology as one of their production methods. They continued with research and development in this area and in 2006 invested in equipment that combines embroidery and laser processing. (Jacob Schlaepfer, 2010) Jakob Schlaepfer view laser technology as an integral part of their innovation process and are currently actively involved with research into lasers and advanced materials. (Huddlestone and Whittaker, 2009). They have produced fabrics using laser processing for several design houses such as Creation Bauman, Chanel and Dior. Figure 33 shows detail of laser cut and laser etched suede from a dress from by John Galliano Fall/Winter 1996/97 collection. (Metropolitan Museum of Modern Art, 2005.46)

Ann Smith conducts research as part of the Textile Futures Research Centre (University of the Arts, London). Her project entitled *Altered States* focuses on the exploration of the aesthetic and commercial viability of the application of laser cutting. (Smith, 2010)

Figure 33 : Dress and detail (right). Laser cut suede. John Galliano 1996/97. Metropolitan Museum of Modern Art 2005.46

Laser processed garments are increasing to be found on the high street. An examination of products during spring/summer 2010 showed that laser processing was used by both Ted Baker and Karen Millen for embellishment of ladies clothing. Figure 34 shows a skirt (27S03YLPL) made from laser cut sold by TopShop. (TopShop, 2011)

Figure 34 : Laser cut skirt. TopShop. (27S03YLPL 2011)

2.5.6 Laser processing summary

This section has described the current use of laser technology with textiles. It is clear that lasers play a role in fabric finishing in both high-end couture fashion, mass market applications such as decoration of jeans and in large scale industries such as automotive. Machinery manufacturers have developed systems to process high volumes of fabric and are integrating laser technology with other textile manufacturing processes. A limitation of the process is thermal degradation. All laser processing of textiles described here occurs at the end or near the end of the textile manufacturing process. The cost of laser processing equipment is reducing dramatically making the technology more accessible both to textile manufacturing companies and designers. A medium sized flatbed 40W laser cutter may be purchased in the UK for under £5,000. (HPC Ltd, 2010) Opportunity arises from integrating laser processing earlier in the manufacturing chain. A new process that does this is described in chapter 6. A new process that combines laser processing with pleating is detailed in chapter 5. A new application of laser sintering directly on textile substrates is explained in chapter 7.

2.6 Other trends

This section discusses trend in textile manufacturing and design that are creating opportunities and therefore relevant to this research.

2.6.1 Smart Textiles

Smart textiles is a term which refers to group of textiles also known as intelligent or technical textiles. The term 'technical textiles' was developed in the 1980s to refer to textiles developed more for their technical properties and manufacturing techniques rather than their appearance. Hongu describes 'tech-textiles' as being employed in a wide range of

> *"high technology areas including the aerospace industry …, the transportation industry (as tyres), the marine industry (as ropes and fishing nets), the civil engineering and construction industry (as re-enforcing materials) and the sports industry (as tennis rackets, golf shafts and ski plates*)." (Hongu et al, 2005,1)

These textiles take their input from a range of disparate sectors - science and technology, design and human sciences and their development requires cross-disciplinary research. To promote this in the UK, the EPSRC funded *Smart Textiles Network* which was formed in 2004 to promote and stimulate development and comprised the following industries – "application based industries; defence industries; cognitive and social scientists; computer scientists; electronics specialists; electrochemistry specialists; textile and fibre engineers; fashion, textile, industrial, interior and architectural designers; economists; future trend forecasters." (Smart Textiles Network, 2006)

As has already been discussed, materials play a pivotal role in the development of textiles. The development of products using smart textile technologies is closely related to how the materials respond under certain circumstances. The grid in Figure 35 shows how selected smart materials may respond to external stimuli. For example a textile printed with thermo-chromic inks will experience optical changes when exposed to heat.

The technical textiles sector in the UK is already of economic importance, £1.3 Billion per annum and worldwide accounts for around 25-30% of all textile manufacturing. (Byrne, 2006) The *Techtexil* exhibition, first held in 1985 to reflect the growing interest in technical textiles, is now held biennially alongside *Avantex* to present the latest developments in smart and intelligent textiles to garment manufactures and fashion designers. (Avantex, 2006) *100% Materials* showcases new materials in this area annually at *100% Design*, a trade fair held in London in October each year. (100% Design, 2008)

Response					
Stimulus	Electrical	Magnetic	Optical	Thermal	Mechanical
Electrical			Electrochromic Electrolumin-escent Electro-optic	Thermo-electric	Piezo-electric Electrostrictive Electro-rheological fluids
Magnetic			Magneto-optic		Magnetostrictive Magneto-rheological fluids
Optical	Photoconductor		Photochromic		
Thermal			Thermo-chromic Thermolumin-escent		Shape memory
Mechanical	Piezo-electric Electrostrictive	Magneto-strictive	Mechanochromic		Negative Poisson ratio

Figure 35: Stimulus –response matrix for selected smart materials (Smart Textiles Network)

Some products using smart textiles are finding their way into the market place. Relevant to this research is the development of electronic textiles, which use fabrics that include conductive fibres to conduct electricity and transfer information. Quinn describes three possibilities – threads coated with metals, threads made from metals or conductive polymers and the incorporation of minute silicon chips and components (Quinn, 2010, 10-11) Examples are sportswear that can monitor your heart rate such as the Cardio shirt from *NuMetrex* (NuMetrex, 2011), jackets with inbuilt iPod controls such as ski wear (Tog24, 2011) and roll up textile keyboards for laptops. (Elektek, 2010) Other areas that are benefiting are the military, police and emergency services through equipment for protection from hazards arising from heat, fire and radioactivity and chemicals, climatic, electrical and mechanical situations. Quinn gives examples of fabric that can withstand temperatures of $3000C^0$ (Quinn, 2010,

262) and suits that protected workers from radioactive debris post Chernobyl. (ibid, 263)

Nanotechnology developments are adding exciting properties to textiles. It is possible to produce, among others, medical textiles that promote faster healing, fabrics that have scents embedded and textiles that stay clean. Future applications will be for healthcare where innovative technologies such as micro-encapsulation for drug delivery is being developed. (Institute of Nanotechnology, 2011) Marks and Spencer currently utilise this technology in a range of clothing under the brand Stormwear™ including jeans,100% cotton trousers and 100% wool suits which have been treated to make them shower proof yet still washable at 30°C. (Marks & Spencer, 2010) Key drivers that will influence how smart textiles develop are the sympathetic integration of materials and devices, miniaturisation, durability and cost.

2.6.2 **Sustainability**

Increasingly manufacturers and consumers are aware of the need to use sustainable raw materials and processes that do not harm the environment. Writing in her book on design for sustainable fashion and textiles, Fletcher (2008) describes sustainability as a complex issue incorporating diversity of materials (raw materials renewability, biodegradability, chemical, water and pesticide use and pollution); ethical production (from raw textile fibre to finished textiles included manufacturing and labour); use (environmental impact from use, laundering, production and disposal); and re-use, re-cycling/re-processing and zero waste. Fletcher argues for initiatives to be embraced by designers as a vehicle for social change.

Some companies are supporting these. An example of the use of materials is *Sustainable Cotton* where disease resistant varieties are grown organically without the use of synthetic fertilisers. Fibre production is achieved using methods, which avoid the use of chemicals. (Sustainable Cotton, 2010) Raw materials are recycled and reused. *Patagonia*, an outdoor clothing manufacturer, makes polyester fleece from fibres manufactured from plastic drinks bottles. (Patagonia, 2010)

Not all these processes are environmentally sustainable however as often there is an impact on water usage and yield. However sustainable methods are being integrated into textile supply chains and consumers are becoming more conscious of individual responsibility. Levi Straus have announced their Water<Less jean technology which

reduced the water consumption of their manufacturing process for their products by between 25% and 96% (Levi Strauss, 2010)

Designers are playing an important role is raising profile and testing ideas. An example is TED, the Textiles Environment Design network, which was established in 1996 to examine the way in which designs can influence sustainable design and provide a toolbox of design-led solutions. Outcomes have been presented in exhibitions such as the Craft Council's touring exhibition *Well Fashioned Eco Style in the UK.* (March 06/March 07) raising the profile of these issues amongst the general public.

Cradle-to-Cradle certification by MBDC assesses a product's safety to humans and the environment and design for future life cycle against criteria in five categories - Material Health, Material Reutilization, Renewable Energy Use, Water Stewardship, and Social Responsibility. Their website shows evidence of take-up of certification by a number of large manufacturers and product specifiers. (MBDC, 2011)

2.6.3 Biomimicry

Biomimetics is defined by Abbott and Ellison as "developments informed by biological structures that aim to transfer functional properties of biological 'mechanisms' into the man–made world". (Abbott and Ellison, 2008, 117) A well known textile application of this was the invention of Velcro in the 1950s, which used a system of hooks modelled on the burr. (Abbott and Ellison, 2008, 118) A methodology of extracting solutions from observing nature in detail is leading to innovation in engineered textile solutions. An example is *Fastskin®* launched by *Speedo* in 2004 which looked at the surface qualities of sharkskin as it moved through the water and designed textiles for swimwear to offer similar advantage. (Speedo, 2010) A further development took into consideration the formation and placing of seams to direct drag to where it is most useful. Another illustration is given by Rossback et al. *Morphotex* manufactured by the Teijin Fibre Corporation displays colours of blue, green and red, which are achieved structurally without pigments by constructing a fibre that is manufactured from alternate layers of nylon and polyester. Inspiration for this was the South American Morpho butterfly. (Abbott and Ellison, 2008, p127) These examples illustrate advantage that may be gained from collaboration between researchers in different disciplines.

2.6.4 Cross disciplinary studies

There is increasing evidence of the potential for new opportunity that may be gained through cross-disciplinary investigation. Japanese textile and fashion designers excel in this area. An example is Issey Miyake who worked from the beginning of his career in the 1970s with technologists developing and incorporating new fabrics and new technologies. (Fukai et al, 2010, 85) Another is Junichi Arai who cofounded the Nuno Corporation that develops and produces innovative functional fabrics. (McCarty and McQuaid, 1998, 102) Cross-disciplinary research is also conducted in the United Kingdom. Hemmings describes three cross-disciplinary studies employing fashion designers and chemists - *Victimless Leather*, a Tissue Culture and Art project, Suzanne Lee's *Bioculture* and Helen Storey's *Wonderland* – that investigated textiles as a second skin and brought together "the art gallery, science laboratory, and class room ... as places where textiles and fashion can provoke renewed debate, demand reconsideration, and suggest alternative materials for our future use." (Hemmings, 2008) In his book *Textile Designers at the Cutting Edge*, Quinn (2009) provides many examples of innovative textiles for fashion, interiors and architecture that have arisen through collaborations between textile craft practitioners and engineers or scientists. It is clear that the fusion of ideas and practice lead to exciting new developments.

2.7 Conclusion

The work described in this chapter has reviewed textile manufacturing and three-dimensional textiles. Although not exhaustive, it has provided an overview of the various stages in textile production and discussed most techniques to create three-dimensional textiles. A categorisation of these textiles and the relevant processes was made. The review has informed understanding and demonstrated that techniques exist to make these textiles by construction, by additive and subtractive processes and by reforming two-dimensional materials.

A forming process, fabric pleating was examined in detail. The review showed that although it is possible to fold fabric using a range of manual and industrial methods, no processes were found that enabled previously cut fabric to be pleated. Industrial machines are limited to horizontal pleating and freedom of design is limited. The research described in chapter 5 responds to this opportunity and develops a process for pleating with full design freedom. The new process has application not only in fashion and interiors, but other areas such as architecture and works with both textile and non-textile materials.

The review examined applications for laser processing and showed that although laser processing is used extensively in textile manufacturing, negative effects of the process limit further take-up of the technique, particularly when it is applied to natural fibres. Chapter 6 describes research for three-dimensional surface patterning that addresses this issue on cashmere, a luxury natural fibre, and shows that by intervening earlier in the manufacturing cycle, not only may the effects be mitigated but that laser cutting and etching may be employed to add value to woven textiles. The process has potential to be applied to other natural fibres.

Other applications for laser technologies were investigated. It was shown that although additive manufacturing techniques are used to manufacture a limited range of textiles from polymers, no evidence was found of this process being applied directly onto woven textiles. In addition, the review gave examples of how the development of smart textiles is providing an impetus to textile innovation. The research in chapter 7 details a new process using additive manufacturing and woven textiles, which could have application for both smart textiles and three-dimensional surface patterning.

From this review, it is clear that opportunities for design arise through a combination of three elements – processes, materials and interventions at different process stages. Both the application of non-textile techniques to textile materials or the re-invigoration of traditional textile processes with new materials give rise to new opportunities. Inspiration for the development of new textiles and novel processes may be generated by and achieved through the collaboration of designers and researchers from different industries and disciplines. The following chapter describes the methodology that has been adopted for the validation and communication of this research.

3 Methodology

This chapter describes the methodologies and methods used in this research. It has already been explained that this is cross-disciplinary research situated in the discipline of art and design but informed by the field of engineering. The methodology chosen to conduct the research must be appropriate for such a study. Initially the nature of research is considered. Research in the two domains of science and art, craft and design is discussed. The current debate concerning research in the field of art and design and the integration of practice with research is also highlighted. The chapter concludes with an explanation of the selected research methods for cross-disciplinary research to inform textile design and manufacture.

The terms used in this chapter are defined to add clarity

Art, craft and design. *T*he definition of *Art and Design* for research submissions used by the National Research Assessment Exercise for the Art and Design unit of assessment (UOA 63 Panel O) says that it

> "encompasses all disciplines within art and design, in which methods of making, representation, interrogation and interpretation are integral to their productions." . (RAE 2008)

The statement goes on to say that research assessed would include "applied arts and crafts" and "design". The term *art, craft and design* has been adopted here to reflect the fact that this research, whilst located in the discipline of art and design, is applied craft.

Design in this context refers to the broad discipline, which encompasses thinking, pure and applied research, problem solving and practice. Design is both a verb and a noun and is clearly a very wide subject. Friedman (2005) describes designing as a profession, a discipline and a field embracing six domains namely natural sciences; humanities and liberal arts; social and behavioural sciences; human professions and services; creative and applied arts; technology and engineering. According to Love, it is a "non-routine human activity that is an *essential* aspect of processes that lead to a design of an artefact". (Love, 2002, 359). Schőn considers that designing is a 'reflective conversation with the materials of a situation'. (Schőn,1983, 172). The research here will develop new processes, which may be used both to design and/or create artefacts. It is hoped that outcomes will be communicated such that practitioners may use the new processes for both for design and making.

Manufacture describes the process of fabrication or creation of an artefact or artefacts either by hand or by machine or a combination of both. Intrinsic to manufacture is the concept of repeatability i.e. that following the same process with the same material or materials, it would be possible to achieve the same outcome.

Together design and manufacture define processes that start with the definition of a problem through to the implementation of a solution. In the field of art, craft and design, the solution is usually the physical embodiment of an artefact. This research is concerned with the exploration of processes that incorporate laser technology in the design process or as part of the manufacturing process. The use of laser technology will have an impact both on how a three-dimensional textile is designed and how it is manufactured and thus provides new opportunity.

Research is defined as a search or investigation directed to the discovery of some fact by careful consideration or study of a subject. It is a course of critical or scientific inquiry. (Oxford English Dictionary) Although requiring qualities such as curiosity, research is more than discovery. Phillips and Pugh differentiate academic research from intelligence gathering by suggesting that research is based on an open system of thought where data and the sources of data are examined critically, and generalized theories are developed. (Phillips and Pugh, 2005, 48-49). Gray and Malins define academic research including practice as

> "a process with explicit questions to be asked in relation to a context, a clear methodological approach, the outcomes and outputs of which are open to critical review, and the research has some benfit and impact beyond the individual practitioner researcher." (Gray and Malins, 2004,4)

In order to be able to do this, research strategies and tools need to be developed to locate the inquiry in a wider context, gather and generate information, and evaluate, analyse and interpret the evidence. These strategies and tools are known as methods and methodologies. According to Gray, the terms are often used interchangeably but there is a distinct difference between them. "Methods are specific techniques and tools for exploring, gathering and analysing information… Methodology is the study of 'the system of methods and principles used in a particular discipline'." (Gray and Malins, 2004, 17) She goes on to say that the aim of a methodology is not only to enable the products of an enquiry to be understood, but the research process itself.

As Langrish says, as academic areas are different, research questions that are asked will differ. Consequently the methods that are used to investigate them as well as the type of evidence that is acceptable to a peer group in the same area, will differ. (Langrish, 2000). As this research is cross-disciplinary, it is important that the methods used are defined in such a way that the research is both accessible and has the potential to be validated across disciplines. As Gray explains, if the overall methodology is inappropriate, then the validity of the research will be in question and similarly if there are flaws in the selection or application of methods, data will be limited in providing evidence for analysis. (Gray and Malins, 2004, 129)

3.1 Research in the Sciences

Research in the fields of science and social science have had a long tradition, over 300 and 150 years respectively, (Gray and Malins 2004,19) and as a consequence methodologies and methods are well defined. Scientific research is pertinent here as research in the engineering disciplines makes use of scientific research models.

Scientific research is defined as a “systematic, ordered investigation in which the evidences are based on observed facts rather than on personal beliefs with an aim to build generalisable knowledge.” (Antonisamy et al, 2010, 277) They expand the definition to contain three elements namely *systemisation* where work starts from a definition of a research question and proceeds in an orderly fashion with logical steps through design of the study and collection of data; *empirical evidences* where data is observed and should be “verifiable and repeatable”; and *generalisability* where the work is applicable to others. These three elements enable experimenter bias to be minimised.

In discussing research in the science tradition, Archer describes five widely accepted categories of systemic enquiry (Archer, 1995):

- Fundamental research which is directed towards new knowledge without any particular application
- Strategic research which fills gaps in fundamental research and narrows gaps between fundamental research and possible application

- Applied research which furthers knowledge for use in particular applications
- Action research which employs investigation through practical action to devise and to produce communicable knowledge
- Option research where enquiry for information is used to provide basis for decision

In classic scientific research, the research is objectified. Evidence is collected and hypotheses are proposed. Experiments are designed to test or disprove these hypotheses. Theories are developed from the validation of the hypotheses. Through thorough explanation of methods and full disclosure of results, it would be possible for a different group of researchers to repeat the body of experiments in the same way and obtain the same results, thus verifying the research. Furthermore in scientific research, the researcher is detached from the research. The research here has aspects of the above categories. It could be considered as applied scientific research as it has as it goal the generation new processes for design and manufacture. It could also be said that the research falls into the category of fundamental research as questions are asked that have no immediate application. As will be explained in more detail later, it is primarily considered to be action research because design practice is used to formulate investigation and communicate results.

3.2 Research in Art and Design

Research in the field of art, craft and design has a much shorter history and doctoral and academic research in this area is still being defined. The first UK awarded doctoral degree (PhD) in art and design was conferred in 1957 with only 138 such degrees being awarded in the period 1957-1985. (Mottram, 2009, 7) Higher degree awarding institutions themselves have undergone much change in recent years. The majority of higher education in art and design in the UK is provided by universities and a small number of specialist institutions such as the Royal College of Art. Two groupings exist, namely the old universities and advanced technology colleges, which became universities in the 1960s and former polytechnics, technical institutes and art schools which became incorporated as universities in 1992 and who provide most of the higher education in art and design. The first group have a tradition of doctoral work and research. A research ethos is still emerging in the second encouraged by the National Research Assessment Exercise (RAE), which assesses research quality including the activities of research staff. The result of this is to determine quality-related research (QR) funding provided by the Higher Education Funding Council (HEFCE) for each institution. The last RAE was held in 2007/08.

The definition of research output valid as submissions for RAE 2008 was wide. Permitted outputs included traditional research activity such as books, publications and conference contributions. However provision was also made for the submission of artefacts, both physical and virtual, in the form of for example, designs, products, performances and exhibitions. These definitions contribute to the ongoing debate as to what constitutes research in art and design and what type of research is valid for doctoral research. Durling in discussing research in this area suggests the problem is that

> "For some it indicates research, for others it indicates practice. For some it refers to objective findings that are disseminated through refereed journals, for others it refers to subjective opinions and exhibited artefacts." (Durling, 2003)

There have however been attempts to define what research in art, craft and design should be. Frayling in discussing the issue said that the debate has revolved around a series of stereotypes of what research *is*, what it *involves* and what it *delivers.* *(*Frayling,1993). He outlines three distinct possibilities – research *into* art and design, research *through* art and design and research *for* art and design. Research *into* art and design would encompass studies where art and design is the subject of the research - traditional historical and aesthetic studies in these fields including a variety of theoretical perspectives. Research *through* art and design would use creative practice as an integral part of the research, the vehicle of the research and a means of communicating the results. It could include materials research, development research which customizes an accepted technology or action research which documents experimental studio work. He comments that this type of research in art and design is particularly suitable to collaboration with scientific communities. Research *for* art and design would have as its purpose the creation of artefacts, which embody the thinking and the results of the research. Frayling considered this latter category the most problematic.

Newbury (1996,217) however argues against a perception of art and design, which reinforces an institutional divide between theory and practice, and practical work and communicable research. However it is clear that not all practice will be research.

"Some practice may be routine practice, some will be investigative i.e. have a research intention, and some of it will be the kind of research that is suitable for PhD investigation." (Durling,2003)

This debate will continue but issues will be resolved through the definition of models and consequent methodologies for research in art and design as more doctoral research is concluded. It would seem though that the following statement from an editorial in Design Studies remains valid.

> "The best examples of design research are purposive, inquisitive, informed, methodical, and communicable. This requires articulation and shared knowledge within and across the field. Objects and artefacts alone cannot communicate this knowledge". (Cross, 1995, 3)

Doctoral research here falls within Frayling's second category of research through art and design where practice is used to generate research questions and conduct research. The doctoral thesis is being used as the vehicle to communicate outcomes and not artefacts created through practice.

3.3 Reflective practice

In discussing research positions in art and design, Malins and Gray (2004,20) discuss the role of the practitioner

> "…the practitioner *is* the researcher; from this informed perspective, the practitioner identifies researchable problems raised in practice, and responds through aspects of practice. The role is multifaceted, sometimes it is:
>
> - A generator of research material – art/design works, and participant in the creative process
> - A self observer through reflection on action and in action, and through discussion with others …."

When comparing the role of the reflective practitioner-researcher, who is located inside the research, to that of the scientific researcher who would normally be situated outside the research, it must be acknowledged that challenges arise over objectivity, validity and reliability, which must be addressed through the research methods that are selected. It will be discussed later how this is resolved in this research.

It is important to consider types of knowledge that are generated through practice. Knowledge and understanding that is acquired through doing, repetition, trial and error, such as knowledge about materials or processes, may be tacit or explicit. As tacit knowledge, it informs the activity of practice but is not articulated. Sennet, in describing research into workmanship, comments

> "…much of the knowledge craftsmen possess is tacit knowledge – people know how to do something but they cannot put what they know into words." (Sennet, 2008, 94)

Schőn refers to this as *knowing-in-action* (Schőn, 1983, 50). Explicit knowledge however, may be precisely communicated to others. It is a goal of this research that outcomes and insights gained are communicated as new knowledge.

It would seem that reflection is the key component that enables unarticulated knowledge gained through practice to be extracted while conducting research.

> "Reflective practice therefore attempts to unite research and practice, thought and action into a framework for enquiry which involves practice, and which acknowledges the particular and special knowledge of the practitioner." (Malins & Gray, 2004, 22)

In his book *The Reflective Practitioner* (Schőn,1983), Schőn argues against the positivist position of the grounding of professional knowledge, which he refers to as "technical reality", which does not acknowledge the inherent knowledge in practice. He introduces the idea of reflection-in-action, which enables a practitioner

> "….to experience surprise, puzzlement or confusion in a situation which he finds uncertain or unique. He reflects on the phenomena before him, and on the prior understandings…He carries out an experiment which serves to generate both a new understanding of the phenomena and a new understanding." (Schőn,1983, 68)

This would indicate that reflection-in-action enables knowledge and new understanding to be advanced on two levels simultaneously. Firstly as experiments are conducted, perceptions of what is being investigated, for example material behaviour, are explained. Secondly overall understanding of how everything may fit together is clarified.

Furthermore the process of reflection-in-action generates ideas for next steps and provides a direction in which the research may proceed. In considering an example of engineering design, Schőn describes the research process or inquiry as a "conversation with the materials of the situation" which had various stages.

> "At each stage students were confronted with puzzles and problems that did not fit known categories - had a sense of theories that might explain phenomena. Each reflection gave rise to new phenomena, troublesome or desirable, which led to further reflection and experimentation." (Schön,1983, 176)

Although reflective practice or more specifically, reflection-in-action is able to produce fruitful enquiry, it is clearly only valid as a model for research containing rigour if, as Schön says, "an epistemology of practice can be developed which places technical problem solving within a broader context of reflective enquiry.. and links the art of practice in uncertainty and uniqueness to the scientists art of research" (Schön,1983, 69)

3.4 Action Research

Action research is such a model. Dick describes action research as "a process by which change and understanding can be pursued at the one time. It is usually described as cyclic, with action and critical reflection taking place in turn. The reflection is used to review the previous action and plan the new one." (Dick, 1997)

The process of action research may be described as a cycle with reflection embedded at each stage, namely

- Reflection-prior-to-action or alternatively reflection-for-action
- Reflection-in-action
- Reflection-after-action

The process is iterative with reflection-after-action leading to new reflection-prior-to-action cycles, each pass through refining understanding and obtaining evidence. For this reason, the cycle is often referred to as a spiral. The action-research process enables two possibilities. Firstly through cyclical iterative steps a single idea is pursued and detailed knowledge is gained. Secondly new ideas emerge as the researcher is confronted and reflects on unexpected results. These events are often referred to as ‘happy accidents’ and have in themselves no value unless the conditions, which caused them, can be harnessed in such a way that they may be repeated. Framed within an action research model, such events may be reflected upon and do not pass by unnoticed or unrecorded. Furthermore as reflection and data collection has taken place prior-to-action and in-action, the steps and events may be replicated.

Although initially trained, many practitioners are autodidacts, acquiring new knowledge and understanding through practice and trial and error. The ease and speed of this process is facilitated through action research because tacit knowledge is made explicit more quickly through reflection. What does and doesn’t work is articulated and profitable avenues of discovery may be explored over those that show less promise.

Conventional research starts with a very defined question from which a very precise study can be constructed. Dick (1997) describes the initial question in the action-research as being very “fuzzy”. He goes on to describe a fuzzy question leading to fuzzy methods, which in turn generate a fuzzy answer. As has already been described, reflection takes place at each of these stages, which allows the question and methods to be redefined and thus becoming less fuzzy and more precise after each iteration. This process is illustrated in Figure 36.

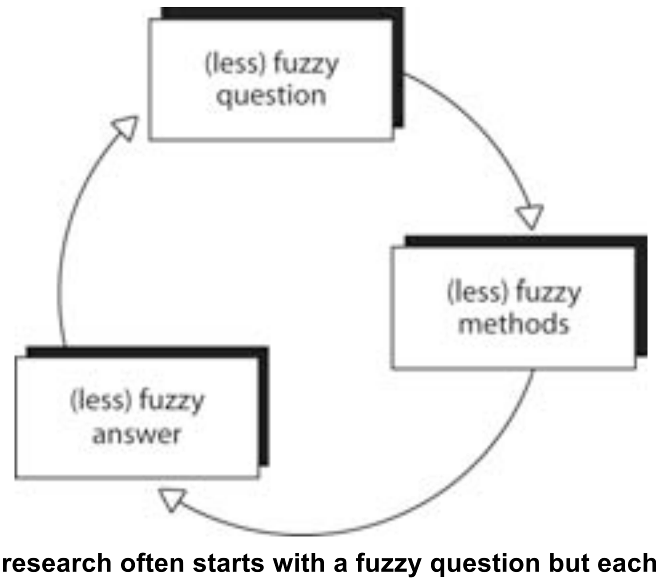

Figure 36: Action research often starts with a fuzzy question but each cycle adds to the clarity generating understanding. Diagram adapted from Dick (1997)

Figure 37 shows the action research cycle expanded to show decision making generated by reflection. The reflection-prior-to-action step sets out intention, aims and expectations. The reflection-after-action step reviews what has been achieved and considers what the next cycle should be. The steps allow for continuation to a new cycle or refining the current cycle.

As Dick says, the main advantage of this methodology is "simultaneously to achieve better understanding and results." In quoting Kolb (1984), Dick says that when practitioners use action research, it has the potential to increase the amount they learn consciously from their experience and that the action research cycle can also be regarded as a learning cycle.

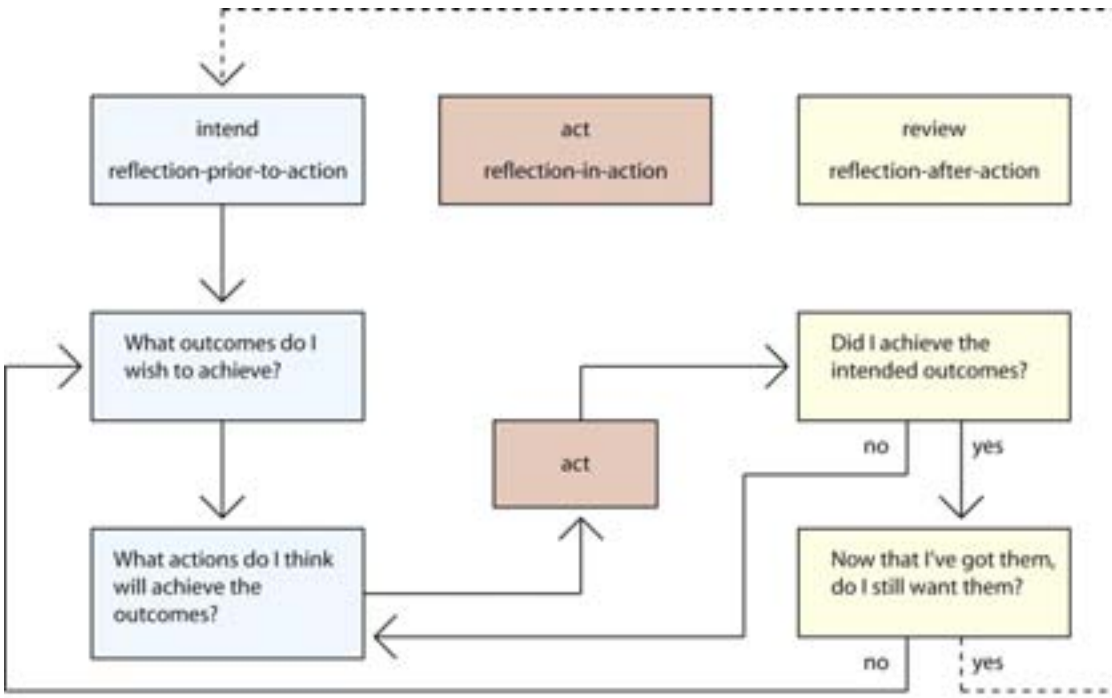

Figure 37 : An expanded view of the intend-act-review cycle. Diagram adapted from Dick (1997)

He does however maintain a focus on rigour. Both the quality of the data and the interpretation of the data are important. In the context of this research, the results from individual inquiries, embedded in action research cycles must be capable of validation by a scientific community and therefore a system of documentation is required. Sufficient information must be provided to enable all trials to be replicated. Using the same experimental methods, another researcher should obtain the same results. The system of documentation will be detailed below.

3.5 Aims of this research

The aims of this research were fourfold, firstly to fully understand the nature of the interaction of the laser and textile materials. It was obvious from the author's practice that different fabrics responded differently to laser processing. Prior knowledge of textile laser processing had been obtained through trial and error. It became clear that without a proper understanding of the role that fibres, fabric constructions, finishing treatments and laser parameter selection played, it was impossible to reliably predict how a given material would behave or whether the laser processed fabric would have an aesthetic appearance or not. As has been explained, this knowledge was not available in the public domain in a way that is accessible to practitioners without scientific training.

A second aim of this research was to automate or determine a method for reducing the time it took to produce lengths of laser cut and pleated fabrics. As explained in the contextual review, no evidence of a pleating machine for cut fabric had been found and a process that relied on hand folding numerous pleats was not commercially viable.

A third aim of this research was to experiment with laser processing with a view to determining new processes for the equipment. As explained in the contextual review, laser processing is used for cutting and marking. Research into the nature of laser processing of textiles offered the opportunity to derive other process capabilities.

Evidence from the author's practice showed that processing of some materials produced unaesthetic or negative side effects – burning, melting and odours. A fourth aim of this research was to devise methods of mitigating these effects and, as a consequence, enable laser processing to be successful on a greater range of textile materials.

3.6 Research methods in this research

This section details how this research has been conducted.

A contextual review was undertaken to establish the area of research. The diagram in Figure 38 shows that the contextual review explored four areas – textile manufacturing and textile materials, three-dimensional textiles and techniques used in their creation, laser processing of textiles, and opportunities and issues material to contemporary textile design. Through critical review, opportunities for inquiry were selected. These formed the initial ‘fuzzy questions’ for action research cycles. As can be seen in Figure 38, there were initially two main areas of enquiry namely experiments into the effects of lasers on textile materials and experiments into the different process areas. Research commenced initially into pleating processes. Next laser sintering of textiles was explored and then mitigation of the negative effects of laser processing. Once a new process was developed, designing took place and new materials were introduced. Analysis of designs was conducted and a full description of the process was made in order to be able to document it fully. Material/laser behaviour was revisited throughout the research as further insights were required. The contextual review was updated throughout the course of the research. Further detail of each of the action research cycles is given below and shown in Figure 39 - Figure 42.

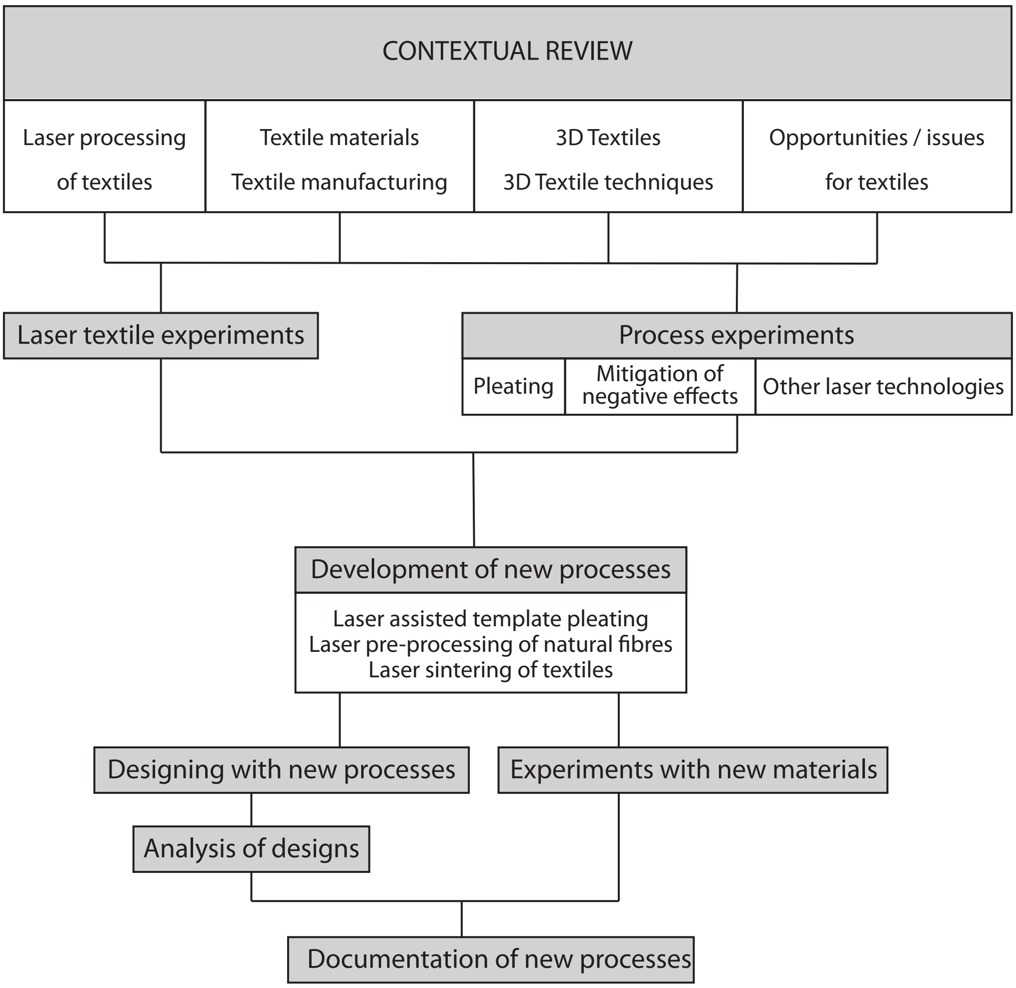

Figure 38 : Diagram showing research process undertaken

Iterative cycles took place where an idea was explored through the construction of documented repeatable experiments. Both results and detailed scientific observations were made. Reflection took place before, during and after each experiment. Where results were consistent with expectation, further iterations were made to confirm outcomes and refine new developments. Where 'surprises' were observed or phenomena were not understood, new 'fuzzy' questions and research or enquiry cycles were conducted to explore these avenues. Where cycles did not generate results considered to be of value, the cycle was aborted but results and reflections were still recorded. Cycles of enquiry were stopped when it was considered that results were not furthering the aims of the research. In some cases, when further understanding was achieved, the aborted cycles were returned to later. Both results and reflections were discussed with colleagues in both design and engineering communities and with potential commercial partners where appropriate. Comments and opinion were incorporated into the action research cycle to add to the insights gained.

Documentation took the form of log books which are custom and practice in both the scientific community and by designers where they are normally referred to as sketchbooks. These recorded on a day by day basis

- *Reflection-prior-to-action* - aims and intentions of experiments, equipment and materials to be used, questions to which answers were being sought and potential issues and problems that may arise
- *Reflection-in-action* – parameters and materials that were used, changes that were made to experimental set-up, scientific observations that were made, ideas that occurred, new questions and problems that were encountered
- *Reflection after action* – results of experiments, scientific observations, new questions and what to do next

Figure 39 shows an overview of the cycles undertaken in researching material behaviour. Cotton and polyester were initially selected as materials to investigate as being representative of the most widely used natural fibre and manufactured fibre respectively. A series of experiments were conducted as described in Chapter 4. Once an understanding of the effects of parameter selection was understood, investigations were expanded in several areas – role of focal height, differences between laser cutter and laser marker, role of fume extraction, the software interface, a design sampler, development of methodology for parameter selection. Other materials that were used in the authors practice were tried such as a range of cottons, linens, silks together with a variety of other materials in common use such as wools, polyesters and nylon together with blends. Results were recorded following observation and touch, photography, and microscopy. Outcomes were validated by employing knowledge gained on a new laser that was installed in the School of the Arts.

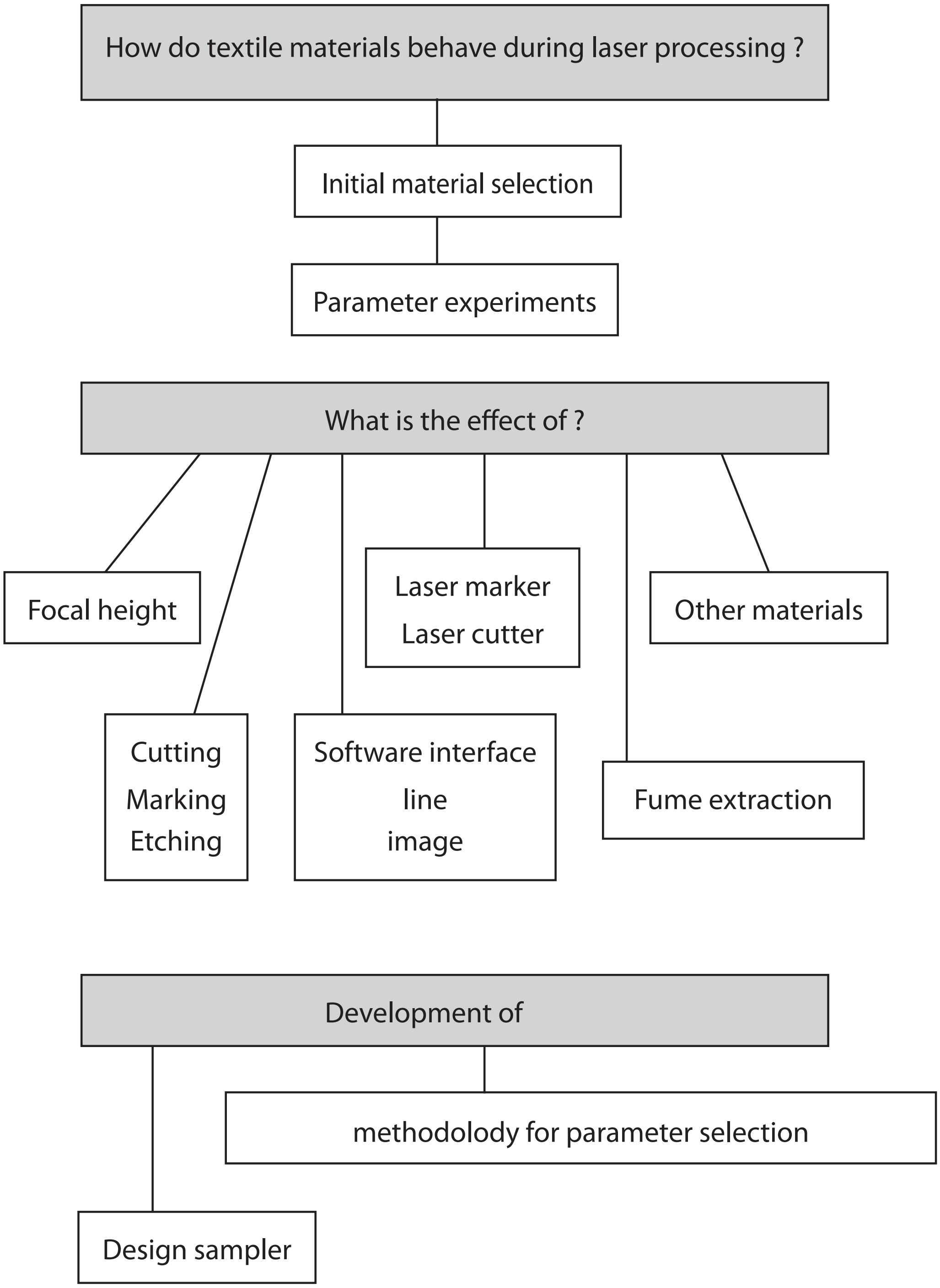

Figure 39 : Diagram showing overview of action research cycles for investigation of material behaviour during laser processing

A second line of enquiry was to derive a process to automate or speed up the production of laser cut pleated fabrics. (Figure 40 and Chapter 5) Research started by replicating historical and contemporary pleating methods to gain an understanding of the issues that were involved. Two prototype machines were developed. Template pleating was extended to incorporate CAD, laser cutting and perforations. Further investigation included materials for templates, an analysis of designs that would work with this method, and materials that would work with the process that were not of a textile origin. The commercial potential of the process was validated by preliminary conversations with a major high street retailer, civil engineers, boat builders and a producer of gas masks. Details of these meetings have not included due to their commercial sensitivity.

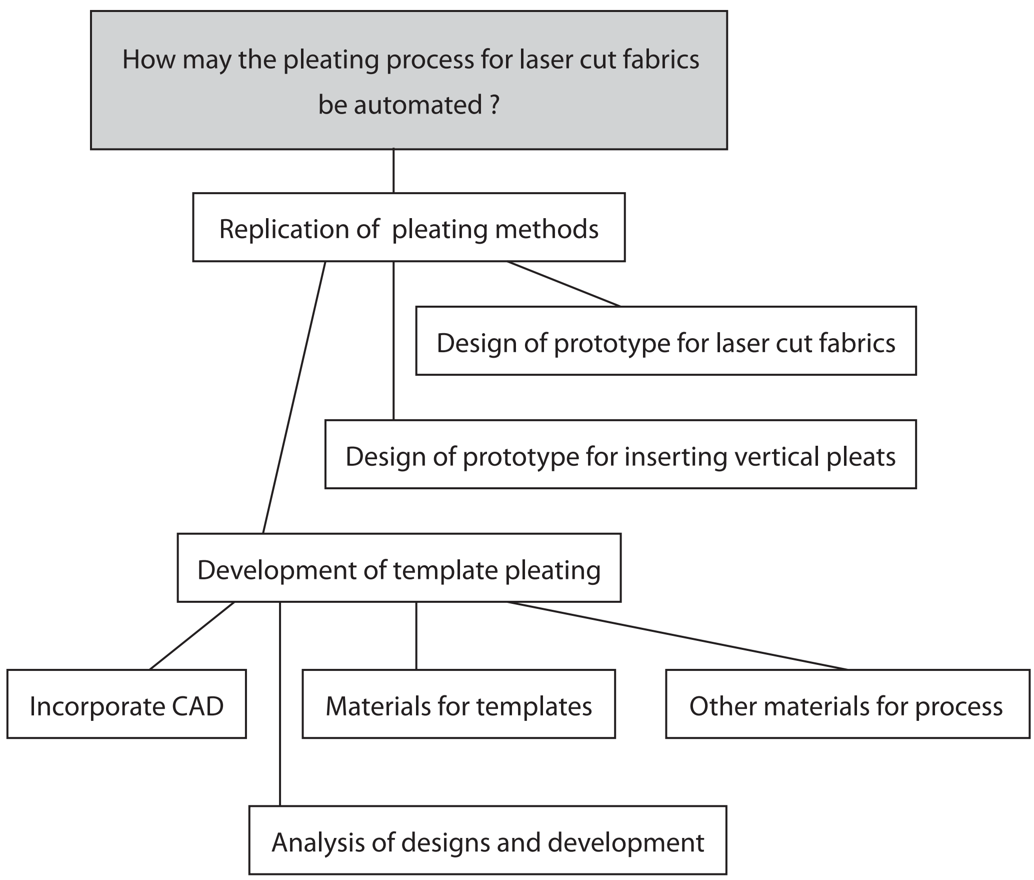

Figure 40 : Overview of action research enquiry for pleating processes

In order to conduct research into ways of mitigating the negative effects of laser processing, research was carried out on cashmere for a British manufacturer. (Figure 41 and Chapter 6). Enquiry focussed on what could be done with the existing product range and was then expanded to experiments on loom state fabric with various fabric constructions. Both etching and cutting tests were conducted. Results were recorded following observation and touch, photography, and microscopy. Results were validated in conversation with the manufacturer and their clients.

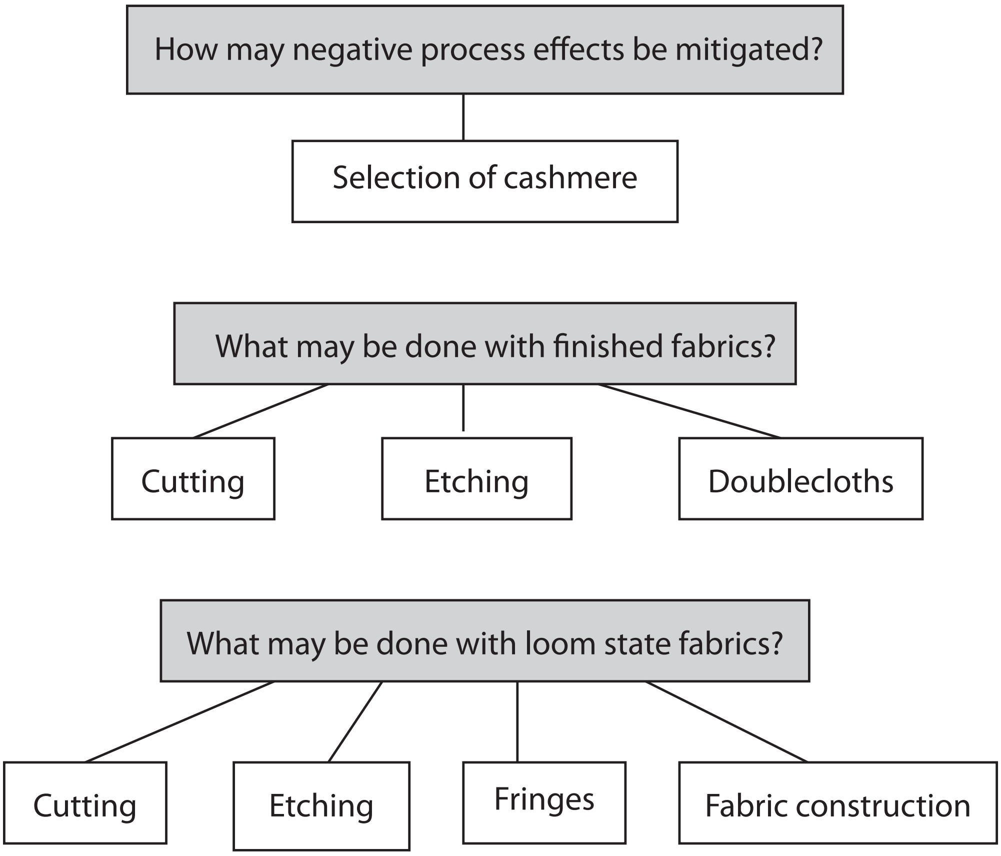

Figure 41 : Overview of enquiry cycles for mitigating effects of laser processing on cashmere

The final area of enquiry focussed on using laser sintering techniques directly on fabric substrates. (Figure 42 and chapter 7) Research began with an initial selection of materials – polyamide powder and paper nylon. When it was demonstrated through microscopy and microtome testing that the process worked, enquiry continued with other powders and substrates. A variety of natural and manufactured fabrics in common use were selected. Tests were then conducted to determine if the new process could be used for design.

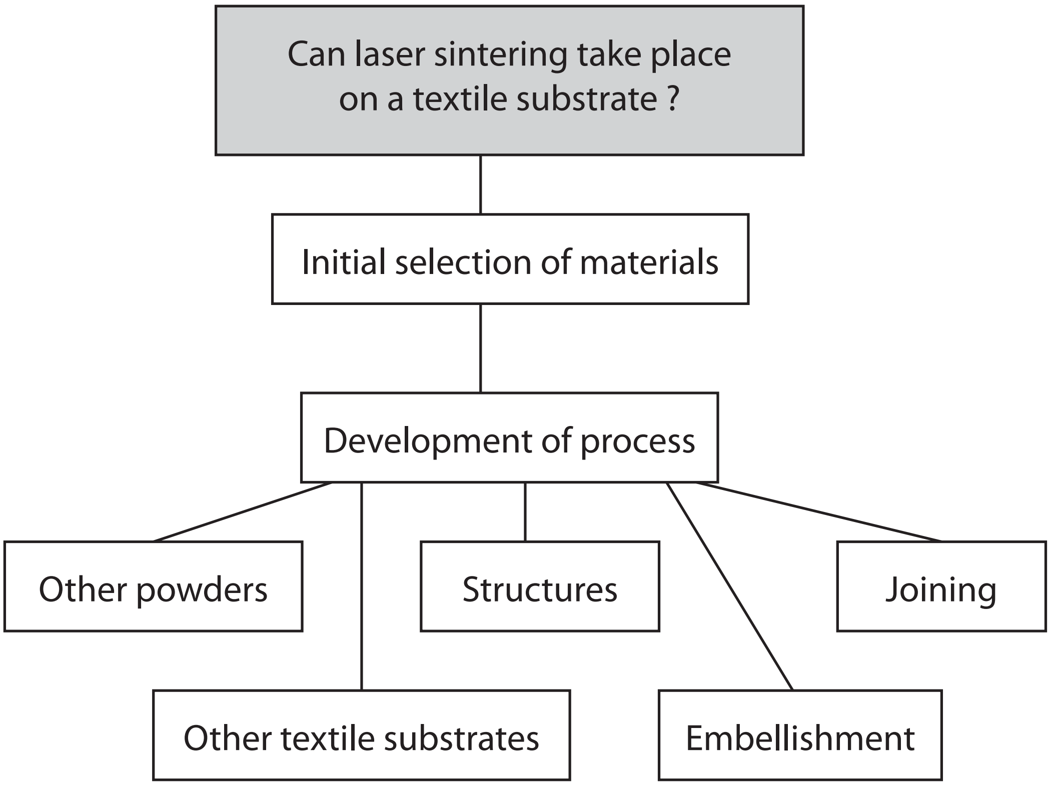

Figure 42 : Overview of enquiry for laser sintering on a textile substrate

The action research methodology combined with scientific methods added knowledge and understanding, whilst simultaneously facilitated new areas to be explored. Thorough documentation provided an audit trail enabling rigour of methods to be verified and research to be replicated. Knowledge and understanding grew whilst new processes for design were being developed. The outcomes of the research are communicable. It would seem that an action-research methodology as described here is successful for collaborative cross-disciplinary research because both the research methodology and the research methods are explicit. Individual experiments may be verified and together the research may be both engaged with and validated across disciplines. Furthermore the research can be effectively communicated to and shared with other disciplines.

4 Laser Processing

This chapter will consider the use of laser processing of textiles. Although laser processing is embedded in textile manufacture and employed for garment sampling, information in the public domain is not in forms easily accessible by designers. Research conducted by the author on behalf of the Association of Fashion and Textiles Courses into the nature and scope of provision in the UK in 2010 indicated that teaching of these techniques to designers in sufficient detail, for example on undergraduate courses, does not routinely take place. (Matthews, 2010) The consequence of this lack of familiarity is that much of the laser processing seen in art and design applications is of poor quality. Although capital costs of equipment are reducing rapidly, experimentation is hampered by the high setup charges and hourly rates charged by bureaux services. If a designer is not present during processing or able to experiment, interventions are not made to capture and control observed effects. Nor is an understanding of the potential of the process achieved. Where a designer is able to personally experience laser processing, in university departments for example, time is often spent in rediscovering known effects due to the lack of published literature. This is expensive in both time and materials and knowledge moves little further than basic cutting and etching. The aim of this chapter is to provide an overview of the laser process in general and develop a methodology which designers may use to control the process and mitigate negative effects though the correct selection of processing parameters and other conditions in order to achieve desired outcomes. Success in this area will move the process beyond just a tool that cuts and marks textiles and open up other opportunities.

A designer may wish to use a variety of materials and exploit a range of effects including those that may not be considered as ‘correct’ cutting and marking. It will be shown that natural and manufactured fibres react in very different ways to a thermal process such as CO_2 laser processing. As the structure and density of the material also plays a role, it may not always be known in advance how a given material will react so a methodology for testing new materials is given in section 4.4.

Computer software provides the interface between the designer and the laser. An ability to exploit the laser process requires a detailed knowledge of the software or access to technicians with this knowledge. The opportunities that are available for creative use depends on the specific software used by both the designer and the laser operating systems. This is not the place to give detailed operating instructions but it is however possible to describe a methodology and this is discussed in section 4.3. The following section provides an overview of laser technology. It is informed by attending two third year modules at Loughborough University in 2006/07 namely 06MMC910 Laser Materials Processing and 06MMC606 Rapid Prototyping and through discussion with members of academic staff and laser technicians in the Wolfson School of Mechanical and Manufacturing Engineering at Loughborough University.

4.1 Laser technology

A laser system generates monochromatic, coherent photons in a low-divergent beam. As monochromatic, the light is of a single colour. As coherent, all the emissions originate from a stable oscillator with a uniform constant frequency and have the same wavelength. As low-divergent, the beam does not spread out significantly with distance, which allows it to be manipulated across cutting tables in laser systems. In contrast, light from an incandescent light bulb for example, will consist of several wavelengths and have random polarisation and phase making it difficult to focus with sufficient intensity to be useful for processing. A laser beam is either randomly polarised (not polarised) or has linear polarisation in which case beam is polarised in one direction. For even processing in all directions, a linear polarised beam will be depolarised.

It is useful to compare the energy of a laser beam to sunlight focused with a magnifying glass. Focussed sunlight forms a high-density beam of around 7.5W over an area of say 1-2mm in diameter[1]. Lasers typically used in fabric cutting have a focus area of 0.1mm in diameter and energy of 75W. The area is 100 times less and the energy higher by a factor of 10 making laser processing 1000 times more energetic than sunlight.

The laser beam is passed through a series of optical lenses to ensure that it will have the desired shape and size for processing. A system of mirrors will deliver the beam to the work piece for processing to take place. Figure 43 shows the beam directed with mirrors to a nozzle, which contains the focussing lens. Further explanation on beam delivery systems is given in section 4.2.2.

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[1] Assume solar radiance of $1000W/m^2$, 100mm diameter magnifying glass, a focal area of $0.0075\ m^2$

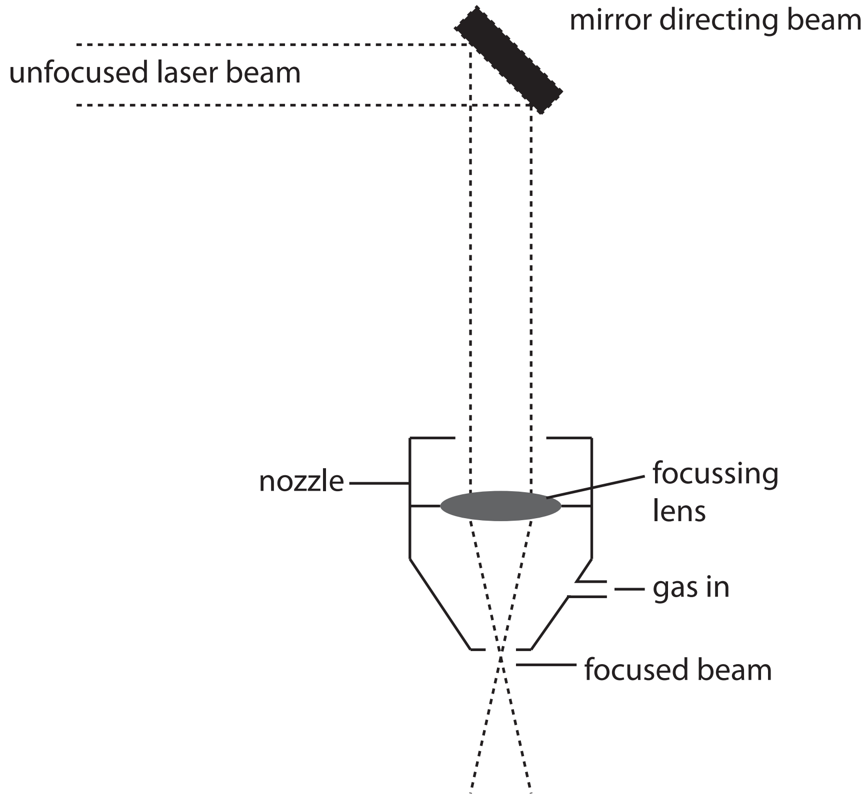

Figure 43: Diagram showing how a laser beam is directed, using a mirror, to a lens which focuses the beam to a spot. The lens is housed inside the nozzle, which has an air intake on the side for an assist gas

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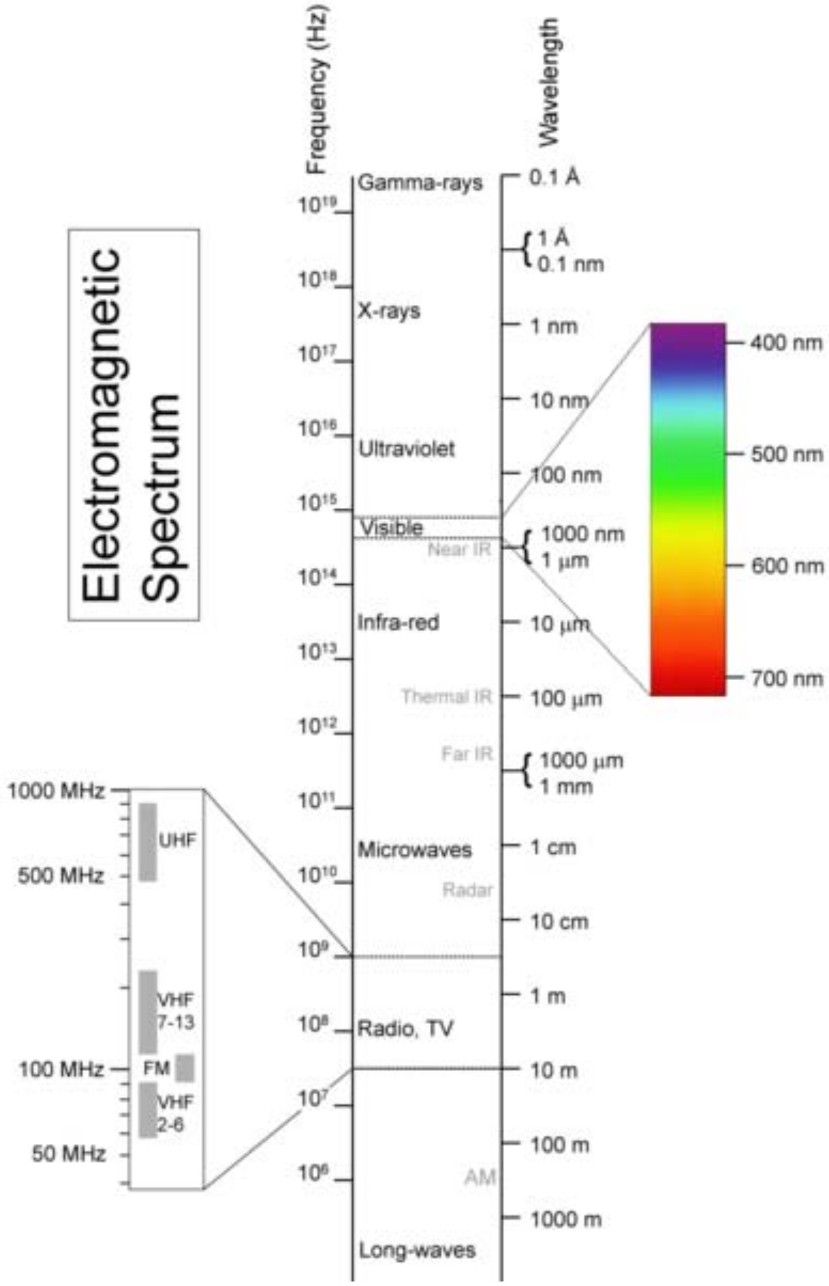


Figure 44: Diagram showing electromagnetic spectrum. The right-hand columns dives the wavelengths corresponding to wave in the central column.

http://en.wikipedia.org/wiki/File:Electromagnetic-Spectrum.png#file

Both the wavelength and power of a laser beam will depend on the medium that is used to produce it. Figure 44 shows a diagram of the electromagnetic spectrum. The central column gives common applications for waves of different lengths and the legend on the right corresponding wavelengths. It may be seen that the visible light spectrum has wavelengths between 400 nanometres (nm) and 700nm. Ultraviolet light has a shorter wavelength and infrared a longer wavelength. Figure 45 shows the wavelengths generated by different lasers together with average powers.

Laser	Spectrum	Wavelength ($nm=10^{-9}m$)	Wavelength ($\mu m=^{10-6}m$)
CO_2	far infra-red	10,600	10.6
Nd:YAG	near infra-red	1,064	1.064
Fibre	near infra-red	1,000	1
Nd:YAG x2	visible green	532	0.532
Nd:YAG x3	UV	355	0.355
Nd:YAG x4	UV	266	0.266
Excimer	UV	198	0.198

Figure 45: Common lasers for fabric processing with their wavelengths

The photon contains energy expressed in electron volts (eV). The energy of a photon is inversely proportional to its frequency so a photon of light in the infra-red spectrum will have a lower energy than a photon in the ultraviolet spectrum. For example a photon with wavelength 10.6μm has an energy of 0.13 eV and one with a wavelength of 1.06μm has an energy of 1.3eV. Materials consist of molecules that are bonded together. Different molecular bonds may be expressed in terms of energy and the application of sufficient energy will enable these bonds to be broken. The energy contained in an infrared photon however, is insufficient to break the molecular bonds found in textile fibres. When a textile is laser processed, photons are absorbed by individual molecules and the energy is transferred as thermal energy. This process is known as fresnel absorption. If sufficient photons are delivered, the increased heat build up will cause the bonds to break down and the material may melt or ignite. Processing of textiles with infrared lasers therefore causes thermal damage. Photons in the UV spectrum have sufficient energy to break molecular bonds directly and textiles processed in this way do not demonstrate thermal degradation. The process is known as 'cold cutting' but is as yet not employed in textile manufacture due to the high capital and running costs of UV lasers and lack of knowledge of their potential.

Within the focussed region, the material is subject to very intensive heating within a very small region. As explained above, laser energy is absorbed as heat and the material rapidly heats leading to melting as a phase change from solid to liquid takes place. Some of the molten liquid tries to move, driven by surface tension of the liquid. (Figure 46) The remaining liquid heats very rapidly, boiling and releasing vapour as another phase change takes place from liquid to gas. The boiling also throws out 'blobs' of molten material. This spatter of vapour and molten material is ejected from the surface of the material, some of which moves into the incoming beam, superheating rapidly to form plasma, which in turn absorbs some of the incoming beam.

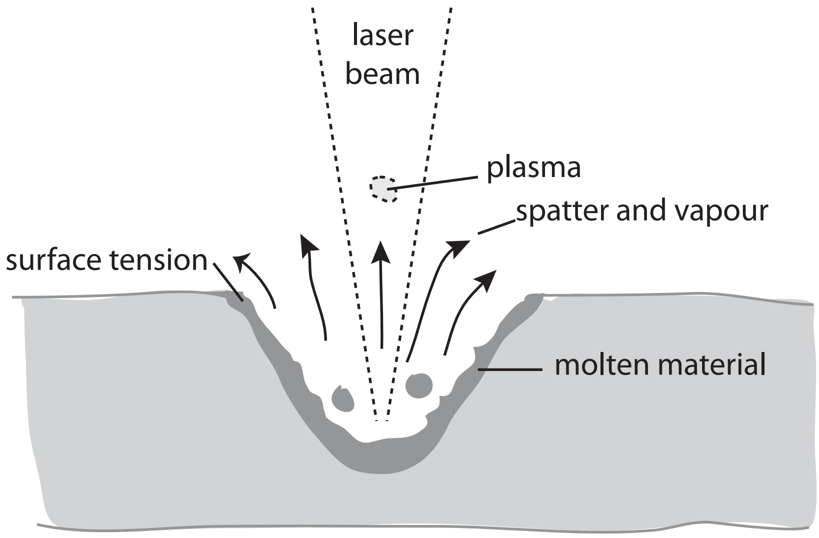


Figure 46 : Diagram showing molten material and vapour at the beam interface during laser processing

Natural fibre materials tend not to melt and so the temperature build-up results in combustion or thermal degradation if oxidation cannot be supported, for example in an inert atmosphere. Again the combustion products will be ejected upwards, some into the incoming beam and will be superheated to form bursts of plasma. The effect of plasma on fabric may be seen in Figure 47. Control of ejected material is an important process to be suitably managed otherwise it absorbs laser power, produces variable results and may degrade or discolour the work piece. Further details are given in section 4.2.4.

Textile processing is predominately carried out with CO_2 lasers in the infra-red and near infra-red spectrum (10.6μm) although there is evidence of some research using UV Excimer lasers (Lau et al, 1997). CO_2 lasers are available across a wide power range and those with lower power ratings, 200W and under are appropriate for use with textiles. This research used 150W, 50W and 10W CO_2 lasers.

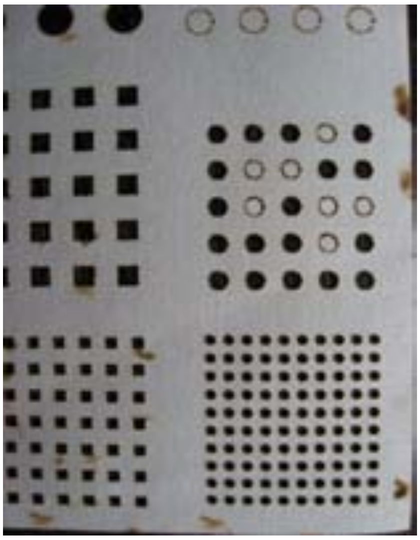


Figure 47: Laser processed cotton showing charred marks due to plasma igniting during processing.

Textile laser processing consists of:

- Laser marking or etching where only the surface of the fabric is processed. Insufficient energy is applied to process fibres completely or the process is used to vaporize dyes.
- Laser engraving where controlled cutting takes place to a depth.
- Laser welding where a manufactured material is processed so that it melts. On resolidification, the molten material joins or welds two or more layers of fabric together.
- Laser cutting where sufficient energy is applied to cut through a fabric.

4.2 Laser processing systems

This section describes laser processing systems used for textile processing.

As may be seen in Figure 48, they consist of the following component parts:

- the laser system
- a system for delivering the beam
- the work bed on which the materials to be processed are placed
- fume extraction systems
- a housing which encloses the system.

The system incorporates software to operate the laser and requires designs created using design software which may be external to the system. These will be discussed in the following sections.

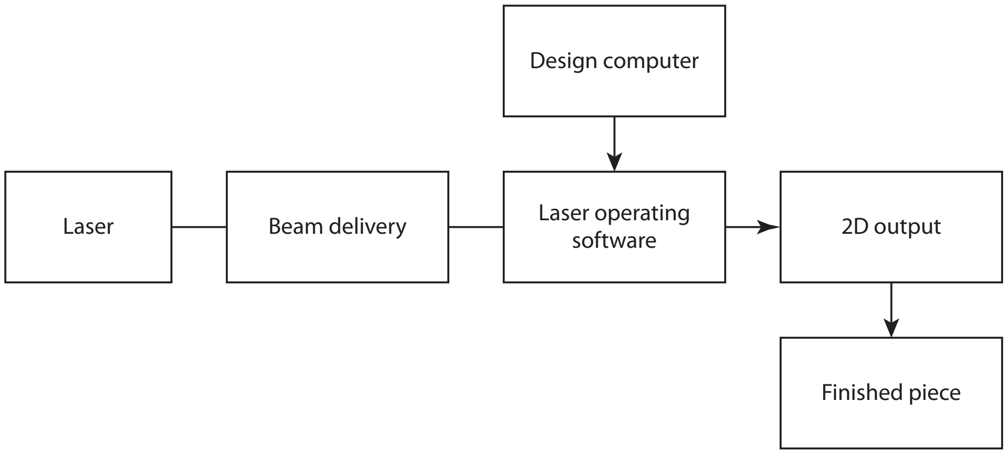


Figure 48 : Diagram showing a textile laser processing system

4.2.1 The laser system

The laser system comprises a CO_2 laser of a given power and a software interface to control it. This programme allows processing parameters to be set and initiates processing. Depending on the sophistication of the software, it may contain additional features such as drawing tools for design, a materials library to store previously determined parameters and material optimisation facilities. This research used two different laser control systems - APS Ethos (CadCam Technology Ltd, 2010) and WinMark (Synrad Inc, 2011). The process initiation screen for APS Ethos is shown in Figure 49.

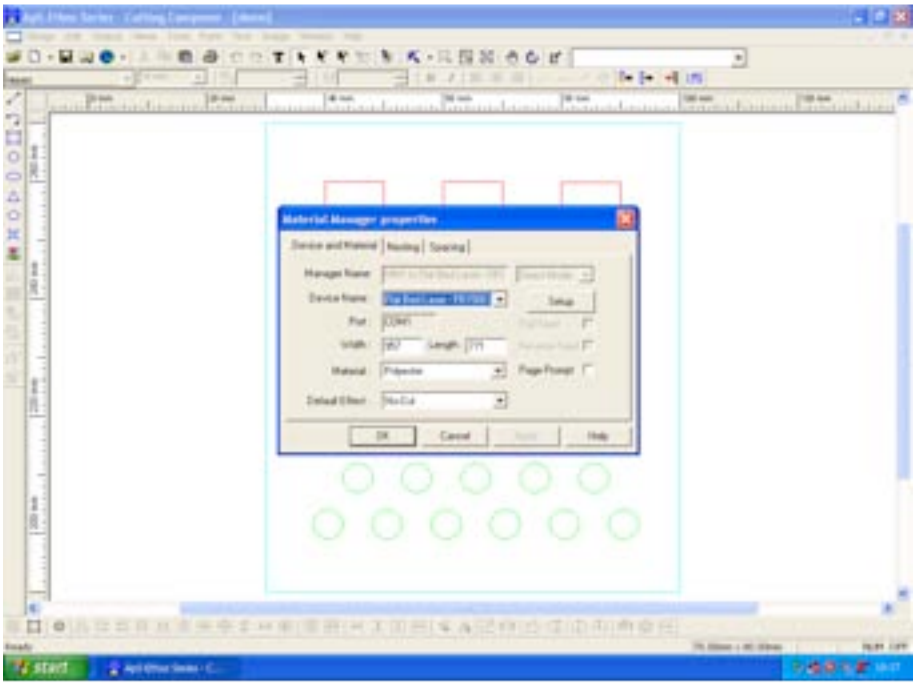


Figure 49: APS Ethos screen showing design to be processed (background) and processing screen.

4.2.2 Beam delivery systems

Beam delivery systems use optics, mirrors and lenses, to guide a laser beam under software control to the materials to be processed. The following types of systems are available:

- the work bed is stationary and the beam is guided to the work piece via mirrors and a belt driven nozzle which can move across the work piece in what is known as the x- and y- directions, x corresponding to length and y to the width, or vice versa. This is known as a flying optics or plotter system and may be seen in Figure 50.
- the work bed is held stationary and the beam is directed via motorised mirrors, a galvanometer across the work piece again in the x- and y- directions. See Figure 51.
- the beam is stationary and the work bed is moved underneath in the x- and y- directions.
- the beam is delivered by means of a robotic arm which may move in all three directions x- and y- and at right angles to the work piece. This vertical direction is by convention known as the z-direction.

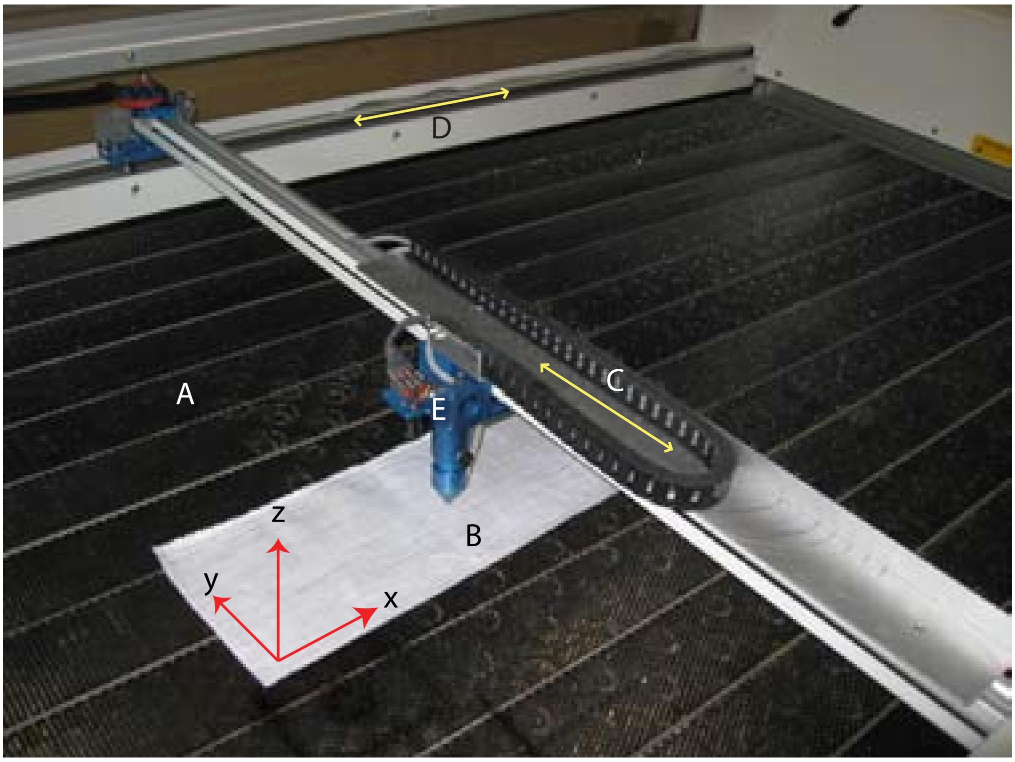


Figure 50: Flying optics system showing work bed (A), work piece (B), belts (C and D) driving nozzle (E) in horizontal and vertical direction i.e. across the materials being processed

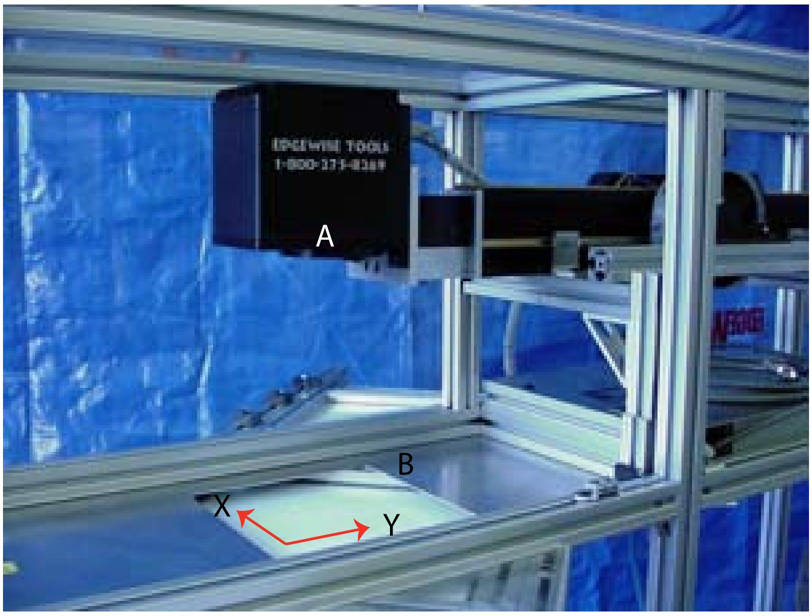


Figure 51 : Galvanometer laser system. The beam is directed by mirrors from A on the work bed B and is able to process in both the x- and y- directions. The whole system is contained in a housing. (Edgewise Tools, 2011)

Two types of beam delivery systems are predominantly used for textile processing - flying optics for laser cutting systems and galvanometer or mirror-driven systems for laser marking. Both systems however may be used for laser cutting and laser marking.

4.2.3 Work bed

Materials are placed on the work bed for processing. Work beds for textile processing are usually fabricated from metal, either of a honeycomb construction as in Figure 50, metal rods as in Figure 55 (right) or from metal slats containing tiny holes. The reason for this is that fume extraction often takes place from below the work piece and the spaces or holes enable the gases to circulate and for processing debris to be sucked away from the work area. This also allows the fabric to be held through suction onto the work area during processing. If the air suction is not sufficient to hold material in place, masking tape may be used to attach outside edges to the work bed. Automated systems are available to enable roll-to-roll processing. See Figure 52.

Figure 52: Eurolaser automated conveyor and feeding system which allows fabric to pass from a roll onto a flatbed where laser processing takes place.
<http://www.eurolaser.com/typo3temp/pics/8b9b16e1f7.jpg, 2010>

4.2.4 Assist gases

During processing, compressed air may be delivered to the work piece via a nozzle or a shield. Figure 55 shows a hose delivering an assist gas to the base of the processing nozzle. Figure 64 shows a close up of a laser processing nozzle and the white tube delivering the compressed air to the base of the nozzle may be clearly seen. The use of compressed air has a dual purpose. Firstly, to assist the thermal reaction during processing as compressed air contains oxygen which facilitates burning and secondly, to remove processing debris by blowing it away from the processing area. In the case of natural fibres, these will be carbon deposits. The charred marks are reduced if they are blown away. Figure 53 shows a sample of silk dupion that has been cut with compressed air applied to the side of the nozzle. The charred deposits are all on one side of the cut, blown by the jet of compressed air. The image suggests that the alignment of the nozzle may need to be changed for some applications. For example, the appearance of the cut may be improved if the deposits were to be blown through the cut.

Figure 53: Silk dupion processed on flying optic system with compressed air. Charring is blown to one side of cut

In the case of manufactured fibres, which melt, the molten fibres are prevented from solidifying together if the molten area is disturbed or blown away during processing. Figure 54 (left) shows a sample of polyester, which was processed on a laser marker with no assist gas. Figure 54 (right) shows the direction of cutting, which initiates at point A and proceeds in the direction of the arrows. By the time laser reaches point A again and the whole square is cut, the molten fibres at point A will have cooled. Although the individual squares have been cut successfully, they have not been removed or blown away by the assist gas before the polyester solidified and have reattached themselves.

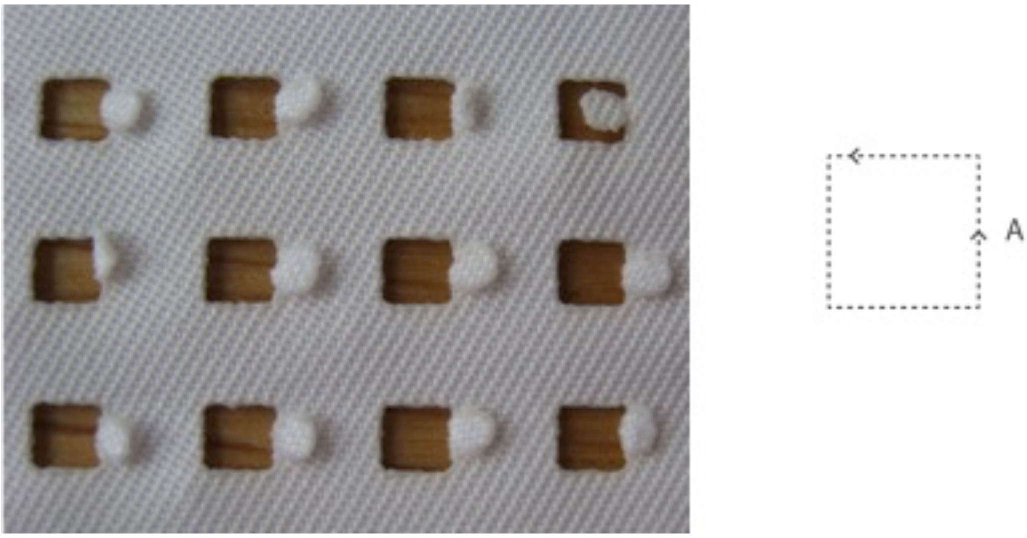


Figure 54: 2mm squares processed on polyester without an assist gas. Molten polyester is not blown away so detached squares re-adhere. (left). Cutting is initiated at point A and proceeds in the direction of the arrows.

It is possible to use other assist gases to aid or inhibit processing. Although not used in this research, gases such as helium and nitrogen, may be used instead of compressed air to inhibit plasma formation and potentially reduce charring.

4.2.5 Optical camera recognition

Optical cameras and software may be fitted to textile manufacturing systems to facilitate the processing of laser cutting or marking together with printing. An image is printed containing registry marks, normally black dots. See (B) in Figure 55. The system recognises the dots and aligns the image to be processed with these positions, enabling repeatability. This facility was not used in this research.

Figure 55: eurolaser system fitted with optical camera recognition. The black dots (B) are recognised by the camera and processing take place enabling repeatability

4.2.6 Laser safety

A beam that has the potential to cut fabric would be harmful if it came into contact with skin or eyes. Laser processing that uses beams in the non-visible spectrum has the potential to cause eye and other injuries as the beam cannot be seen. To avoid accidents, laser systems are controlled by international safety regulations (IEC 60825-1). These define categories of lasers according to their power. Lasers that output more than 500mW are defined as class IV and safety regulations ensure that users are prevented from directly coming into contact with a beam by enclosing the laser and the work piece in cabinets controlled by interlocks, which prevent the laser from being operated when the cabinet is open. Measures are taken to ensure any deflected beams are not able to emerge.

Fumes that are generated during processing may also be hazardous. Laser systems are fitted with extraction systems that remove processing gases from cabinets. Particles are filtered out before the cleaned air is allowed to pass into the environment. A suitable extraction system is a legal requirement.

4.3 Software

Laser control systems accept designs for processing in the form of data files which may be produced in other systems. An advantage to a designer is that designs may be produced offsite and then sent for processing reducing the time required on a laser processing system.

Two fundamental types of file formats are used in laser processing. Vector files describe lines to be laser cut or laser marked. Whether lines are cut out or marked will depend on the energy parameters assigned to the line. The laser processing software makes it possible to assign parameters such that some lines are cut and others are marked with different intensities on the same piece of work. Multiple passes of the laser are also possible. Secondly images may be laser etched with raster files. The greyscale image is broken down into thin strips by the laser processing software, proportioning greyscale to energy so that dark areas are assigned more energy than lighter areas. When processing takes place, the laser moves across the work piece in parallel lines. The gap between lines may be specified, as may the direction of processing.

Industry standard programs may be used to prepare images for processing as they all have provision for exporting files in the appropriate formats. Files used for etching would usually be saved in an image format i.e. JPG or BMP. Files used for marking and cutting would be exported in the industry standard document exchange format (DxF). This research used *Adobe Illustrator* and *Adobe Photoshop (*Adobe Systems Inc, 2011) and formats JPG and DxF. Other programs such as *CorelDRAW (Corel Inc, 2011)* are commonly used.

4.3.1 Laser cutting and laser marking

An example case study, undertaken by the author, is shown here to illustrate the possibilities and to give an indication of the software manipulation that may be required. The digital photograph in Figure 56 has been manipulated in Adobe Illustrator using Livetrace to produce vector lines for marking. Several parameters may be controlled to influence the detail of the lines produced. When doing this, the software first converts the image into grey scale areas. The software allows the number of grey scale colours to be determined. Another option is to determine the minimum size of an area. Figure 57 has the number of areas set to 6 and the minimum size of an area to 10 pixels. The drawing in Figure 58 has the number of grey scale areas set to 3 the minimum size of an area to 20 pixels generating a very much more simplified outline. This image would be suitable for laser marking. It is not however suitable for laser cutting as too many lines intersect and the fabric, once cut, would fall apart into a number of pieces. An example of a further simplified image is shown in Figure 59 where several lines have been removed. It would be necessary to carry out test cuts on the desired fabric to ensure that the cut out lines are not too close and further modifications made if necessary.

Figure 56: Digital photograph, resolution 300dpi

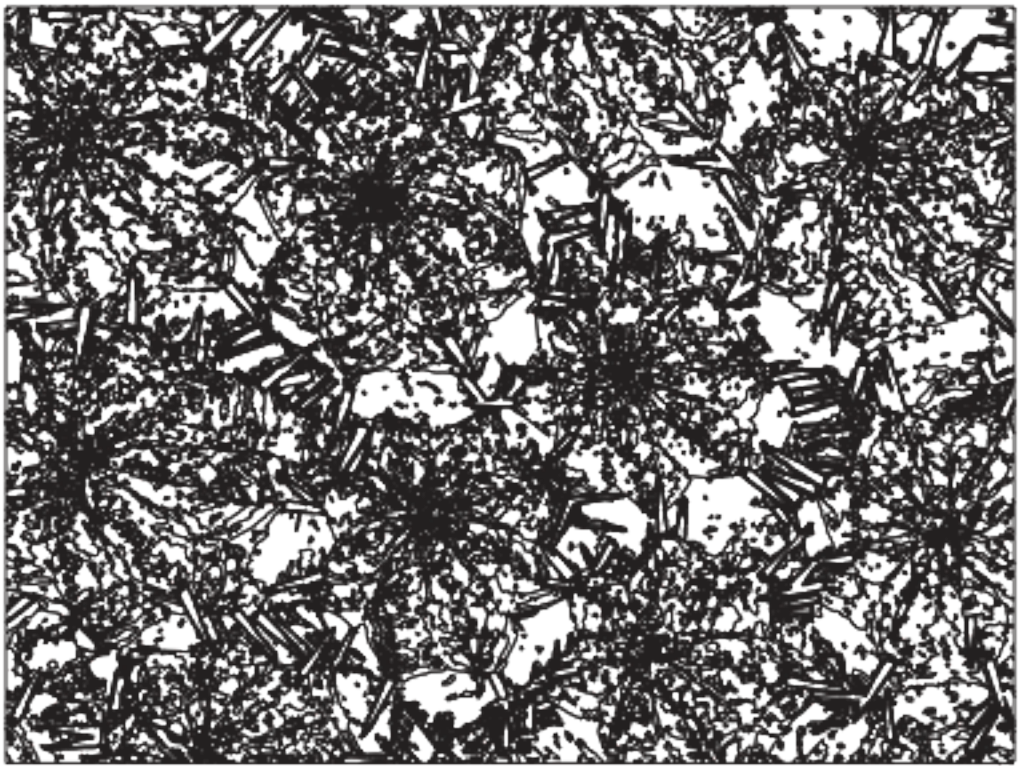


Figure 57: Vector drawing using Livetrace of above image

Figure 58: Simplified vector drawing of above image using Livetrace

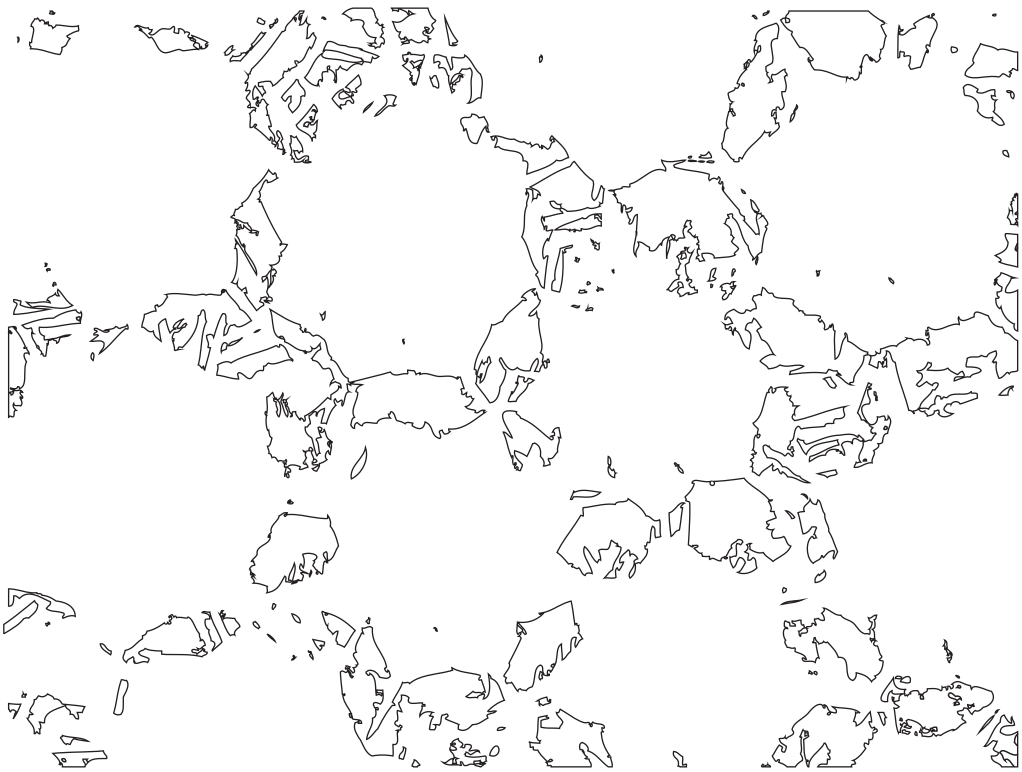


Figure 59: Further simplified vector drawing suitable for laser cutting

4.3.2 Laser etching

A digital image is required for marking. If drawn by hand, it may be digitally scanned and saved as an image file. Alternatively a digital photograph may be used or an image may be constructed from the tools available in the drawing and photo manipulation software, here *Adobe Photoshop* and *Adobe Illustrator*.

In the example shown below, the digital photograph in Figure 56 has been manipulated using the Livetrace facility in Adobe Illustrator. Three gray scale shades were chosen. The laser processing software will allocate energy parameters to these shades and etch the image in slices. If a greater contrast between the areas is desired, the image may be further manipulated using Adobe Illustrator commands. Figure 61 shows the same image but the lightest area has been removed so no etching will take place, the darkest area has been changed from 69.02% to 80% and the medium area from 21.18% to 40%, thus increasing the contrast. Selected areas could be deleted or modified in shape.

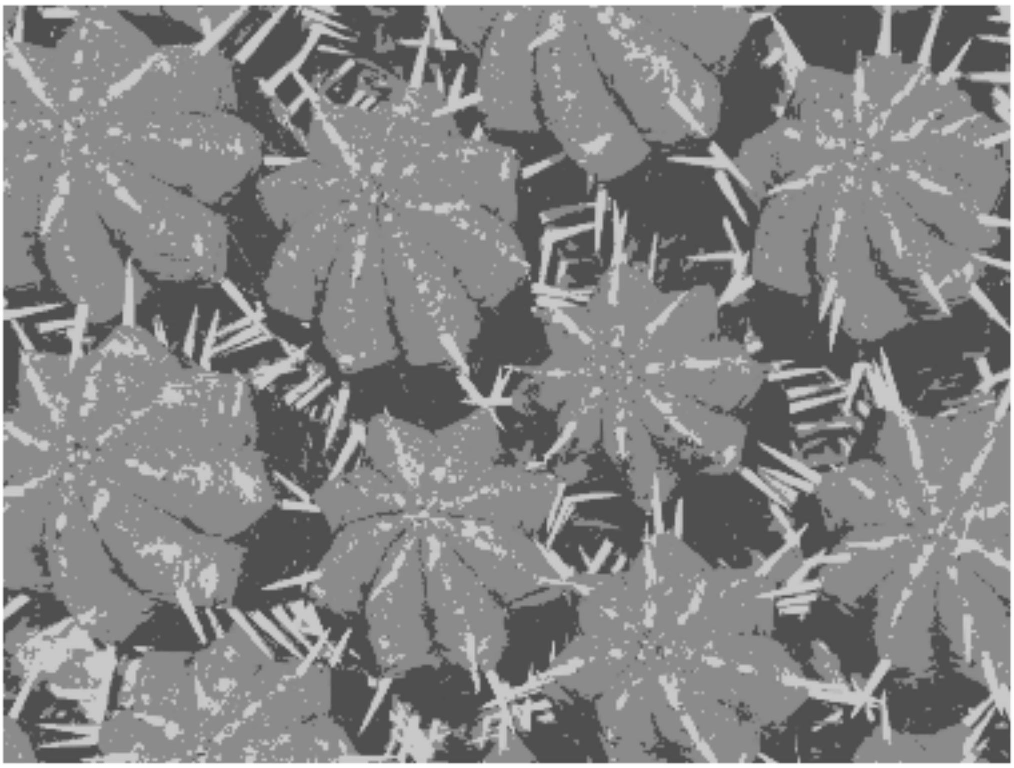


Figure 60: Grey scale image of photograph in Figure 56 created using Livetrace

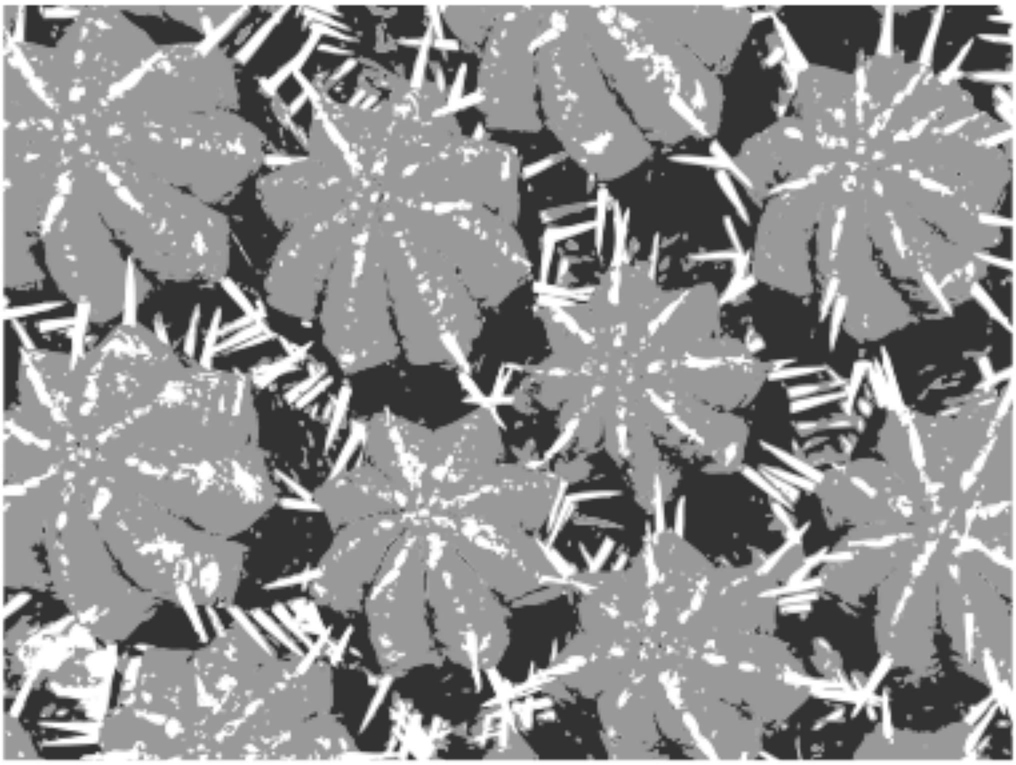


Figure 61: The image above modified using Adobe Illustrator

As has been explained, vector and raster images are imported into the laser control software for processing. This process is not totally reliable and some unexpected results may be encountered. An example may be given. If a vector file contains large radii, the importing process converts these to long straight lines. It was found through experimentation that if the long curves are cut so that they are made up of lots of shorter lines, that the conversion process works correctly. Methodical notes should be made to allow repeatability of designs.

4.4 Methodology for determining optimum parameters

This section describes a methodology for determining optimum processing parameters. Although with experience it is possible to predict how a given material will react to laser processing, very often, the exact composition of the material is not known and characteristics such as thickness, density and finishing treatments or coatings require quite different parameters to be used.

Section 4.1 showed how the effects achieved through laser processing are the result of a thermal reaction, which results when light energy from a laser beam is applied to the material being processed. These effects are directly linked to the amount of energy applied by the beam to a specific area, the area of the focussed spot. Energy applied to area is known as energy density and may be measured. The energy applied to the spot is affected by the energy of the beam and the length of time the energy is applied to that same area. The following circumstances may arise :

- A low energy beam is applied to a material for a fixed period of time. Less energy will be delivered than if a high energy beam is applied for the same period of time.
- A beam of known energy is applied in one place for a very brief period of time. Less energy will be delivered to the material than if a beam of the same strength is applied for a longer period of time.
- A beam in focus is applied to a material for a fixed length of time. Less energy will be delivered to the same area of material if the beam is out of focus. This is because a beam out of focus has a larger spot size covering a larger area. See Figure 62.
- A beam of known energy is applied for a fixed period of time. If the optics (lenses and mirrors) are soiled with processing deposits or are out of alignment, some of the beam's energy will be absorbed or deflected before it reaches the material so less energy will be delivered.

In summary the lowest energy is delivered to an area of material when a low energy beam is delivered for a very brief period of time. The highest energy is delivered when a high energy beam is delivered for a long period of time. The period during which energy is delivered is known as the dwell time. It will be demonstrated that the same effects may be achieved by using a lower energy beam for longer as a higher energy beam for a shorter period. In terms of textile manufacturing and production, the shorter time period is more desirable as a greater machine output is possible.

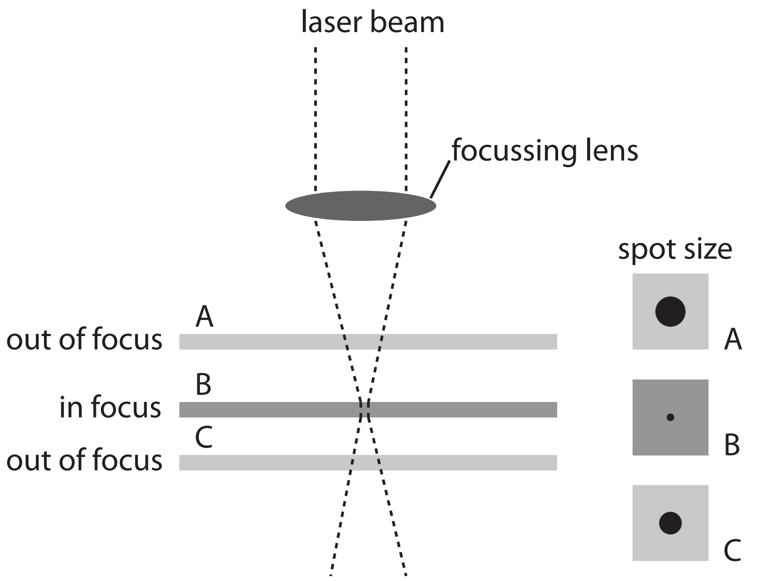


Figure 62: Diagram showing how where the materials to be processed should be placed to achieve maximum energy from a focused beam. The beam is in focus on the top surface of material B and the spot size is the smallest. Materials A and C are out of focus.

This section will now describe steps that may be taken to determine optimum processing parameters for a given material. It is important to note that although the methodology is transferable, the parameter values will be machine dependant. As already mentioned laser systems are available with lasers with different power ratings. At maximum efficiency, a 10W CO_2 laser is able to deliver a beam with a maximum energy (100%) of 10W and a minimum of 0.3W assuming the minimum power parameter is 3%. A 150W laser will be able to deliver a beam with a maximum energy of 150W and a minimum of 4.5W assuming the same maximum and minimum power parameters. Clearly if the optimum energy parameters for a given material are very low, the higher power laser may not be suitable and vice versa. A 1000W laser is not suitable for processing textiles and a 10W laser will not cut metal sheets.

In addition, as lasers age over time and with use, their maximum power rating reduces. This means that a 50W laser may not actually be capable of delivering a maximum of 50W. In practice what this means is that as long as the laser is able to deliver beams within the required energy range, optimum parameters may be determined. It does mean however that specific parameters quoted in this research may not be applicable absolutely on other systems and may need to be altered up or down for application elsewhere. They may however be used as a starting point. The method described here may be followed for parameter optimisation.

4.4.1 Focal height

Before laser processing, the focal height of the system must be correctly set for the optics being used and the materials being processed. This will ensure that the spot size of the beam is as small as possible and consequently the maximum energy is being delivered to the surface of the material. The exact process will differ from system to system and the laser technician and operating instructions should be consulted. On a laser marker where the beam is delivered by galvanometric mirrors, the distance between the top surface of the fabric and the laser should be set to the appropriate fixed distance, (A in Figure 63) usually by moving the work bed on which the material has been placed, up and down (z-direction). The beam focuses at this fixed distance indicated by the arc. This means that at the extremities of the work area, the beam will be out of focus. (B in the diagram) Consequently as the beam meets the work bed at an oblique angle, the spot will have an elliptical shape. Sample processing should be carried out to see if this effect is material.

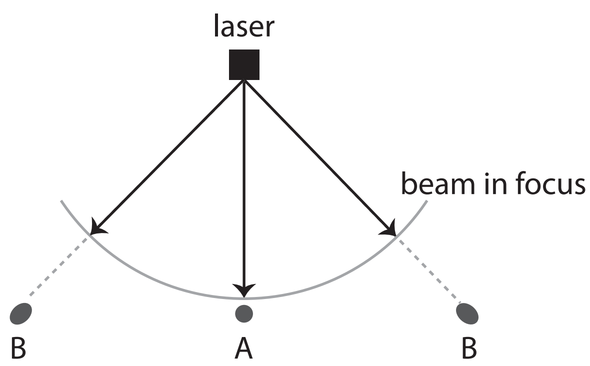


Figure 63 : Galvanometer driven system. Work is in focus at point A

On a flying optics system, the correct nozzle should be fitted for the type of material being processed and the gap between the end of the nozzle and the top surface of the material set. This is easily achieved by placing a spacing plate of the correct thickness, between the material to be processed and the nozzle. In Figure 64, the plate has a thickness of 1mm and the screw on the side of nozzle (C) is loosened to lower or raise the nozzle to the correct focal height. It should just touch the plate, which will set the correct height. As the nozzle travels over the work area to deliver the beam, the beam on a flying optics system will always have a round spot and will remain in focus.

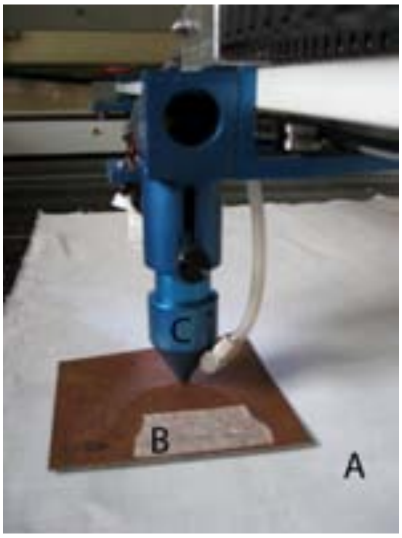


Figure 64: Work area flying optics system. Material (A) is placed on the work bed. A plated (B) of known thickness is placed under nozzle (C) and the gap adjusted.

Figure 65 - Figure 67 show views of some nozzle types that may be used on a flying optics system. The gap between the nozzle and the top surfaces of the work piece would be set to 1mm for the nozzle in Figure 65 and 8mm for the nozzle in Figure 66. These values are machine dependant. The attachment on the side of each nozzle is for assist gas hoses.

Figure 65: Nozzle usually for processing thin materials such as textiles and paper.

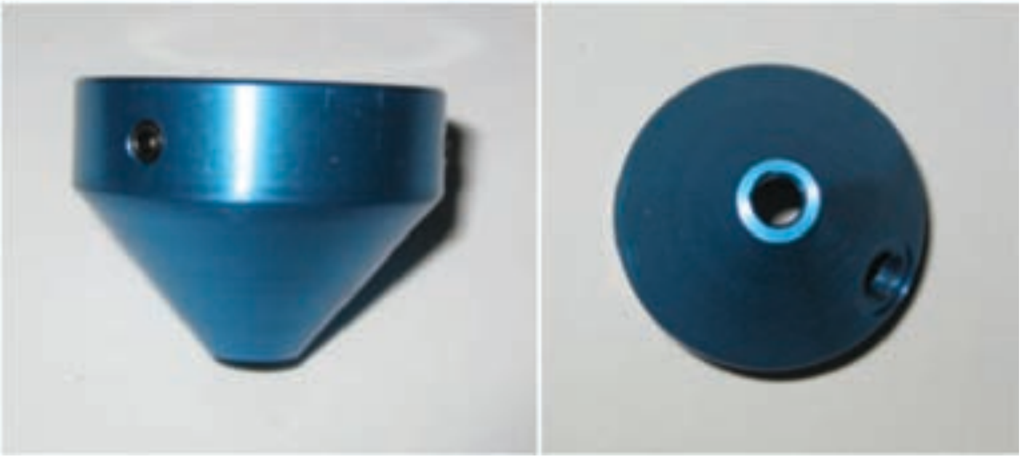


Figure 66: Nozzle used for processing thicker materials

Figure 67: Nozzle used for processing very thick materials and 3D objects

It is possible to tell by the examination of a series of sample marks or cuts whether a system is in focus or not. For a given energy and speed, the processed line will be as sharp and narrow as possible when a beam is in focus. If the beam is focussed above or below the surface of the material, the width of the marked line will increase. Figure 62 shows a diagram relating the focal height to the spot size of a beam. The effects of an out of focus beam may be seen by comparing Figure 68, where the beam is in focus at 1mm above the work surface to Figure 69, where the focus has been set to 4mm above the work surface and Figure 70, where the focus has been set to 8mm above the work surface. Power and speed settings, are the same in all three images – only the focal height has been changed. In Figure 68 the fabric is cleanly cut, whereas in the out of focus samples, the cuts become marks and the surrounding charred area becomes wider. Whilst not desired effects for normal textiles manufacturing, they may be used to advantage by a designer if the focal height is noted and used consistently.

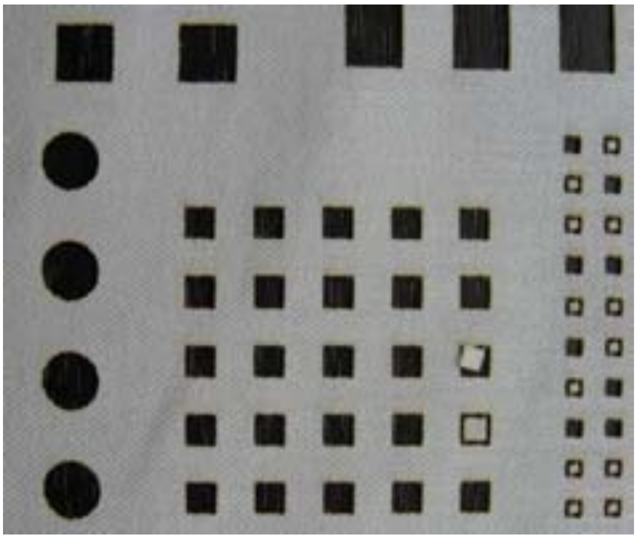


Figure 68: Cotton processed with beam set to correct focus height (1mm)

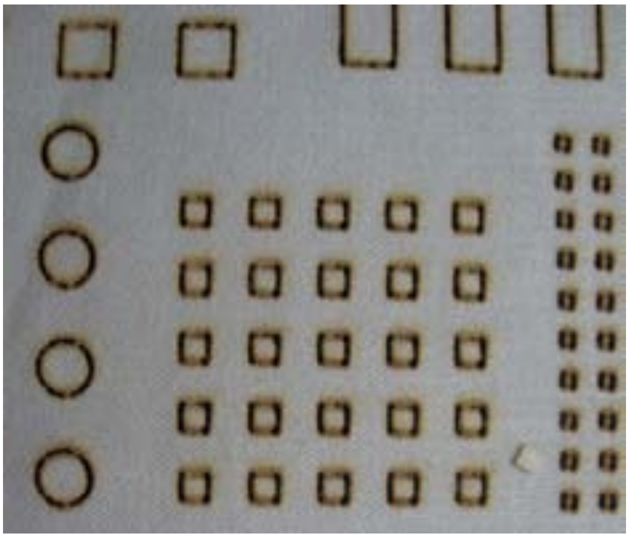


Figure 69: Cotton processed with beam set out of focus height (4mm above work surface)

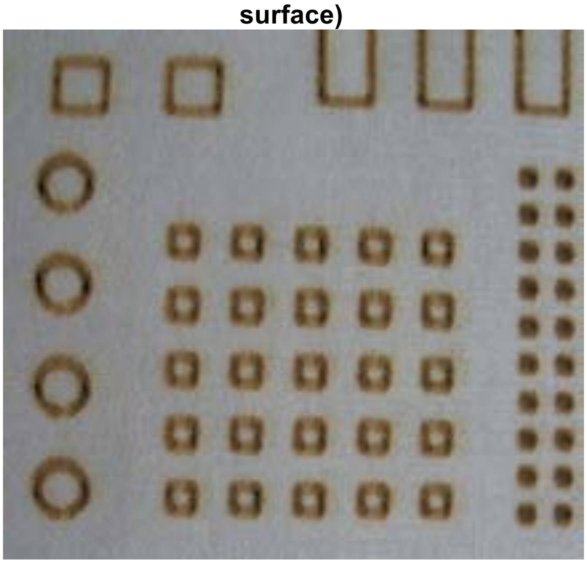


Figure 70: Cotton processed with beam set out of focus height (8mm above work surface)

Care should be taken when processing materials that do not have a consistent thickness. The focal height should be set such that there is always sufficient clearance for the nozzle. This is particularly important on systems with flying optics where a nozzle moving at high speed may be damaged if it comes into contact with a rigid material. It will not be possible to process uneven materials with the correct focal height at all times. Decisions will have to be made to either process the material in sections, changing the focal height where appropriate, or to accept that the processing parameters will not be optimum. In this case inferior results will be achieved in parts. As mentioned above, it is possible use systems where the beam is automatically adjusted to maintain a constant distance between the laser and the material avoiding the need to manually adjust the focal height.

4.4.2 Trials to determine initial parameters

The methodology for parameter optimisation described here as three stages:

- Determining initial parameters – this section
- Determining parameter charts - section 4.4.3
- Adjusting parameters for specific designs – section 4.4.4

The materials to be processed should be placed as flat as possible on the work bed. If necessary they should be secured with masking tape to ensure there is no movement during processing. The focal height should be set correctly.

The steps in determining optimum parameters for a given material are:

a. Create a test file consisting of evenly spaced lines as in Figure 71.
b. Set the initial power parameter to a low setting. Set the speed parameter of each line such that it starts high (very fast) and decreases by constant amounts
c. Alternatively, set the initial speed parameter to a fast setting. Set the power parameter of each line such that it starts low and increases by a constant amount.

The initial parameters are selected in such a way that the lowest energy is delivered to the material being processed. The laser technician could be consulted or alternatively the minimum power and maximum velocity settings for the equipment being used could be selected as initial parameters. If no mark is made with these settings, incrementally increase the power parameter (e.g. by 5%) or incrementally reduce the velocity parameter (e.g. 5mm/s) until a mark is visible.

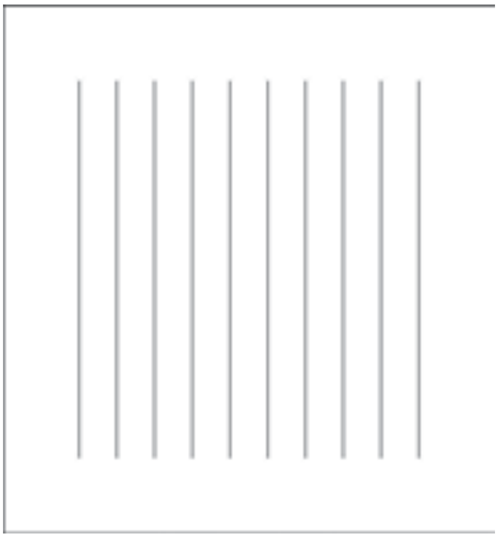


Figure 71: Test lines, 100mm lines, 10mm apart

The approach described in option b) may be seen in Figure 72 (left) where power was set to 10%. The speed parameters were 60cm/s (A), 50cm/s, 40cm/s, 30cm/s, 20cm/s (B) and 10cm/s (C). As the speed decreases, more energy is applied to the materials and the laser has a greater effect changing from marking the fabric in line A to just cutting in line B and cutting through in line C.

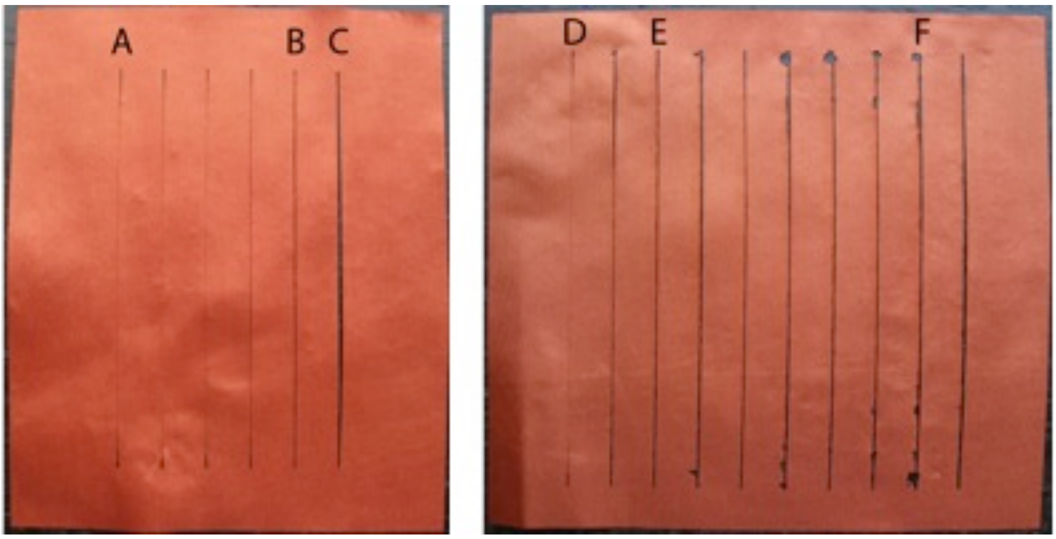


Figure 72: Polyester process using a low power parameter with speed decreasing line by line (left), Polyester processed using a high speed parameter with power increasing line by line (right)

The approach described in option c) may be seen in Figure 72 (right) where a high speed was chosen 60cm/s and the power was increased starting with 10% (D), 20%, 30% (E), 40%, 50%, 60%, 70%, 80%, 90% (F), 100%. As the power increases, the laser has a greater effect from just marking the fabric in line D, to cutting in line E and significantly degrading the fabric in line F.

It should be pointed out that line A in the first sample and line D in the second sample, have the same processing parameters (10%, 60cm/s). From a careful examination of these samples, a starting point for both power and speed may be selected for further trials. If marking is required, experimentation may take place with parameters used for line A (10% power, 60cm/s). If cutting is required, parameters may be selected either as in line B (10%, 20cm/s) or as line E (30%, 60cm/s). This demonstrates that there is a range of parameters that will achieve the desired effects – lower power/ lower speed or higher power/higher speed. This will now be explored further.

An examination of the lines in Figure 72 shows that they have not been evenly processed. The start and finish points have had more energy applied than the centre sections. These samples were processed on a flying optics system and due to inertia, the speed parameter that has been set is not achieved until a little way into processing. The beam has been applied for longer whilst the nozzle is speeding up at the start of a cut and again whilst it is slowing down at the end of a cut. As a consequence more energy has been delivered during this period. On some systems it is possible to compensate for this by reducing processing power through software settings. Options may also be given to specify exactly where processing starts and in which direction. For example, when cutting a square, cutting may be initiated at a corner or halfway along an edge. The system used for this research has a facility to specify a maximum and minimum power. The maximum power is applied during normal processing and the minimum at the beginning and the end of each cut/mark. It was not however possible to reduce the minimum below 3%. When designs that contain detailed curves are processed, this processing characteristic needs to be considered. Different parameters will be needed to obtain the same effects on, for example, both long lines and tight curves. To take this into consideration, the test design was modified to include lines, circles and squares. An example may be seen in Figure 73. The image in Figure 74 demonstrates that parameters may be set such that a line is cut, whereas the circles remain attached. This applies to marking too where elements may be marked very faintly other others much darker. See Figure 75. Note also that the start point of processing for the circle is marked with a point. This is due to the fact that the area is processed twice, one at the beginning and once at the end. The design could be modified to have an almost complete circle to avoid this effect.

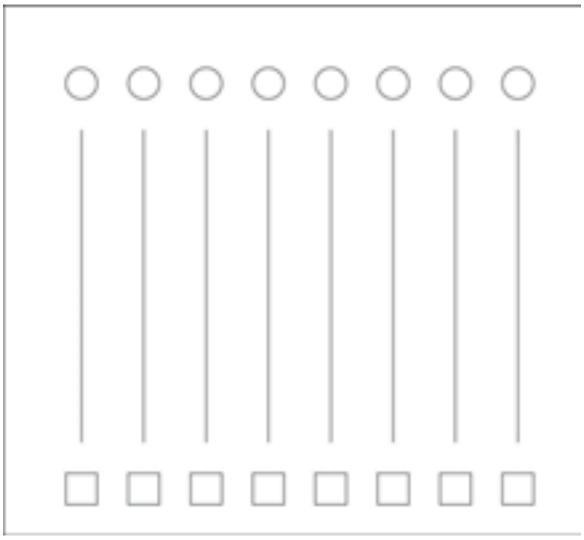


Figure 73: Test cuts including squares and circles

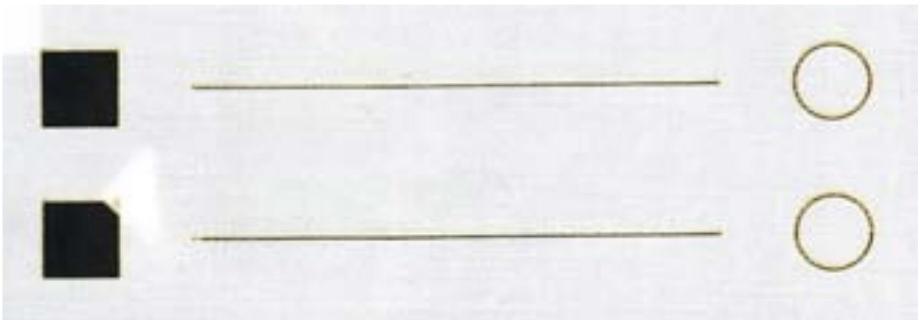


Figure 74: Cotton processed such that the squares and lines are cut, but the circles remain attached.

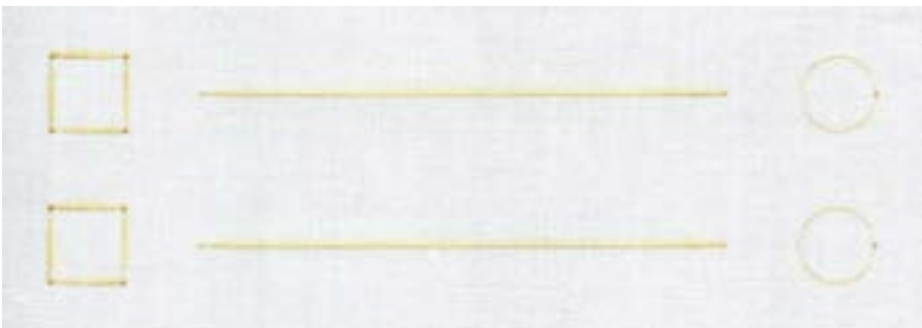


Figure 75: Cotton showing uneven marking, the circles are much lighter that the lines and squares

Optimum parameters for a given material are therefore design dependent. See section 4.4.4 for an explanation on how to modify the parameters based on designs.

There will be a range of processing parameters that are successful for a given material. A selection of the parameters to be used will be based on whether cutting or marking desired. If marking is required, the depth or intensity of mark is relevant. A sample test such as that shown in Figure 73 should be used as described below to determine the range of parameters that will cut or mark the material successfully. Further trials are then required using elements of the design to be used to fine tune the selection. If a given design consists both of say long lines and detailed curves, the design may be separated into sections, which may be processed with different parameters.

4.4.3 Determining a parameter charts

This section describes a methodical approach, which may be used to trial a given material over a range of parameters for both cutting and marking and record results. The parameter charts obtained by this method may be used to predict the likely behaviour of a material.

The method involves systemically cutting several test samples incrementing the power and decreasing the speed in equal intervals. The examples here use :

- Speed – 5cm/s, 10cm/s, 15cm/s, 20cm/s, 25cm/s, 30cm/s, 35cm/s
- Power – 5%,10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95%, 100%

With an unknown material, it is better to start with the higher speed/low power parameters, as there is less opportunity for too much energy to cause the material to ignite.

The samples should be closely examined and the grid shown in Figure 76 completed to indicate where 'good' cuts and marks take place. A 'good' cut (c) is considered to be a cut that separates the fibres cleanly without degrading the material with excessive charring and burning. A 'good' mark (m) is considered to be a mark that does not cut the material, but may be clearly seen. More than one parameter combination may meet these conditions. Combinations should be omitted from trials if it is obvious from previous tests that the mark will be too pale or the cut will excessively degrade the material. Figure 76 - Figure 79 show completed grids or charts for cotton, polyester, wool and silk respectively. The charts show that optimum parameter combinations lie on a diagonal line and that the optimum range is material dependent. Materials of other fibres, yarn densities, fabric constructions, or with coatings will show similar but different results.

Cotton sateen mantra white																				
	Power %																			
Speed cm/s	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
5		c	c																	
10	m			c	c															
15	m				c	c														
20	m					c	c													
25		m					c	c												
30		m	m						c	c										
35			m									c	c							

Figure 76: Cotton, 50W laser, cutting (c), marking (m)

Polyester																				
	Power %																			
Speed cm/s	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
5	c																			
10		c	c																	
15			c																	
20	m			c	c															
25	m				c	c														
30	m					c														
35		m				c	c													

Figure 77: Polyester, 50W laser, cutting (c), marking (m)

Wool crepe																				
	Power %																			
Speed cm/s	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
5			c	c																
10	m				c	c														
15	m								c	c										
20		m								c	c									
25		m	m										c	c						
30			m	m													c			
35			m													c	c			

Figure 78: Wool crepe, 50W laser, cutting (c), marking (m)

Silk dupion																				
	Power %																			
Speed cm/s	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
5		c	c	c																
10	m		c	c	c															
15	m			c	c	c														
20		m			c	c	c													
25		m				c	c	c												
30			m					c	c	c										
35			m						c	c	c	c								

Figure 79: Silk dupion, 50W laser, cutting (c), marking (m)

The information contained in these charts may be used to predict the likely parameter combinations that may be used for a material of the same fibre. When a test sample of the new material is processed, the resultant cut or mark may be plotted on a similar grid. A comparison to the chart for the same fibre or similar materials will indicate whether the parameters should be increased or reduced to improve the appearance of the processed material.

The charts may also be used to predict the likely parameter combinations for processing the same material on another laser system. These trials took place on a 50W system. To cut cotton, a power of 60% (30W) is needed at 35cm/s. If a 150W system were to be used, the power parameter would need to change to 20% as 20% of 150W delivers 30W. On a 10W system, insufficient power would be delivered at 35cm/s, as the maximum power (100%) is 10W so a lower speed would need to be selected. From the chart for cotton, at 5cm/s the power parameter is 10% delivering 5W. On a 10W system at 5cm/s a power parameter of 50% could be selected to deliver the same energy.

The initial trials described in 4.4.2 indicated possible processing parameters - marking (lines A and D), cutting (lines B, C, and E). These could be used a starting parameter combinations for methodical trials with charts which would reduce the number of tests that need to be conducted as they give an indication to points in the cutting and marking range and show points that lie outside – either do not mark at all or damage the fabric with too much energy.

Once the parameter range has been determined for a given material, further design dependent trials are needed. These are described in the next section.

4.4.4 Design dependent tests

This section shows by means of an example how design dependent tests may be conducted to fine turn processing parameters to a specific material and a specific design. If a design is to consist of small cut out areas, a sampler such as that in Figure 80 may be used. It could also contain components of the chosen design. In this case a range of small cut outs – circles, squares, rectangles and ovals – was selected with a variety of sizes and spacing described in the table in Figure 81. The aim this sampler was to determine the minimum size of holes, shapes and spacing that could successfully be cut on various materials.

Figure 80: Sampler containing small cut-outs of varying shapes, sizes and spacing

	HOLE SHAPE	HOLE SIZE	HOLE SPACING
A	Circle	1mm	1mm
B	Circle	1mm	3mm
C	Circle	1mm	5mm
D	Circle	2mm	2mm
E	Circle	2mm	4mm
F	Circle	2mm	5mm
G	Circle	3mm	3mm
H	Circle	3mm	4mm
I	Circle	4mm	4mm
J	Circle	5mm	5mm
K	Circle	6mm	6mm
L	Circle	7mm	5mm
M	Circle	5mm	5mm vertical, 2mm diagonal
N	Circle	5mm, 2mm	6mm apart, 2mm holes centralised
O	Square	1mm	2mm
P	Square	2mm	3mm
Q	Square, circle	3mm, 3mm	4mm
R	Square	4mm	5mm
S	Rectangle, rounded corners	2mm x 4mm	4mm
T	Rectangle, rounded corners	3mm x 8mm	5mm
U	rectangle	4mm x 10mm	4mm

Figure 81: Dimensions of cut outs in sampler

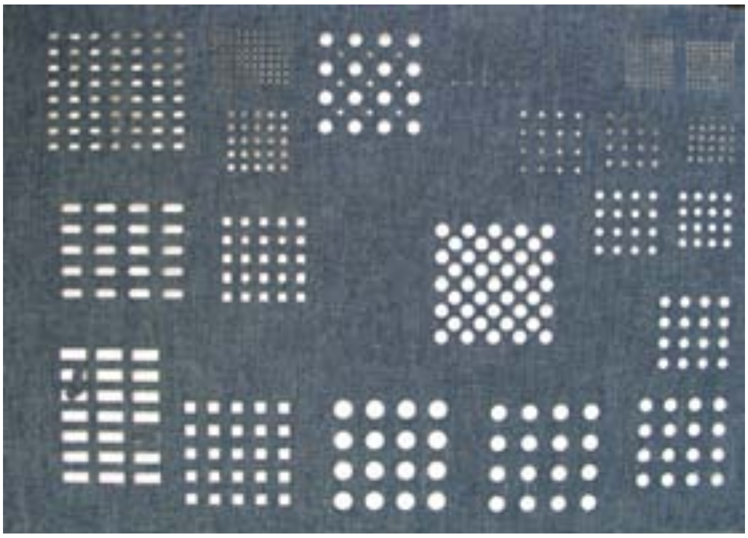


Figure 82: Sample test file above to test the spacing of small holes on denim/lycra

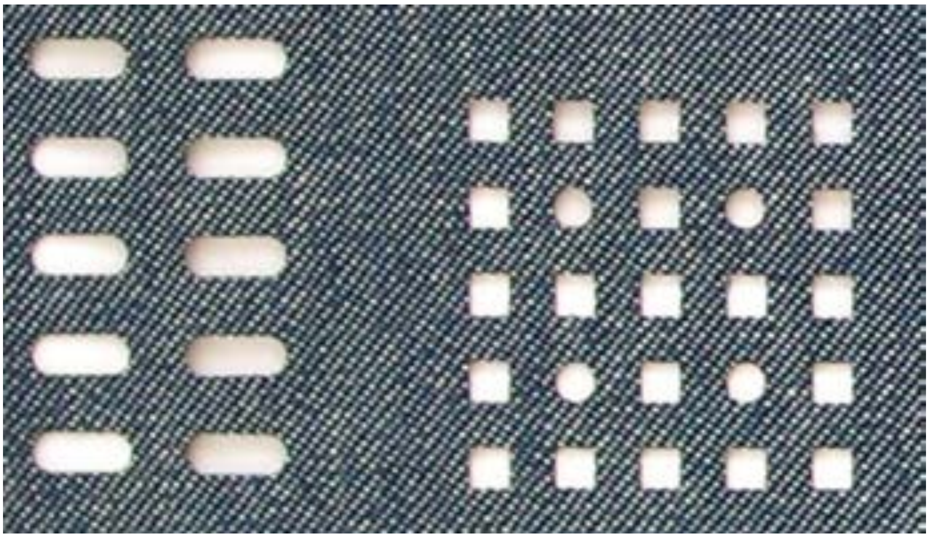


Figure 83: Sample test file (detail) shows no fabric degradation

The images in Figure 82 and Figure 83 show the sampler cut on denim. The parameters that were chosen are successful for all these holes. If the energy was found to be too intense, the power parameter should be reduced or the speed parameter increased. If the shapes did not detach completely, the energy would be increased or the speed would be reduced.

Excess energy

The samples shown in Figure 84 and Figure 85 demonstrate how excess energy may be absorbed by the addition of extra material. Both samples were processed with identical parameters – the fastest speed and lowest energy. As can be seen in Figure 84, there is degradation in parts due to sparks from plasma, an indication that too much energy is being applied. As it was not possible to reduce the energy further, thick cartridge paper (Daley Rowney 96g/m^2) was placed under the fabric during processing. This absorbed the additional energy and no plasma was formed, allowing the sample to be processed with a very detailed design without damage. See Figure 85. Care should be taken with the choice or paper or other additional materials. If for example the paper chars excessively, it may leave deposits on the fabric.

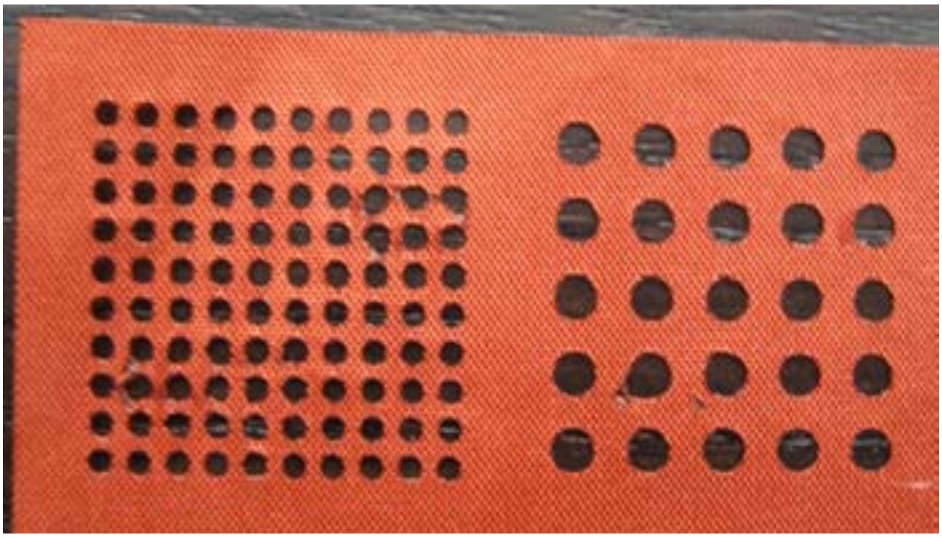


Figure 84: Polyester processed with the lowest power/highest speed parameters. Degradation due to plasma may be seen.

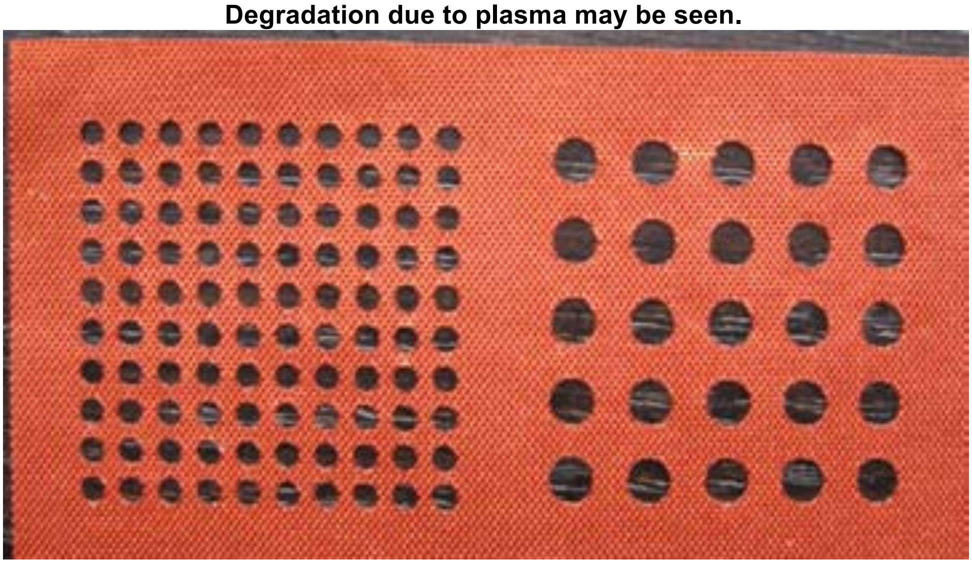
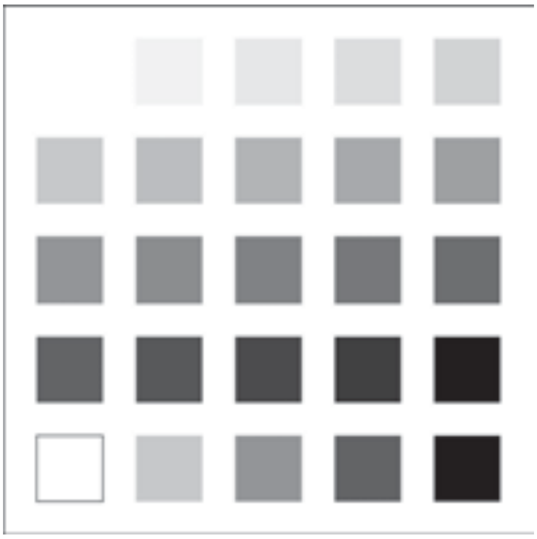


Figure 85: Fabric processed with the same parameters but laid on paper during processing which absorbed the excess energy - no degradation.

4.4.5 Design dependent tests - etching

Etching tests need to be carried out in a similar methodical way. Having run tests such as those as described in 4.4.2 and 4.4.3, start parameters that mark but do not cut, will be known. Again a sampler test file should be used but in this case the test marks are blocks which vary in intensity rather than cut out shapes. Figure 86 shows a test file, which contains 2cm x 2cm blocks, which vary from 0% to 100% black, in 5% increments. The bottom row goes from 0% to 100% in 25% increments. This file



should be processed using the chosen starting parameters.

Figure 86: Test pattern for laser etching

Results should be evaluated and increased/decreased power and increased/decreased speed parameters be experimented with until the desired level of etching is achieved. Again it is important to record results to enable repeatability.

Two further parameters may be varied:

- Distance between etched lines (also known as hatching). It is possible to alter the distance between each etched line. Too far apart and the lines may be viewed. Too close together and the fabric may be degraded.
- Direction of etching. Etching may take place, parallel with the length of the work bed or at right angles to it. Research showed that etching results were usually better in one direction than the other and this depended on the fabric construction. Placing fabric at an angle of 45^o will allow etching to take place along the bias.

4.5 Conclusion

This chapter has provided an overview of laser processing and how it may be applied to textile processing. A methodology has been developed for determining and recording optimum processing parameters - cutting, marking and etching - for a given design on a given material. Results obtained through applying this may be used as a basis from which to select or modify process parameters for a similar material on the same laser system. A method for translating parameters for processing other laser systems has been provided. Aspects of software manipulation have also been discussed highlighting that the issue that controlling the laser process is a combination of both software interventions and correct parameter selection. Chapters 5, 6 and 7 will describe how laser processing may be used to create three-dimensional textiles.

5 Laser Assisted Template Pleating

The contextual review indicated that an area for further research is the use of folding or pleating to create three-dimensional textile surfaces and structures from materials with a two-dimensional origin. Traditional and contemporary methods of pleating were discussed in section 2.3.3.1 of the contextual review. This first part of this chapter (section 5.1) details practical explorations into these methods. The second part (sections 5.2 and 5.3) describes three new processes for pleating that were investigated. One process *Laser Assisted Template Pleating* offers considerable advantage and this is developed further. (Section 5.4) The way in which origami, the traditional method of folding paper is used as a design inspiration is discussed in section 5.4.2. Section 5.4.3 shows design families that have been used and developed for laser assisted template pleating. The new process may be applied to other materials for applications other than traditional textiles. This is described in section 5.4.4.

5.1 Experiments in pleating

The review of historical and contemporary processes and the author's own practice has enabled the following observations concerning pleating to be made. In order to form pleats in a length of fabric, folds need to be formed. Folds may be made by hand, manually with the assistance of tools or by machine. The placement and type of pleats and the fibre type and construction of the fabric, all play a role in how easy or difficult pleating may be. Manual methods, whilst time consuming, enable freedom of design whereas industrial pleating machines already in the market neither offer design flexibility nor the possibility of processing fabric with cuts.

This section describes experiments that were carried out to replicate historical and contemporary manual fabric pleating processes and ideas that were developed from this enquiry. The aim of this study was to understand fully the possibilities and limitations of the different processes and to determine new methods of pleating that would be accessible to designers and offer design flexibility. For ease of analysis, the investigation is broken down into the following categories:

- Hand pleating (5.1.1)
- Pleating using a tool (5.1.2)
- Pleating using a machine (5.2)
- Pleating using a process (5.3)

5.1.1 Hand pleating

Initial experiments were concerned with hand pleating. Simple hand pleats of 5mm were formed on dry, damp and wet fabric every 10mm. Even-weave linen was used as this was similar in construction and weight to the observed Egyptian fabrics and not too dissimilar from the Miao hemp and heavy cotton. Tests were conducted using a single layer of fabric (Figure 87 and Figure 88) and were repeated using four layers of fabric (Figure 89 and Figure 90). Results similar to observed Egyptian samples shown in section 2.3.3.1 were achieved. By folding parallel to the grain and creasing the linen fabric with fingers, it was possible to achieve fairly even pleats. The best results occurred when the fabric was pleated whilst fairly wet and allowed to dry completely before examining the folds. Contrary to expectation, pleating four layers together gave an acceptable level of sharpness on folds on all layers of fabric although the pleats were more rounded. See Figure 90.

Figure 87: Hand pleated linen, one layer, 5mm pleats 10mm apart

Figure 88: Hand pleated linen, one layer, very sharp edges

Figure 89: Hand pleated linen, four layers, edges more rounded.

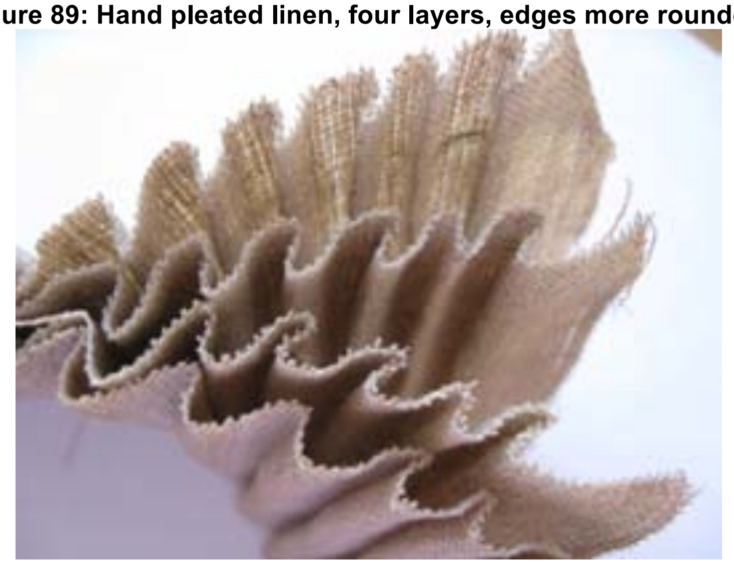


Figure 90: Hand pleated linen, four layers, internal folds are more sharply creased

As has already been mentioned, the authors own work is achieved through hand-pleating laser cut panels of fabric. A variety of fabrics made from natural fibres in a range of weights were used. Pleated designs varied in scale from 5mm to 50mm folds. Figure 91 shows an example of hand pleated laser cut cotton where the folds are aligned with cuts and follow the grain of the fabric. The design consists of many small pleats that are folded flat. The full panel (63cm x 102cm) took 8 hours to pleat. The application of spray starch facilitates both the folding and retention of pleats on finer fabrics. Other examples may be seen in the contextual review. (Figure 29 - Figure 30)

Figure 91 :Hand pleated linen (detail). Pleats 1cm high, 0.5cm wide. Janette Matthews 2006

It is therefore possible to successfully pleat by hand both simple and complex designs with and without cuts. The method offers design freedom as a variety of pleat styles may be achieved on many types of materials. It is however difficult to maintain consistency with a large number of pleats across wide fabrics. Furthermore the method is very time consuming.

5.1.2 Pleating using a tool

This section examines hand pleating methods that are assisted with tools. The purpose of these experiments was to understand the advantage gained in using tools to assist folding and to determine any limitations of the tools.

5.1.2.1 Pleating using gathering stitches

A series of experiments were conducted using gathering stitches similar to the Miao technique and the Princess Pleater discussed in the contextual review. Three pairs of evenly spaced lines of running stitches were inserted parallel to both edges along the length of the fabric, one pair at each edge and one in the centre. (Figure 92)

These stitches were drawn up tightly and secured. During this stage, the fabric bundle was pulled width-wise under tension while the pleats were encouraged to form by hand along the folds produced where the fabric was pinched by the stitches. Figure 93 shows the fully drawn up pleated fabric. Once dry the gathering stitches were removed. The technique resulted in fairly even pleats and worked best with damp fabric. (Figure 94) On wider widths, it was necessary to stitch lines of intermediate gathering stitches to maintain even pleats across the whole width. By varying the spacing of the gathering stitches, it would be possible to change the dimensions of the pleats. However, it would be necessary to match precisely the stitch spacing on all rows of gathering stitching to ensure straight even pleat sizes.

Figure 92: Two rows of evenly spaced gathering stitches

Figure 93: Pleats fully drawn up and secured during drying

Figure 94: Pleats, sharp edged but some variation in dimension, gathering holes may be seen.

5.1.2.2 Pleating using an embossing tool

This experiment was based on a method used by the Miao Chinese. Wet linen was scored with vertical lines along the grain using a metal round headed embossing tool. Subsequent folding took place along these lines. The fabric pleated much more easily along the scored lines than when no lines were present resulting in very even pleats. The best results were achieved when scoring lines were made alternately on both sides of damp fabric corresponding to the alternate directions of folds. Figure 95 shows pleated fabric achieved by this method. The pleats are much more even than the hand pleated example on the same fabric in Figure 87.

Figure 95: Pleating on wet linen after scoring with an embossing tool alternately on each side

Further research is necessary to determine if this would be the case for all weave structures and fabric weights. It is felt that the method is more likely to be successful with thicker, stiffer fabrics or those that have had a thickening agent applied such as starch.

5.1.2.3 Pleating using moulding tools

These experiments were conducted to investigate the use of moulding boards similar to the one viewed at the British Museum (Figure 96 and Figure 97) and referred to in the contextual review. (2.4.3.1) Two identical wooden boards were made similar in scale and size to the Egyptian tools. (Figure 98 and Figure 99)

Figure 96: Wooden slat with 13 grooves. 25.4cm x 5.5cm x 1.7cm. Egyptian, though to be used for pleating textiles. British Museum

Figure 97: Detail of Egyptian boards, above, showing profile.

Figure 98: Boards fabricated as replicas of the Egyptian boards, above. (Top view)

Figure 99: Boards fabricated as replicas of the Egyptian boards, above. (Side profile)

The slats on the two moulds were positioned in such a way that the moulds would be able to be placed on top of one another for the to slats interlock. Even weave linen was pleated. Damp cloth was laid over the slats on one of the boards. Compressing the two moulds together did not allow sufficient fabric to be inserted deep enough into the grooves. It proved necessary to use doweling rods to push the damp fabric into the channels of the bottom board one groove at a time. It was necessary to work slot by slot from one end of the mould to the other. Three rods were employed – one with a square profile identical to the groove - to hold the fabric in place in the groove, and two others to push it into place between the next two slats. (See Figure 100) If this systematic approach was not used, inserting the fabric in one groove would remove it from the previous one.

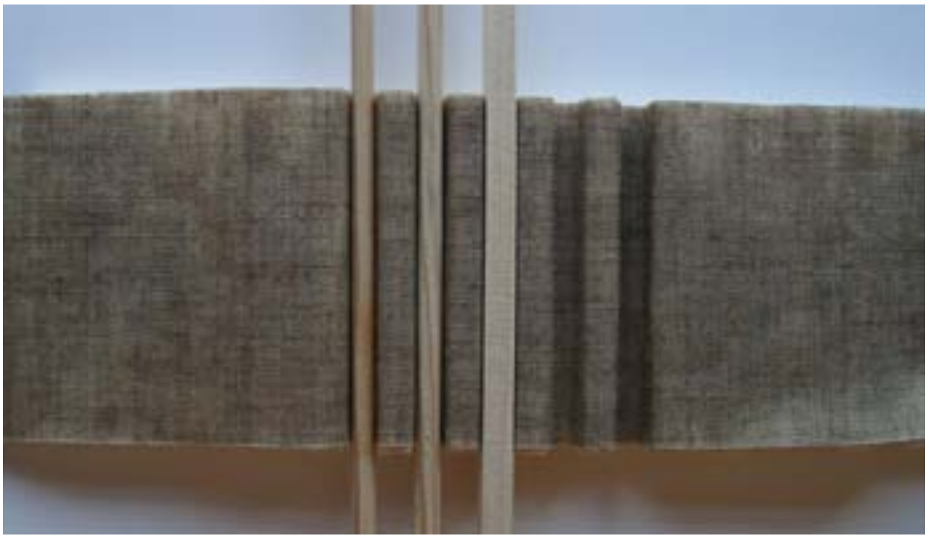


Figure 100: Linen placed on slatted board. Dowling used to push fabric between slats prior to placing second board on top.

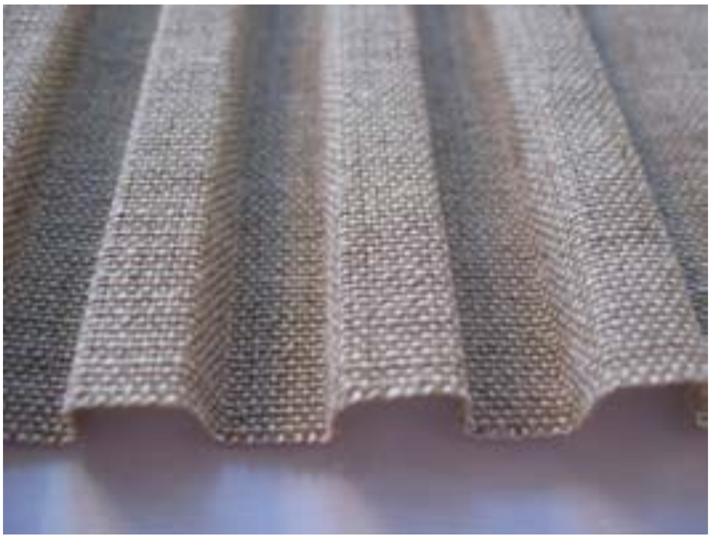


Figure 101: Folded linen produced using the slatted boards

Once all the grooves contained fabric, the two boards were compressed together with the fabric between them and the fabric left to dry. Pleating or corrugation was successfully achieved. (Figure 101) The pleated fabric however, does not resemble the Egyptian examples shown in Figure 13 and Figure 14 in the contextual review. It would seem that although moulding boards could be used for pleating, it is unlikely that moulding boards of this construction would have been used for this type of pleating. The experiments were repeated using only one board. As long as the fabric was sufficiently inserted into the grooves when wet, good pleating was achieved.

To investigate whether other styles of pleats such as flat pleating, could be achieved, a board was constructed with a zigzag profile as shown in Figure 102. Based on the results of the experiments above, only one board was deemed necessary.

Figure 102: Board with slats that have a zigzag profile

Damp, even weave linen was applied to the surface of the board, again working from one end to the other and this time using tensioned string to push the fabric into the tight channels or slots between each zigzag form. (Figure 103) When the fabric was dry, it was removed from the mould and a concertina or knife type pleat was achieved. (Figure 104) By pressing these pleats by hand to one side, it was possible to flatten the fabric. The pleats were even and the folded edge was sharp.

Figure 103: Wet linen placed on the board shown above with string being used to push the fabric to that bottom of the slots

The above tests show that it is possible to pleat fabric using moulds. The profile of the mould will determine the type of pleat that is produced and a variety of designs would be possible, varying both in scale and fold direction. The dimensions of the mould would need to correspond to the dimensions of the fabric to be pleated. For example to pleat a length of fabric 1m wide x 2m, a mould 1m wide would be necessary. The length of the mould that would be required would be determined both by the pleat dimensions and the profile or shape of the pleats. The surface area of the mould would need to be at least the length of the fabric. In this example, it would require a surface area length of 2m. It would be possible to mechanise this process and a different mould would be required for each design type.

Figure 104: Linen pleated on the above board. Very even pleats

5.1.2.4 Arashi Shibori pleating

These tests replicated the *shibori* method of wrapping a long length of fabric around a cylinder. The traditional technique is described by Wada (1983, 103-122) and a contemporary method, by Sparks (2005). Fabric is wrapped around a cylinder. A strong thread is secured and wound with even spacing over the fabric. (Figure 105) The fabric is compressed along the length of the cylinder pushing the wrapped thread lines close together. (Figure 106) This pushes the fabric into pleats. The process continues until all the fabric is pleated. The bound fabric is steamed while on the cylinder, allowed to dry and cool. When unwrapped, the pleats are revealed. (Figure 107) Best results were obtained with finely woven fabric, which was wrapped onto the cylinder on the bias so that pleats were formed diagonally to the grain of the fabric. Even with very careful, evenly spaced binding, it was not possible to achieve even structured pleats as the different layers did not all move together while the fabric was being compressed. The size of the pleats could be controlled to some extent by the spacing of the binding. Close binding resulted in tiny pleats.

Figure 105: Fabric wrapped round cylinder with binding taking place

Figure 106: Bound fabric compressed and ready for steaming

Figure 107: Unstructured pleats

The previous two sections have described a variety of methods that may be used to manually pleat textiles. It has been shown that it is possible to pleat by hand and with the assistance of tools. Some of these methods offer design freedom. Constraints are imposed both by the fabric type and thickness, and the method itself. The main disadvantage is that the methods are very time consuming.

The next two sections describe research that was conducted to develop a process for pleating that would automate the process to a greater or lesser extent. An aim of this part of the research was to develop a process or a machine that offered design freedom, would allow cut fabric to be pleated, could be used for structured pleats of different dimensions and would allow alternative pleat placements.

5.2 Pleating using a machine

As described in the contextual review, industrial machines have been developed to pleat fabrics and are used for textile finishing. The main disadvantage of these machines is that they offer little design freedom and a separate machine is required for each design type. Research here describes two ideas that were investigated – the first would enable insertion of structured pleats along the length of fabric and, the second, an ability to pleat fabric that contains cuts.

5.2.1 Pleating using a machine with slots

This experiment is based on an idea generated from shibori pleating and the method used by Hiroyuki Shindo described in section 2.3.3.1. Shindo's method winds a long length of fabric under tension from one cylinder to another. Simple uneven flat pleats are inserted by hand as the fabric is rolled, resulting in the fabric being pleated along the length with small, unstructured pleats.

The new method described below also pleats fabric from one cylinder to another and places pleats along the length parallel to the selvedge. It however enables a variety of structured pleated designs.

To test the idea, a rectangular model was made from laser cut Perspex. Figure 108 shows a diagram and Figure 109 the model. Fabric is initially rolled onto the cylinder on the left of the machine, labelled A in the diagram. Fabric then passes through the shaped holes, which are cut into a series of slots, labelled S1, S2, S3 and S4. Once pleated, the fabric rolls up onto cylinder B on the right of the machine. The slots (S1-

S4) contain the profile of the design to be pleated. The image in Figure 109 and detail in Figure 110 show the fabric passing through these cut-outs and being encouraged into folds according to the specified design.

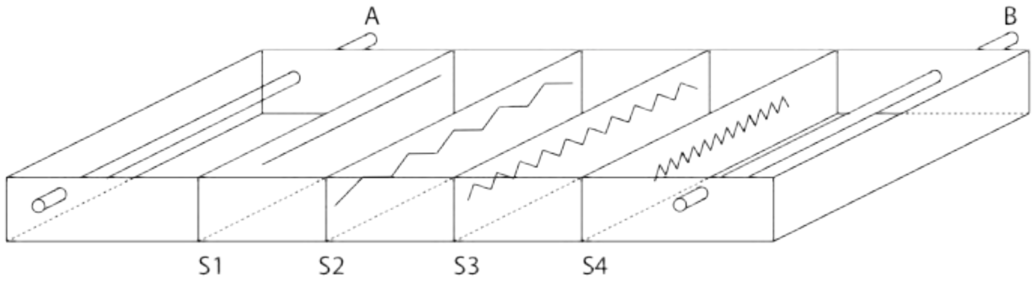


Figure 108: Diagram of machine. Fabric passes from cylinder A through the cut-outs on slots S1-S4 and then onto cylinder B.

Figure 109: Fabric from the cylinder is passing through the cut-outs on the slots S1-S3 and is gradually being pleated.

Figure 110: Top view of two slots showing cut -outs with different profiles and pleats being inserted.

The number of pleats and their form is determined by the profile of the cuts made in slots S1, S2 …... The machine has provision for up to 8 slots. In this case S1 is flat, S2 introduces a zigzag profile, S2-S6 gradually tighten and flatten the pleats so that evenly spaced, overlapping flat pleats are wound onto cylinder B. (Figure 111)

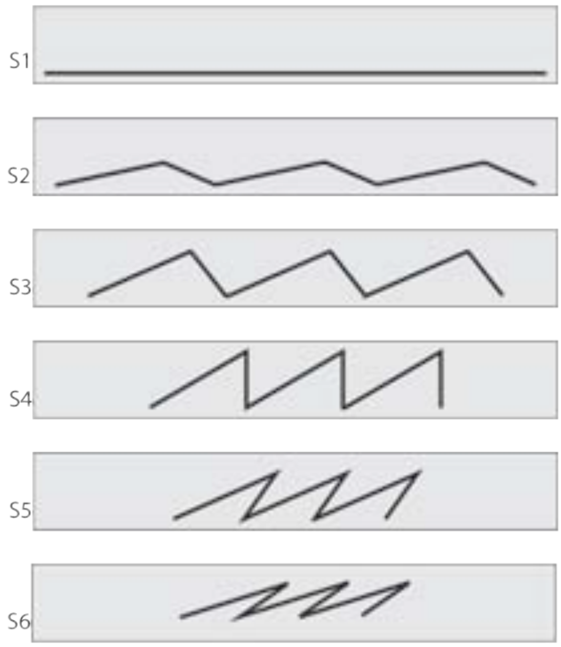


Figure 111: Example of 6 slots that may be used for evenly spaced overlapping pleats

By altering the profile of the cut-outs on the removable slots, the same machine could be used to pleat different types of designs, for example pleats with different dimensions and directions of fold. It would also be possible to mechanise this process.

Initial work suggested that this method would be effective to achieve structured pleats of a pre-determined design along the length of the fabric, which represents novelty. Further research is required to determine the optimum distance between slots for a given weave/weight of fabric and to exploit design potential. Although it offers design freedom, it is not evident that this method would be appropriate for pleating fabric that contains cuts as the cuts may not pass smoothly through the cut-outs. For this reason it was decided not to proceed with the development of this machine for this research.

5.2.2 Pleating using a machine with levers

This investigation is based on a replication of the manual process used in the author's own work and described in the contextual review. Experiments were conducted to determine whether it would be possible to pleat laser cut fabric using a machine to automate a very time consuming process. A simplified stepped design consisting of four cuts and six folds, in two directions, was chosen for these experiments. (See white rectangles in Figure 112 and design diagrams in Figure 113 and Figure 114)

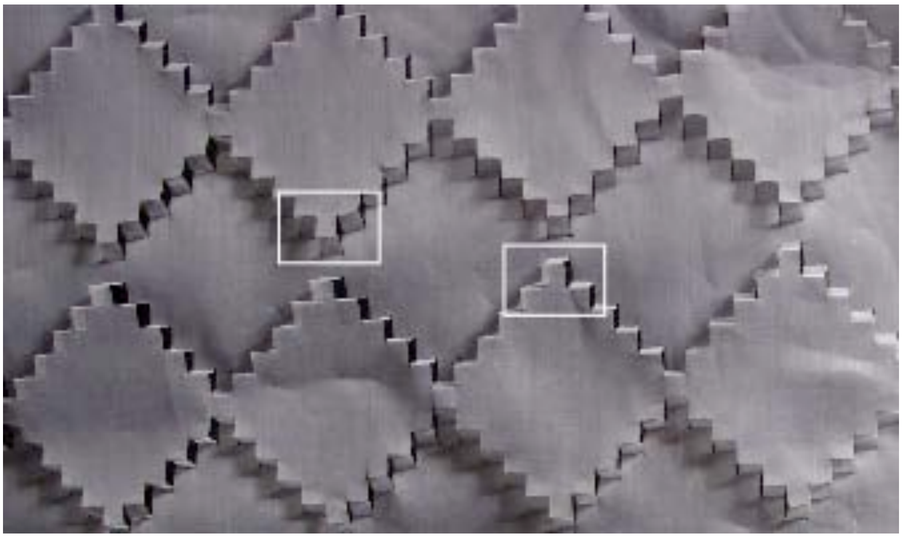


Figure 112: Stepped design. White rectangles shows design element selected for these experiments

The manual process was analysed and the manual process steps are as follows:

- Laser cut the fabric (Figure 113)
- Lay the fabric flat on a surface

- Select a set of cuts. Use a small diameter dowel rod or to assist the manual process of inserting folds in the correct positions into the fabric. (Figure 114 three folds in one direction and three in the other)
- Heat set the folds by ironing
- Repeat for next set of cuts.

Figure 112 shows the type of design that would be achieved.

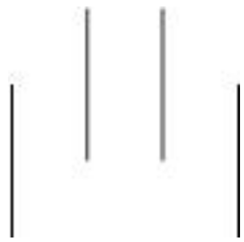


Figure 113: One set of cuts that would be made in fabric or card for the design used in this experiment

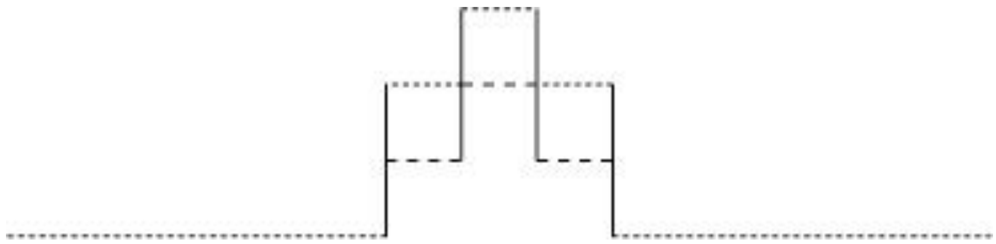


Figure 114: Dotted and dashed lines show folds that would be made to create the three dimensional surface.

Following the analysis a new process was developed which uses rigid flaps or levers attached to templates to lift fabric and move it in a specified direction to create a fold. The following steps are needed to create a pleat:

- Prepare two templates A and B (described below)
- Laser cut the fabric to be pleated
- Place the fabric on and under the purpose designed templates. Raise the levers on the template through 180^0 which places folds in the correct positions
- Set the folds in place
- Repeat for the next set of cuts

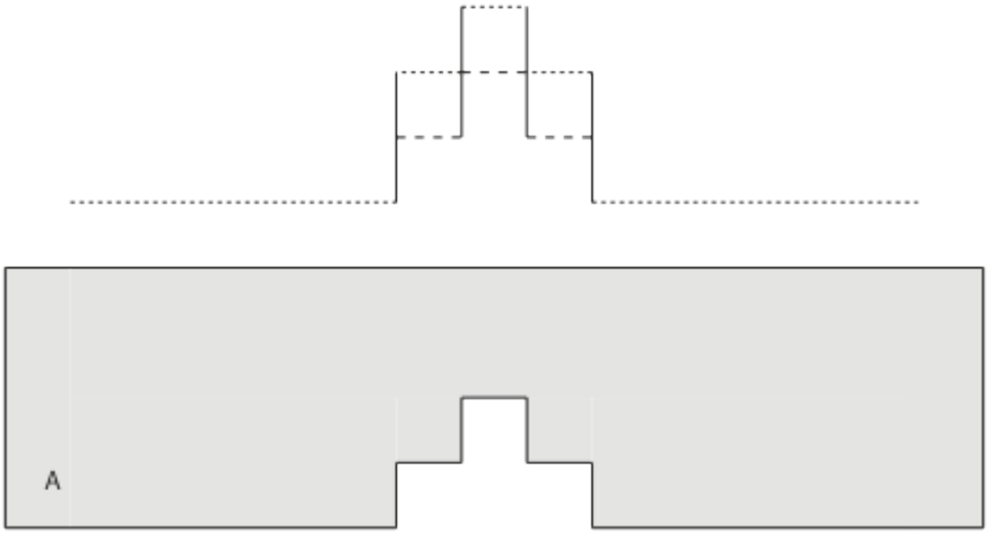


Figure 115: Design top and template A bottom. The template is flat and has profile of the fold

The templates were constructed using two pieces of stiff card (Template A and Template B). Template A (Figure 115 and Figure 116) is flat and contains the negative shape of the folded design. Template B (Figure 117 and Figure 118) contains the positive shape of the folded design and has attached to it, hinged flaps or levers in positions where folds are desired. The levers may rotate i.e. move through 180^0 from being completely folded back on Template B to completely forward. Figure 118 shows the levers standing up in the position they would be in part way through pleating. The vertical dimension of the lever corresponds to the depth of the fold.

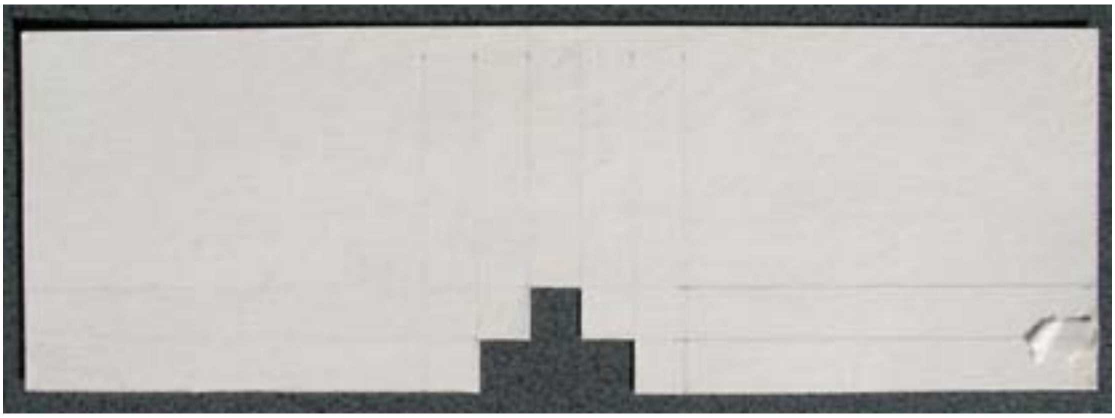


Figure 116: Template A based on the design in the previous image

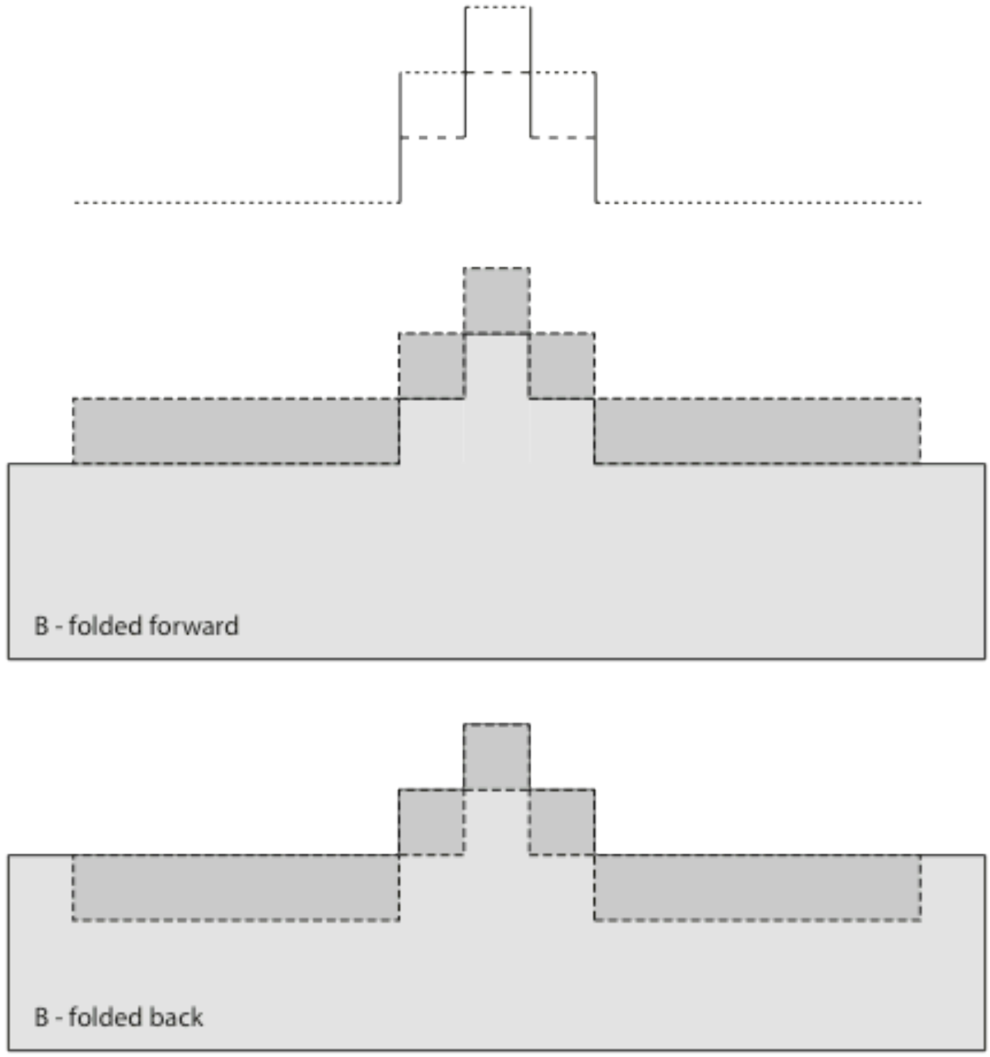


Figure 117: Design (top), Template B (centre and bottom). The shaded areas are flaps or levers which may move through 180° from lying flat on the template (bottom) to fully open (centre)

Figure 119 shows the two templates A and B placed together with the levers on template B raised. When pleating takes place the templates are in this position with the fabric placed over template B and under template A. Pleats are inserted as follows:

- Place Template B, with the levers folded fully back (Figure 117 bottom), is placed under the fabric with cuts in the fabric aligned to the profile of the template.

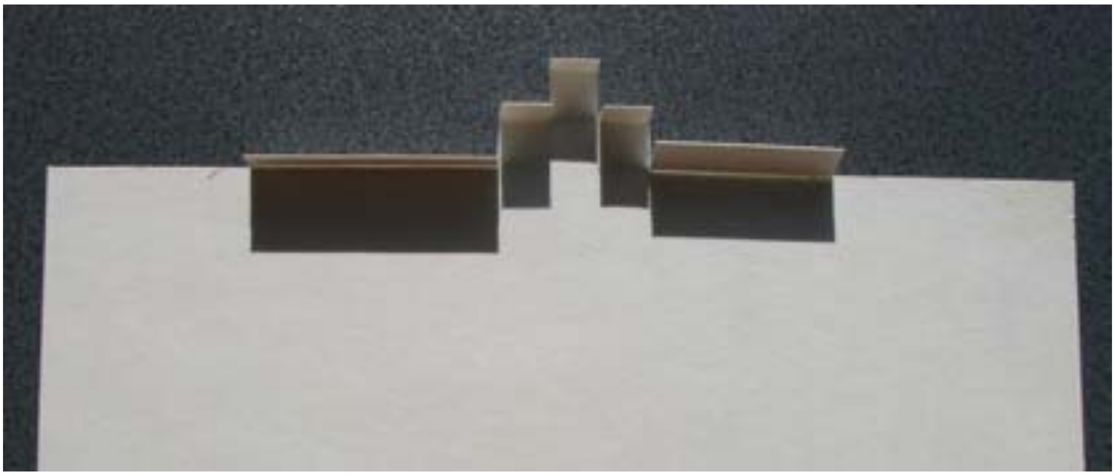


Figure 118: Template B showing flaps at 90° to the work surface

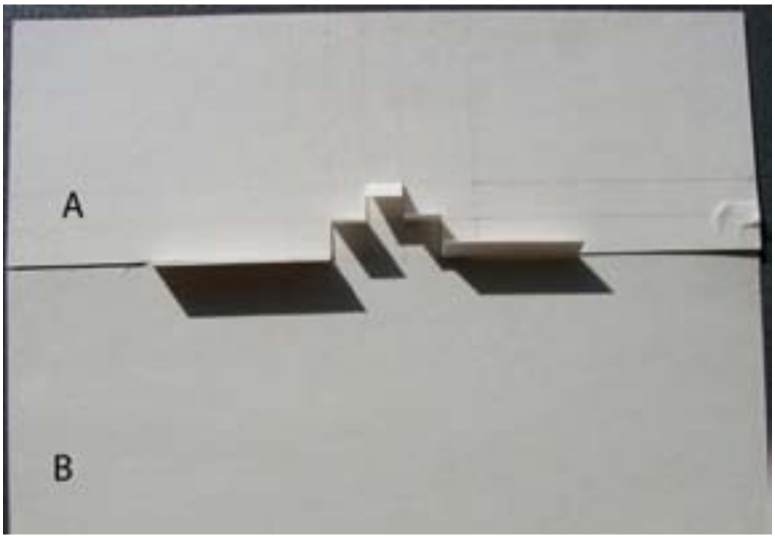


Figure 119: Part A (above) and Part B (below) without fabric shown positioned as they would be for folding. Lever will lie flat on Part B and fabric will pass under Part A and over Part B

- Template A is placed on top of the fabric butted up to template B. (Figure 120)
- To create the fold, fold the hinged levers forward through 180$^{0.}$ When the levers are moved upwards, the fabric is lifted. As they move beyond 90^{o}, the fabric is pulled forward. During this process, two creases begin to form – one at the join between template A and template B and the second, in the opposite direction, where the front edge of the hinged lever meets the fabric. This may be seen in Figure 120. Once the levers are completely flat, lying forward on top of Part A, a roller or an iron is passed along the fabric to press the folds in place. Both templates A and B are removed and the fabric re-aligned to the next set of cuts to insert another set of folds. Each required pleat would be processed in this way. (Figure 121)

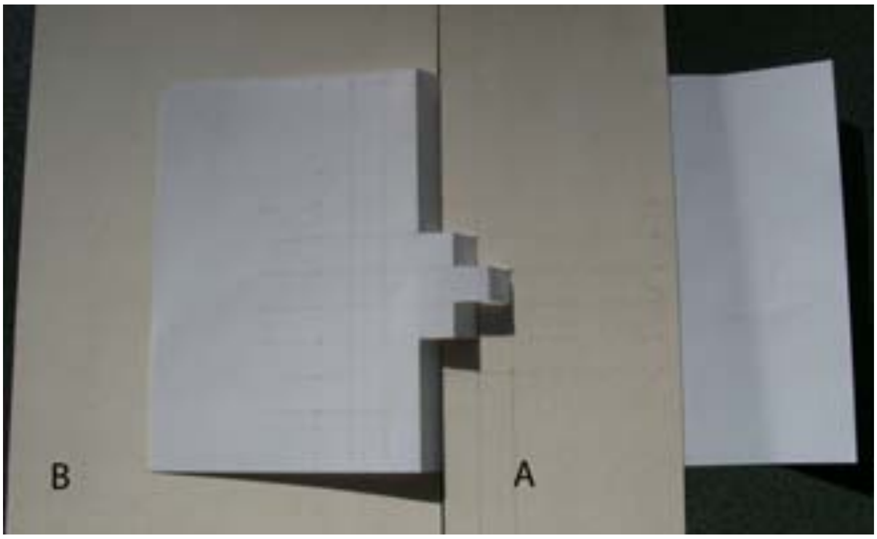


Figure 120: Templates A and B are butted together with paper simulating fabric placed over template B and under Template A. The flaps have been moved through 180^{o} so the folds have been formed

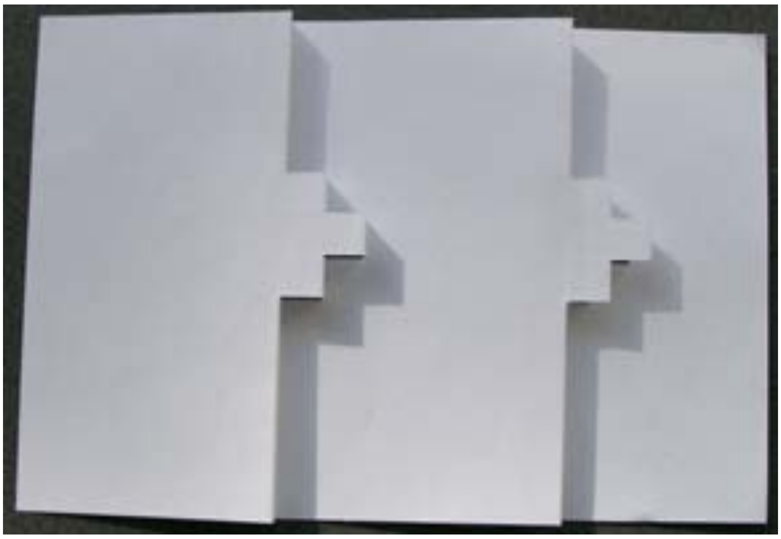


Figure 121: The templates have been used twice, creating two folds

The experiment was repeated with a more complicated design with many cuts and folds. A pair of templates may be seen in Figure 122, which would be used to pleat the folds labelled C1 in Figure 123. A set of similar templates with a different profile would be needed to pleat the folds labelled C2.

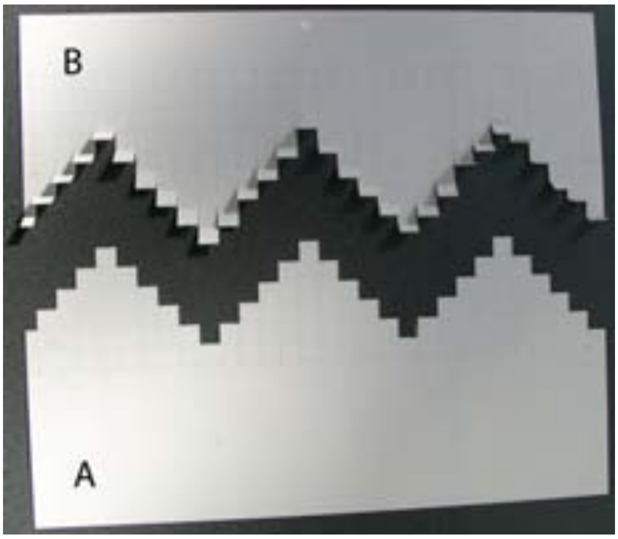


Figure 122: Templates A and B for the design shown in the next image. There are flaps or levers on the edge of template B

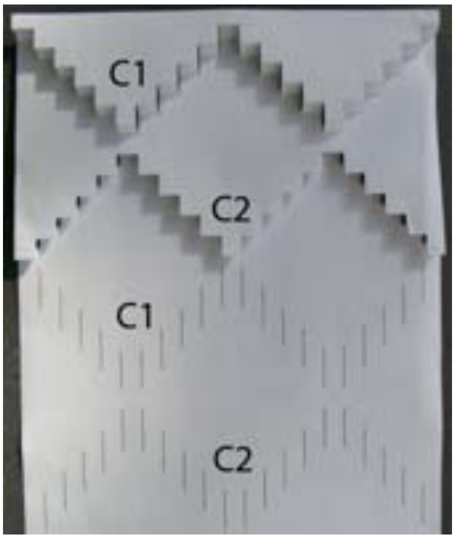


Figure 123: A design which may be pleated with templates in the previous image. Two different set of pairs of templates with different profiles are needed.

This new process offers a method for automating the folding of cut designs when there is a requirement to align cuts precisely with folds. The process requires one pair of templates to be produced with profiles that correspond to each different set of folds used in the design. Templates could be reused if they were made from appropriate materials for example metal. It would be possible to mechanise this process by devising systems to perform the following steps :

- load the fabric into position on a flat bed,
- laser cut the fabric where needed,
- raise required levers through 180^{o},
- heat press the folds in place,

- move the fabric
- move the levers back through 180^{o} to a flat position

This process would be repeated for the next set of folds. In this way, it would be possible to use this novel method to pleat and fold lengths of fabric. The process offers design freedom within the constraints of the templates and laser processing could take place in situ.

5.3 Laser assisted template pleating

This section describes a new process that was developed incorporating laser processing both to cut fabric and to generate corresponding pleating templates.

As has already been described, the author's practice uses pleats and cuts to form three-dimensional surface designs. In this work, cuts are made in the fabric by laser. Pleats are formed by hand by placing folds at the base of these cuts and in some cases along the cuts. A 2mm diameter dowel rod is used to assist with the positioning of the fabric for the formation of pleats. The folds are held in place by heat pressing the fabric with an iron or millinery heat tool. The process is extremely time consuming.

An investigation was conducted using the template pleating method seen at F. Ciment described in the contextual review. This process sandwiches fabric between two pre-folded identical paper templates. Steaming takes place to fix the pleats. A constraint of this process is the time it takes to hand draw, score and fold the templates. They may however be reused many times. These experiments explored whether a process similar to this could be used to pleat designs containing cuts.

A design was selected that had semi-circles, which protruded from the edge of folds. (Figure 124 and Figure 125) Initial experiments used 150g watercolour paper. Two sheets of paper and a piece of polyester organza were laser cut with this design. The two templates were hand scored along the indicated fold line, then folded and flattened. The polyester organza was sandwiched between the two identical sheets of paper aligning cuts. They were all folded together and steamed. Figure 126 shows the layer of organza on top of the bottom template after steaming. This method achieved the desired result of pleating a previously cut piece of fabric, with the folds aligned with the cuts.

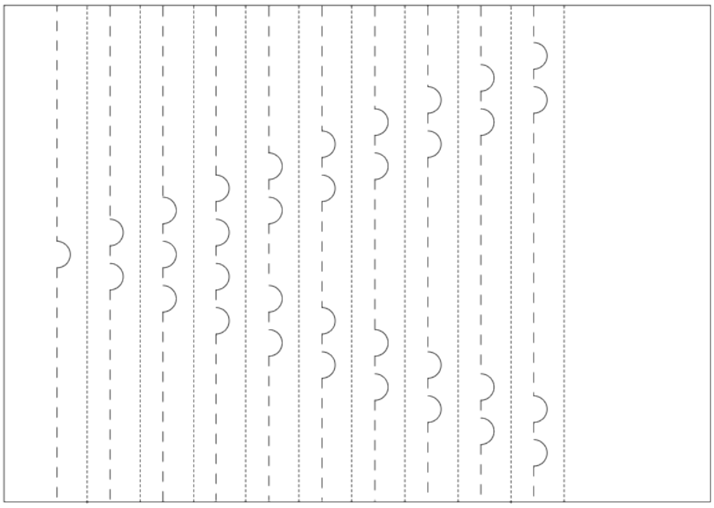


Figure 124: Design for template. Solid lines represent cuts, dashed lines folds in one direction, dotted lines folds in the other

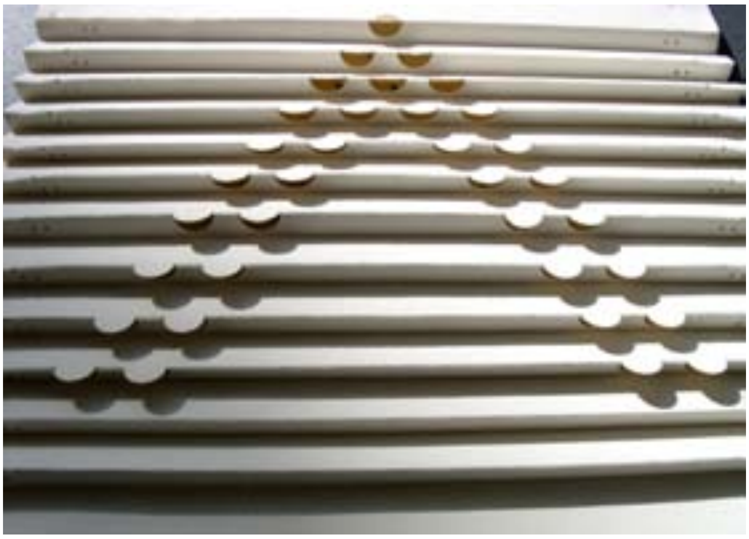


Figure 125: Design above folded on watercolour paper. Laser cut and hand folded. Registry marks on edges

The experiments were repeated to determine whether both templates were required. They used a single sheet of card, i.e. only one template, in conjunction with a method of attaching the fabric to the folded template such that the two layers of card and fabric would be aligned and folds would be produced in the desired places. Two alternatives were tried:

- stitching the fabric to the paper along the four outer edges
- using an adhesive fabric spray to attach the fabric to the template

In both cases, the results were not as successful as those obtained with dual paper templates. It would appear that two templates are needed to apply sufficient tension and pressure to hold the fabric in place. pressure to hold the fabric in place.

Figure 126: Laser cut polyester organza shown attached to the bottom template, after steaming

A second design was tried, using nylon chiffon. The process was repeated several times using different weights of paper varying in stiffness from very thin paper to heavy card. In each case the design was laser cut three times – firstly onto the fabric and twice onto card or paper to form two pattern templates. Registry marks, small holes, were added along the edges to assist with aligning the fabric to the pattern. The paper patterns were scored along fold lines and folded by hand. Fabric was pinned to one of the pattern pieces to align the cuts on the paper pattern and the fabric. The second pattern was attached. All three layers were folded together and then clamped in place during the steaming process. The fabric pleated along the folds dictated by the design successfully in all cases however results were better with stiff paper and card than thin paper. The card patterns, however, were slower to fold.

The process in detail is as follows :

- Laser cut lines on fabric (Figure 127)
- Laser cut two card or stiff paper templates. Score along fold lines and fold. (Figure 128 left)
- Unfold the paper templates. Place the fabric on the bottom template aligning cuts and registry marks. Secure. Place the second template on top of the

fabric aligning cuts and registry marks. Fold all three layers together and clamp in a folded position. (Figure 128 right)

- Steam to set pleats
- Allow to cool
- Remove from templates (Figure 129)
- Templates may be reused

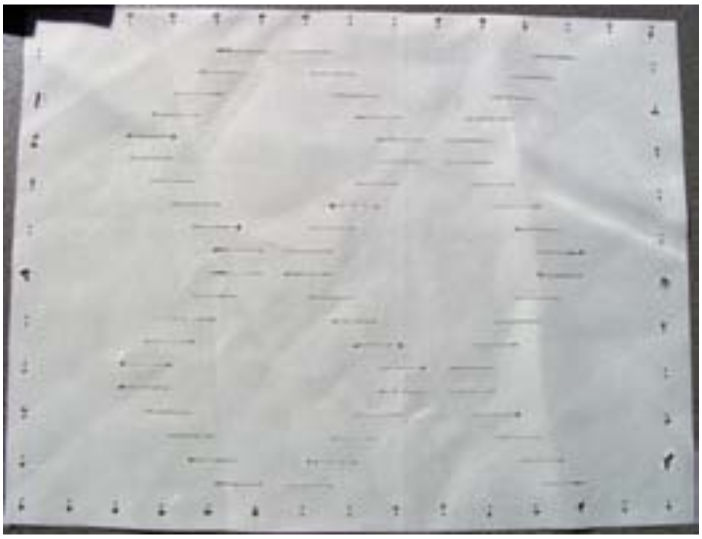


Figure 127: Laser cut fabric prior to pleating. Registry marks may be seen on fabric edges

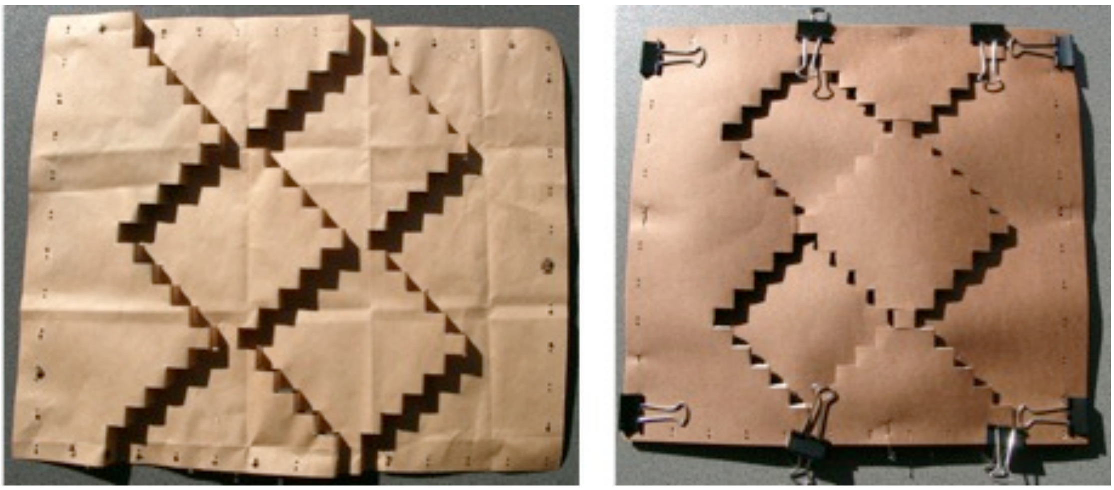


Figure 128: Folded paper template. Two identical forms are required (left), Two templates with fabric in between, folded and clamped ready for steaming to set pleats (right)

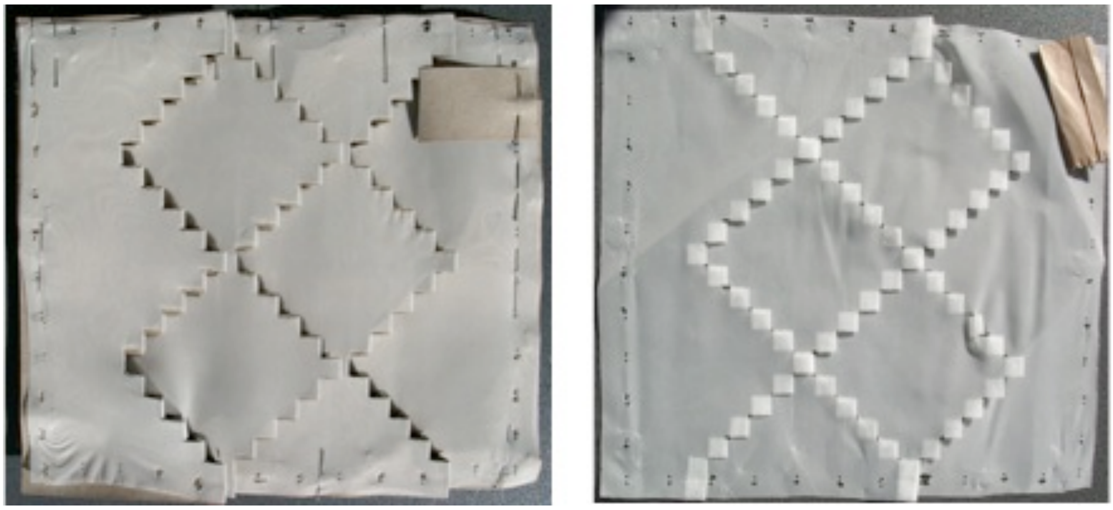


Figure 129: Bottom template with fabric post steaming (left), Nylon chiffon after both templates have been removed. Folds have been set in place (right)

On the basis of this investigation, it was considered that this method would be a viable process to permanently fold laser cut fabrics for a variety of three-dimensional designs. The next section describes the development of the process.

5.4 Development of Laser Assisted Template Pleating

The laser assisted template pleating process described in the previous section has been developed into a novel tool to design sophisticated three-dimensional surfaces and structures. This section details how templates may be created (5.4.1), how origami may be used as a design inspiration and a language to describe designs (5.4.2), the families of design that have been developed to use with this process to date (5.4.3) and finally how the process has been applied to non-textile materials to create opportunities in other areas (5.4.4).

5.4.1 Template design

Traditional template pleating uses hand scored templates. As already described, templates contain laser cuts where needed to give a three-dimensional surface. A new development, instead of hand-scoring fold lines prior to folding, was to laser etch perforated fold lines. An example based on the previous design is shown in Figure 130. This offers advantage as perforated lines both facilitate folding and indicate where folds should be positioned. It is also easier to fold a perforated line than a scored line particularly on thicker paper and card. In addition, there is a considerable time saving as the necessity to hand draw and hand score templates has been removed.

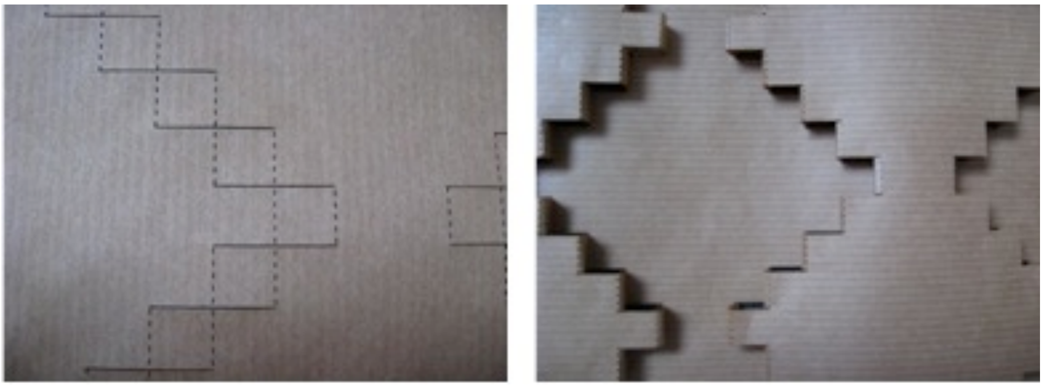


Figure 130: Detail of unfolded template. Solid lines are cuts, perforated lines are fold lines (left), detail of folded template (right)

Please note that it is not necessary for designs to include cuts to generate three-dimensional surfaces and structures. Examples will be shown in 5.4.3.4.

This development represents an integrated design and manufacturing process. A single design is generated in CAD, which may be used to laser cut and etch the templates as well as laser cut the fabric. During laser processing of the fabric, the process parameters are configured such that the etching of fold lines does not take place. As has been explained in chapter 4, this research uses *Adobe Illustrator* to generate designs. To produce a new design, the following steps are undertaken :

- Experiment with initial ideas using paper, pencil and scissors
- Translate these ideas into A4 designs using *Adobe Illustrator.* Use one colour for fold lines and another for cuts. Test the design in one of two ways - Print and using scoring implements and scissors, or laser process and test fold the design
- Scale the design up to the required size. Note that folding reduces the finished size of a design so it may be necessary to work in one or both dimensions (the length or the width) larger than A3 to end up with an A3 design. In the example design shown here, the depth of the folds is 10mm. If the pleated design is folded flat, the design will lose 20mm for each set of folds.
- Registry marks may be added along the edges to assist with alignment.
- Import the design into the laser processing software, here *APS Ethos.* Configure the laser processing parameters to process the card that is being used for templates such that solid lines cut the card and the coloured lines perforate the card. Process twice to create two templates.

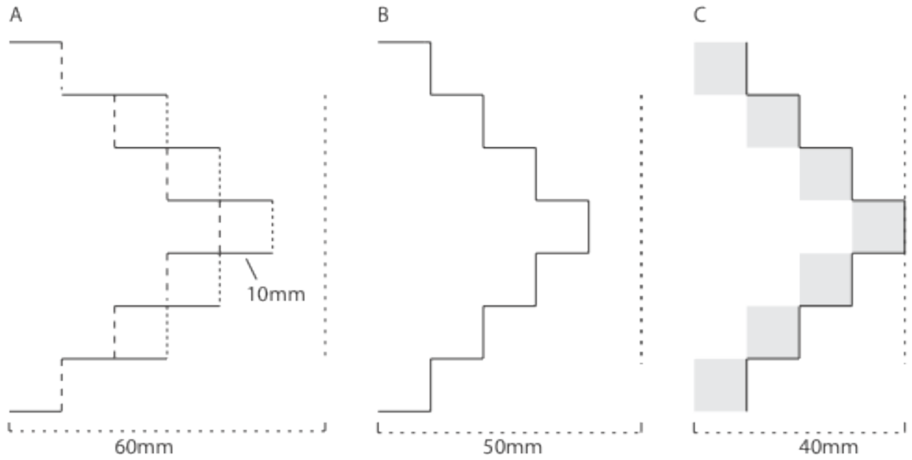


Figure 131: A demonstration of how a design contracts. Fold depth is 10mm. A (left) shows design unfolded, B (centre) shows design with fold at 90° forming a step and C (right) shows design folded over flat.

- When processing the fabric, configure the laser processing parameters such that solid lines cut the fabric and perforated lines are ignored. In this way, the same design may be used for both the template and the fabric.
- When folding the templates. Fold along the perforated lines.
- Sandwich the laser cut fabric between the templates aligning cuts and registry marks. Fold and clamp.
- Steam or heat press to retain pleats. Allow to cool and remove. Repeat if necessary with more fabric.

It is possible on some laser systems to etch perforated lines with a combination of user defined dots and dashes. In this case, create the original design in three colours – one for cuts, one for folds in one direction and one for folds in the other. (See mountain and valley folds in section 5.4.2) When configuring the laser, differentiate between the two colours by different perforated lines. All folding instructions, both position and direction of pleat, will then be contained within the template.

Templates may be made from a range of papers and card. Experiments have been conducted with 80g printer paper, 90g printer paper, thin brown parcel paper, thick brown parcel paper, cartridge paper, 150g watercolour paper. All pleat successfully. It is easier and less time consuming to fold thinner or lightweight paper templates. However heavier weight papers withstand repeated folding and the subsequent steaming process better. A decision needs to be made based on the complexity of the design, the material being pleated and the number of times a template is required to be used. The size of the design may also affect the paper choice. It is possible though to join sheets of paper or folded templates to form larger templates for large designs.

The choice of fabric is determined by the end use. As with all pleating, fabrics made from natural fibres such as cotton or linen may be pleated but will not retain the pleats after for example washing. The application of starch may used to assist with pleat retention. Fabrics made from manufactured fibres with the correct properties will allow pleats to be permanently set by a thermal process such as steaming or heat pressing. Blends such as polyester/cotton may offer advantage.

Laser assisted template pleating is a novel process that offers full design freedom within the constraints of producing templates. There will be limitations for example in terms of the minimum pleat dimensions and as will be shown in section 5.4.3, there are rules relating to how cuts and folds may be placed in relation to one another to achieve three-dimensional surfaces. The process does however enable a potentially unlimited array of designs to be produced. Although a manual process, it reduces the need to process each pleat individually. The next section describes how origami may be used as an inspiration for design for this process.

5.4.2 Origami

Origami is a traditional Japanese paper-folding technique that creates three-dimensional forms through folding single pieces of paper, generally without cuts or glue. Very complex designs with great variety are possible. An example is shown in Figure 132. Chinese paper folding thought to pre-date origami is known as Zhe zhi.

Figure 132: Koi fish folded from one piece of paper, 15" (Lang, 2002)

Although an ancient art, in existence for some 15 centuries, origami has undergone much innovation in the last 60years. (Lang, 2003, 3) Traditional design development evolved both through a process of trial and error and the publication of folding sequences. Organisations with an international membership such as BOS (The British Origami Society) organise regular conferences and workshops with instruction in folding and maintain a library of diagrams. According to Lang, impetus for the recent advances has come from the development of more sophisticated design techniques stimulated by mathematics, computer science, number theory and computational geometry. (Lang, 5) In spite of this, there remains an imbalance between the number of origami folders and origami designers. Published materials concentrate more on how to fold a specific design rather than design techniques. Whilst it is possible to define rules, many design methodologies are intuitive. Joisel, who uses wet-folding techniques to make figurative models, describes his creation process as one that starts with some basic assumptions, develops crease patterns (see below) and progresses with intuitive modifications often taking several years to refine a model. (Joisel, 2010)

Traditionally a system of diagrams first devised by Akira Yoshizawa (Lang, 2003,13) is used to describe origami models. This system uses dotted and dashed lines to indicate folds and symbols to show other operations such as ‘turn over’ or ‘push here’. These are shown in Figure 133 and Figure 134.

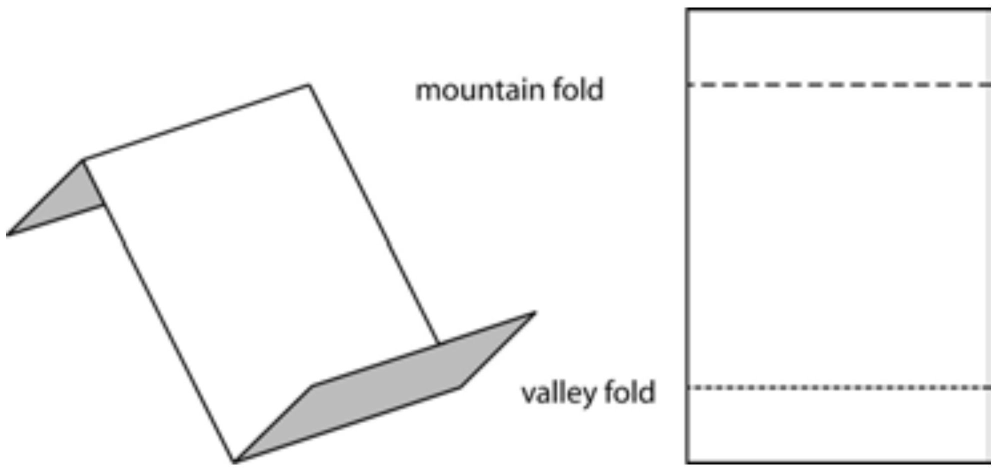


Figure 133: Diagram (right) showing origami folding symbols corresponding to three-dimensional folds (left) (Adapted from Lang, 2003, 14-17)

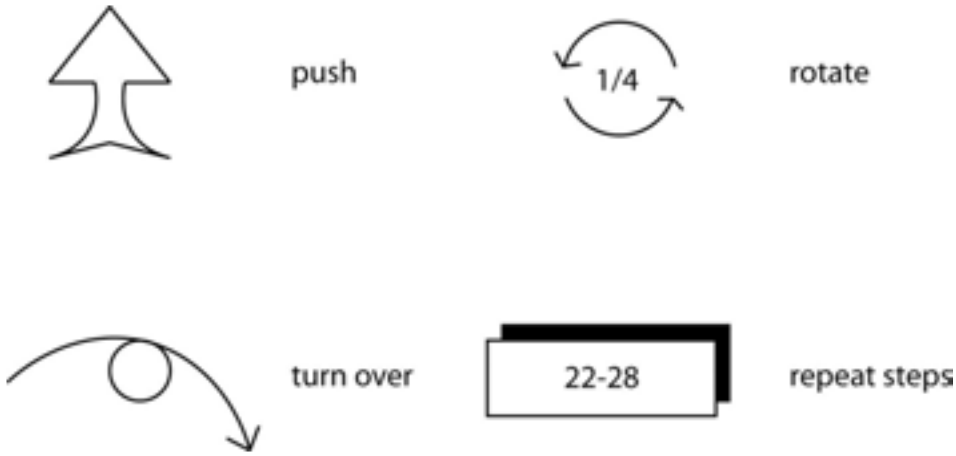


Figure 134: Common origami symbols used to annotate model diagrams (Adapted from Lang, 2003, 14-17)

The order in which the diagrams are presented indicates the fold sequence or order in which the instructions should be carried out. Figure 135 shows the fold sequence for a crow. The model is depicted at each stage as it would appear after each set of folds and symbols had been executed. Written instructions are used to give the instructions for each stage. The written text is often omitted making it easier for folders to cross a language barrier.

Figure 135: Sequence instructions to fold a bird. (Lang,2003,129)

Also employed by origami designers are crease patterns, which show all the fold lines of a finished origami model. See Figure 136 which shows the crease pattern for a frog. The folds for the feet may be visualised from the four corners and the head in the middle. The initial crease pattern system used dotted lines but Lang had modified it to use coloured lines to differentiate between mountain and valley folds. (Lang 2003, 21) He maintains that crease patterns contain more information than fold diagrams as it is possible to see the entire model all at once. They do not however tell the modeller the order in which folds should be made and without this, it may not be possible to fold the design. Working from crease patterns is a design technique that he employs, as it is possible to take an existing crease pattern and make modifications through addition, subtraction and scale changes.

Figure 136: Crease pattern (left) for the folded model of a frog (right). Mountain folds shown in balck and valey folds in brown (Lang, 2003, 143)

Not all origami design is suitable for template pleating. Clearly models with repeated folds that are not able to be unfolded would not lend themselves to a process where two identical templates are formed into a sandwich. Although not yet explored, the process would lend itself to designs where two non-identical but corresponding templates would be used.

Tessellations are one area that has been shown to have potential. Repeating complex geometric designs have been developed in Islamic architecture. Examples may be seen at the Alhambra Palace and Critchlow shows how design modules from Islamic patterns may be developed into tessellations using geometrical constructions. (Critchlow, 1976). Gjerde defines origami tessellations as “geometric designs folded from a single sheet of paper, creating a repeating pattern of shapes from folded pleats and twists”. (Gjerde, 2009, 2). According to Gjerde, Shuzo Fujimoto first developed these ideas in the 1970s and important contributors to the development of this form of origami are Ron Resch, Yoshihide Momotani and Chris Palmer. Palmer has developed a method of creating repeating origami patterns from any regular polygon. Most tessellated designs are based on a grid of equilateral triangles or squares. Using CAD to produce the templates for tessellated patters will allow superfluous lines to be omitted from the design. Section 5.4.3.4 shows examples of origami tessellations used with laser assisted template pleating.

The majority of origami design consists of straight folds. Curves are achieved either by folding a series of very short lines or by using wet folding methods. In this case, paper is manipulated when wet and lines are smoothed to form curves. An early reference to curved origami was from the preliminary course in paper study taught at the Bauhaus by Albers in 1927/28. (Demaine, 2008). When stiff paper is folded in concentric circles, it bends or self-folds to form organic forms. The models in Figure 137 were exhibited in *Design and the Elastic Mind* held at MOMA in 2008 and are examples of computational origami. This field of research is being conducted by Demaine to determine mathematical algorithms for folded surfaces. (ibid, 2010) This work has practical application for example, deployable objects such as satellites and, at a very small scale, stents used in cardiac surgery. Typically textile fabric is not as stiff as paper so may not demonstrate the same behaviour when manipulated. However these methods may be of interest for laser assisted template pleating if fabric is stiffened as part of the setting process. This will be further discussed in section 5.4.4 where the process for non-textile applications is described.

Figure 137: Computational origami (2003-07) , Demaine

Some academic papers by Demaine and Lang have been presented but generally they have high level of mathematics content, which is beyond the scope of this research and not directly applicable to textile design. Software applications have been developed to assist some aspects of origami model design. *Treemaker* has been developed by Lang and allows the design of complex crease patterns to be developed. (Lang, 2010) He however uses this as tool to design elements of models and resolve issues rather than produce designs in their entirety. *Tess*, a downloadable resource from Gjerde, assists in the design of crease patterns for tessellations. (Bateman, 2010)

Another area of design that may provide design inspiration for laser assisted template pleating is paper engineering. Examples may be seen in popup books where a two-dimensional page unfolds to become a three-dimensional design and fold flat again when the page is turned. Siliakus et al have developed models for famous buildings. (Siliakus et al, 2009)

This research has used origami conventions for describing design and has drawn on origami techniques for developing designs for templates. This is discussed further in the next section.

5.4.3 Design families

This section systematically details design types that have been found to work with the laser assisted template process. Clearly not all folded designs are suitable for this process. By the same token there is the potential for three-dimensional surfaces and structures not mentioned here to be developed.

The following method of explanation has been adopted. A series of designs will be described as line diagrams using the origami conventions discussed in 5.4.2. Line diagrams will also be shown with corresponding photographs so a three-dimensional representation may be seen.

Figure 138 shows the symbols that are used to represent cuts, folds and the directions of folds.

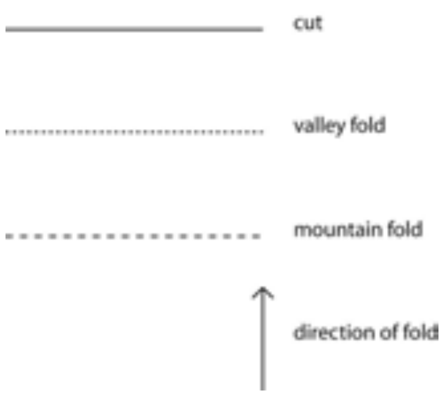


Figure 138: Conventions used in describing designs

The designs that have been tested and developed for laser assisted template pleating fall into four broad groups:

- Designs with cuts at an angle to folds
- Designs with cuts on folds
- Designs where double cuts fold
- Designs without cuts

The following section explains how designs may be developed from a single unit, described here as a fold module, which consists of combination of folds and cuts. It is envisaged that a designer will be able use the explanations given here as a starting point for further development.

5.4.3.1 Designs with cuts at an angle to folds

Designs in this group are developed from a series of linear cuts, usually but not always at 90^0 to folds. Consider the CAD design in Figure 139 for a single cut and fold, illustrated in Figure 140. For the design to fold successfully, the dimensions of the depth of pleat, the gap between two fold lines, must be equal. The size of the depth of pleat, may vary from design to design. When the cut, shown as a solid line, is twice the depth of pleat as in the top design (A1), the shape of the hole formed when folding takes place, will be square.

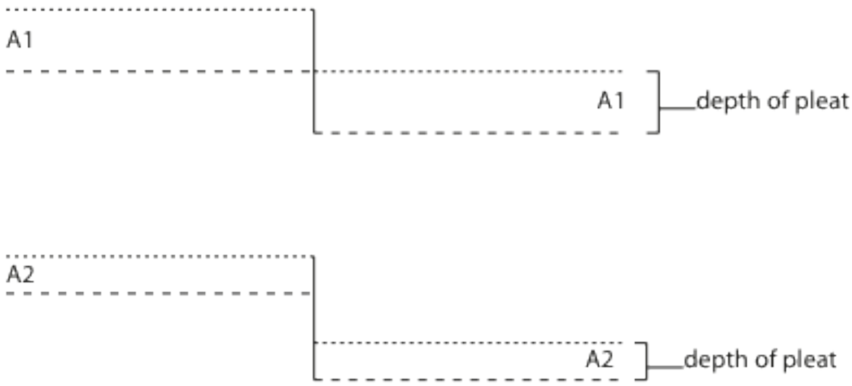


Figure 139: One cut and fold. The top design has a deeper pleat (A1) than the bottom design (A2)

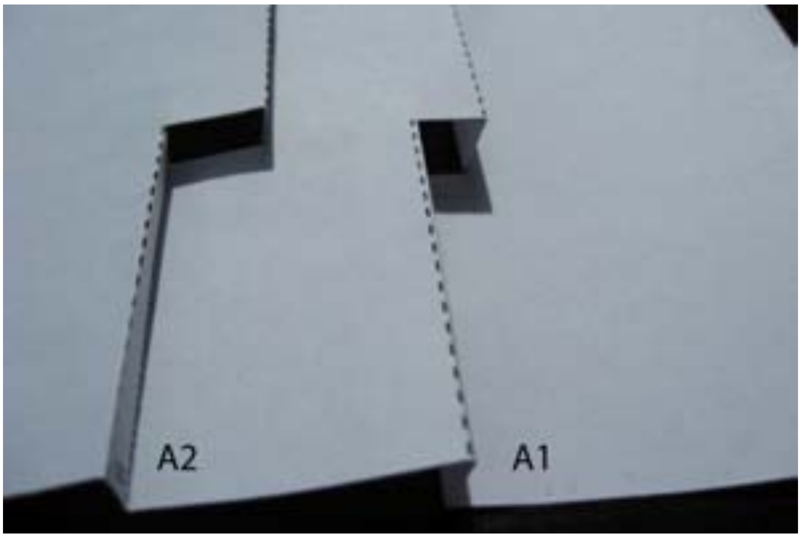


Figure 140: The diagram above folded. It can be seen that A2 forms a fold with a deeper profile.

The single cut and fold unit may be combined into a fold module such that there is still one fold combined with several cuts. Figure 141 shows three variations of one example. The spacing between cuts (a and b) is variable as is the depth of fold, c. The folded diagram may be seen in the image in Figure 142.

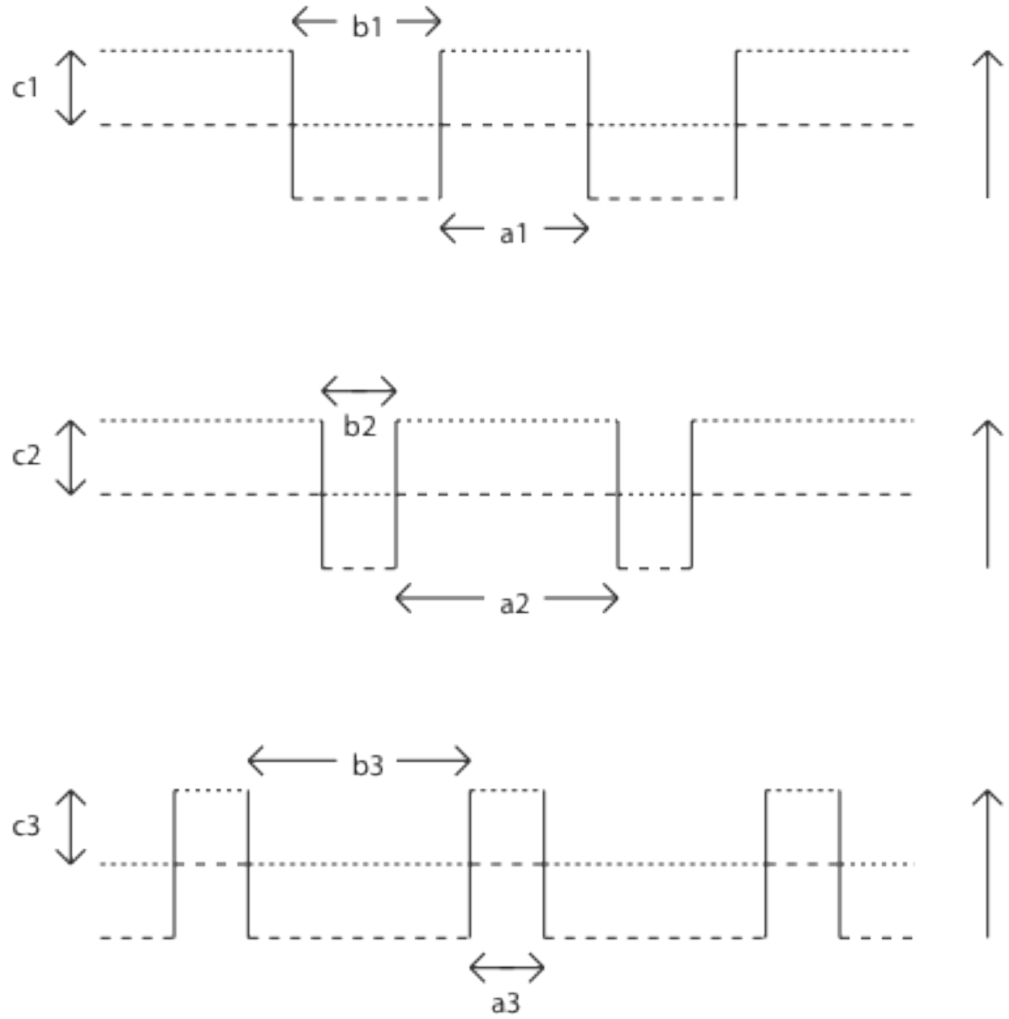


Figure 141: One fold combined with several cuts. Dimensions a, b, and c are variable

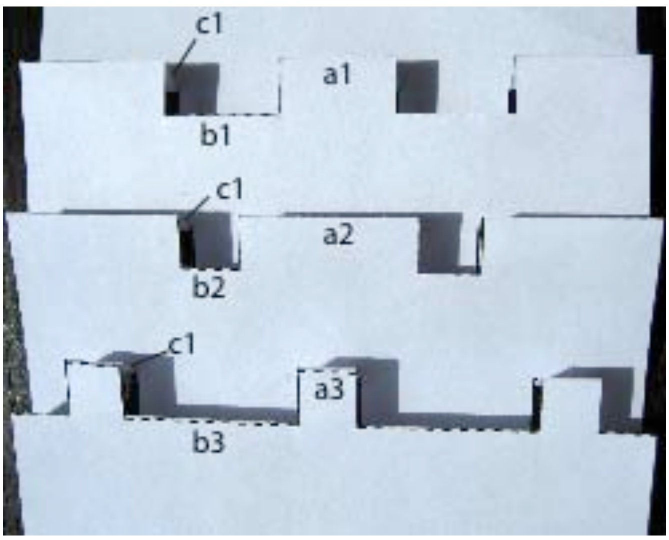


Figure 142: Folded diagram in previous image

A series of fold modules may be used together to form a three-dimensional surface. The following diagrams and corresponding photographs show how the fold/cut module from the top of Figure 141 may be used. The cuts and folds in the following two examples are identical. Only the spacing between the fold modules is varied (10mm in Figure 144 left, and 20mm in Figure 144 right) changing the appearance of the resultant three-dimensional surface.

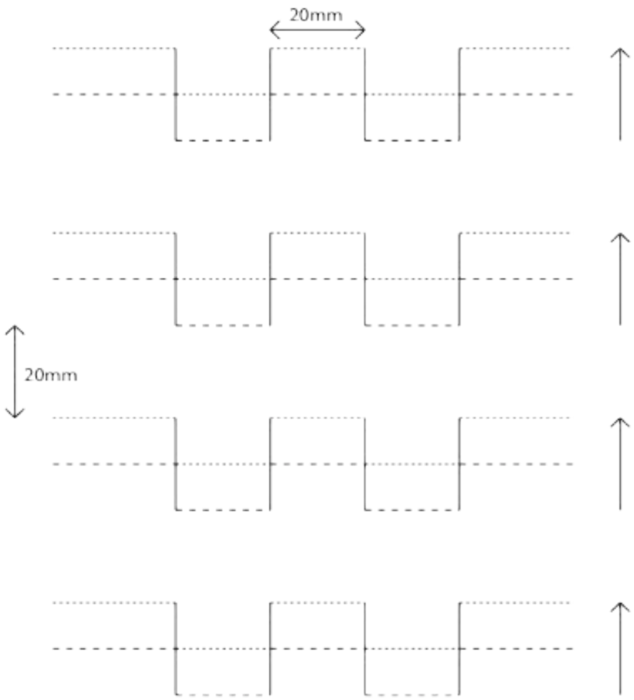


Figure 143: Evenly spaced cuts and folds. Cuts are 20mm in length. Each fold module is 20mm apart. Folds are all in the same direction

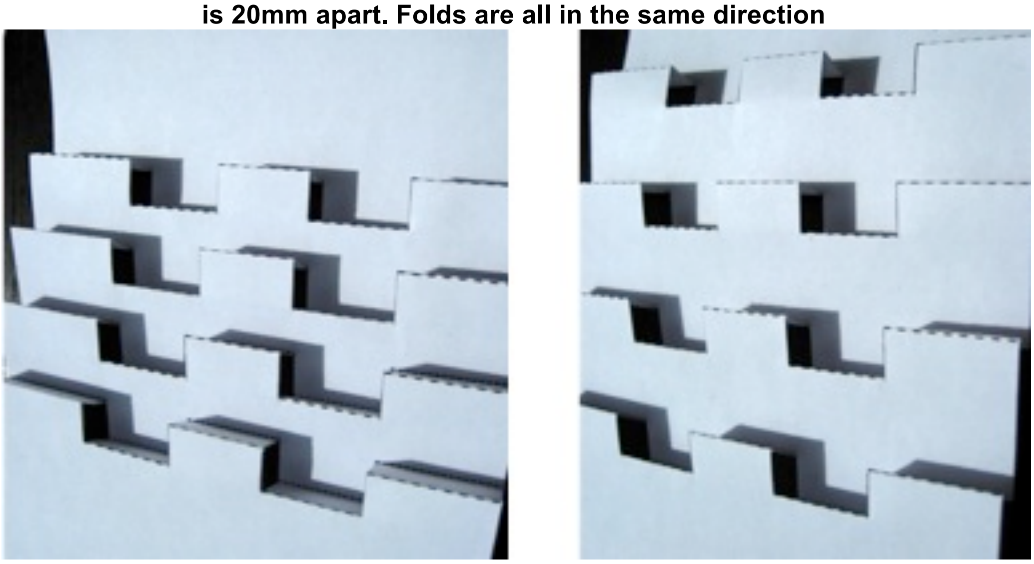


Figure 144: Image of fold diagram above. The gaps between the fold modules vary – 10mm (left) and 20mm (right)

The direction of folding may be alternated. This allows the same cuts and folds with the same spacing between modules to produce very different surfaces. The design in Figure 145 has the same cuts as the design in Figure 143 however every alternate fold is reversed. An image of the folded design is shown in Figure 146. The resultant three-dimensional surface is very different.

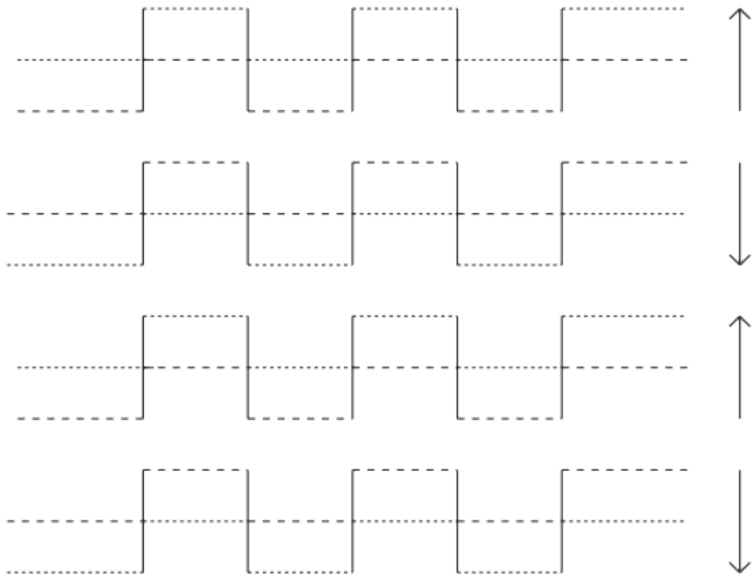


Figure 145: The same cuts as the previous design, but alternate folds are reversed

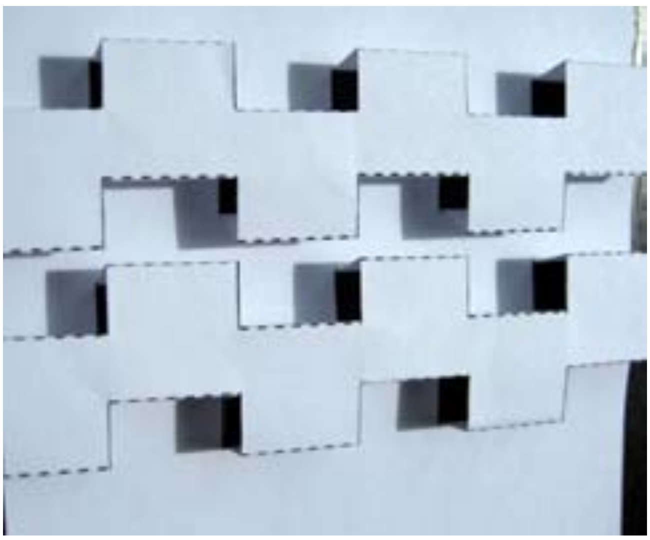


Figure 146: Three dimensional surface produced from the above diagram

Depending on the spacing, it is sometimes possible to compress a three-dimensional surface constructed from alternate folds such that it becomes flat. The design in Figure 146 will fold completely flat as may be seen in Figure 147. The design now appears to interlock. If this design layout is changed, by moving the fold modules horizontally, so that the protruding edges are opposite one another as in Figure 148 and Figure 149 (left), the spacing is such that the folded edges would overlap. In order to achieve a three-dimensional surface that will fold flat, it is necessary to move the fold modules further apart. This may be seen in Figure 149 (right).

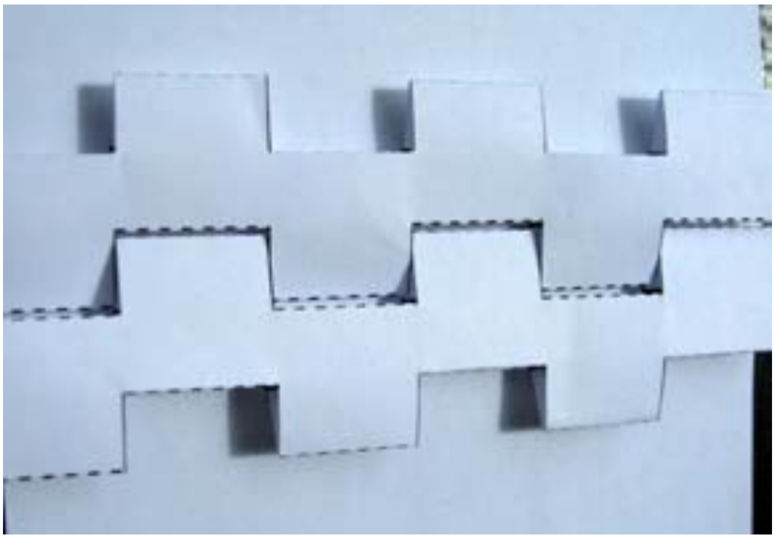


Figure 147: The above image is able to fold completely flat

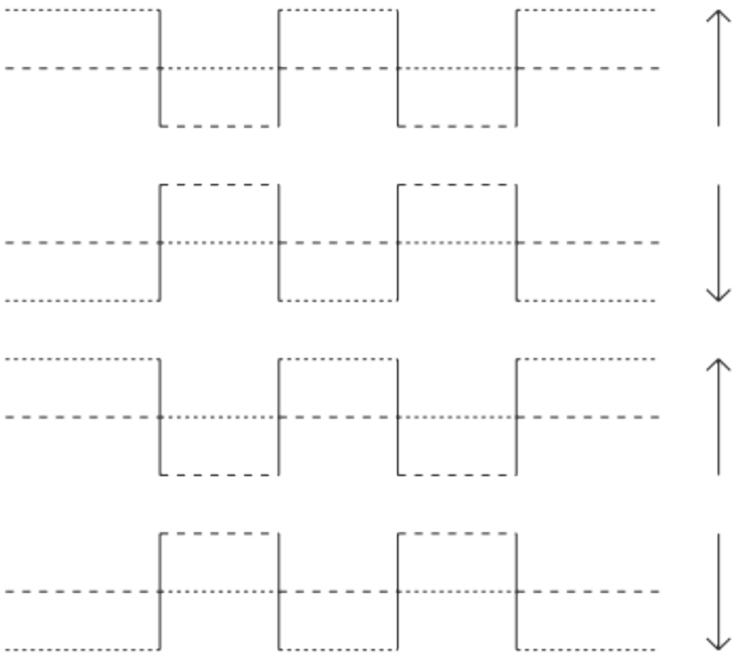


Figure 148: 20mm cuts, fold modules 10mm apart with fold directions alternating. The image below will not fold flat without fold edges overlapping.

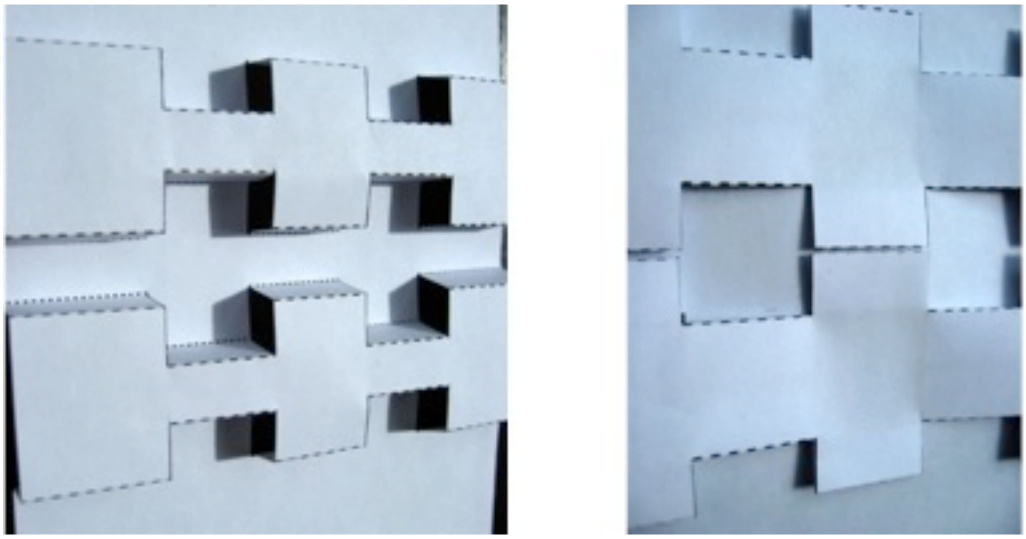


Figure 149: The design in Figure 148 folded (left), Spacing has been altered for the design on the right so that fold modules are 20mm apart. It is now possible to fold the three-dimensional surface flat with the protruding fold edges just touching.

In summary, the following characteristics determine this family of folds :

- cuts are positioned at an angle to the folds, generally 90° but Figure 166 shows an example where the angle between the cut and the fold is oblique.
- Several cuts and a fold form a fold module
- The spacing of cuts within a module may be varied
- The depth of folds may be varied but not within a module
- The direction of fold of each module may be varied. Design with the same cuts and spacing will have a different three-dimensional surface by varying the direction of folds.
- Cuts on different modules may be positioned in relation to one another for example opposite or offset.
- The scale of cuts and folds may be varied.

The following photographs on the following pages (Figure 150- Figure 168) illustrate designs from this group. The images show a variety of arrangements of fold modules. Different scales of cuts and fold have been used. The fabric used also influences the three-dimensionality of the folded surface.

Figure 150 - Figure 152 use the same cuts and folds however spacing is varied. Additional cut outs are omitted in Figure 151. In Figure 151 and Figure 152, the fold directions, instead of being alternate, are made twice in one direction and then twice in the other, producing a three dimensional fabric with three levels instead of two. Figure 153 - Figure 155 have fold modules arranged to form diamond patterns. The

scale of pleats varies. Organza is a transparent fabric so the three layers of fabric achieved by the pleats gives a tonal difference across the design. Figure 155 is made from organdie which is a dressed cotton so the fabric is stiff and holds a three dimensional form. In addition the direction of the folds alternates, creating a proud diamond shape. The folds in the previous design are all in the same direction. The directions of folds in Figure 156 and Figure 157 are the same. The effects Figure 156 are achieved by shifting the fold modules to the right. Every third row is identical. In Figure 157, the spacing between rows decreases. Figure 158 and Figure 159 show the difference in appearance between the same design from the front and the back. The direction of folds is alternate, creating raised bands, and the fabric used is linen which is stiff and so hold the folds in a three dimensional form. In Figure 160, the bands in the previous design are reversed, creating a diamond shape. Folds are placed so that three layers are created. A reduced number of cuts are used with wider spacing to form raised jagged lines in Figure 161. In Figure 162, the spacing between cuts within the same fold module is altered to give the illusion of curve. A linen was selected so the design holds its three dimensional form. Shadows enhance the illusion of depth. Figure 163 uses an element from the fold module in Figure 151 linked with flat pleats. The band that is formed is repeated on alternate rows shifted to the right. In Figure 164, the band in the previous design is combined with the design in Figure 154 and viewed from the reverse side. Figure 166 is an example of what may be achieved by alternating fold direction. This design is a simplified form of Figure 151. Every alternate fold module has been removed and spaces created in between. The linen that has been selected is closely woven and softer creating a very fluid three-dimensional textile. The three designs in Figure 166 - Figure 168 are similar in spacing and scale to those already discussed but have cuts at 45^0 to the folds creating a zigzag appearance.

Examination of these designs shows the considerable scope that may be achieved when designing through careful consideration of the scale of cuts and folds, the direction of folds, the spacing between fold modules, the spacing between bands and the choice of fabric density and texture. It is clear that many other designs are possible.

Figure 150: 10mm cuts, 5mm apart, folds in alternate directions. Cotton.

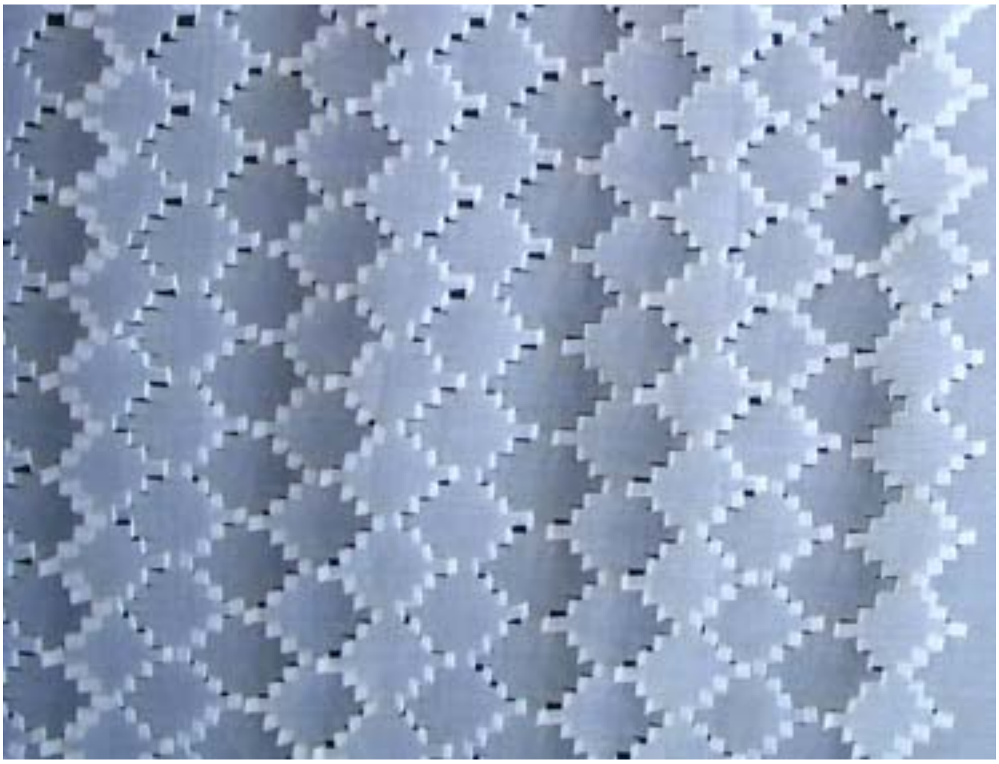


Figure 151: 10mm cuts, 5mm apart, two folds in the same direction, two alternate creating a design with three surfaces. Cotton organdie.

Figure 152: Design uses the same cuts and folds as Figure 151. Additional laser cut rectangles. Cotton.

Figure 153: 10mm cuts, 5mm apart arranged in zigzags forming diamond shapes when folded. Silk organza.

Figure 154: 10mm cuts, 10mm apart, arranged in zigzags. Silk organza.

Figure 155: Two different scales have been used. Black organdie.

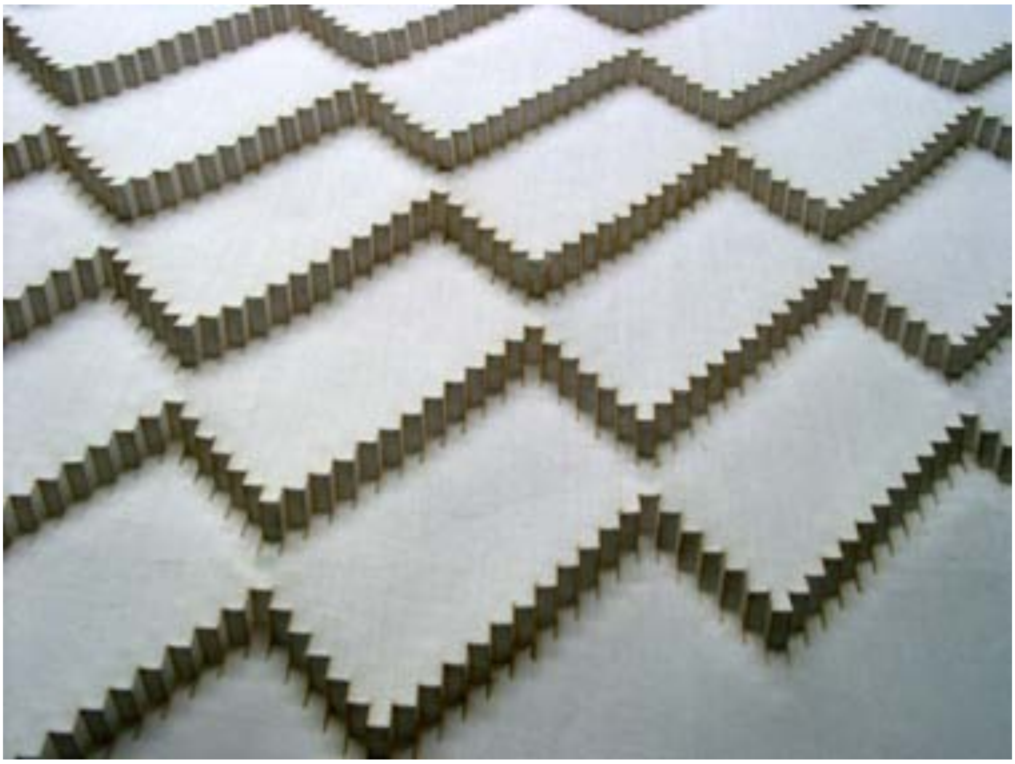


Figure 156: 15mm cuts, 5mm apart, arranged in uneven zigzags. All folds in the same direction. Cotton.

Figure 157: 15mm cuts, 5mm apart arranged in zigzags. All folds in the same direction. Spacing between fold modules varies.

Figure 158: 15mm cuts, 5mm apart. Alternate folds in opposite directions creating bands. Linen.

Figure 159: The reverse of the design in Figure 158.

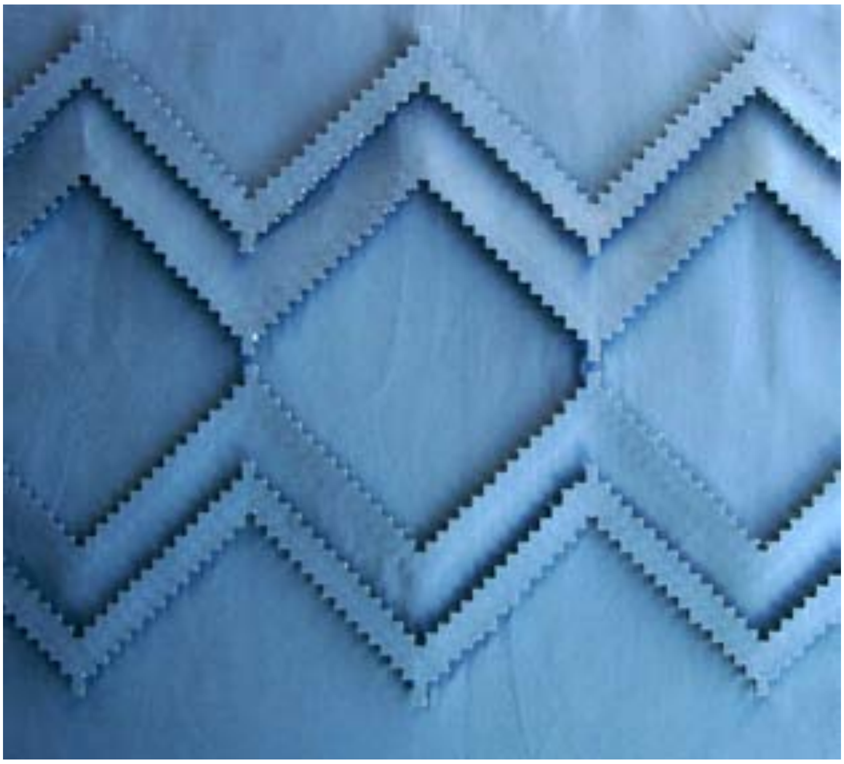


Figure 160: Zigzag bands. Fold directions are altered to create three surfaces. Directions of zigzags are reversed. Cotton.

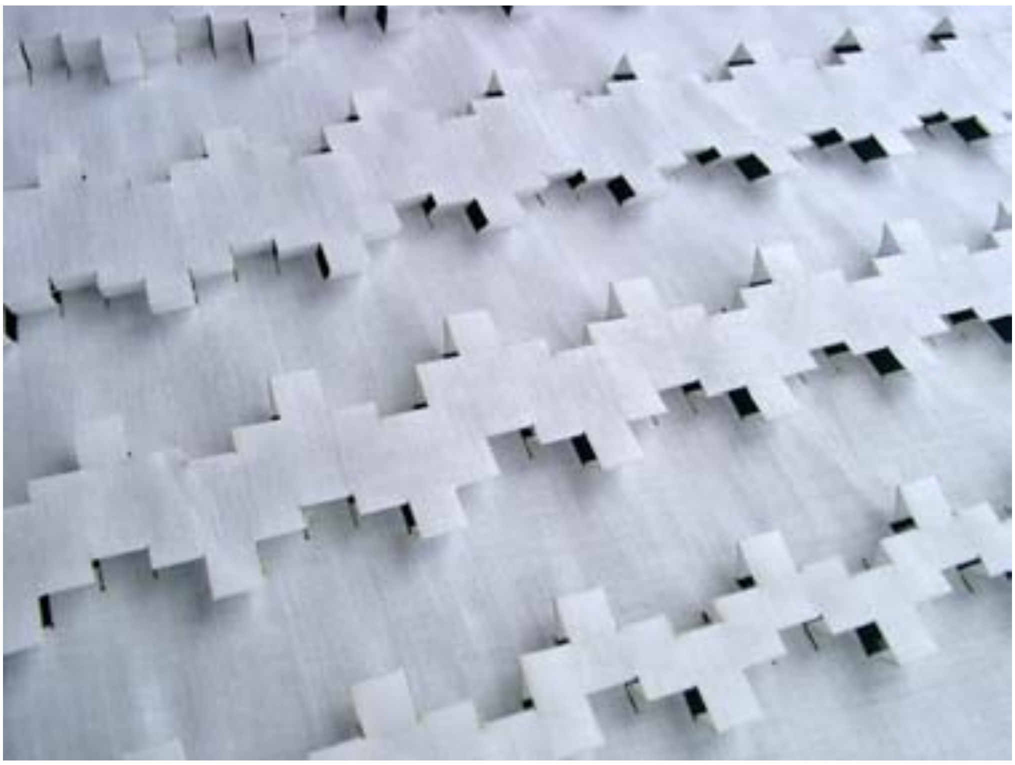


Figure 161: Simple stepped fold modules with varying space between them creating thinner and thicker bands. Linen.

Figure 162: Spacing of cuts varied to give the illusion of curves. Linen.

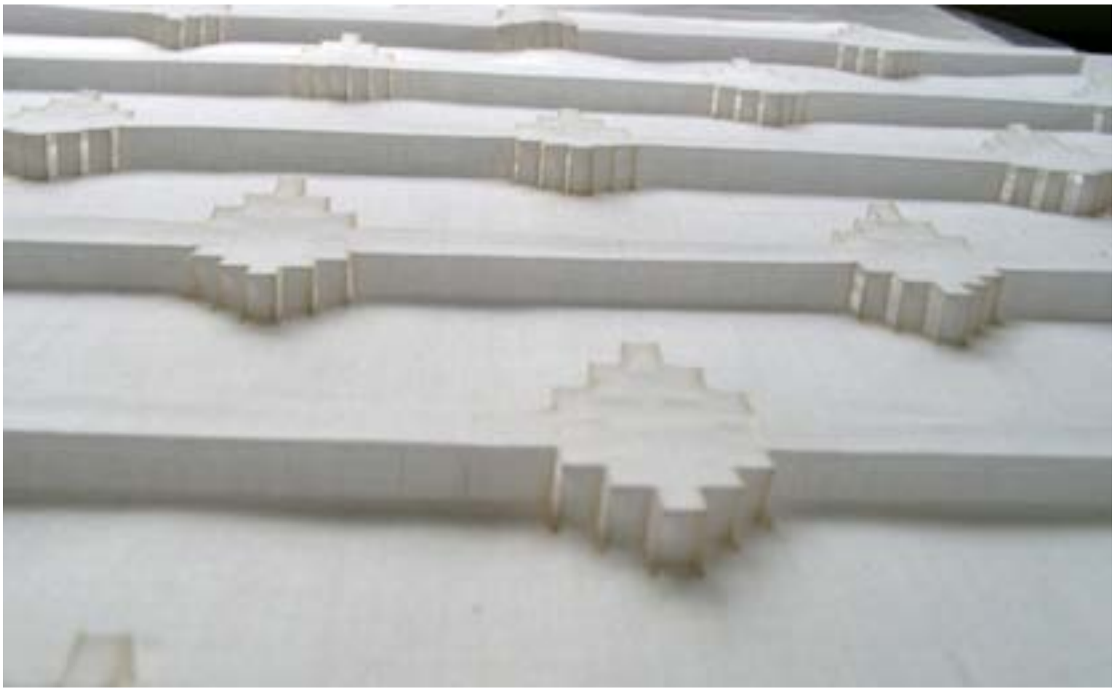


Figure 163: A group of cuts widely spaced from the next creating folded bands. Cotton.

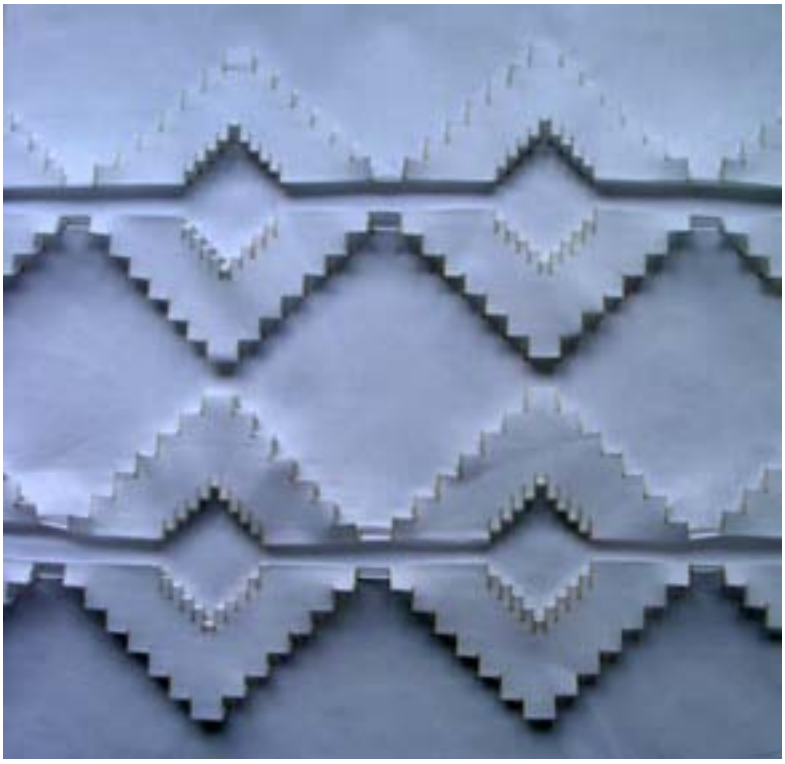


Figure 164: A combination of the design in Figure 163 with a zigzag band creating raised chevrons. Cotton.

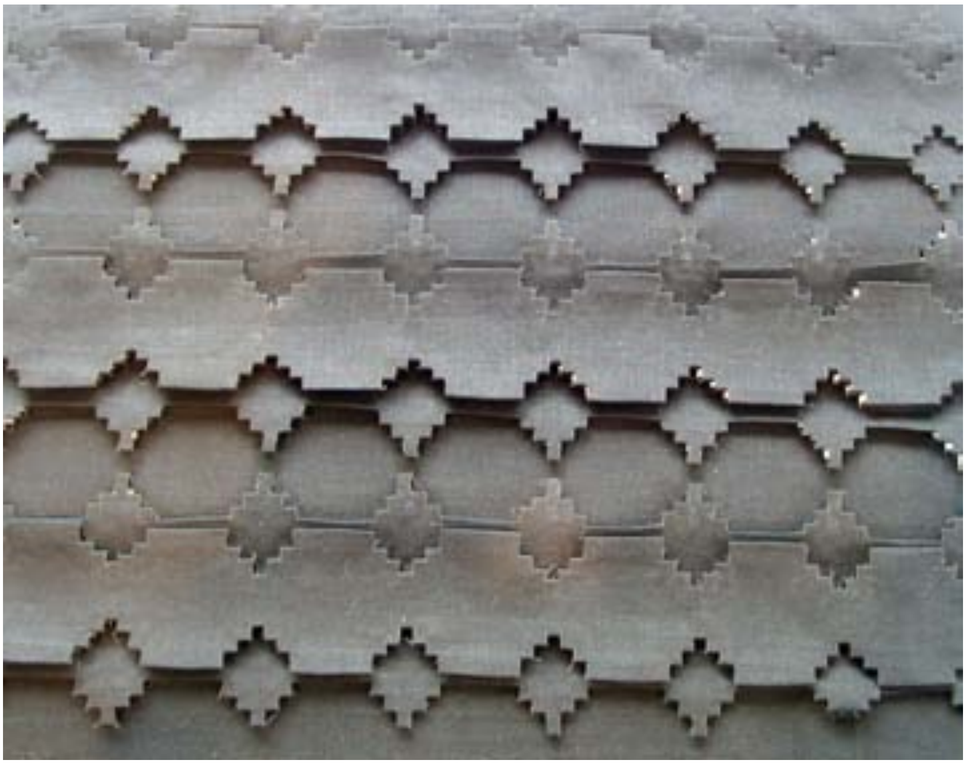


Figure 165: Profile of cuts and folds reversed on alternate rows. Design has three surfaces. Linen.

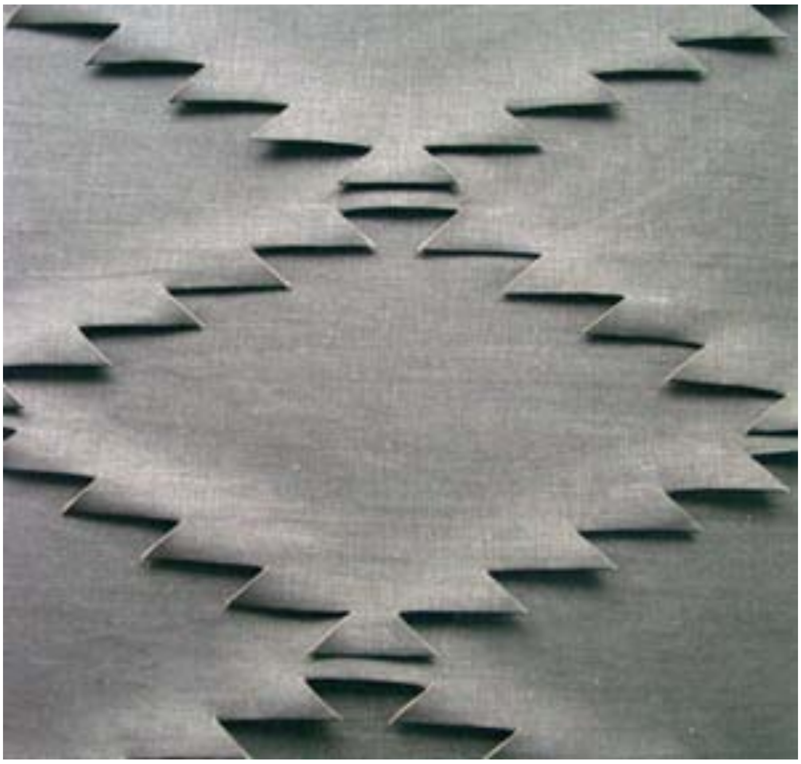


Figure 166: Cuts at a 45^{o} angle to the fold. Linen.

Figure 167: Design similar to that in Figure 157 except cuts are at 45^{o}. Linen.

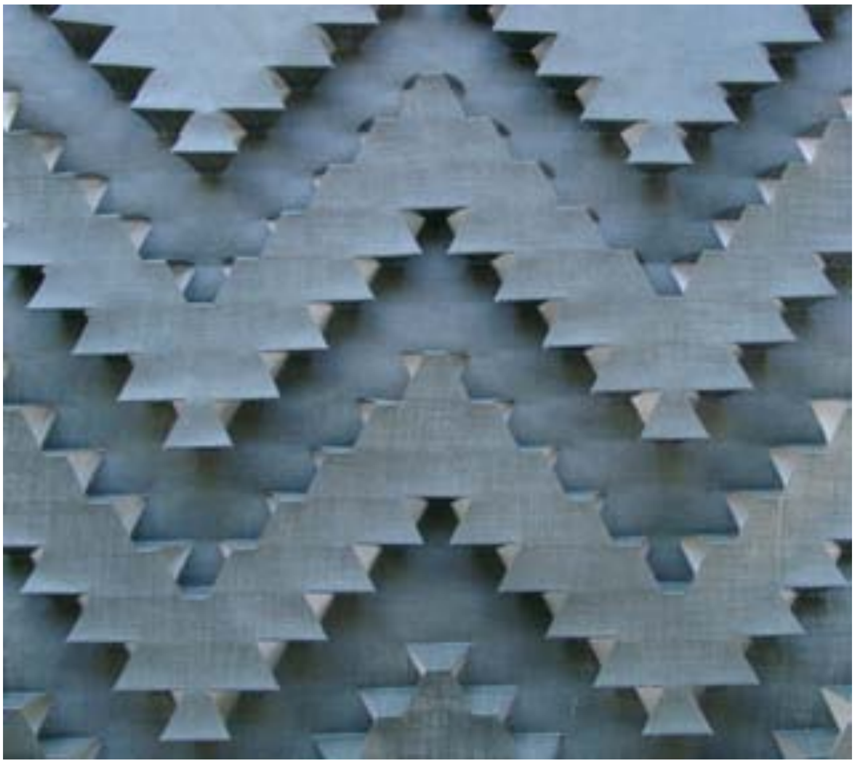


Figure 168: Large scales cuts at 45o. Folds in alternate directions creating bands. Linen.

5.4.3.2 Designs with cuts projecting from folds

This section describes the second group of designs. Instead of placing cuts at an angle to folds, cuts are placed so that flaps produced by them project from the folds. The cuts may have any form creating flaps with different shapes. Examples shown here have semi-circular flaps (Figure 170), rectangular flaps (Figure 175) and diamond flaps. (Figure 176)

The designs use simple flat pleats, which may all be positioned in one direction or may alternate in bands. In the examples demonstrated here, the scale of the pleats remains constant but, as demonstrated in the previous section, changing the scale of folds provides design opportunity. The spacing between the fold modules is such that the flaps create a pattern when the design is folded. For example a flap may overlay the adjacent flap or may just meet it. Often the reverse of these of these designs offers potential as both the flap and the cut-out that results from it may be used to create pattern. (Figure 173)

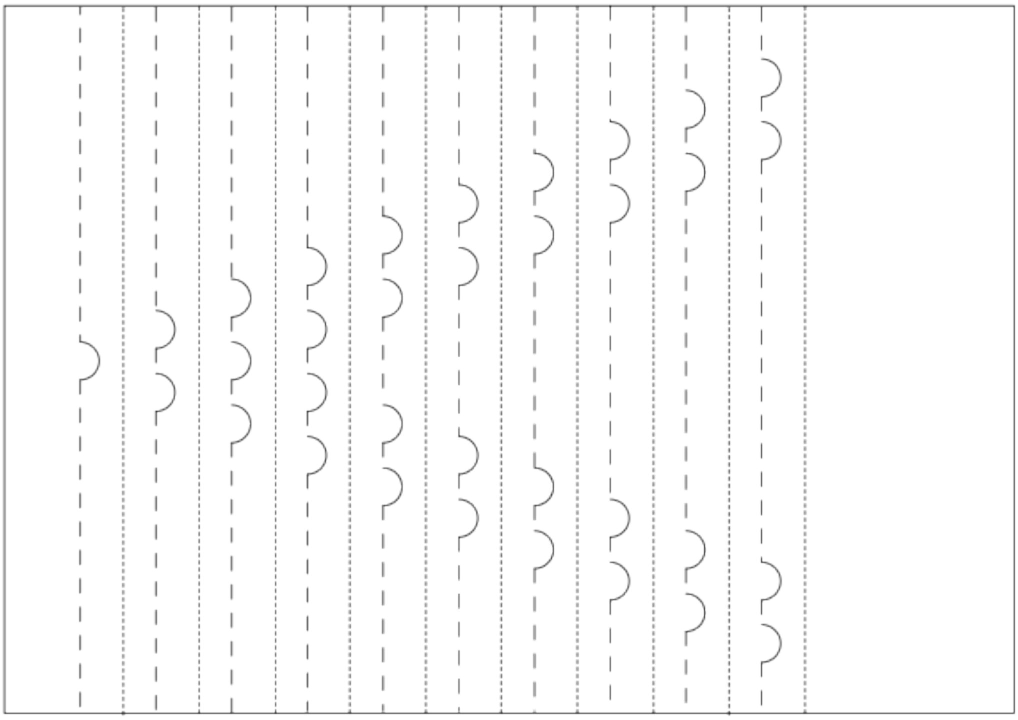


Figure 169: Design with semi-circle flaps protruding

Figure 170: Image of the design when folded. Cuts and folds are spaced so that a pattern is formed.

Figure 171: The reverse of the previous design.

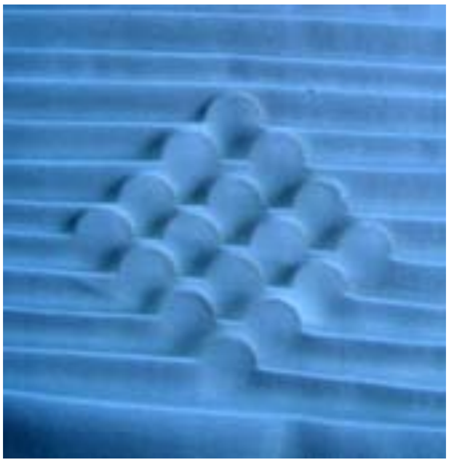


Figure 172: Semi-circular cuts placed to when folded a diamond is formed

Figure 173: Semi-circular cuts placed so that, when folded, a chevron is formed. The folds are reversed so that the full circle shape may be seen.

Figure 174: Semi-circular flaps and folds arranged to form diagonal bands

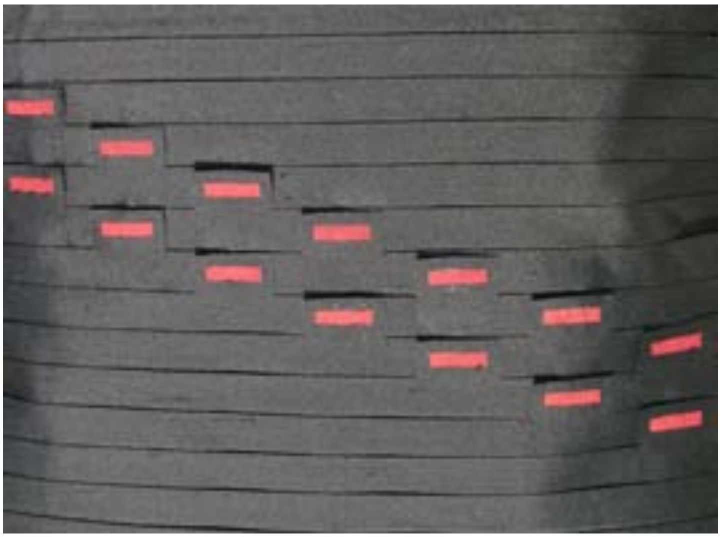


Figure 175: This design uses rectangular cuts on the edges of folds. Cuts are positioned so that a diagonal band is formed when the design is folded.

Laser cutting may be used to introduce other elements into the design. In the example in Figure 175, the rectangular flap has a rectangular cut-out. Red fabric is bonded on the reverse to add colour. The diamond shaped flaps in Figure 176 are further cut to create a lace-like effect.

In summary these designs are formed by creating flaps though cut-outs on the edges on folds. The position and scale of the folds, the size and shape of cut-out and further embellishment all off considerable design potential.

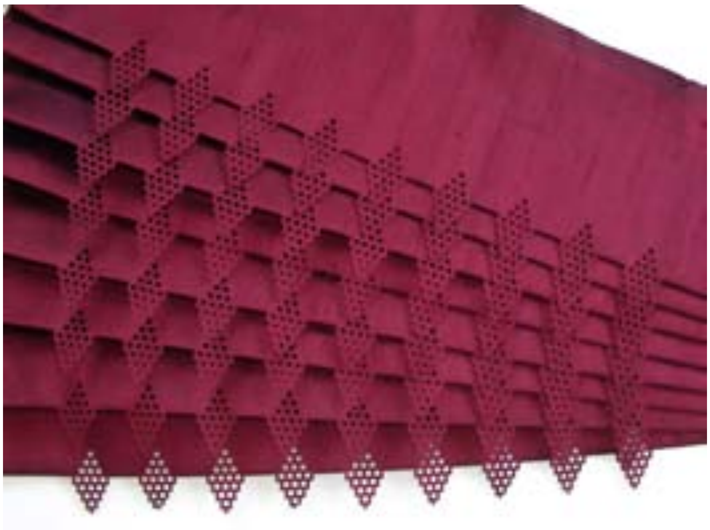


Figure 176: Diamond cuts on the edges of folds. The diamond flaps are further cut.

5.4.3.3 Designs where cuts are folded

This group of designs is based on the following principles

- Symmetrical cuts are made in a row, for example semi-circle or a v-shaped cuts
- The row is pleated, folded in half, so that the cut is halved (positions A1, A, B1, B2 in Figure 177
- The pleat is folded again alternately folding the flaps first to one side and then to the other

The diagram in Figure 177 and corresponding photographs in Figure 178 show two pairs of fold modules pleated in this way. The folds from the pair on the left in the diagram meet when folded, for example flap C1 will meet flap C2 . The pair on the right align alternately. Flaps D1 and D2 are folded in the same directions so will not meet.

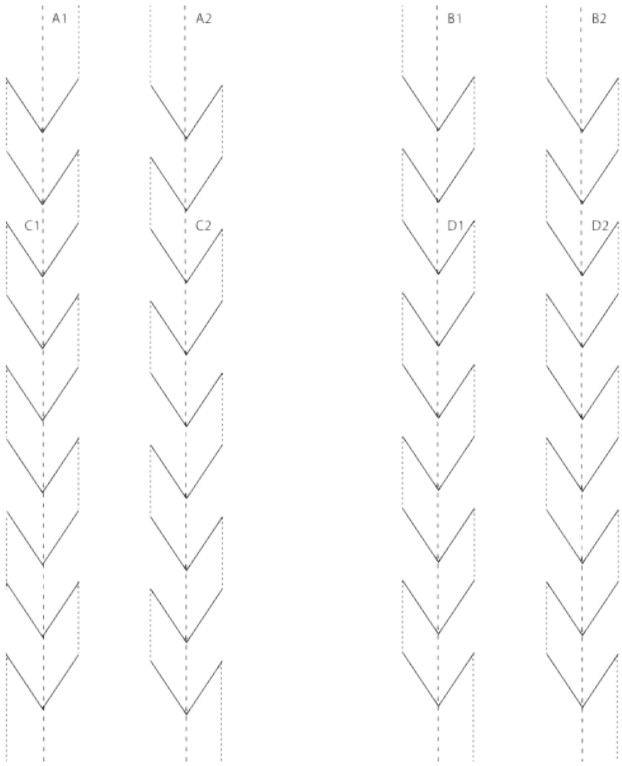


Figure 177: CAD diagram for folded cuts. The two fold modules on the left meet fold in opposite directions so C1 will meet C2. The two on the right are alternate (D1 will be folded in the same directions as D2)

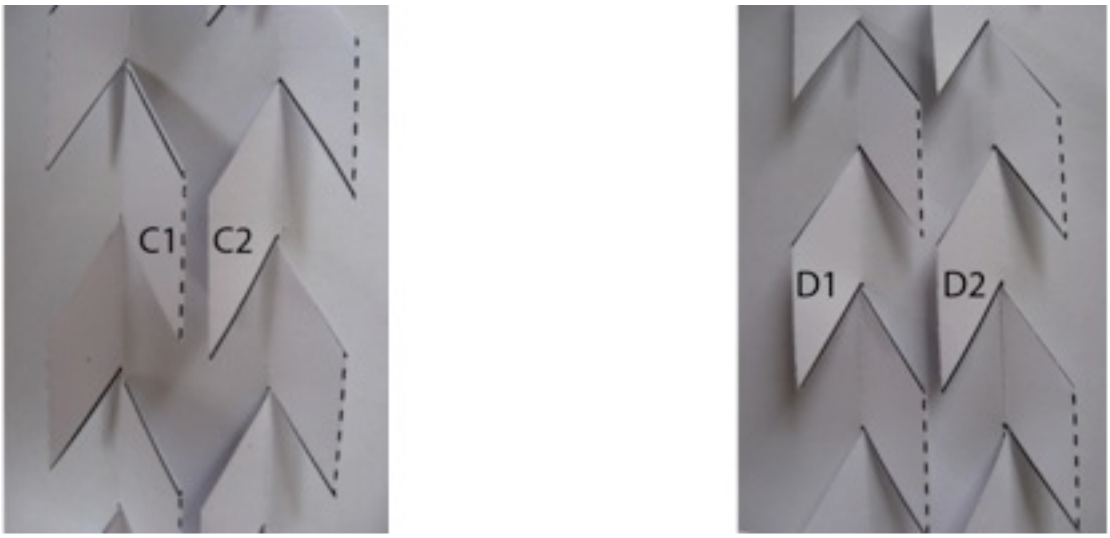


Figure 178: Detail of the fold diagram above.

The images in Figure 179 and Figure 180 give further examples. As can be seen from these two photographs, both the scale and the spacing between the fold modules may be altered for design effect. The shape of the cuts plays an important role. Furthermore it is not necessary for all cuts to have the same scale.

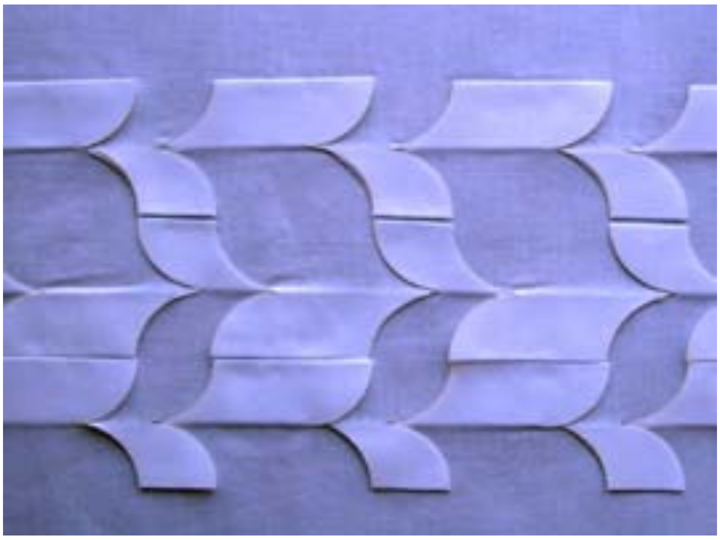


Figure 179: Vertical fold, cuts pleated alternately, large scale, adjacent folds meet

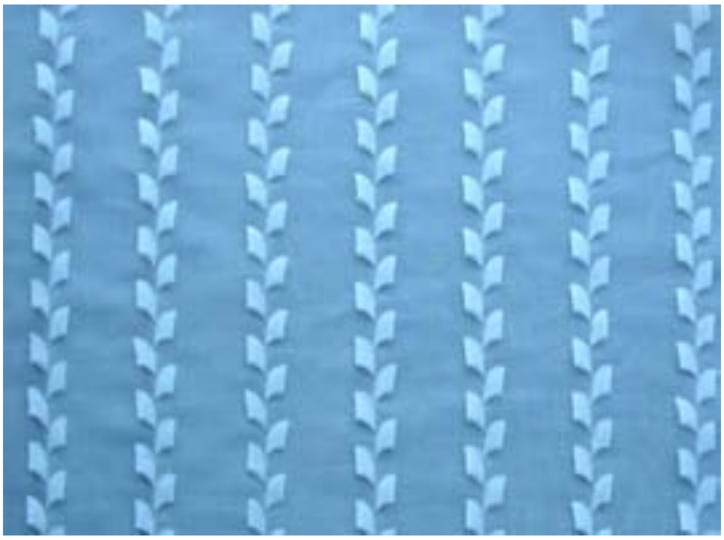


Figure 180: Vertical fold, cuts pleated alternately, large scale, adjacent folds meet

If a fabric with sufficient stiffness used such as a linen or medium weight cotton, the different fold direction and friction from the cut edges lock the design in place so that is does not unfold. When laser assisted template pleating is used to obtain this type of three-dimensional surfaces, the fabric will need to be completely unfolded when the template is removed and then re-pleated manually along the fold lines.

5.4.3.4 Origami folded surfaces

The designs in this section are based on origami folded designs. Some origami designs have been previously applied to textiles. These were discussed in the contextual review. (Reiko Sudo). An example of an origami folded surface is shown in Figure 181. Two variations are shown as design diagrams - Figure 182 which has even pleats and spacing between fold modules, and Figure 183 where the pleat dimensions vary both horizontally and vertically. Although dimensions ‘b’ may change, the angles ‘a’ must be equal within a design for it to be possible to fold the diagram into a three dimensional surface. It is not necessary for the pleats to be parallel.

Figure 181: Origami folded surface. The design will look similar to Figure 183

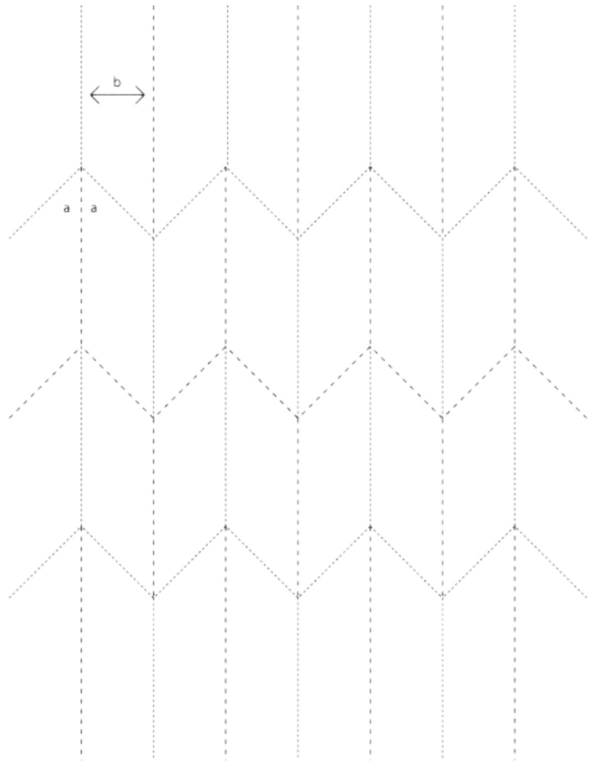


Figure 182: Origami design, even pleats, even spacing

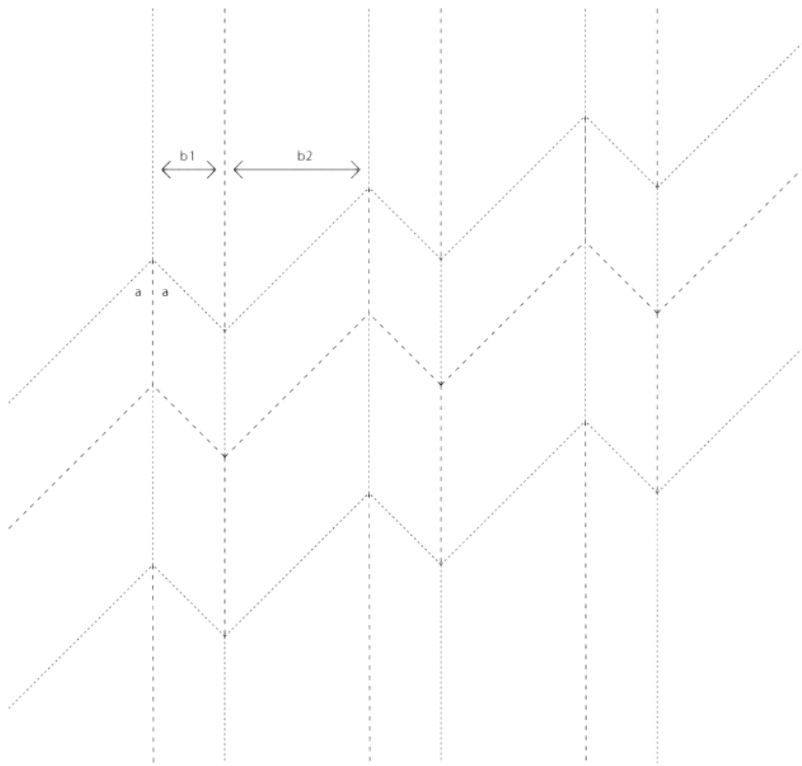


Figure 183: Origami design, uneven pleat spacing

Another origami design type that was found to be successful is based on tessellated squares. Two squares of different sizes are arranged as in Figure 184 and repeated. The pattern may be folded to form templates (Figure 185). In this case the templates were used to pleat silk organza (Figure 186).

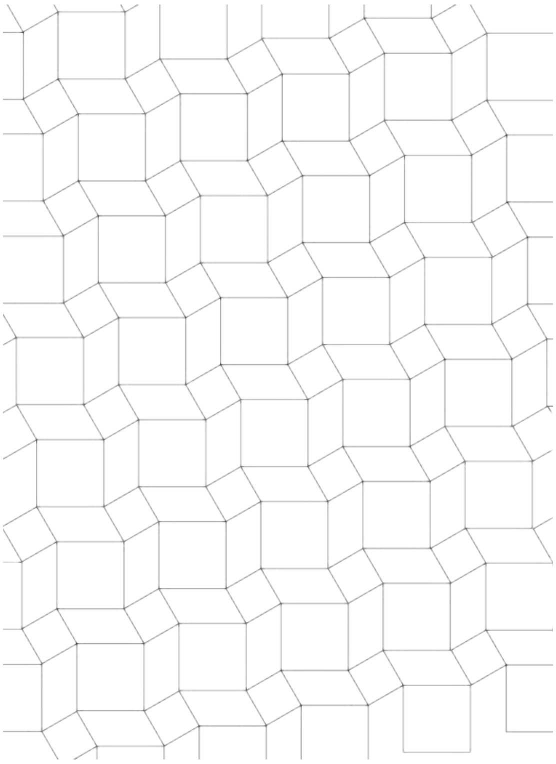


Figure 184: Tessellation made up from 2.5cm and 1.5cm squares

Figure 185: A pleating template formed by folding the tessellated square design above. Fold lines were laser marked as perforations.

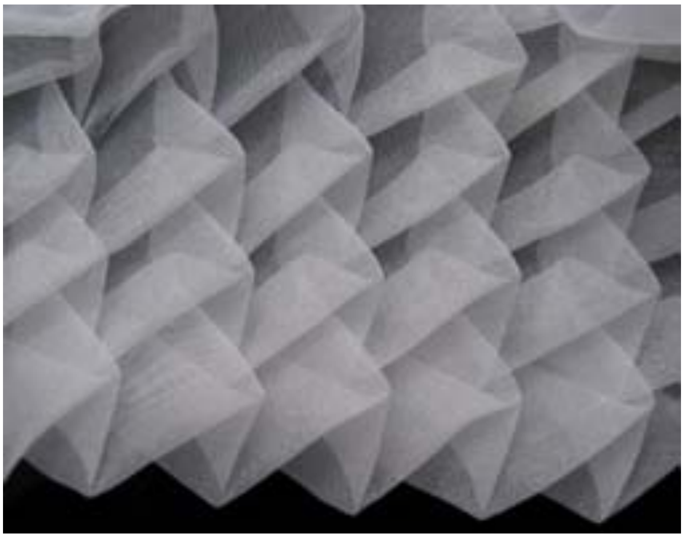


Figure 186: Silk organza pleated using the above templates.

The same design was tried successfully at a larger scale with squares with dimensions of 5cm and 3cm. For this type of design to fold successfully, both the proportions of the two squares and the angle between them must be correct. In the design shown in Figure 184, the angle between two squares must be 120^0 as shown in Figure 187. The design will not fold if these requirements are not met as the proportions will be incorrect. It is beyond the scope of this work to analyse the mathematics behind this type of folding, however ideas for designs not considered to date may arise were such a study to be carried out. This is discussed in section 10.1.2.

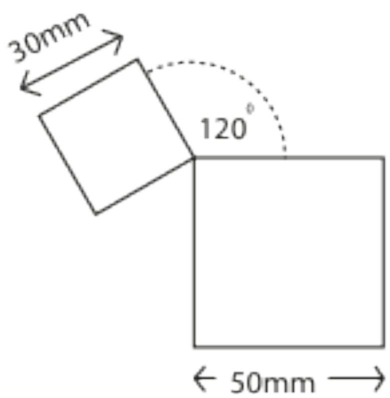


Figure 187: Detail from the tessellated design above showing required angle for the design to fold.

5.4.4 Materials

Laser assisted template pleating was found to be successful on a range of textile fabric types both natural and manufactured of different weights. Fine fabrics pleated very easily with sharp edges. As long as it was possible to fold the template sandwich, the method was found to be viable with thicker fabrics. More pressure may be required during heat setting.

5.4.4.1 Metal

The method is also successful on fine woven metals. The image in Figure 188 is woven stainless steel, which has been laser cut and template pleated using the design and same templates as in Figure 112. In this case it was only necessary to apply pressure to retain the pleats in the stainless steel as the metal did not require heat setting.

Figure 188: Stainless steel formed into a three-dimensional surface with laser assited template pleating

Following the presentation of a paper (Laser Assisted Design of 3D Pleated Structures", First World Conference on 3D Fabrics and their Applications, Manchester, 10-11 April 2008), an exploration of carbon fibre composites was inspired. Papers were presented on a variety of uses for woven carbon fibre such as the aeronautical industry and for body armour. Woven carbon fibre composites are available in a resin pre-impregnated sheet form usually called 'pre-preg'. The template pleating method was used with this material. Heat curing takes place by baking in an oven.

5.4.4.2 Carbon fibre

Laser assisted template pleating represents a new method for manipulating carbon fibre composites enabling the manufacture of rigid folded structures without employing costly moulds. The method allows the pliable carbon fibre to be manipulated into a desired shape, set in position using a paper template and then cured into a rigid form. (Figure 192 and Figure 193) The template used for this structure is shown in Figure 189. The same template was used to create the organza structure in Figure 190. It may be noted than thinner materials result in sharper folds due to shearing characteristics although at large scale, this would be less of an issue. This may be seen through a comparison between the organza and carbon fibre structures. At a much larger scale, these kinds of structures could have application in architecture as collapsible shelters where window apertures could be included, or as the support structure for a foam layer. Modular structures could also be used as roofing panels. Other industries may be considered such boat building, where currently rigid moulds are used to manufacture carbon composite hulls with moulding methods such as vacuum, press or infusion moulding. Discussions have been held with a carbon composite fibre manufacturer who confirmed that the process offered huge potential. (PRF Composite Materials, 2009)

Figure 189: Folded template used to create structures similar to those below

Figure 190: Folded polyester organza achieve with templates illustrated in Figure 189

Figure 191: Carbon fibre sandwiched between two pre-folded templates. This will be refolded prior to heat setting.

The resin pre-impregnated carbon composite materials were heat set or cured through baking in an oven at a temperature of 180^{o} for 20 minutes and then cooled. The rigid structure was then removed from the templates. To protect the resin, the materials are covered in a plastic film. This bonds to the card templates during curing so unlike laser assisted template pleating with fabrics, in this case it is not possible to use the templates more than once. Further research is needed to determine materials from which templates could be made so that they could be reused.

Figure 192: Rigid carbon fibre structure formed from the template in Figure 189

In addition to the form of the template itself, the position of the mould during curing defines the shape of the resultant structure. The structures in Figure 192 and Figure 193 have been produced using similar templates to the one in Figure 189. During curing the structure in Figure 192 was left open to produce a tunnel whereas the structure in Figure 193 was positioned to form a shell. The same template may therefore be used to make very different three-dimensional structures. This characteristic does not apply to pleating fabrics due to their pliable nature.

Figure 193: Rigid carbon fibre structure formed from the template in Figure 189.

Pleating adds strength in engineering structures. Templates may be used to give features to architectural fabrics which, depending on the resins that are used, may be cured either thermally or with ultraviolet radiation. The impact could be significant in the architectural community for large rapidly deployed temporary buildings, which could be cured at the point of use. Large three-dimensional structures with intrinsic mechanical strength offering environmental benefits could be achieved without the need for concrete, plaster etc. The absence of rigid moulds offers a new method of construction for industries such as boat building. The ability to manipulate pliable materials such as paper for templates enables through re-entrant folding, shapes to be produced, which are not otherwise possible.

5.5 Conclusion

This research described has described a new laser cut template pleating process to create three-dimensional surfaces and structures through pleating. Historical and contemporary pleating methods have been presented as no evidence of comparative analysis of all pleating processes has been found elsewhere.

Investigations determined the limitations and possibilities of the pleating process drawing on traditional and contemporary methods for folding. An emphasis was placed on finding processes to pleat textiles that have previously been laser cut as this offers a novel method of creating three-dimensional surfaces and structures from textiles with a two dimensional origin. No evidence has been found to-date of machines that are able to pleat previously cut fabric. Nor is there any evidence of machines that have the facility to position folds precisely according to a predetermined design. Textile designs that utilize cuts and folds to achieve three-dimensionality also offer novelty.

The composition and structure of the fabric, the weight of the fibres and the finishing of the fabric all influence the ease of folding. The position of pleats, and the quantity and scale of pleats make folding more or less difficult. These factors all inter-relate. As an example, it is easier to pleat an even, close weave, stiff fabric, along the grain.

The issue of placing pleats is further complicated if a printed or woven design is taken into account or, pleats are required to be placed precisely adjacent to cuts. The new process addresses this problem.

A second issue is retaining the pleats. This usually involves setting the folds either with some form of glue-like substance or heat. Folds need to be held in place while the setting takes place. Often stitches or some form of clamping or binding are used.

The ease of achieving this again depends on the fabric type and construction and the pleating design. The setting of pleats is not necessarily permanent. The new process holds the design in position while pleat setting takes place.

Historical processes to produce pleated surfaces are entirely manual using a limited range of tools to assist the hand process rather than automate it. Contemporary mechanised processes may be automated but pleat the fabric horizontally across the width and offer little design freedom.

This research has proposed three new alternatives - a machine using levers to pleat and fold laser cut fabric to a specific design; a machine to pleat fabric vertically to a design determined by a series of cut-outs in removable panels: laser assisted template pleating - a process to pleat fabric and other materials using laser designed paper patterns.

Laser assisted template pleating has proved to be the most advantageous. It offers the following:

- Full design freedom within the limits of the process. Designs are produced as CAD specifications with cuts and folds where desired. No new tooling is required for a design change. There is a vast range of design types that will work with this process.
- Design may be visualised through CAD on paper prior to using materials. It is easy to iterate and develop a design,
- Templates are produced from paper or card, which are relatively cheap materials any may be reused many times.
- The process may be used with a variety of both textile and non-textile materials to generate three-dimensional textile surfaces and structures that have application in many industries.

In addition, the research demonstrated that origami techniques may be used to generate designs for laser assisted template pleating.

Used with carbon fibre composites, laser assisted template pleating represents a new method of construction for architectural engineering and for industries such as boatbuilding where manufacture may take place without the need for moulds.

6 Laser processing of woven natural fibres

The contextual review described how laser processing is used in fashion applications for cutting and marking. No evidence was found of laser applications for three-dimensional surface patterning of textiles. As was explained in chapter 4, infrared laser treatment causes a thermal reaction which presents difficulties with natural fibres as processing causes burning and consequential unacceptable changes to fabrics such as staining and odour. This research describes a new approach for natural fibres and interventions that may be made through laser processing to produce textured three-dimensional surfaces.

6.1 Background

This section summarizes the context for the research, the fibre, fabric constructions and equipment that was used.

6.1.1 Context

Cashmere is a luxury fibre used in the fashion industry for high-end luxury accessories. Recent developments in manufacturing process for natural fibres such as cashmere, lambswool and silk have resulted in products reaching the consumer at greatly reduced prices. The high-street retailer *Marks & Spencer* were selling a range of printed woven cashmere scarves under their *Autograph* label retailing between £19.50 and £69.50 in autumn 2009. (Marks & Spencer, 2009) The luxury clothing manufacturer, *Burberry* were offering a range for the same fashion season which contained 100% cashmere scarves and stoles with price points between £250 and £450. (Burberry, 2009) Purchasers of luxury goods buy into a brand identity and to justify the price disparity, high-end manufacturers are required to differentiate their products in other ways than just the yarn content as differences in yarn quality or manufacture may not be obvious to the customer.

This research was done in consultation with Heritage Cashmere Ltd, a British manufacturer and supplier of luxury accessories and with advice on woven textiles from K.Walton, lecturer in textiles at Loughborough University School of the Arts. The company specialises in designing and producing bespoke accessories made predominately from cashmere although their range also includes items made from lambswool and silk. Most items in the range are manufactured with a 100% fibre content. The company controls the entire process starting with the sourcing of high quality fibre, the spinning of yarn, the weaving, dyeing and finishing outsourcing many of the manufacturing processes in a global supply chain. They work closely with their customers in a highly competitive market to produce a differentiated luxury product. Given that volumes vary according to demand with short lead times, it was considered desirable to develop processes, which could be applied either to finished products or selectively at an intermediate stage late in the manufacturing cycle, allowing flexibility and the ability for the same product to be customised for different product lines.

A two-fold approach was taken in this research. Section 6.2 describes investigations on the existing product range and demonstrates that with the appropriate fabric construction, it is possible to produce three-dimensional surface patterning through laser processing fully finished woven textiles. Sections and 6.3 and 6.4 discuss novelty that may be achieved through laser interventions prior to finishing and the construction of woven textiles specifically for laser processing.

This chapter will commence with an explanation of the fibres and fabric constructions that were used. As the finishing processes employed are intrinsic to the generation of three-dimensional surfaces, they are also described here.

6.1.2 Fibres

Cashmere, lambswool and silk are all natural protein fibres. Cashmere fibres come from the downy undercoat of the Asiatic goat, (*Capra hircus laniger)* and from feral goat populations in Australia, New Zealand and Scotland. (Denton, 2002, 57) There is a great variation in quality. All three fibres are available as staple fibres and silk is also available as a filament fibre. This research was confined to yarns used by the company, predominantly cashmere sourced from China. No investigations were made into the effects of fibre quality for example staple length on laser processing.

6.1.3 Weave structures

As explained in section 2.3.1.1, a woven textile consists of interlaced sets of warp and weft yarns. The manner in which they are interlaced determines the weave structure of the resultant fabric. The following structures are widely used by the manufacturer and commonly used in the industry and were consequently selected for this project:

Plain weave. This is the simplest interlacing in which the warp thread operate over one weft thread and under the next alternating on each row or pick. (Figure 194)

Figure 194: Diagram for plain weave construction (left) showing cross sections (Denton, 2002, 283). Example of plain weave, snow warp, caramac weft (Warp 2/05)

T*will* is a weave structure that repeats, to form diagonal lines on the face of the fabric. The weft yarn may pass over or under more than one warp yarn e.g. in a 2/1 twill, the weft passes over two warp yarns, then under one. In a 1/3 twill, the weft passes under three warp threads and over one. On the following pass through or pick, the interlacing moves along one warp thread creating a diagonal pattern. This pattern may be seen clearly in the images (Figure 195 and Figure 196). The loose threads lying on the surface are known as floats. A weft faced fabric will have more weft floats on the top surface whereas a warp faced fabric will have more warp threads on the top of the fabric. The twill pattern is further emphasised if the warp and weft threads are of different colours. In an unbalanced twill i.e. where the weft yarn passes over and a different number of warp threads, more of one colour will be shown on the faces of the cloth and the reverse will be different. (Figure 195) An even twill e.g. 2/2 twill however, will show the same proportion of colour on both sides. (Figure 196)


Figure 195: 3/1 Twill weft face, snow cashmere warp, caramac cashmere weft (left), 1/3 Twill warp faced, snow cashmere warp, caramac cashmere weft (right)

Figure 196: 2/2 Twill, snow cashmere warp, caramac weft, even proportions of colour on both sides of the fabric

Double cloth. A double cloth is a compound fabric consisting of two layers, which are woven separately but simultaneously and parallel to one another on the same loom. The layers may be held together by different methods - centre stitching, where a series of stitching threads binds the two together; self-stitching where threads from one fabric interlace with the other eg a back warp thread over a face weft thread; or interchanging where the two fabrics have warp and/or weft threads which interchange with each other. The fabric may appear as one cloth, but on close examination, may be pulled to separate in parts. The double cloth effectively contains pockets. This structure can produce different surface effects on the face and back of the cloth. Figure 197 shows an example.

The structure of a cloth, the appearance and the manner in which it responds to laser processing is determined by a combination of the fibres used in the yarns; the count or thickness of the yarns employed; the densities of the warp and weft yarns; the weave structure; whether it is a compound or simple cloth. All of these may vary across the cloth as may the colour of the yarns.

Figure 197: Double cloth (cashmere), checked layer interwoven with plain layer. The weave structure of the two layers is very different

6.1.4 Loom

Some fabrics were purpose woven for this research. Two different hand looms were used.

- table loom
- dobby loom

These looms enabled flexibility of design. Weave structures were designed by K.Walton and weaving was carried out by W. Maw at Loughborough University.

6.1.5 The finishing process

During manufacture, once woven, loom-state fabric undergoes a series of physical and or chemical treatments to impart a range of characteristics to the final cloth. In the case of cashmere, the cloth will undergo several washing treatments, which allow the fibres to relax. Some shrinkage occurs. The surface of the cloth may be mechanically beaten and brushed to break open individual fibres, which rise to create the distinctive soft pile. These treatments are known as finishing.

Colouration through the application of dyes may take place on yarns prior to weaving, pre-finishing or on the finished fabric. This research did not investigate the effects of dyeing on the process. Where colour played a role, cloth made from yarns, which were dyed prior to weaving, was used enabling colour variations in the cloth to be observed and used to effect.

6.1.6 Laser processing

It has already been described in chapter 4 that natural fibres burn when laser processed with CO_2 lasers. The charring effects are aesthetically unattractive in most applications, and an unpleasant odour is produced from the fumes emitted during processing, which remains with the product and would be unacceptable to the customer base. The effects of heat applied by laser processing may be seen in Figure 198 and Figure 199, which show enlarged images of cutting and etching fabric made from cashmere and polyester. The blend is in the fabric construction, here threads in one direction are polyester and in the other cashmere. It may be clearly seen in both images that the polyester fibres melt and the cashmere fibres char and turn brown.

The degradation in the fibres and yarns may cause the cloth to become fragile and unstable. The surface modification of the yarn may cause a change in handle, and where weft or warp threads are melted or burned away, there is no longer a complete structure. Previous attempts to apply laser cutting by this company to its' product range were not successful as they were not able to fully mitigate these negative effects. It will be demonstrated that through determining an appropriate fabric construction, finely controlling laser parameters, intervening at the right stage of manufacturing, and with appropriate post processing that new processes may be developed which use laser processing to create three-dimensional surface pattern which may add value to products in the luxury market.

Figure 198: Laser cut polyester/cashmere cloth. Horizontal thread (2) is cashmere showing charring. Vertical polyester thread (1) shows melting and no charring

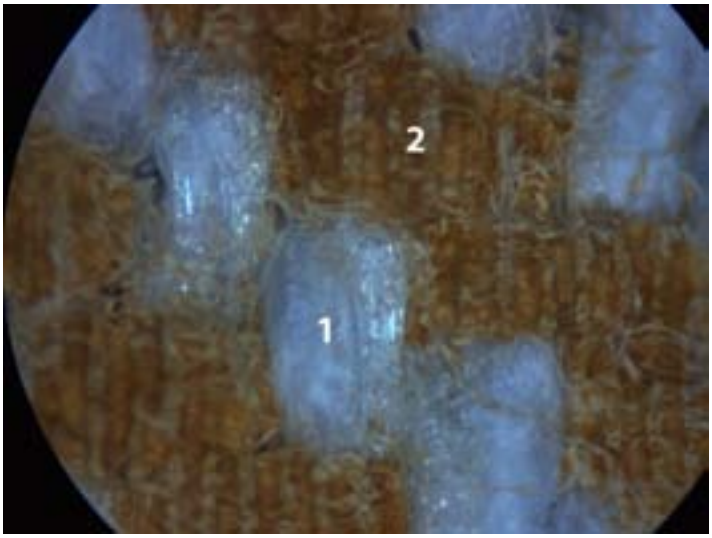


Figure 199: Laser etched polyester/cashmere cloth. Cashmere fibres (2) show charring, polyester fibres (1) show some melting

The next section describes research that was conducted on the existing product range. It will be shown that this has limited success and is only appropriate for small range of fabric constructions.

6.2 Research on finished product

A series of investigations consisting of cutting and etching were conducted on finished cloths with deep piles. The methodology to determine optimum laser processing parameters for a given material has already been described in chapter 4. Figure 200 shows etching (top left) where effects vary from just removing the top surface to obliterating the fabric; and cutting (bottom) where the effect varies from cut out circles to lightly marked circles. Figure 201 shows a variety of grids and small holes, which were used to examine the stability of the cloth with cut-outs. A flatbed 50W CO_2 laser was used with flying optics, as described in chapter 4.

Figure 200 : Initial cutting and etching tests

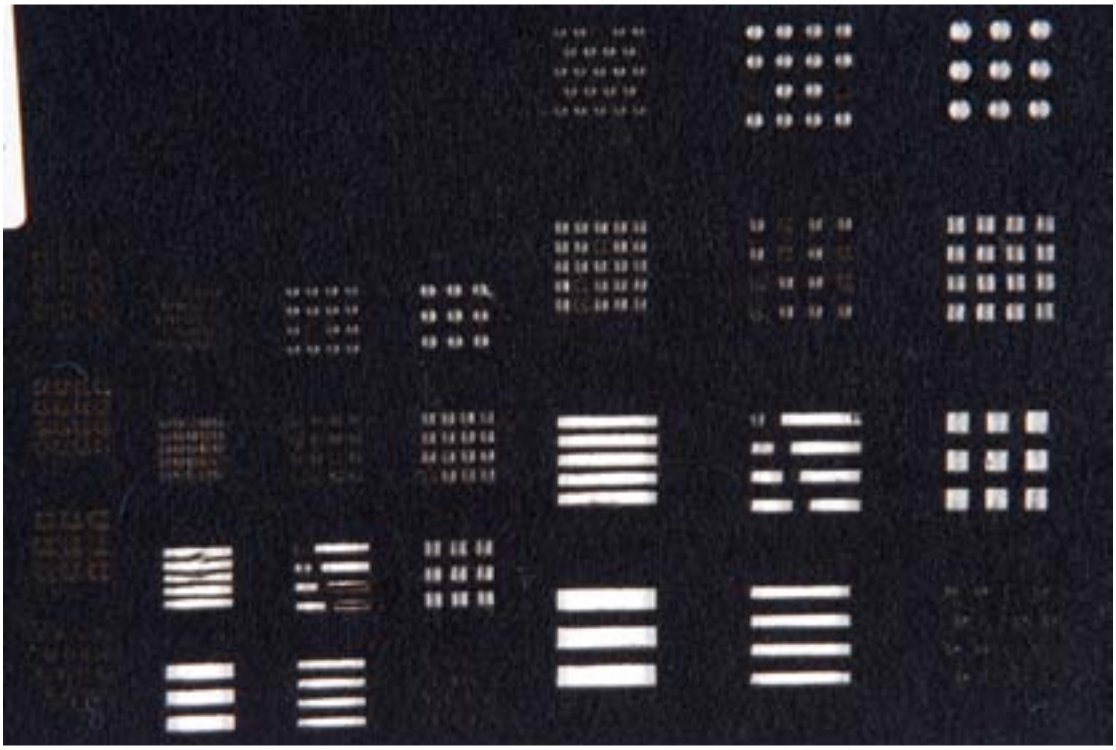


Figure 201 : Cutting tests to determine stability of fabric with detailed designs

Designs were generated in CAD (Adobe Illustrator and Adobe Photoshop) and files exported to the laser control software (APS Ethos). Three parameters were controlled :

- Power which is expressed as a percentage. Two values are entered.
  - Maximum power which may vary between 2.5W (5%) and 50W (100%). This is the power applied during cutting and etching.
  - Minimum power, which may vary between 1.5W (3%) and 50W (100%). This is the power applied while the nozzle is reaching the determined velocity i.e. during start-up and slow down
- Velocity of the nozzle, which may be set from 0cm/s to a maximum of 60cm/s. The velocity is attained after a period.
- Focus height. This is usually set such that the nozzle point is 1mm above the surface of the cloth. On uneven materials, it is adjusted such that there is clearance which may mean that the beam is, at intervals, out of focus and, as a result, processing may not be accurate at all times.
- Etching distance. When laser etching the laser beam is passed across the fabric in parallel lines. The distance between the passes may be set. Too close and the fabric is over processed, to far apart and lines may be observed. The setting used here was normally 0.2mm .

After laser processing, textile samples were post-finished by washing. The following methods were employed:

- *Hand washing*. Although hand washing of small samples was successful, the weight of the wet yarn in larger samples was unmanageable. It was not possible to finish these by hand without causing the already fragile fabric to tear.
- *Machine washing* using a *Miele* W3724 domestic washing machine. All items were initially processed using the *Wool* programme with the addition of a small quantity of non-biological washing powder. Some items were processed a second time using either the *Delicates* programme or the *Cottons* programme. Trials were made with temperatures of 30^0C, 40^0C, and 60^0C. The higher temperatures were found to be too harsh and resulted in too much felting and a reduction in the soft handle of the fabric. As a result, the temperature was set to a maximum of 30^0C in successful trials.

Programme	Water level	Wash rhythm	No of rinses	Spinning
Delicates	High	Sensitive	3	Final
Wool	High	Handwash	2	Interim and final
Cottons	Low	Insensitive	2-4	Interim and final

Table 3: Differences in washing programmes (Miele W3724 instructions, p.23)

This post processing removed any odours and loose debris and resulted in the soft handle of the fabric. Better and more consistent results were achieved with machine washing as the processed fibres were not further weakened through being unevenly handled. Although the *Cottons* cycle worked well on small samples, it was found to be too harsh once larger samples or several small samples were processed together. This is probably due to the combined weight of the cloth and absorbed water further weakening the fibres during agitation which causes the cloth to disintegrate.

6.2.1 Cutting tests on finished product

A double-faced plain weave with blue yarn on one side and black on the other was used as this structure is commonly used in the product range. Whilst initial results looked aesthetically pleasing (Figure 202 left), these textiles failed during post processing as the cutting had caused underlying weave structure to become compromised and as a consequence, the cloth became very fragile, tearing easily along the cut edges. Although the odour was removed, the edges frayed and, in places, the weave structure unravelled. The post-processed example may be seen in Figure 202, right. This behaviour was considered inappropriate for customer acceptability. Further research would be necessary to determine whether a denser or more tightly woven cloth would be less likely to rip and fray and thus be more successful.

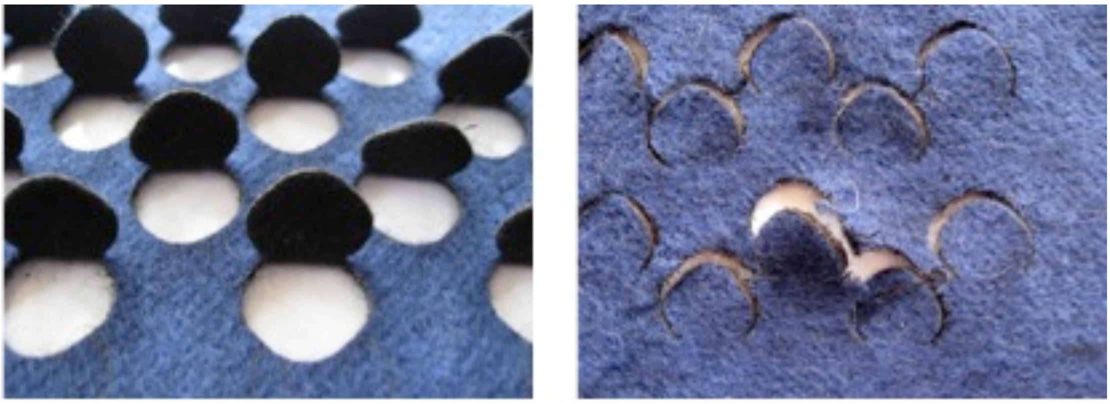


Figure 202: Laser cut (5/20/3) and pressed double faced plain weave – blue on one face and black on the other (left), sample after post processing. (right) Edges show fraying and the fabric has disintegrated in parts

6.2.2 Etching tests on finished product

Pile etching tests concentrated on the selective removal of cashmere fibres making up the pile only. The aim was to reveal the unfinished cloth. In the case of cloths with different colours on either side, marking or etching attempted to remove the pile and floating threads to reveal those that remained of a different colour. In all cases, there was the intention not to compromise the stability of the cloth. The results were as follows:

6.2.2.1 Double faced plain weave

Whilst it was possible to successfully remove the pile fibres and still retain a stable cloth, (Figure 203 left) the removal of sufficient fibres to reveal the colour underneath degraded the fabric structure to render it unstable. (Figure 203) The contrast between the cloth with pile and the cloth without was not considered sufficient to offer any advantage.

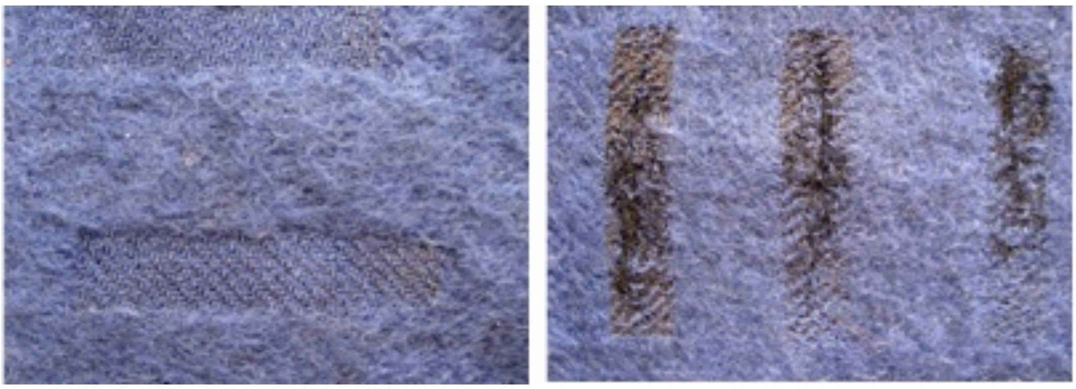


Figure 203: Double faced plain weave with laser marking (10/6/2/0.2) Blue pile has been removed and fabric is stable. (left) Sufficient blue pile has been removed to reveal the black under layer but has damaged the fabric structure (right)

6.2.2.2 Cashmere twill

These results were very successful. It was possible to remove the pile fibres to reveal the underlying twill structure with out compromising the fabric stability. Where the cloth is manufactured from two different colours of yarn, the pile is a combination of the colours of the two fibres e.g. if a camel yarn is used as the warp and a white yarn as the weft, a beige or paler pile results. (Figure 204) Removing this pile through laser marking enables the underlying diagonal twill pattern to be revealed. It was considered that this effect is most successful when colours with a strong contrast are used. (See Figure 204 - Figure 206). It was possible to process both sides of the cloth in this way without compromising the stability of the textile. The figures in brackets show the laser processing parameters - % power, maximum speed, minimum speed, etch distance. For example 17/5/3/0.2 indicates a power of 17% (1.7W); a normal processing speed of 5m/s; a start up/slow down processing speed of 3m/s; and 0.2mm between each etched line.

Figure 204: Camel/white twill with pile removed to reveal weave structure (15/5/5/0.2)

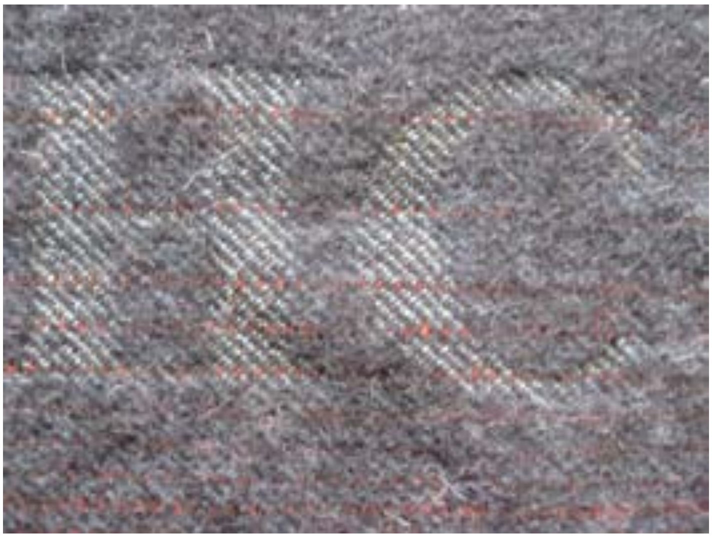


Figure 205: Grey pile removed to reveal twill structure (15/5/5/0.2)

Figure 206: Red to blue and black graduated twill with pile removed to reveal structure and colour contrast (15/5/5/0.2)

6.2.2.3 Silk twill

Results were also successful. In this case there was no pile so the etching removed the floating threads on the surface of the cloth. As can be seen in Figure 207, it was possible to remove the orange surface of the textile such that the cloth did not become fragile and the pink threads that remained did not degrade. However it was only possible to process one side of this cloth in this way i.e. the side with orange floating weft threads. This technique could offer an alternative to the chemical devoré process where screen printed chemicals and the application of heat are used to dissolve specific fibre types, leaving others with which the chemical does not react.

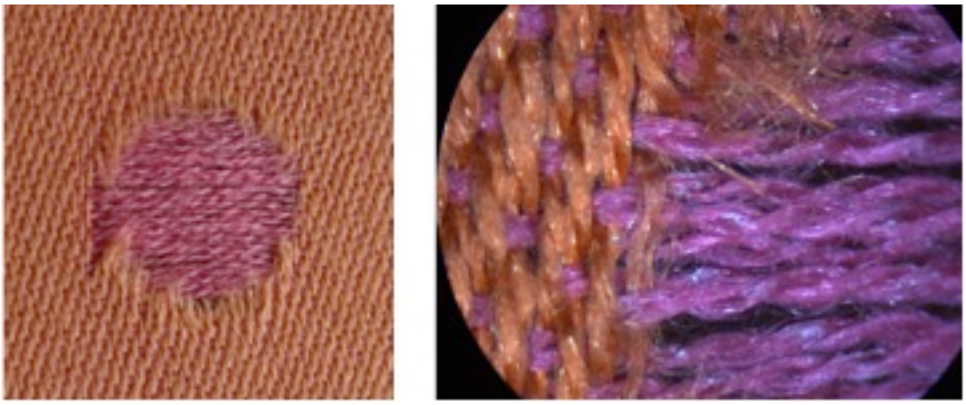


Figure 207: Silk twill with top surface removed by laser marking. (left) Pink warp threads intact (20/5/3/0.2). Detail (right)

6.2.2.4 Cashmere double cloth

Mixed results were obtained on these fabrics. It was possible to remove either side of this double cloth without compromising the underside layer. (Figure 208) However the structure of the double cloth that was selected did not lend itself to this manner of processing for two reasons. Firstly the interlinking threads were widely spaced resulting in unattached flaps, which would not be aesthetically pleasing on a luxury item. Secondly the weave structure of the individual layers was relatively loose which caused the edges of the marked areas to fray during post-processing. Whilst still stable, it was not considered that this appearance added value to the product.

Figure 208: Double cloth with bands of top the checked layer removed to show the navy blue under layer (10/6/3/.2), (left), : 'C' etched on reverse of double cloth - insufficent detail and frayed edge (10/8/3/0.2 x 2), (right)

Further research is necessary to determine a double cloth weave structure that would be more acceptable. Such a cloth would be linked at closer intervals that corresponded well to the design to be etched. In addition, each individual layer would need to be selected such that it behaved in a desirable manner i.e. was dense enough to remain stable and not fray easily.

Although acceptable results were achieved on some finished product, namely etching on twill, it is clear from the above results that the appearance, stability and three-dimensionality of the resultant textile depends on the construction of the cloth, the fibre content and the finishing. It was felt that intervening with laser processing earlier in the manufacturing process specifically prior to finishing may offer advantage. The next section describes these tests and conclusions.

6.3 Research on loom state cloth

The research described in this section was conducted on industrially woven unfinished 2/2 twill 100% cashmere cloth. The method chosen for this series of tests was to draw a fixed numbers of warp and/or weft threads from plain weave loom state 100% cashmere cloth which results in gaps (Figure 209). Advice from K. Walton indicated that texture may created on a woven fabric through altering the weave structure. This may be achieved on loom during weaving by omitting warp threads or inserting spaces between weft threads. To simulate this, threads were drawn from loom state fabric that was made available by Heritage Ltd. To create a narrow gap (A) remove a few threads, to create a wide gap (B) remove more.

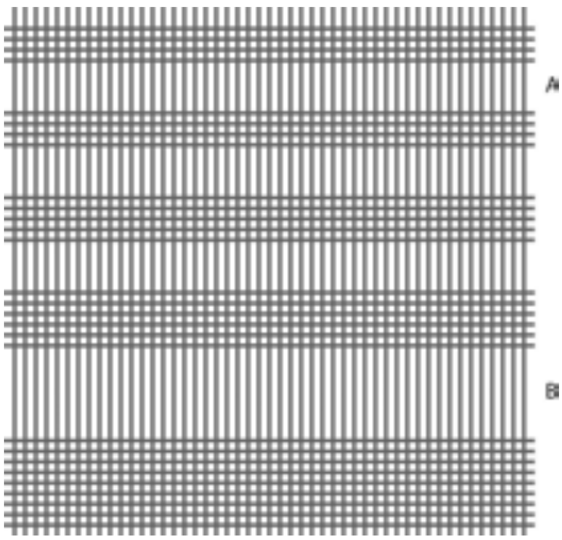


Figure 209: Diagram showing drawing of warp threads. More threads have been removed from B than A

The second step involved laser cutting the remaining warp or weft threads. Figure 210 shows the possibilities that were explored:

- C – cut a fixed number of threads alternately close to one edge of the gap and then the other
- D – cut in the middle of the gap leaving long cut threads
- E cut close to both edges leaving short cut threads
- Varying the length of the cut. This could be even cuts and spaces, long cuts and short spaces or short cuts and long spaces

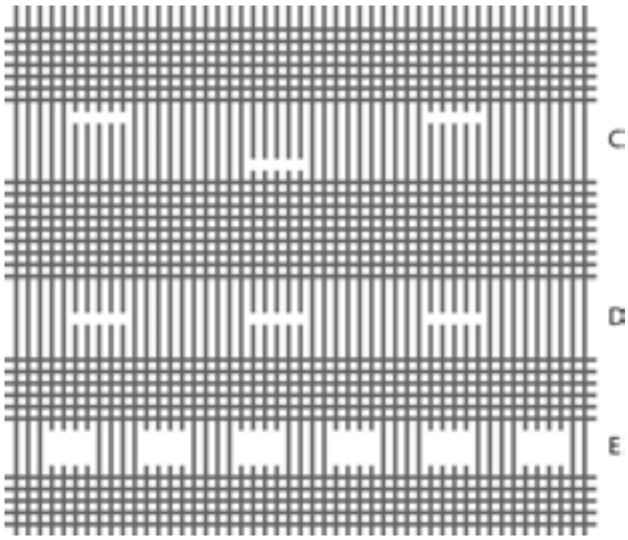


Figure 210: Diagram showing where remaining threads may be laser cut

After laser cutting, the loom state cloth was hand washed and dried flat. Figure 211 - Figure 218 illustrate the results from these trials.

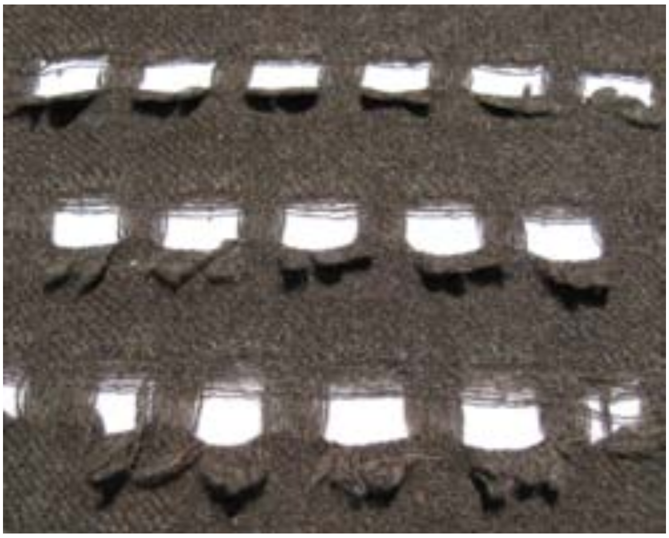


Figure 211: 16 threads removed, 2cm cuts 1cm apart, close to top edge, position of cuts alternates on each row (5/15/5)

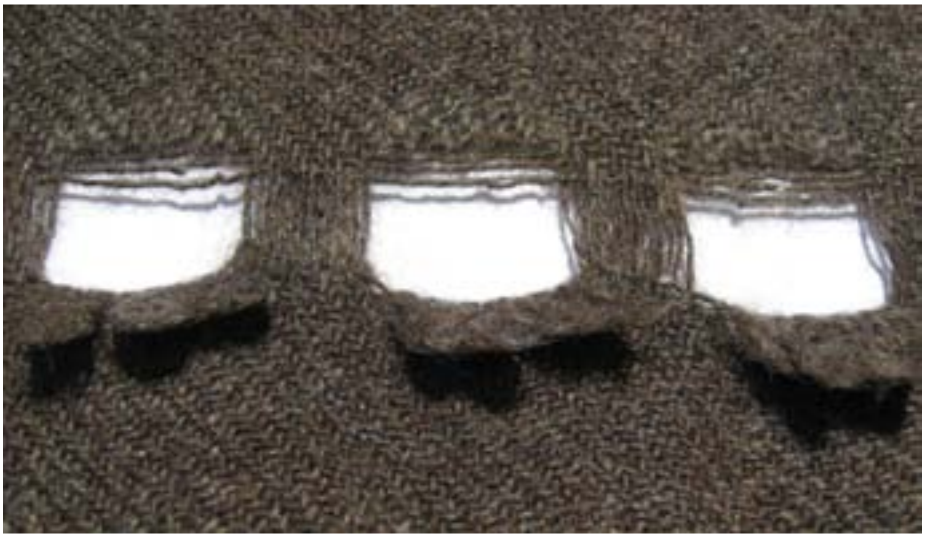


Figure 212: Detail from figure above showing matted fringe on one side of gap

Figure 213: 16 threads removed, 1cm cuts 1 cm apart, alternately close to top edge then bottom edge, position of cuts in same place on each row (5/15/5)

Figure 214: Detail from figure above showing matted fringe on alternate side of gap

Figure 215: 32 threads removed, 1cm cuts 1cm apart in middle of space, position of cuts even on each row (5/15/5)

Figure 216: Detail from figure above showing matted fringe on both sides of gap

Figure 217: 8 threads removed, 1cm cuts 0.5cm apart in middle of space, position of cuts even on each row (5/15/5)

Figure 218: Detail from above image showing thread spacing and bobble surface

As may be seen from the above images, this method namely laser processing loom state cloth and post processing with washing, may be used to create three-dimensional surfaces from woven textiles. The parameters that may be altered may be summarized as follows:

- *Number of threads* – the removal of warp and or weft threads creates spaces. The remaining threads may be cut. The cut ends will create matted fringes when the cloth is finished through washing, generating a three dimensional surface. There will be spreading out of threads on the edges of gaps creating areas of varying density. (Figure 217)
- *Space between bands* – will influence the flat space between areas of three-dimensionality. Narrow spaces will result in a complete or full three-

dimensional surface. (Figure 217) Wide spacing will allow three-dimensional bands. (Figure 211)

- *Position of cuts.* Cuts may placed in the centre of the gap which results in an even fringe on both sides. (Figure 215) If placed on one side of the gap, the will be no or very little fringe on that side. (Figure 211) Cuts may also alternate from side to side (Figure 214)
- *Dimension and spacing of cuts.* Long cuts and narrow spacing will give a very different effect to narrow cuts (Figure 212) and wide spacing as will even cuts and even spacing. (Figure 216) Another option is to align all cuts and spaces (Figure 217) or to make them alternate.

In these experiments, threads were drawn by hand. It is however possible to weave cloth with integral spaces, which could be laser processed as described above. Further trials into this aspect were conducted which are described in section 6.4.3. Further research is required to determine the effects of this method on other fabric constructions, yarn counts and densities.

Given that it is very difficult to source quantities of fabric in low volumes and with given specifications, it was decided to conduct further experiments on purpose woven cloth. These would have a known fibre and yarn content and a specified construction. This work was done at Loughborough University by W.Maw with advice from K. Walton. Results are described in the next section.

6.4 Purpose woven loom-state cloth

The method adopted here was to weave using the table loom a panel referred to as warp 1 (Table 5 in the Appendix) with bands of different yarn types such as cashmere; other natural fibres such as wool, silk and angora; manufactured fibres such as Kevlar, nylon, polyester and acrylic. Coloured marker picks separated the different bands so that they could be identified when separated from one another. The warp yarn was snow cashmere (2/28) and a 2/2 twill construction was used throughout.

Figure 219: Warp 1 showing cutting and marking tests. Photo K. Walton

Figure 220: 1cm circle after 1 wash - fibres relax to form a square

Simple etching and cutting tests were conducted on each band consisting of a circle of 1cm diameter, which was cut, marked and etched. (Figure 219) The warp was washed by hand which allowed the fibres to relax and some of the debris from processing to be removed. Cut out circles changed shapes to become squares as the yarns relaxed and moved into the space. (Figure 220)

There was however still a burnt odour attached to the cloth so the etched sample was machine-washed. A pile was generated which gave the cashmere its normal finished appearance and handle. All odours were removed and it was still possible to see the etched shapes. (Figure 221) Handle changes could be observed where cashmere was used in conjunction with other fibres. (Figure 222)

As a result of these trials, it was decided that further research would be useful in the following areas

- etching on loom state fabric to take advantage of the colour change due to charring
- cut-outs on loom state fabric to determine if shapes other than circles produced different results
- cut-outs of different dimensions on loom state fabric to see if the size of the hole, the spacing of holes and their positions was material
- weave structures containing floats to mimic the gaps discussed in section 6.3
- natural fibres such as cashmere and silk only

Figure 221: 100% cashmere etched. Pile raised post processing and charring mark integrated within fabric

Figure 222: Cashmere polyester blend, cash mere warp, polyester weft. Cashmere fibres removed. No evidence of charring post washing

Two further warps were woven. See Table 6 : Warp 2 and Table 7 : Warp 3 in the Appendix. It was decided to concentrate on cashmere so weft yarns were predominantly cashmere although some silk was used. Warp 3 was produced in two sections so that it could be split vertically down the middle. This would allow for two identical panels of each sample so that experiments could be replicated. The results obtained from Warp 2 generated experiments for warp 3. Results are described below - etching (section 6.4.1) and cutting (section 6.4.2).

Figure 223: Warp 3 on loom showing two panels. Photo K.Walton.

6.4.1 Etching

The results from this group of experiments do not demonstrate three-dimensional surfaces. However laser processing is used here in a novel way to create surface patterning so the outcomes have been included.

Trials from warp 1 showed that the best etching results would likely to be achieved on 100% cashmere using a balanced twill weave construction. Etching tests were therefore conducted on 2/2 twill cloth. Both the warp and weft were 2/28 snow cashmere. Focus height was adjusted such that the nozzle was 1mm above the surface of the cloth which was laid as flat as possible on the laser bed with the warp and weft threads parallel with the edges of the laser bed. The etching direction was parallel with the weft threads. The distance between the rastered lines was set to 0.2mm. Three items were selected for etching. See Figure 224 and Table 4.

1. A sunflower, which was imported to the laser control software as a JPEG file and etched three times with high (1a), medium (1b) and low (1c) settings.
2. A block of fine text which was etched using high (2a) and medium (2b) settings

3. Two large characters (HC) containing both straight and curved edges, which were etched using high (3a) settings. Table 4 shows the parameters that were used.

Figure 224: Loom state cloth etched with text and images at different intensities, pre-finishing

Image	Velocity (cm/s)	Maximum power (%)	Minimum power (%)
Sunflower (1a)	12	5	3
Sunflower (1b)	16	5	3
Sunflower (1c)	20	5	3
HERITAGE (2a)	12	5	3
HERITAGE (2b)	15	5	3
HC	12	5	3

Table 4: Etching parameters for sample shown in Figure 224

Figure 225 (left), Figure 227 (left), Figure 228 and Figure 230 (left) show images of the etched cashmere prior to finishing. An even charred mark is made on the surface of the cloth consistent with the fibres being burnt. The more power that is applied, in this case through slowing down the speed at which the beam moves, the more burning and the darker the mark.

Two finishing treatments were applied. The first was using the *Wool* programme and the second using the *Delicates* programme as described above in section 6.1.5.

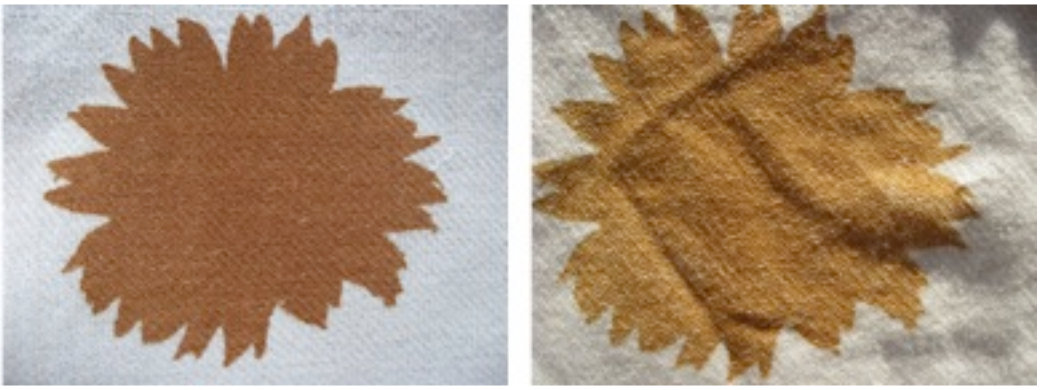


Figure 225: Sunflower etched using high settings (left), Fading and handle change after one finishing wash (right)

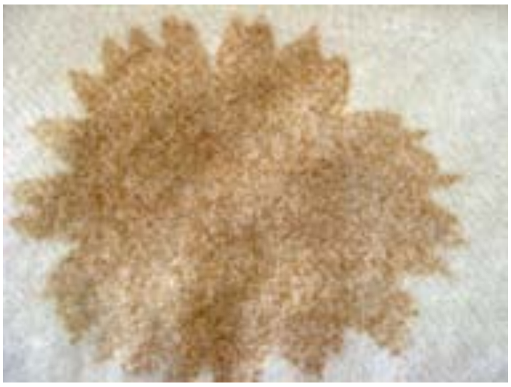


Figure 226: Sunflower in Figure 225 after two finishing washes

The following observations may be made :

- The high, medium and low settings all successfully mark the fabric prior to finishing. (Figure 225 left)
- The marked areas have a crisp handle compared to the soft unmarked areas.
- The fabric has a strong unpleasant odour, which is not removed by airing.
- After one finishing wash, the odour is removed. However the charred mark still seems to have appearance of being recently applied. On larger marked areas, it is still possible to distinguish by touch where marking has taken place. After two finishing washes the mark has been integrated with the fibres, which have felted and both areas have the same soft handle. (Figure 226, Figure 227 (right), Figure 229 (right), Figure 230 (right) and Figure 231)
- Light laser processing after two finishing washes becomes very faint and in some cases not visible.
- The marks are equally successful for large areas, fine text and images.
- After sufficient processing the marked images have been fully integrated in the cloth as it they had been woven in a yarn of a caramel colour.

- These tests have been conducted on snow coloured cashmere. It is unlikely that images would be able to be viewed on anything other that pale coloured yarns.

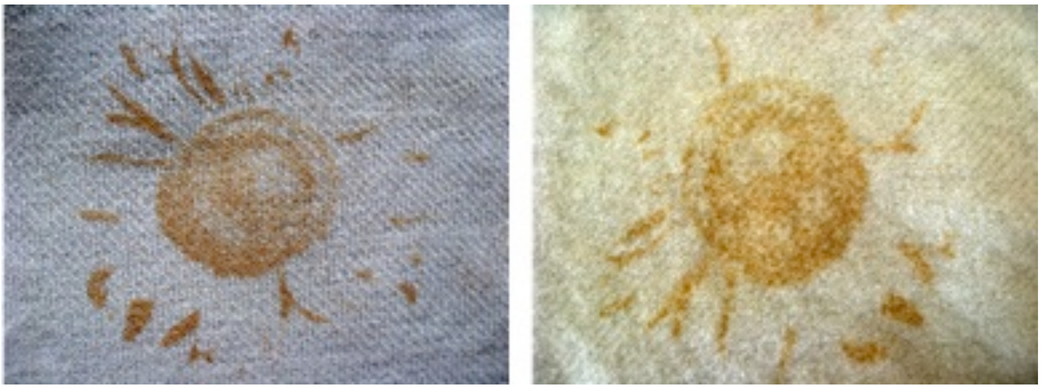


Figure 227: Sunflower etched using medium settings (left), Sunflower etched using medium settings and after two finishing washes (right)

Figure 228: Fine text after etching, light and medium settings

Figure 229: Fine text after one finishing wash. (left) The block of text on the left (light etching) is already very faint. Fine text after two finishing washes. (right) Images show the right most block from Figure 228 (etched with medium settings)

Figure 230: HC text pre finishing (left), HC text after two finishing washes (right)

Figure 231: A large marked design after two finishing washes

Figure 232: Detail of etching in Figure 231 showing the marked areas fully integrated in the fabric with no obvious fibre degradation.

In conclusion, laser etching may be used to apply surface patterning to loom state woven cashmere. The negative effects of the process, charring and odour, may be removed by post-processing through washing. The resulting fabric, after sufficient washes, has a soft natural handle. The surface patterning is integrated into the fabric. The applied pattern may have fine detail. Fabric must not be lightly laser processed as it will not be possible to distinguish the image after post-processing. Further research is required to determine whether this method is suitable for the patterning of other natural fibre fabrics such as wool. Although this work represents an original contribution, this thesis is concerned with the development of three-dimensional fabric surfaces and as process does not achieve three-dimensional patterning, it was decided not to continue with this line of research as this time.

6.4.2 Cutting on loom state cloth

This section describes the results of trials conducted by laser cutting loom state fabric. It will be shown that it is possible to create three-dimensional surfaces with a variety of designs. A three-dimensional surface is achieved through a two-step process. Firstly, unfinished woven cashmere fabric is laser cut with a series of holes in a pre-determined pattern. (Figure 233) Secondly, the fabric is finished through washing which removes charring and odours and allows the fabric to shrink and felt revealing a three dimensional pattern.

Figure 233: Laser cut 10mm circles on 2/2 twill, snow cashmere warp and weft, detail

The process is illustrated in the images that follow. Figure 234 shows the fabric after one finishing wash. The circles have become squares and the structure has contracted a little. Figure 235 and Figure 236 show the fabric after two washes. The fabric has shrunk and felted and areas have become raised.

Figure 234: Fabric after one finishing wash, detail. Circles have started to form squares

Figure 235: Fabric after two finishing washes. Bobbles have formed resulting in a three-dimensional surface

Figure 236: Fabric after two finishing washes, detail of Figure 235

The nature of the surface patterning that may be achieved is determined by the fabric construction, the shape, dimension and density of the cuts. In the pervious example the spacing and shape of cuts was regular. This section details trials that have taken place to illustrates the effects of spacing and cut shape.

Experimentation started by cutting small holes as shown in Figure 237. Although limited effects are observed, holes with a diameter of less than 5mm do not result in much three dimensionality. When shrinking takes place, the holes close up almost completely and insufficient fabric has been removed to alter surface tension.

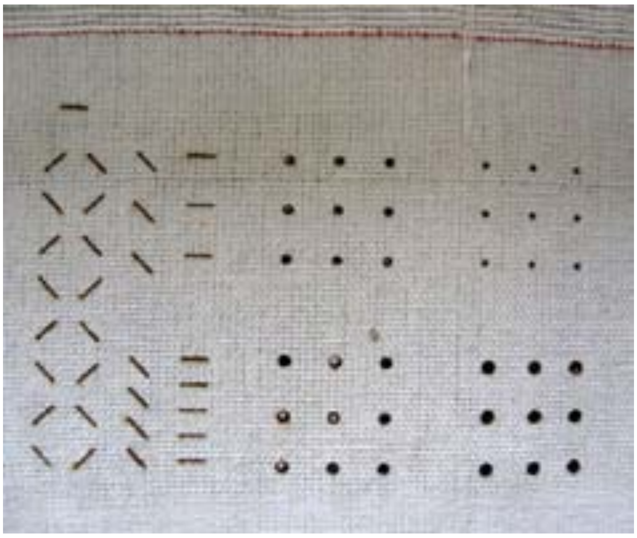


Figure 237: A test sample containing a variety of holes - 2mm, 3mm, 4mm and 5mm. Lines are 10mm in length and placed in patterns.

Experiments looked at the effect of hole shape on three-dimensionality. A test sample is shown in Figure 238. There was little difference in results between circular and square holes. During finishing, a circle would change shape to become a square as already been seen. It was considered though that using a circle allowed the edges to felt more sucessfully.

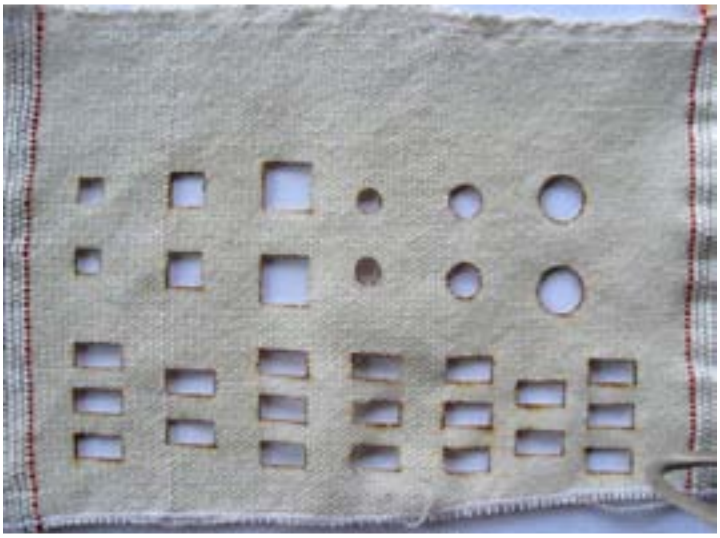


Figure 238: A sample looking at the effect of cut-out shape. Squares (5mm, 7.5mm, 10mm) Circles (5mm, 7.5mm, 10mm) Rectangles 10mm x 5mm

Figure 239: The sample cuts in Figure 238. Large holes cause the fabric to become unstable. Small holes and squares produce three-dimensionality. Photo K. Walton

It appeared that rectangular or oval holes may offer design potential so this aspect was explored further. Figure 240 shows a range of combinations of circular holes.

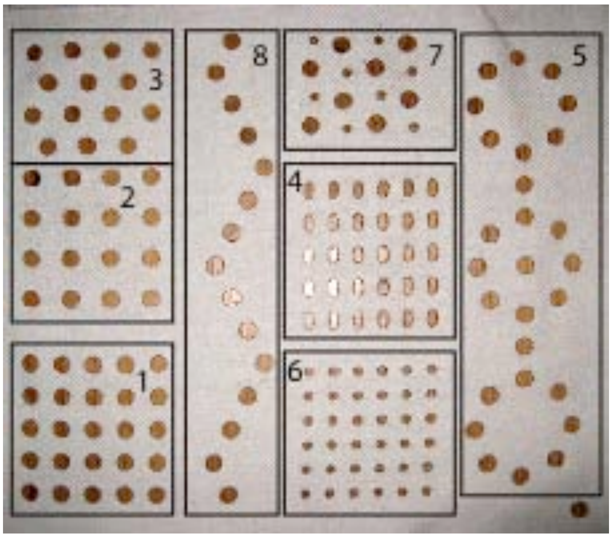


Figure 240: A test sample comparing hole spacing. See for Figure 241 dimensions

	Dimensions of holes in Figure 240
1	A grid of 10mm circles, 10mm apart
2	A grid of 10mm circles, 15mm apart
3	A grid of 10mm circles, 10mm apart, offset
4	A grid of ovals 5mm x 10mm, 10mm apart
5	10mm Circles arranged in a circle
6	5mm circles, 10mm apart
7	10mm and 5mm circles spaced 10mm apart
8	10 mm circles arrange in a line

Figure 241: Table showing dimensions of cut-outs in Figure 240

In addition to circles and ovals, tests were conducted with semicircles and simple crosses. An example may the seen in Figure 242. These test samples were tried on several fabric constructions and fibre mixes from Warps 2 and 3.

Samples were finished by machine washing as described above. The following observations may be made:

- Laser cutting holes removes fabric. When finishing takes place, yarns adjacent to the holes move into spaces that have been created. Shrinkage occurs and the surface of the fabric puckers generating a three-dimensional surface

- *Size of holes*. Best results were achieved with holes between 5mm and 10mm in size. Although not always consistent, greater three-dimensionality is achieved with larger holes.

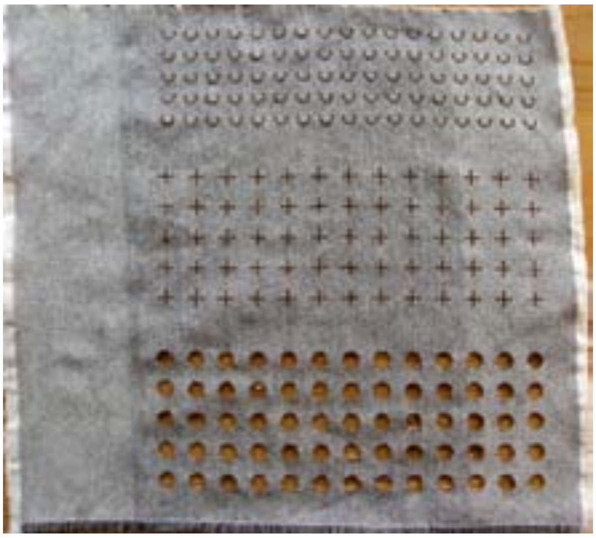


Figure 242: 7.5mm semi circles, 10mm crosses, 10mm circles

- *Spacing of holes*. If holes are placed too close together, less than 5mm, the fabric becomes unstable. If they are placed too far apart, more than 20mm, no effects are observed. An ideal distance would seem to be 10mm on the fabric constructions used. Figure 243 shows the effects of grids 2 (left) and 3 (right) from Figure 240. It can be seen that puckering is greater when holes are in line with one another rather than offset. Figure 246 demonstrates that when the circles are placed too far apart, there is little three-dimensionality.

- *Shape of holes*. The size of hole and spacing played a greater role in achieving three-dimensionality than the shape. Comparing Figure 243 (left) which has 10mm circles with Figure 244 which has 5mm x 10mm ovals orientated vertically, it can be seen than the puckering occurs along the length of the ovals but even on both sides and above and below the circles. Although crosses produced interesting effects particularly on twill with different colours in the warp and weft, semi-circles and circles, produced greater three-dimensionality. (Figure 245)

- *Fabric construction*. The weave construction of the fabric affects the appearance. Three-dimensionality on a plain weave (Figure 247) or a 2/2 twill (Figure 248) produces similar results on both sides of the fabric. A 1/3 twill produces more puckering on one side than the other. (Figure 249 and Figure

250) Although the plain weave produces similar three dimensionality to 2/2 twill, there is less felting on the fabric surface.

- *Yarn colour.* Yarn colour may be used to effect particularly when an unbalanced twill structure is used. Figure 251 - Figure 253 show the effects that may be achieved. A white warp yarn was used with a grey weft and a 1/3 twill construction. The raised bobbles on the front surface are white whereas the back, although three-dimensional in form is predominantly grey.

- *Yarn composition*. The yarn composition plays an important role in the resultant three-dimensionality of fabric. Experiments were conducted with 100% cashmere warps. Wefts of 100% cashmere, silk noil and spun silk were used. It was found that during finishing, the cashmere shrinks whereas the silk does not. Fabric containing a silk weft, had floating silk threads on the surface post finishing, where cuts had been made but did not have a three-dimensional surface. The most effective three-dimensional surfaces were obtained with 100% cashmere warp and weft yarns. Further research is needed to determine whether wool and other natural fibres with similar properties to cashmere would be advantageous for this process.

- *Shrinkage.* During finishing 100% cashmere fabric shrinks by approximately 8%-10% across both the length and the width. This shrinkage needs to be compensated for when designing for this process.

Figure 243: Left, 10mm circles (sample 2) and right, 10mm circles offset grip (sample 3). This image shows that raised bobbles are more regular when circles are placed opposite each other (left) rather than offset (right)

Figure 244: Raised areas produced by ovals (sample 4). Compared with Figure 243, it can be seen than these produce a more pronounced raised area in one direction.

Figure 245: 10mm cross, 10mm apart, 2/2 twill

Figure 246: 100mm circle cut-outs placed in a circle layout (sample 5). The spacing of the cut-outs is too far apart to generate much three-dimensionality.

Figure 247: Plain weave, 5mm circles, 100mm apart - raised surfaces on back and front are similar

Figure 248: 2/2 twill, 5mm circles, 10mm apart – raised surfaces on back and front are similar

Figure 249: 1/3 twill, 5mm circles, 10mm apart, front

Figure 250: 1/3 twill, 5mm holes, 10mm apart, back

Figure 251: 1/3 Twill, 10mm circles, 10mm apart, front

Figure 252: 1/3 Twill 10mm circles, 10mm apart, back

Figure 253: 1/3 Twill, 7.5mm semi circles, 10mm apart

(this section left intentionally blank)

Figure 254: Twill, semi circular cuts

Figure 255: Design in Figure 254. Photo K. Walton

Figure 256: Plain weave, 10mm cuts

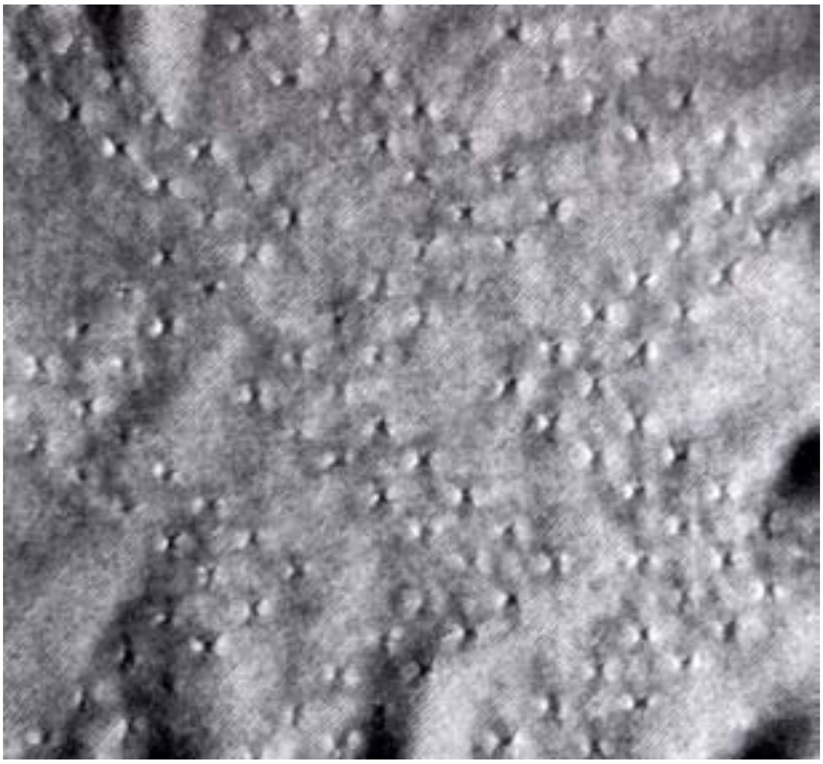


Figure 257: Design in Figure. Photo K. Walton

Figure 258: 10mm holes spaced 10mm apart

Figure 259: Design in Figure 258 Photo K. Walton

6.4.3 Floats

Work described in section 6.3 showed that three-dimensionality could be achieved by cutting some of the remaining warp of weft yarns after some were withdrawn by hand. This section describes results of trials with laser cutting floats that were added as part of the fabric construction. In all cases the warp and weft was 100% cashmere.

Samples were woven with floats as described in Table 6 : Warp 2- Table 7 : Warp 3 in the Appendix. Two examples are shown in Figure 260 and Figure 261. Folded paper was inserted as shown in Figure 262 to protect the fabric ground from the laser beam during processing as it was desired that only the floats were cut and not the underlying fabric. Previous experiments had shown that no advantage was gained by processing both layers identically. Once cut the paper inserts were removed, the fabric was finished in the normal way. The ground shrank and the remaining floats felted into fringes. The resultant fabric was three-dimensional with pockets created by the uncut floats. See Figure 263 and Figure 264.

Figure 260: Warp 2/09 Ground snow, caramac floats, loosely attached to selvedge

Figure 261: Warp 2/08 Ground snow, caramac floats, bound in with two warps

Figure 262: Detail of Figure 261 after laser cutting . Paper inserted prior to cutting to protect the fabric underneath.

Figure 263: Post finishing, the fabric ground and the remaining floats shrink resulting in pockets

Figure 264:The same in Figure 260 post finishing. The fabric ground has contracted and the loose floats have felted forming pockets.

Further experiments were conducted. These involved purpose woven structures where wefts passed over several warp threads creating gaps and card was woven into the weft. This would allow the warp floats to be cut without damaging the underlying yarn. A variety of holes and lines were cut. An example may be seen in Figure 265.

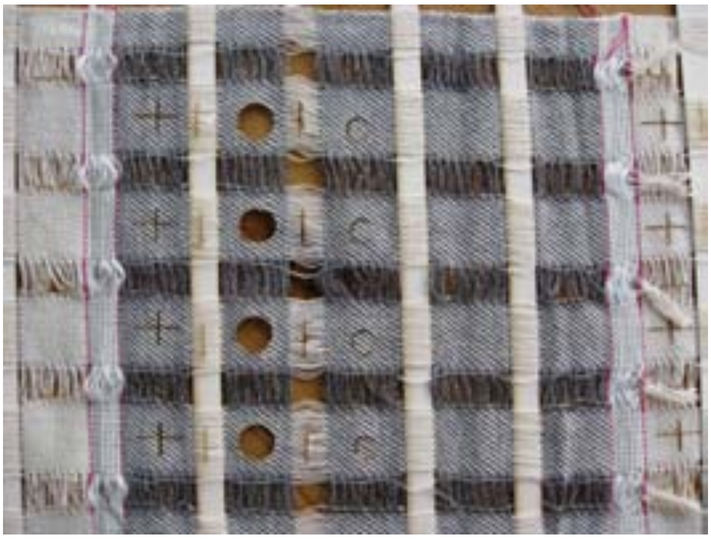


Figure 265: Snow warp, heron weft, card woven in. Laser cut lines, semi circles and holes

The evidence shows that this would be a viable method to create three-dimensional surface patterning. The creation of pockets may offer advantage. Where the floats were long, the fabric obtains an unstructured appearance post-processing, which may not be desirable. It was decided to not continue with this line of research as results without floats were of more interest to the customer. Further research would be required to investigate this technique systematically in detail.

6.5 Conclusion

This chapter has described a novel process for using laser processing to create fabrics made from woven cashmere with three-dimensional surface patterning. By intervening with the laser early in the process i.e. prior to finishing, the negative effects of laser processing on natural fibres, such as charring and odour, are removed by the finishing process. A careful selection of fabric construction, hole size, shape and position and yarn colour allows a variety of three-dimensional patterned surfaces to be determined. Incorporating floats enables fringes to be created. Although best results, are achieved on loom state fabric, it is possible to process some finished fabric constructions such as twills. Refinishing is required to remove the debris and odour caused by laser processing.

In addition the chapter has described a process for patterning woven cashmere using laser etching such that the negative effects of the processing are mitigated and the resultant fabric would be acceptable to a luxury customer base. This process may also be used for customisation such as the application of a logo.

Further research is needed to determine whether this process, which is successful with cashmere, would be appropriate for other natural fibres such as wool or wool/cashmere blends. Research into other fabric constructions including double cloths may lead to further innovation. The effects of parameters such as yarn thickness, yarn type e.g. degree of twist, fabric density, and yarn colours may offer further advantage. Research here has concentrated on woven fabrics. Warp knitted fabrics are limited in surface design options by their construction. Intervening prior to finishing with laser processing as described here may display similar effects to woven textiles and open up possibilities for three-dimensional surface decoration.

7 Laser Sintering of Textiles

The contextual review indicated that additive manufacturing techniques had made a significant contribution to the production of three-dimensional objects through methods that could generate objects not able to be made using traditional processes. This chapter describes research that explores an additive manufacturing technique, laser sintering, on a fabric substrate to create three-dimensional textile surfaces and three-dimensional textile structures.

Selective Laser Sintering uses a high-powered CO_2 laser to fuse small particles of polymer, metal or ceramic powder together to form three-dimensional objects. The process uses data generated from a three-dimensional CAD model split into two-dimensional slices and builds the object layer by layer, one on top of the other. Typically a layer of powder is spread, the laser beam passes over the powder in a path specified by the CAD file, fusing granules together. This process is known as sintering. A new layer of powder is spread on top of the existing unused powder and the fused particles. The laser passes again building a three-dimensional form, layer by layer. Commercially layers may be as thin as 0.1mm. On completion, excess powder is removed and a three-dimensional object is revealed. In contrast to subtractive methods of manufacture such as CNC (Computer Numerical Control) or milling, laser sintering is able to produce complex three-dimensional forms not able to be achieved in any other way such as hollow parts, undercuts etc.

As mentioned in the contextual review, Freedom of Creation and the Loughborough University Additive Manufacturing Research Group have developed laser sintered textiles. Although described as textiles, these have a chain mail type form which gives flexibility and movement and comprise only the material being sintered, usually polyamide (nylon). No evidence has been found of previous work that utilises woven or non-woven textiles in conjunction with laser-sintered materials or any other additive manufacturing process.

The research described here shows how laser sintering may be used create a three-dimensional surface using both woven and non-woven textile substrates. Potential applications for this work have been identified as:

- surface decoration
- an alternative to stitch

- a method of laying down tracks for electronic circuits for smart textiles if conductive materials are used
- the construction of objects such as fasteners directly on or integral to garments
- structural modification to add stiffening and rigidity e.g. for body armour, corsets etc.

7.1 Experiments

The initial aim was to determine whether it would be possible to laser sinter powdered materials onto a woven textile substrate. A second stage would build up layers of sintered material. This section describes tests that were conducted.

7.1.1 Materials

DuraForm PA polyamide powder (nylon) manufactured by 3D Systems Inc is used for sintering by the Loughborough University Additive Manufacturing Research Group. (3D Systems, 2011) As this material (average particle size 58 microns) is commonly used for laser sintering and was easily available, it was selected for the initial trials. Paper nylon sourced from Whaleys Ltd, Bradford was chosen as the textile substrate as it was thought to have a similar chemical composition to the polyamide powder and consequently a similar melting point. It was felt that bonding would be more likely to take place if both the powder and substrate were of the same material.

7.1.2 Equipment

An experimental rig from a previous PhD using Selective Laser Sintering of hydroxyapatite-polyamide composites (Savalani, 2006) was used. The laser equipment used for the investigation was a 10W CO_2 Synrad laser marker controlled by WinMark v2 software. (See Figure 266) The Synrad laser marker has a bed size of 10cm x10cm. The vertical position of this work-bed (A) may be adjusted up and down to ensure that the laser beam, when applied to the materials placed on the work-bed, is always in focus. The laser beam is directed onto the surface of the materials to be processed from above via a system of mirrors. The whole system, laser beam and work-bed, is enclosed within a cabinet with interlocks preventing access to samples whilst the laser is operating. Fumes are extracted by means of a vacuum hose (B). This may be adjusted away from the materials being processed and the powders may therefore be processed without being disturbed.

The Winmark laser processing software enables the following parameters to be controlled:

- The power of laser expressed as a percentage of 10W
- The velocity of marker (mm/s)
- The Line thickness. This setting (Wobble ON/OFF) enables the line thickness to be controlled by marking a zigzag where the width of the zigzag (mm) and the incremental step (mm) may be set.

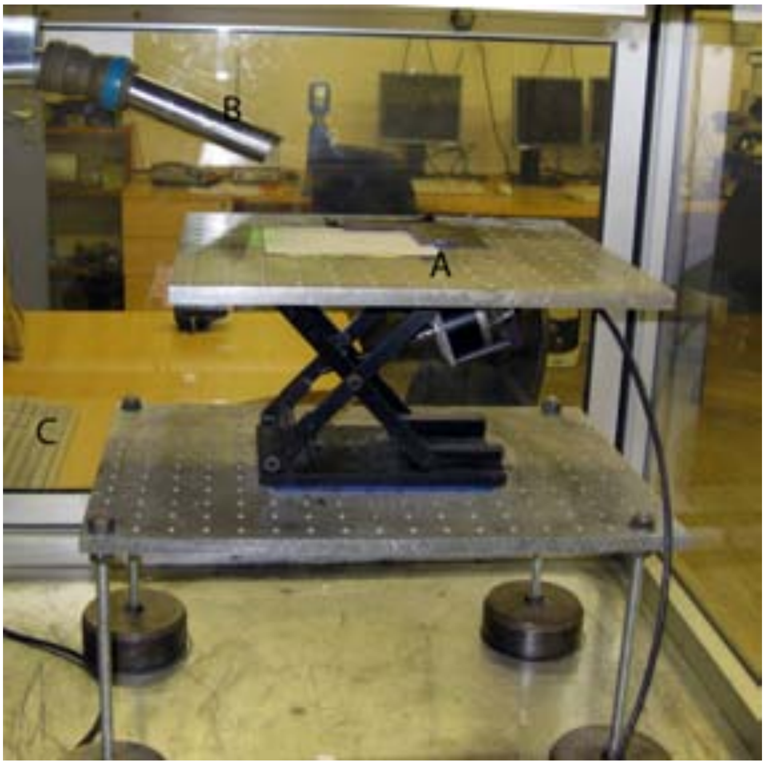


Figure 266: Cabinet housing experimental rig. Synrad laser marker is housed above cabinet, A – adjustable work-bed, B – fume extractor hose, C - Computer outside of cabinet

7.1.3 Method

In order to achieve repetition and consistency of results, the following method was adopted

- One layer of fabric was attached using masking tape as flat as possible to a flat stainless steel plate measuring 15cm x 7cm x 2mm. See Figure 268 (A) and (B)
- Powder was placed on top of the fabric
- The powder was spread thinly using the powder spreader (Figure 267 left) designed by M.Gibson at Loughborough University. Screw B loosens to allow the section labelled A to move vertically up or down creating a gap at the

base of the spreader. The gap size may be measured using a feeler gauge (Figure 267 C) and adjusted to a specified height. When the spreader is moved across a layer of powder, any powder in excess of the height set, will be pushed out of the way. Figure 268 shows a spread layer of powder – the excess at (C) and an even layer (between C and D).

- Laser processing was initiated using the Winmark software.
-

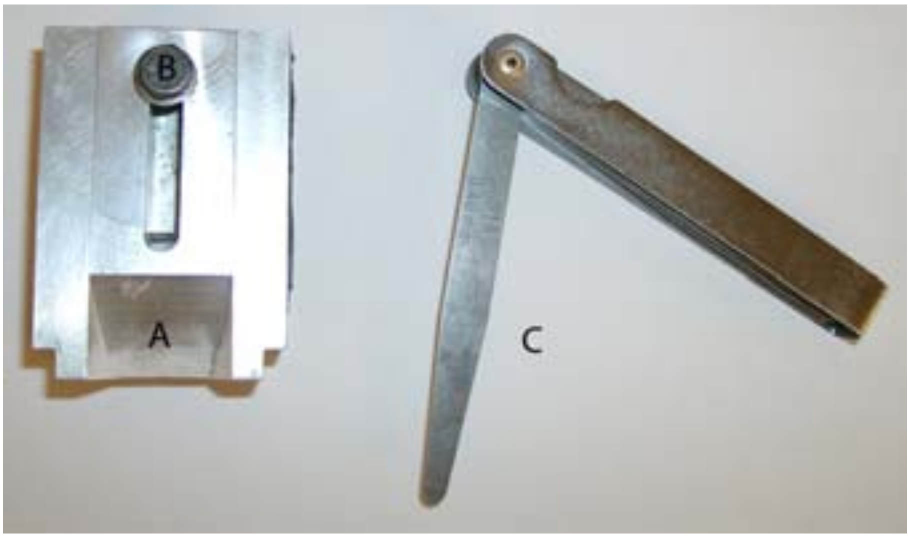


Figure 267: Powder spreader (M. Gibson) left. The centre section (A) may be adjusted up and down to change the thickness of the layer being spread by turning the screw (B). The feeler gauge (C right) is used to set the height of the spreader to the correct setting.

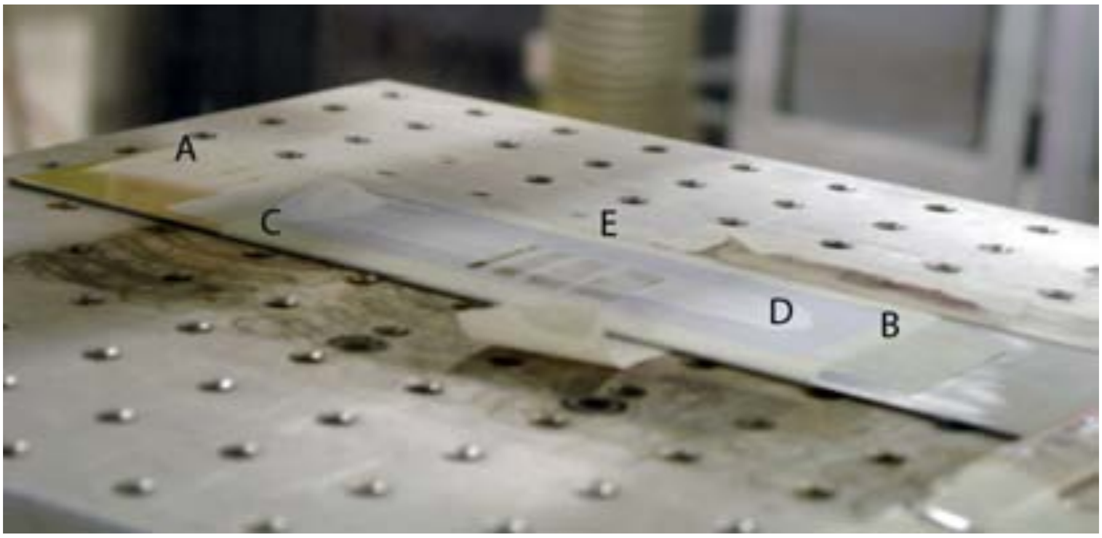
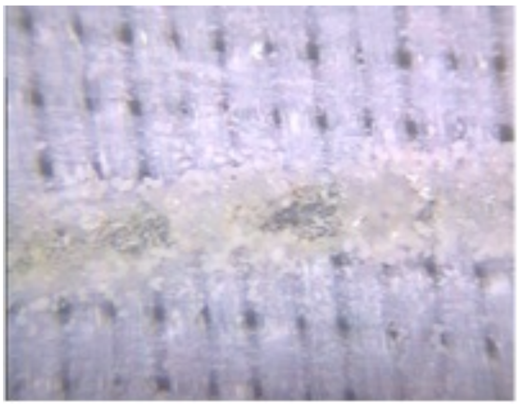


Figure 268: Stainless steel plate (A) on workbed. Fabric (B) is attached. Powder C is spread in a thin layer (D) and lines are sintered (E)

Initial tests processed one layer of white polyamide powder 0.25mm in thickness. Parallel lines of length 50mm, spaced 7mm apart were marked across the length of the spread powder. (See Figure 269) The marking speed was varied in increments between 5mm/s and 100mm/s. The power was varied between 2.5W and 3W. Investigations were made to see the effect of line thickness by trying the Wobble setting with width values of 0.5mm and 1mm and increments of 0.1mm. A comparison was made to see the effect of one or two passes of the beam. Best results were obtained with a straight-line i.e. minimum width or no zigzag, one pass, power of 2.8W and speed at 10mm/s. As can be seen from Figure 270, the powder fused with the textile substrate in parts.

Figure 269: Sample of sintered lines with varying powers and speeds. Powder was spread along the centre of this sample.



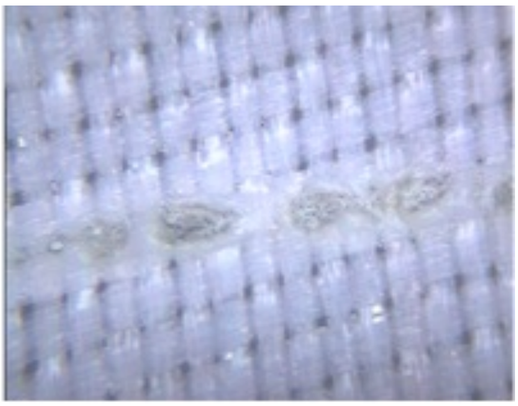


Figure 270: Line of sintered polyamide powder (0.25mm) on paper nylon. Sample 6 - 2.8W, 10mm/s. Top view (left), underneath view (right)

A second group of tests sintered 10mm diameter circles with a view to building multiple layers of polyamide powder. Two layers were sintered, the first measuring 0.25mm and the second 0.38mm. An approximate estimate suggested that the first sintered layer lost half its height when processed due to the granules melting, so the second layer was set to 0.38mm (0.25mm + 0.25/2). Speeds were varied between 5mm/s and 20mm/s. Power was varied between 2.7W and 3W. Using one (0.25mm) and two layers of polyamide (0.25mm, 0.38mm), the best welds were achieved with a power setting of 2.8W and a speed of 6mm/s.

Using layers of polyamide powder (0.25mm, 0.38mm, 0.63mm, 0.9mm), a speed of 6mm/s and a power setting of 2.8W, it was possible to laser sinter four layers with a weld to the polyamide fabric that appeared to be successful as the sintered material was bonded to the textile substrate and did not pull away when rubbed. See Figure 271 and Figure 272, which show the sintered circle and weld on the paper nylon substrate from the top and below. Novelty is achieved here through fusing layers of powder to the substrate. Once this had been achieved, the process then becomes normal laser sintering (SLS), fusing one layer to another, which is well known. For this reason, experiments did not progress beyond four layers.

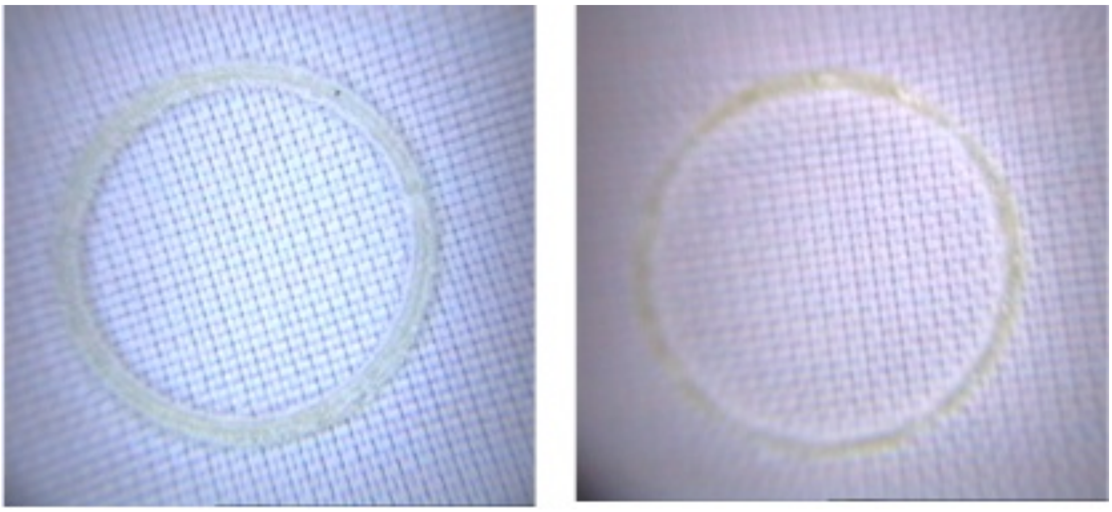


Figure 271: 10mm circle, 4 layers on sintered polyamide powder on paper nylon, Sample 10 :0.25mm/ 0.38mm/ 0.63mm/ 0.9mm, 6mm/s, 2.8W. Top view, (left), underneath view (right)

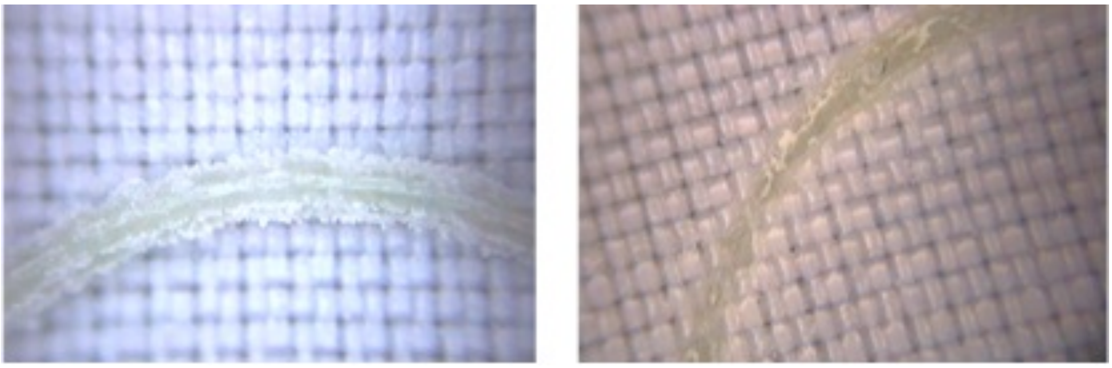


Figure 272: Detail of sample 10 in Figure 271. Top view, (left) shows loose unmelted powder attached to the sintered circle. Underneath view (right) showing the fused weld.

Microtome tests were conducted. During this type of test, a small sample is frozen using liquid nitrogen. A thin slice is cut at right angles to the textile fabric and the cross section may be viewed under a microscope. A cross section of sample 10 may be viewed in Figure 273 and Figure 274 where the warp and weft threads may be seen as lines and dots (A and B). The four layers (L1-L4) may be seen in Figure 273. The image shows that the individual layers have successfully fused together

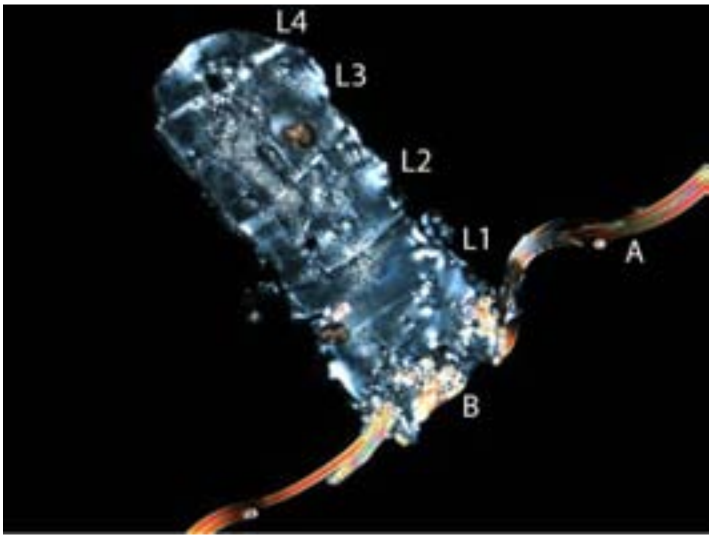


Figure 273: Cross section of Sample 10 showing warp and weft threads (A, B) and four sintered layers (L1, L2, L3, L4)

. Figure 274 shows the weld that has formed between the paper nylon substrate and the first sintered layer (C). It is clear from both images that the powder and textile have both melted and welded together. The small black dots are pigment contained in the polymer. The large black dots are air bubbles.

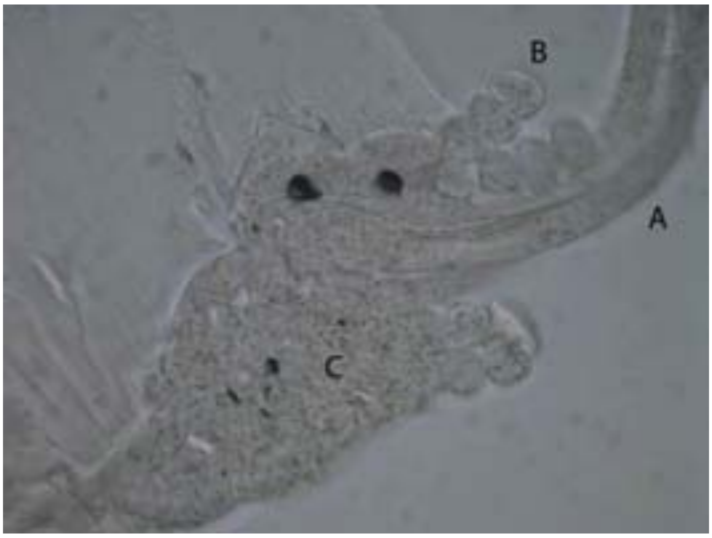


Figure 274: Cross section of sample 10 showing warp and weft threads (A, B) and area were textile substrate and polymer powders have fused

Further research is required to determine the exact amount of shrinkage of powder. It was decided not to conduct tests of this nature at this stage as the shrinkage would not be material to designs created by this method. It however will be determined by a number of factors amongst others the particle size, the volume of particles that melt, the volume of particles that sinter, the penetration into the fabric below, the volume of the fabric substrate that melts, and how the molten fluids are relocated.

7.2 Embossing powders

The polyamide powder used was available in white. From a design perspective, it was felt it would be advantageous to work with more than one colour. In addition as the substrate and the polyamide powder were both white, it was difficult to view what was occurring. Thermography or craft embossing powders are available in a variety of colours. These behave in a similar way to polyamide but have a lower melting point. It was not possible to ascertain the exact composition of the powders used as the distributors would not release this information. The following powders were used Heat it Up available from Design Objectives Ltd – Red (PWR 71102), Blue (PWR 71615), Yellow (PWR 71617) and Personal Impressions – Black (EMP 401)

The above tests with lines and circles were repeated and it was found that it was possible to sinter 4 layers of powder (0.25mm, 0.4mm, 0.6mm, 0.9mm) with a successful weld to the paper nylon. (Figure 275 and Figure 276) Settings used were 2.8W and 9mm/s. It was thought that the faster laser speed was required because the thermography powders had a lower melting point than the polyamide powder. Thermal tests of the powders would be required to validate that this is the case.

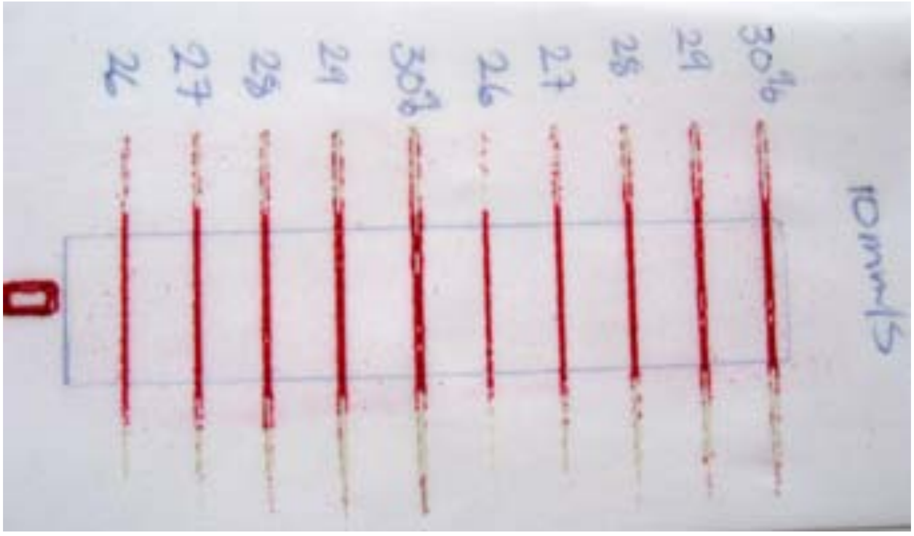


Figure 275: Sintered lines of red embossing powder on paper nylon to determine optimum laser parameters

Figure 276: Red embossing powder sintered on paper nylon, 10mm circles

Figure 277 shows a section of the 10mm sintered circle from above and below respectively. Grains of unsintered powder may be seen attached to the sintered layers. In spite of this, the surface quality of the sintered embossed powders appears to be smoother than the polyamide powder.

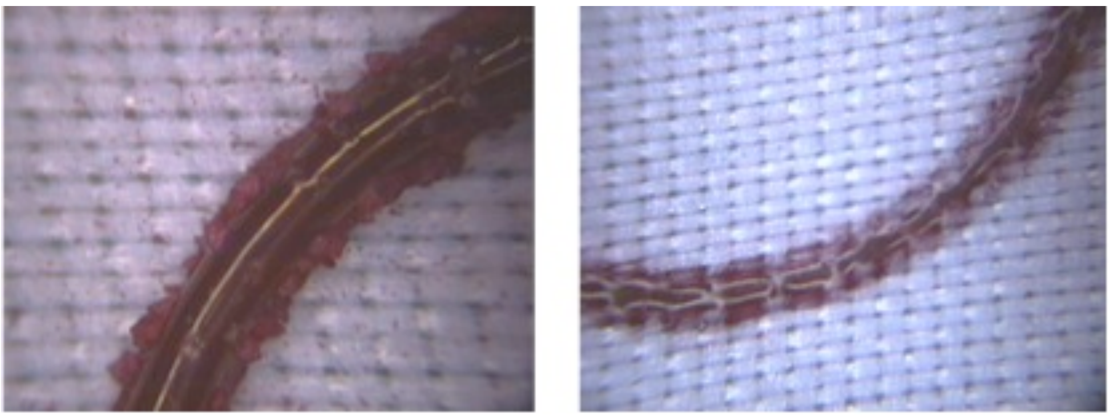


Figure 277: Sample C4 (detail), red embossing powder, paper nylon, 2.8W, 9mm/s, top view(left), underneath view (right)

The sample in the above images was cross-sectioned and analysed with microtome testing. The warp and weft threads of paper nylon may be viewed at points A and B on the image in Figure 278. The fabric at these points is completely attached to the sintered powders. The complete weld may be seen at point C where the paper nylon has fused completely with the red embossing powder.

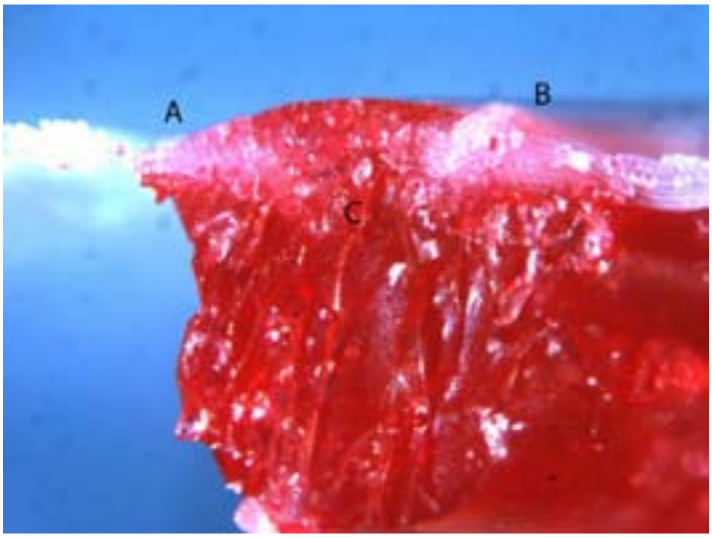


Figure 278: Cross section of sample C4 (fabric at top, sintered layers below.

As the red embossing powders stained the fabric, it was decided to sinter four layers of white polyamide powder on to paper nylon followed by one layer of embossing powder. Settings used were 2.8W, 6mm/s. The layer thicknesses were 0.25mm, 0.4mm, 0.6mm, 0.9mm, 1.35mm. As can be seen from the images in Figure 279 and Figure 280, the embossing powder sintered successfully to the polyamide powder and no staining passed through to the underside.

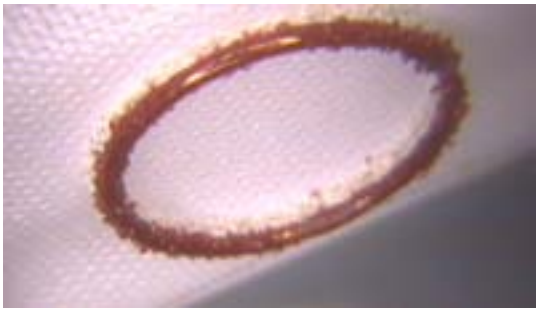


Figure 279: Sample C6. One layer of polyamide sintered onto paper nylon, 4 layers of red embossing powder (top view)

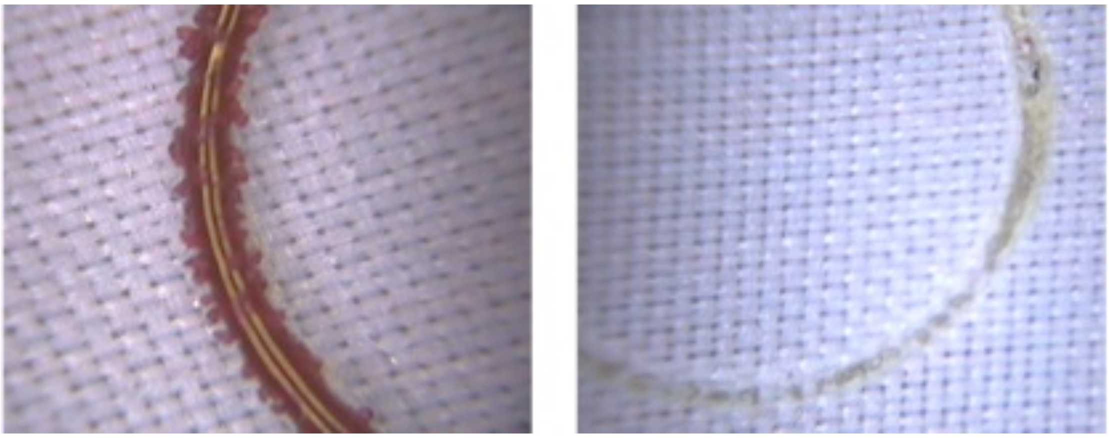


Figure 280: One layer of polyamide sintered onto paper nylon, 4 layers of red embossing powder, top view (left), underneath (right).

A cross section of the sample underwent microtome analysis, which may be seen in Figure 281. Points A and B show the paper nylon fused to the sintered polyamide. Point C shows the surface of the weld. No fabric is visible as it has melted and combined with the melted powders. Point D shows a complete weld between the polyamide powder and the embossing powder.

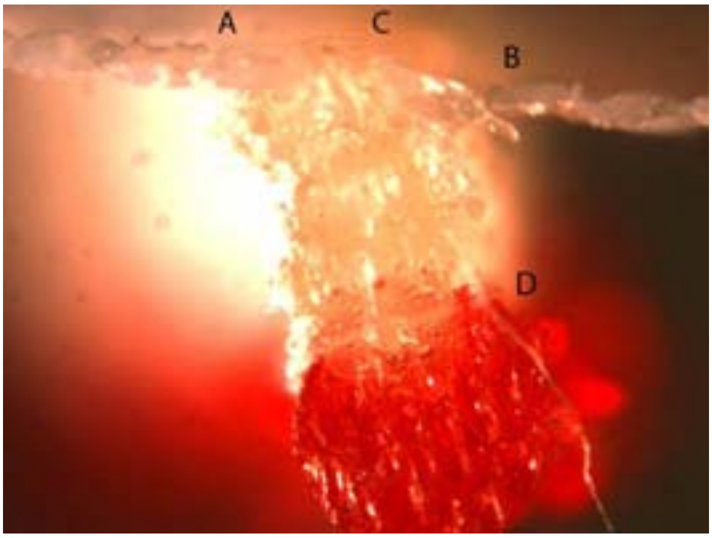


Figure 281: Cross section of Sample C6, fabric at top and sintered polyamide and embossing powder at bottom

As the polyamide fused well with the embossing powder, trials were repeated using a 50/50 mix of polyamide powder and embossing powder. Settings used were 2.8W, 6mm/s with layer thicknesses of 0.25mm, 0.4mm, 0.6mm, 0.9mm. A 10mm circle was sintered. The results indicate that a successful weld was achieved but that the surface of the sintered structure was not as smooth as that obtained with 100% embossing powder. (Figure 282)

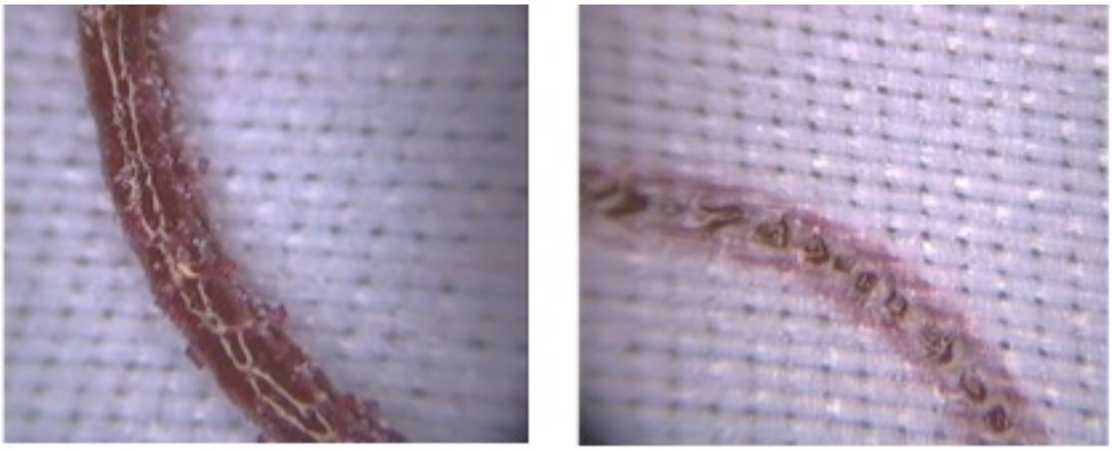


Figure 282: Sample C7 (detail) Four layers sintered onto paper nylon using a 50/50 mix of polyamide and embossing powders, top view (left), underneath view (right)

An experiment was conducted to determine whether it would be possible to sinter more than one colour in the same design. See Figure 283. Red, yellow and blue embossing powders were used on a paper nylon substrate. The design consisted of three concentric circles 12mm, 16mm and 20mm in diameter. The first layer was 0.2mm thick. A layer of blue powder was spread, sintered (12mm circle) and removed; a layer of yellow powder was spread, sintered (16mm circle) and removed; a layer of red powder was spread, sintered (20mm circle) and removed. This process was repeated with the next layer measuring 0.4mm thick. Power was set to 2.8W with a processing speed of 9mm/s.

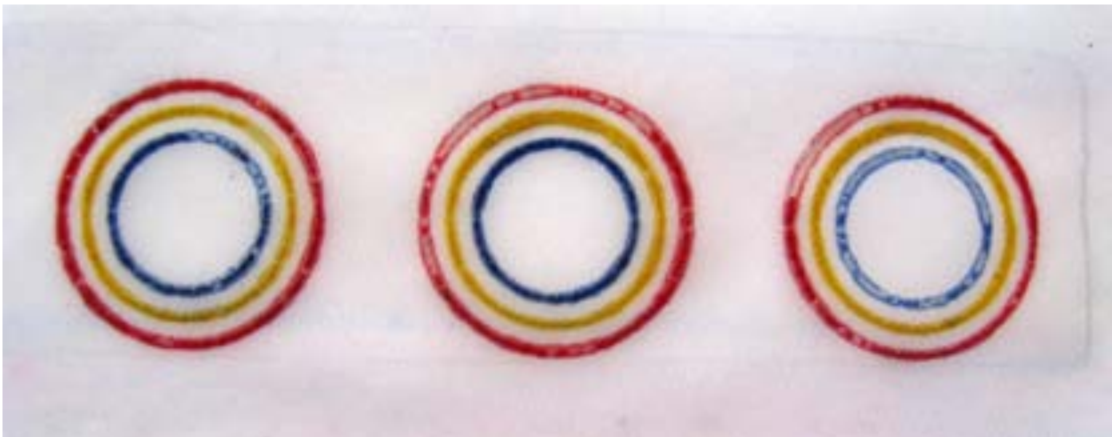


Figure 283: Red (20mm circle), yellow (16mm circle) and blue (12mm circle) embossing powders sintered on paper nylon, 2 layers.

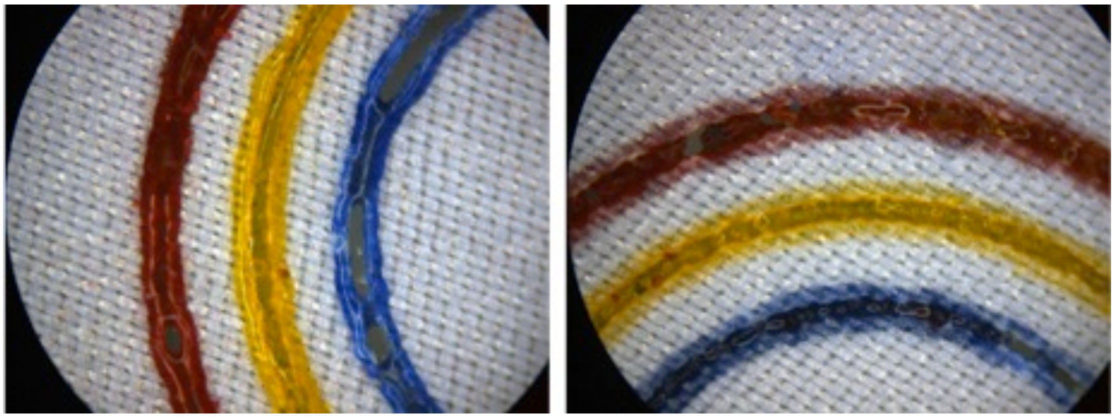


Figure 284: Sample C8, red, yellow, blue embossing powder, detail, front view, (left), underneath view (right)

Although the sintering was successful, it was felt that this was a complicated method of powder application and an alternative method should be sought for multicolour designs. There was also some cross-contamination of sintered particles from one ring to another. See the yellow ring in Figure 284 (right). As only two layers have been sintered, insufficient material has been applied to fully form all welds. Gaps may be seen particularly in the blue ring in Figure 284 (left).

7.3 Structures

This section discusses experiments that were conducted to create sintered structures on a textile substrate. The first group of trials attempt to fuse two layers of fabric using sintering. (See 7.3.1) This would provide an alternative to stitch. The second attempts to sinter larger areas building smooth surfaces. (See 7.3.2) These could be used as design features such as logos.

7.3.1 Structures using two layers of fabric

The aim of this group of tests was to weld two layers of fabric with sintered polymer. Four layers of polyamide powder (0.25mm, 0.38mm, 0.63mm, 0.9mm) were sintered onto paper nylon. The settings used were 2.8W, 6mm/s. Another layer of fabric was placed on top and the circles were marked again. See Figure 285.

Three options were tried :

a. Fabric, sintered polymer layers, fabric.
b. Fabric, sintered polymer layers, additional polymer powder, fabric.
c. Fabric, sintered polymer layers, fabric, additional polymer powder.

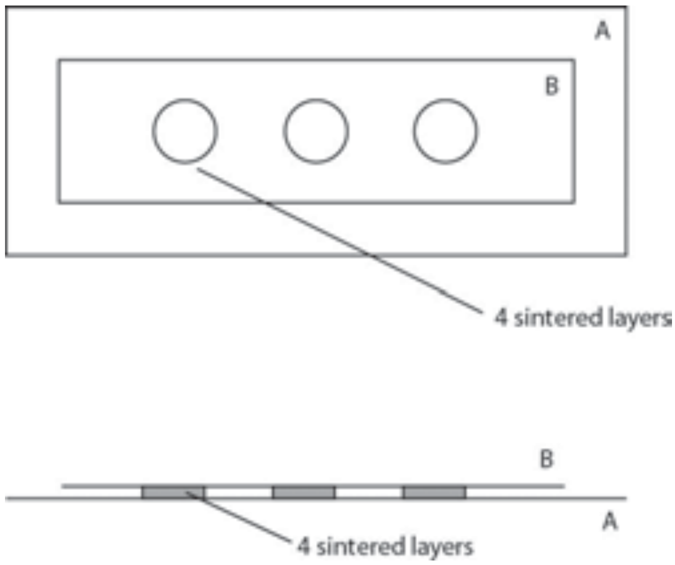


Figure 285: Diagram showing a sintered textile structure (top) and cross section (bottom). A and B are layers of paper nylon

Options a and c were successful in welding the second layer of fabric to the sintered polymer. See Figure 286 - Figure 288. The additional powder in option c protected the second layer of fabric so that it remained intact. In option a, the laser both welded the two layers together and cut the paper nylon so that the resultant structure resembled circular pools with lids. Insufficient heat from the laser beam was able to penetrate the fabric to weld the additional powder in option b.

Figure 286: Three- dimensional sintered structure, polyamide powder, paper nylon top and bottom, 10mm circle 4 layers, option a.

The resultant structures were fragile however and the welded sections could be pulled apart without excessive pressure. Using these specific materials, paper nylon and polyamide or embossing powders, laser sintering does not offer an alternative to stitch in terms of strength. However if the process were to be perfected and alternative materials were used for sintering, it may be possible. As laser processing offers a noncontact process with flexibility of design in three-dimensions, further research into other materials may be beneficial particularly for medical applications. As discussed in the contextual review, alternative joining processes such as stitch or ultrasonic welding come into contact with the materials being processed.

It was also felt that the strength of the weld would be increased if the fabric layers were held under pressure whilst processing was taking place. This would ensure that all materials are in contact at the interface during laser processing. Further research is required to determine a mechanism to do this.

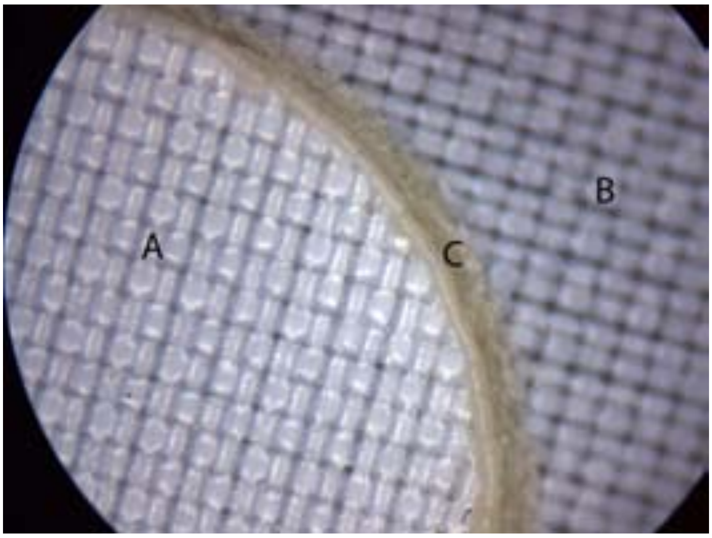


Figure 287: Two layers A (top) and B (bottom) joined by sintered weld (C), option c, top view

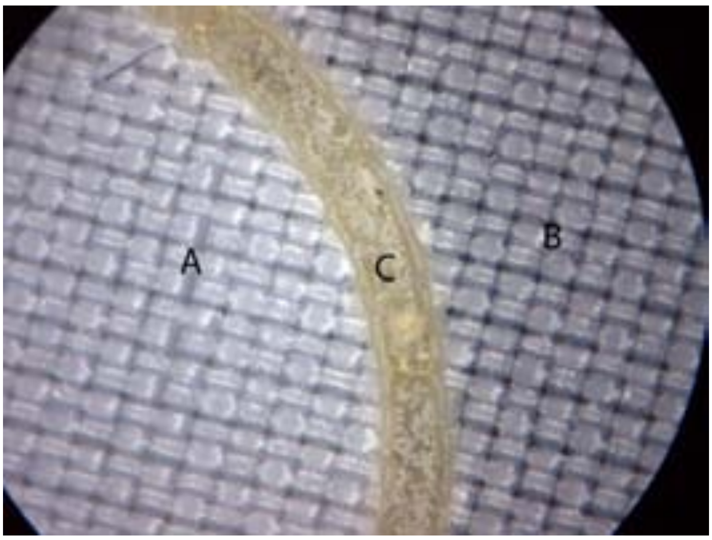


Figure 288: Two layers A (top) and B (bottom) joined by sintered weld (C), underneath view.

7.3.2 Structures using one layer of fabric

Several experiments were conducted to try and determine whether a smooth surface could be sintered from closely spaced adjacent tracks. Design opportunities may be provided if it were possible to sinter larger areas than single lines. Tests were conducted both with polyamide powder and embossing powder. Power and speed settings were kept consistent – 2.8W with speeds of 6mm/s for polyamide powder and 9mm/s for embossing powder. Layer thicknesses were 0.25mm, 0.4mm, 0.6mm, 0.9mm. Track spacing was varied – 0.25mm, 0.5mm, 1mm, 1.5mm, 2mm for polyamide powder and 0.6mm, 0.65mm, 0.7mm, 0.75mm, 0.8mm, 1mm for embossing powders. See Figure 289. Tests with polyamide powder were unsuccessful. Individual lines sintered successfully but it was not possible to fuse adjacent tracks without degrading the fabric or adjacent tracks through application of too much heat. Better results were achieved with the embossing powder. In all cases however, the results were ridged as the layers built up and it was not possible to achieve a smooth surface.

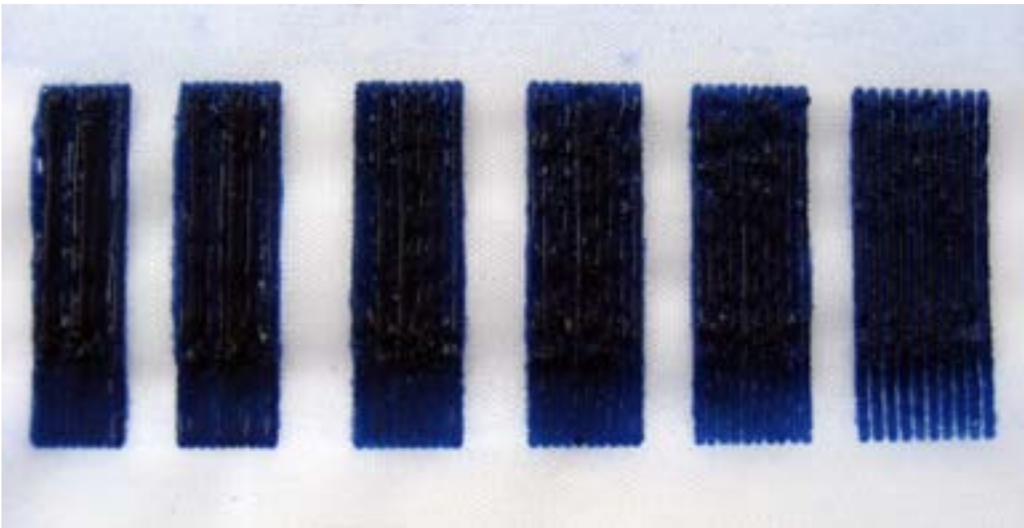


Figure 289: Sample B7, blue embossing powder on paper nylon. Tracks spaced 0.6mm, 0.65mm, 0.7mm, 0.75mm, 0.8mm, 1.0mm, 4 Layers

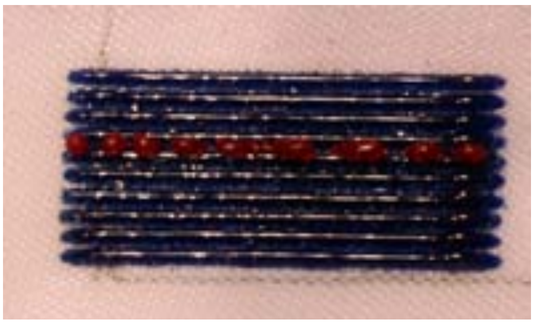


Figure 290: Sample B8. 2.8W, 10mm/s. tracks 1mm apart. Layers 0.25, 0.4, 0.6, 0.9 Blue, 1mm red

The red powder in sample B8 (Figure 290), the fifth layer, does not have an even appearance. Sample B9 (Figure 291) shows an improved surface achieved by passing the laser beam twice, once again on the fourth layer before the application of red powder, and once after. When processing this line, it was off set by 0.5mm so that the red track would fall between the ridges of two blue tracks.

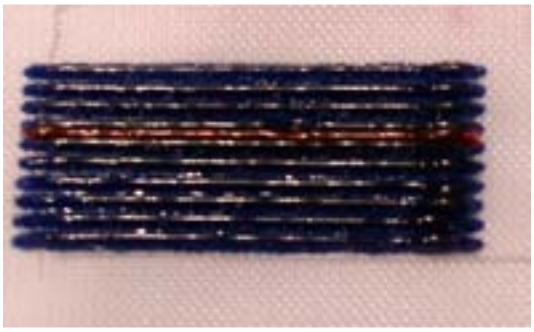


Figure 291: Sample B9. 2.8W, 10mm/s layer 1, 9mm/s layers 2-6. tracks 1mm apart. Layers 0.25, 0.4, 0.6, 0.9 blue, 1mm red

A four-layer sample with embossing powder was also produced with layers 2 and 4 at right angles to layers 1 and 3. This did not produce a smoother surface. See Figure 292 and Figure 293.

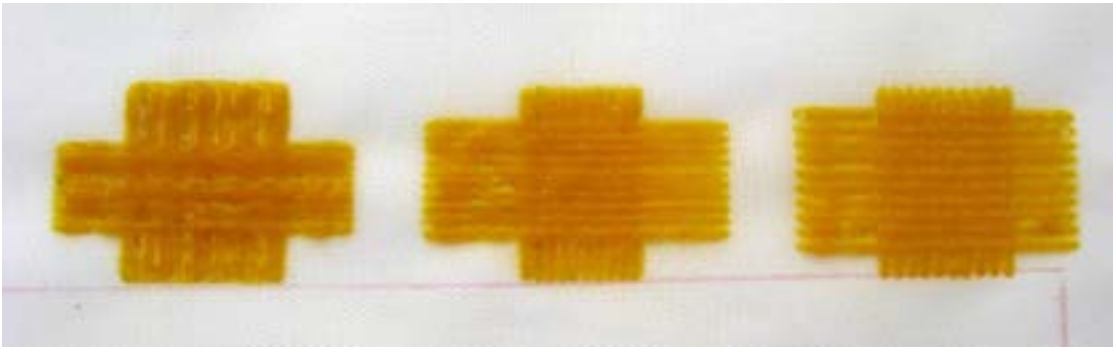


Figure 292: Yellow embossing powders on paper nylon, tracks 0.6mm, 0.8mm and 1mm apart, layers 0.25mm horizontal, 0.4mm vertical, 0.6mm horizontal, 0.9mm vertical

It is not considered that the sintering of tracks close together is a viable method of producing a flat solid area with the equipment used for these experiments. The use of adjacent tracks and layers of different colours however, may be useful from a design point of view for surface decoration and to selectively add rigidity to areas of a textile and it would be possible to use purpose designed SLS equipment for further investigation.

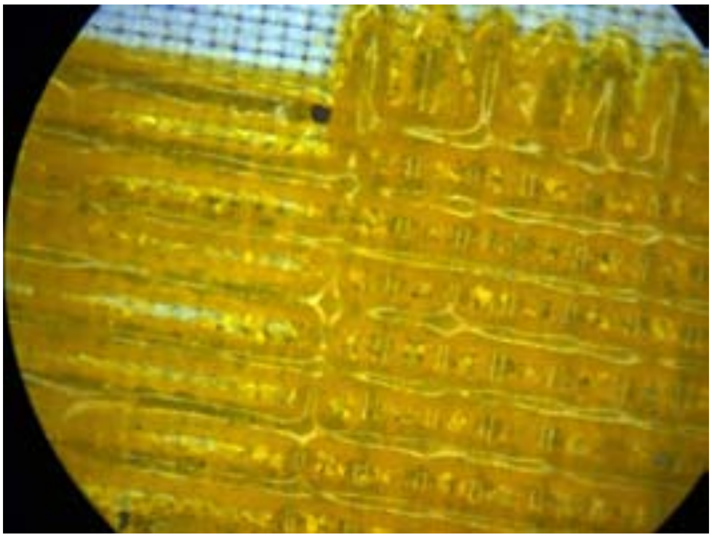


Figure 293:Yellow embossing powders sintered on paper nylon (detail of 1mm tracks in previous image), alternate layers of tracks at right angles, detail. Ridged surface may be seen

7.4 Sintering on manufactured and natural fibre substrates

All the experiments described to date used paper nylon as the textile substrate. This section discusses tests that were conducted to determine if the process would be viable on other manufactured fabrics including textiles made from natural fibres.

Several four-layer samples were produced with embossing powders. The following settings were used

- Power 2.8W,
- Speed 9mm/s,
- Layers heights - 0.25mm, 0.4mm, 0.6mm, 0.9mm

A range of textiles substrates were used namely nylon organza, nylon chiffon, polyester, cotton, linen and silk dupion. See Figure 294 - Figure 299. As may be seen from these images, the method works well on a variety of fabric fibre types and weights. All appeared to fuse successfully without degrading the textile substrate, which suggests that it is possible to laser sinter embossing powders onto a range of fabrics of various densities constructed from both manufactured and natural fibres. Natural fibre fabrics did not melt and fuse with the embossing powder. It would appear that the powders melted and reformed around the warp and weft yarns. (See Figure 294, Figure 297 and Figure 298) Further testing is required to inspect the integrity of these welds.

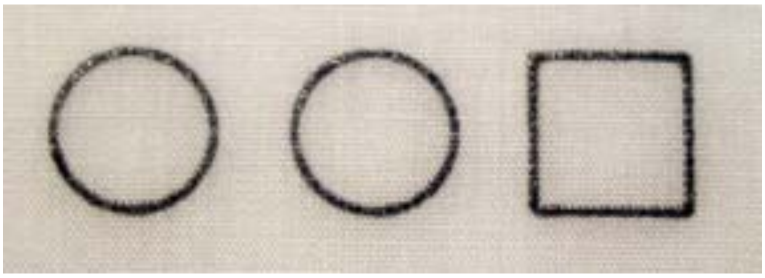


Figure 294: Linen substrate, blue embossing powder, 2.8W, 9mm/s, underneath views showing leaching of melted powder.

Figure 295: Sintered blue embossing powder on nylon chiffon, detail (underneath view)

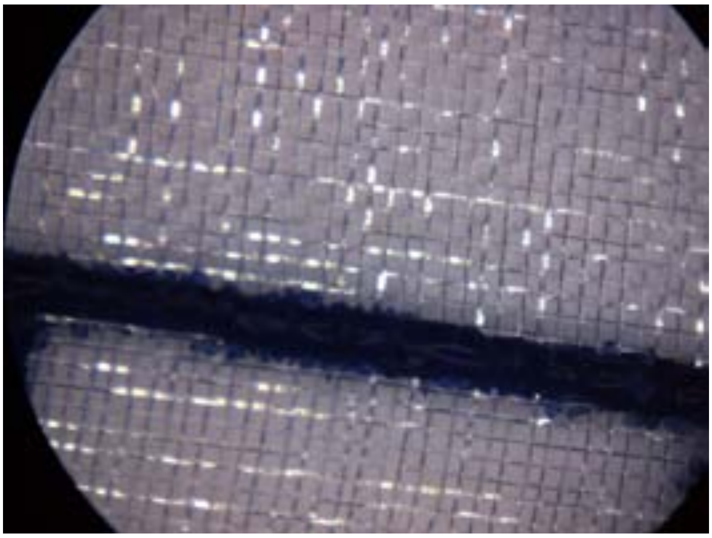


Figure 296: Sintered blue embossing powder on nylon organza, detail (underneath view)

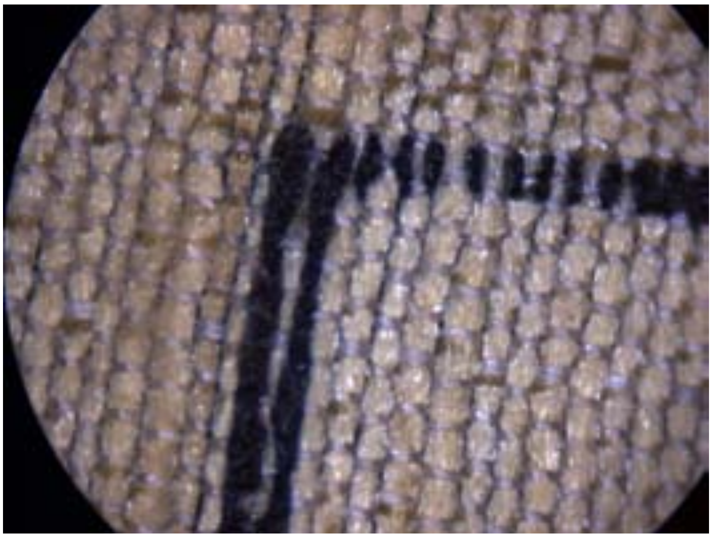


Figure 297: Sintered blue embossing powder on silk dupion, detail (underneath view)

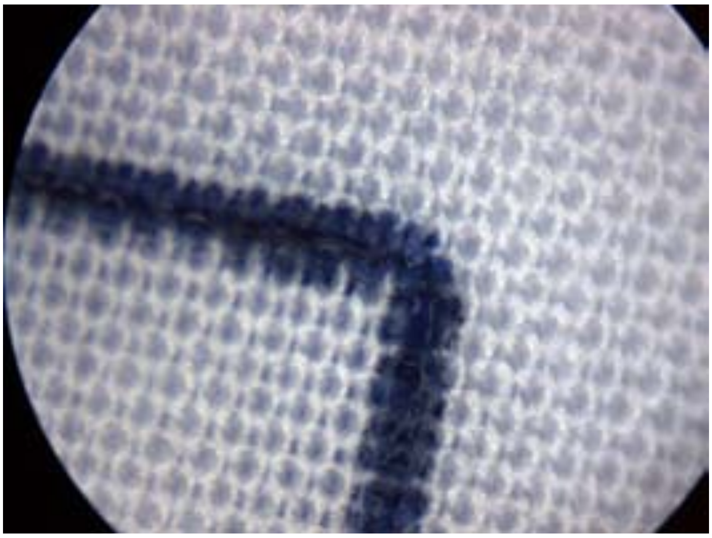


Figure 298: Sintered blue embossing powder on cotton, detail (underneath view)

Figure 299: Sintered blue embossing powder on polyester, detail (underneath view)

7.4.1.1.1 *Sintering onto a dissolvable substrate*

Two tests were conducted to determine whether it would be possible to use a dissolvable substrate. The motivation for this was to explore whether firstly, solid forms could be made by supporting the initial layers on a textile substrate and secondly, the creation of lace like borders with the structure partially supported on fabric. The substrate used was a cold-water dissolvable non-woven, Anchor Aquatics Aquasol manufactured by Coats Crafts UK, which has the appearance of interfacing. (Coates Craft UK, 2011) The first test sintered four layers of embossing powder using an interlocking circle design. See Figure 300 - Figure 302. The settings used were 2.8W with a speed of 20mm/s for the first layer and 9mm/s for subsequent layers. The faster processing speed for the first layer was necessary as a speed of 9mm/s applied too much energy to the fabric and caused it to burn. Layer heights were as described previously.

Figure 300: Blue embossing powder sintered onto Aquasol prior to being dissolved, detail

Figure 301: Blue embossing powder sintered onto Aquasol which has been dissolved

Figure 302: Blue embossing powder sintered onto Aquasol which has been dissolved. Unmelted grains of powder may be seen attached to the sintered forms, giving a rough surface

The second test used the same design and parameters but overlapped the dissolvable fabric with paper nylon. See Figure 303. The Aquasol was dissolved and a lace effect achieved. This shows that it would be possible to create lace or borders using this method. Another application would be to use this method to fuse fabrics of different types. Research would be required to match the processing parameters for the first sintered layer to each fabric such that there was no degradation of the textile substrate. It would be possible to laser mark the first layer in two sections, each with different processing parameters. Subsequent layers would have processing parameters determined by the powders being sintered.

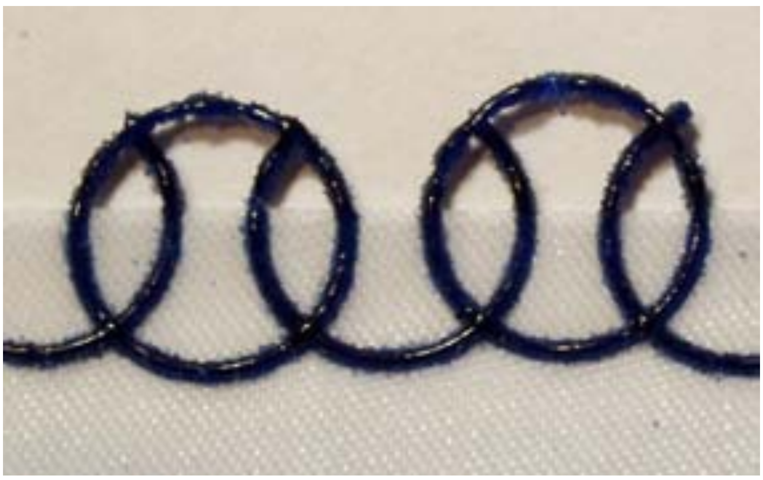


Figure 303: Blue embossing powder sintered onto paper nylon (bottom) and Aquasol, which has been dissolved (top)

7.5 Sintering and cutting

Chapter 3 showed that laser processing may be used to cut fabrics. This experiment demonstrates that there is the potential for laser sintering to be combined with cutting to produce a design similar to broderie anglais, a cotton fabric often used as a lace trim with machine embroidered designs that include small holes with stitching around the edge of the holes. It was envisaged that this could be used as an alternative to stitched embellishment.

A design was produced that consisted of 2mm diameter circles, some of which were to be cut out. Fabric used was 100% cotton with black embossing powders. A layer of powder was spread (0.25mm) and the holes to be cut processed with a power setting of 10W and speed of 200mm/s. The same layer was processed again with a power setting of 2.8W and a speed of 9mm/s to mark the non-cut out circles. Another layer of powder was applied (0.4mm) and processed. The resultant design may be seen in Figure 304 - Figure 307

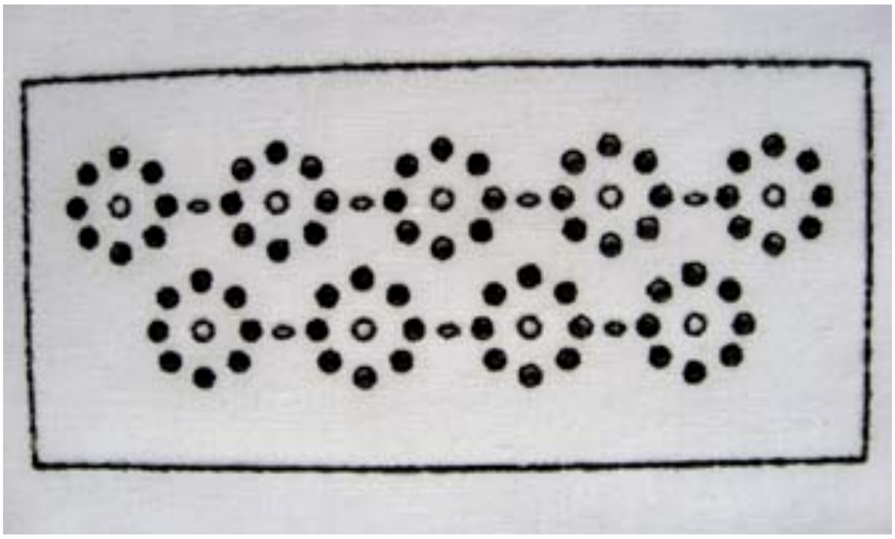


Figure 304: Black embossing powders on cotton, box 40mm x 86mm, 2 layers

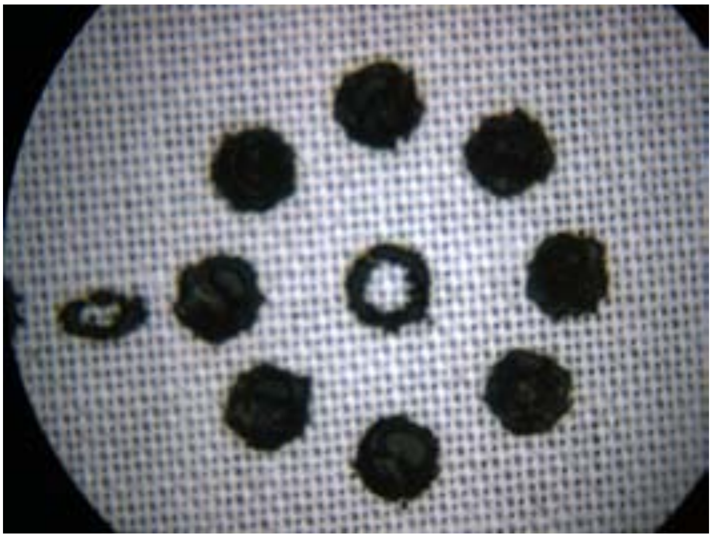


Figure 305: Black embossing powder sintered on cotton, front view showing cut holes and sintered circular shapes (detail, top view)

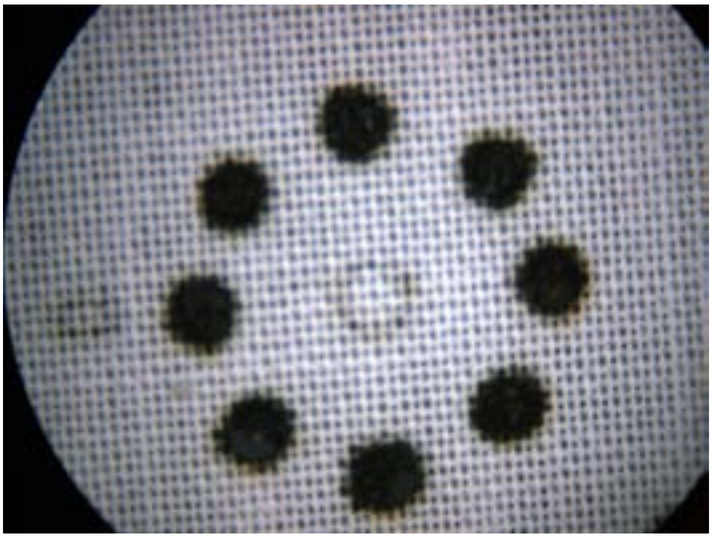


Figure 306: Black embossing powder sintered on cotton, front view showing cut holes and sintered circular shapes (detail, underneath view)

Figure 307: Cut holes sintered with black embossing powder and partially filled

As may be seen from the images, the cut out holes have been sealed by the embossing powder. Where sufficient powder was applied, the holes have been filled with fused powder. Figure 307 shows two magnified holes that have been partially filled. The three-dimensional design may be discerned by touch and has the appearance of broderie anglais.

7.6 Conclusion

This chapter has shown that a three-dimensional surface may be achieved on a textile substrate through the laser sintering of polymer powders. In conclusion, the following observations may be made:

- Textile substrates may be fabricated from natural or manufactured fibres, both woven and nonwoven. The research did not investigate the process on knitted fabrics. The weld on a manufactured fibre is formed when both materials melt and solidify together. On a natural fibre, the weld is due to the powders melting and reforming around the warp and weft yarns. In this case, some of the sintered materials are absorbed into the yarn and leech to the back of the fabric.
- The process works well on fabrics with a range of densities. Very loosely woven fabrics were not used.
- Both traditional sintering powders (polyamide) and other polymer powders may be used. Further research into powders for this process is required. Conductive powders may allow the process to have application in smart textiles.
- Whilst the sintered polyamide is brittle, the sintered embossing powder is more flexible and allows the fabric to move with some flexibility. Further research is needed to determine the optimum composition of powders including particle size, which when sintered, have similar drape qualities to the textile substrate.
- Alternatively, it may be desirable to use this process to add areas of rigidity to a textile substrate. Further research is needed to explore these possibilities.
- Processing parameters, power and speed of the laser, need to be configured such that the laser facilitates the bonding of the first layer without thermally degrading the textile substrate. Processing parameters for subsequent layers should be set such that powder welds to a previously sintered layer.

- Further research is needed to determine optimum layer thicknesses. It may be necessary to apply a thicker first layer to protect the textile substrate from thermal degradation. The thickness of subsequent layers will be determined by the properties of the powders being sintered.
- Further research is required to determine alternative methods of powder application. From a design point of view, it may be advantageous to use alternative methods to spreading. Loose unsintered powders become ingrained in the textile substrate causing staining and it is difficult to apply a variety of colours simultaneously. Other methods to explore could be the deposit of powder in advance of the beam. Alternatively, powders could be applied as a film or combined with a solvent as a paste.
- The distance between the laser and the work piece was set to the correct focal height for the lens at the start of a series of tests. This was not readjusted after each layer. As additional layers are sintered, the work piece grew in height and it is likely that the beam was no longer in focus. With an alternative experimental setup, it would be possible to move the work bed with the correct resolution for each fused or melted layer. Further research would be required to ascertain whether focal height is material on subsequent layers and whether the integrity of sintering welds had been compromised.
- Designs suitable for this process may comprise both lines and holes. Such designs would be created in CAD enabling design freedom. Further research is needed to achieve smooth surfaces over large areas of sintered material as this was not successful. It may be possible to achieve better results by reducing layer thickness and offsetting sintering lines. If this were successful, more layers would be required.

Progress has been made in developing a novel process by sintering directly on a textile substrate. It is clear however that the process would benefit from further research including material characteristics of powders and methods of powder application.

8 Discussion

This chapter reflects and comments on issues concerning and resulting from conducting this research.

During the course of this research, three different approaches or models of research were adopted to develop new processes. Each approach proved to be successful in generating novelty and it is useful to consider them in turn.

Firstly, for laser assisted template pleating, a traditional textile technique was investigated in detail through a literature review and an experimental replication of techniques. This allowed the existing pleating techniques to be understood in depth, limitations to be recognised and opportunities to be identified. Having developed the new process, it was extended in two ways - though the application of a variety of traditional and new materials; and through design ideas borrowed from a different but similar area, paper folding. This research model would be familiar to a researcher with a design background as the first stage of the research is effectively design research, taught at undergraduate level. It would be possible to apply this model to investigate a variety of textile techniques, developing and extending processes in the light of developments in materials and technologies.

A second model was employed for the development of laser pre-processing of woven textiles. This research started with a focus on mitigating the negative effects of a technology – what it cannot do or does not do well, in this case the laser processing of natural fibres. Experimentation, asking ‘what if’, seeing what did happen, led to the conception of a new process. The approach necessitates developing a thorough and in depth understanding of both the chosen technology and the material behaviours. Essential elements of this model of research are a cross-disciplinary team and a dialogue, which allows the ‘unexpected’ to be noticed, identified and explained. ‘What if’ questions may then be explored which lead to opportunity.

The third model, used for laser sintering of textiles, was more akin to traditional scientific research but favours a researcher who is an outsider to the discipline. The approach is initiated by asking a ‘fuzzy’ question, considering something that in normal circumstances would not be considered - in this case why not introduce a material (textiles) that has not been employed before. Again a cross-disciplinary team is desirable to provide insight into technologies and materials.

In order to progress any of these models of research and achieve meaningful results, it is essential that all experiments be conducted with scientific rigour. As well as results, reflections before, during and after must be recorded and discussed. The dialogue with colleagues from many disciplines, both in the supervisory team and elsewhere, is particularly important as the researcher may not always appreciate the significance of the observations that are made, particularly early on in the research whilst knowledge and understanding of other disciplines is being acquired.

Each of these approaches or models has led to the successful development of a novel process. It is unlikely however that this research would have been possible without input from all the various disciplines involved. An essential element was the cross-disciplinary dialogue, which developed over time and was not without its challenges. For example, it was evident that between the various disciplines there were different working practices, different research methods, a different working vocabulary, different assumptions about prior knowledge and experience and preconceptions. It was important to establish a common ground, credibility, and nurture a culture where no question or observation was 'silly'. Indeed it became apparent that it was in this space that opportunity arose. This project was very successful in this area and it is fair to say that there was a mutual exchange of ideas, which proved beneficial to all those involved. Crucial to the development of the dialogue was the establishment of a common vocabulary and a language to describe the research. This was a key driver for looking for methods of visual communication such as origami, which in turn proved beneficial to design aspects of the research

The project concludes with three novel processes in different stages of commercial readiness. The least advanced in this sense is the laser sintering of textiles. Outcomes here may be considered proof of concept and the process would need to be studied much further both in terms of techniques and materials, to become commercially viable. Designing to illustrate the process possibilities would be a second stage. Laser pre-processing of natural fibres was conducted with input from a commercial partner but still requires an additional phase of integration into the existing manufacturing cycle. The current economic climate is preventing this from occurring at this point with this partner. Laser assisted template pleating has been developed to the stage where it could be adopted by designers for the commercial production of designs. Some exploratory meetings have been held with a view to commercialising the process but it is evident that a portfolio of working designs to demonstrate the scope of the process is required.

This research has been fruitful both in terms of outcomes and starting points for further work. A model of cross-disciplinary research involving the School of the Arts and the Wolfson School of Mechanical and Manufacturing Engineering and including other departments such as Chemistry and Materials has been established. An issue in moving forward is funding under the current economic constraints. It remains to be seen whether future bids for cross-disciplinary research of this nature will be successful.

9 Conclusion

Through a focus on historical and contemporary textile manufacturing techniques and cross disciplinary investigation, knowledge has been advanced through the development of three new processes employing laser processing for the creation of three-dimensional textiles.

Knowledge of the opportunities and limitations of the pleating process was gained through thoroughly investigating traditional and contemporary pleating. This led to the development of a novel process, laser assisted template pleating, which has application for fashion and interiors and in other areas such as architecture and medical textiles. Laser assisted template pleating employs laser processing to produce templates, which are in turn used to pleat textiles. The new process offers novelty in the following areas:

- Design freedom. Unlike existing methods for pleating, this process allows pleats to be positioned only where they are required, for example, on a printed design or precisely aligned with cuts. A variety of fold types may be used including areas of no pleating combined with pleats of different scales.
- Designs for templates are produced in CAD. This allows visualisation, flexibility and ease of design development. Design elements may be modelled, combined, rescaled and tested with ease. There is the potential to link design for this process to digital design systems such that folds may be visualised and the cutting templates reverse engineered.
- This research has shown that origami design may be used to provide design inspiration for laser assisted template pleating. These techniques offer potential for further design development. Computer aided origami design systems such as those being developed by Lang may be used for the generation of laser assisted pleating designs.
- Three categories of design that may be used with laser assisted template pleating have been developed, explained and illustrated with examples namely cuts at an angle to folds, cuts on folds and folds with no cuts. These are by no means exhaustive and future work has indicated areas, which offer opportunity.
- An issue was the communication of design categories. This research has shown how origami symbols may be used as a language to describe designs

that have been developed. This technique is important as it shows that the work produced here is communicable.

- Where a design includes cuts, the same design may be used both for laser cutting fabric and the production of pleating templates reducing work. In addition, the new process offers advantage as existing pleating systems are not able to pleat fabric that contains cuts. Laser assisted template pleating is able to achieve this.
- Where laser assisted pleating is being employed to fold fabric, templates made from stiff paper or card may be reused on a number of occasions reducing work.
- The research has applied laser assisted template pleating to several different materials including fabrics made from natural and manufactured fibres, metals and carbon fibre composites. This work offers a new process to form resin impregnated carbon fibre structures without the use of costly moulds.
- Carbon fibre pleating has been shown to be scalable from small structures to those suitable for buildings and boat building. Unlike existing methods of manufacture, rigid moulds are not required. The use of a flexible membrane such as paper allows re-entrant folding facilitating shapes that may not be achieved with rigid materials. Pre-folded pre-preg composite structures may be rapidly deployed as temporary buildings.

In addition this research has contributed to new knowledge through developing prototypes for two new machines that could be used to pleat textiles with dissimilar folds:

- A pleating machine with levers that automated a manual process of pleating previously cut fabric. It enabled folds to be placed in precise positions at right angles to and at the base of cuts.
- A pleating machine that enabled structured pleats to be inserted parallel to the length of fabric by passing the fabric through a series of shaped slots which encourage the fabric to fold according to a pre-specified design. The series of shaped slots were removable and offered the possibility of design freedom in the direction of the folds.
- Both machines had the potential to be automated.

Laser pre-processing of natural fibres for example cashmere is the second novel process that has been developed. Laser processing of natural fibres has limitations due to the side effects of the process such as charring and odours. This new process overcomes this and offers a method of generating three-dimensional surface patterning with innovation in the following areas:

- Laser pre-processing of cashmere employs laser processing earlier in the manufacturing cycle predominantly on loom-state fabrics. The post-laser processing finishing both develops three-dimensionality and removes the by-products such as charring debris and odours.
- One aspect of the new process uses laser cutting to process fabrics to a pre-determined design pre-finishing. This research has shown that the position, size and shape of cuts in combination with the weave structure of fabric will generate a three-dimensional surface patterning. It has also demonstrated that warp and weft yarn colours play a design role.
- A second aspect of the process employs laser etching to colour the surface of a pale coloured natural textile to a pre-determined design pre-finishing. Whilst laser etching of denim is not novel, novelty is achieved here by employing laser etching prior to finishing so that the colour generated through processing becomes an integral part of the cloth enabling selective patterning.
- A third aspect of this process employs laser etching to remove the pile of previously finished cashmere fabrics woven with certain fabric structures. Post processing reveals both three-dimensionality and colour changes and removes processing debris and odour.
- A fourth aspect of this process uses laser etching and laser cutting to selectively remove parts of a layer from certain multi-cloth constructions. Innovative fabrics may be engineered to take advantage of this process.
- Design creation and development for all the laser interventions may be facilitated with CAD allowing for design freedom, flexibility and ease of development.
- This research demonstrated that this process could represent an alternative to devoré on certain fabric constructions made from natural fibres such as silk avoiding need to use potent chemicals. This could represent an innovative more ecologically acceptable development.
- Opportunity may be offered through engineering a fabric with specific fibres, yarns, densities and constructions that will respond to this novel process.
- The process may be able to be applied to other natural fibres with high shrinkage such as wool and to other fabric constructions such as warp knitting or non-wovens. All of these represent high volume textile markets and, if successful, would offer considerable opportunity.

The third novel process to which this research has contributed employs lasers for additive manufacturing techniques to apply polymer powders directly on textile substrates. This research showed that:

- Polymer powders may be applied to both natural and manufactured fibre substrates in such a way that a physical and/or chemical bond was formed between the polymer and the fabric.
- Application of subsequent layers enabled the formation of three-dimensional surfaces.
- The process may be used to form textile structures consisting of two layers of textiles with polymer layers in between. This represents an alternative to stitch for joining two textile layers.
- The process offers the potential for direct application of polymer structures on textile such as fasteners or to add rigidity in areas for body armour, for example. The use of conductive polymers has application in smart textiles.
- The process may be combined with laser cutting to create designs similar in appearance to *broderie anglaise*
- Dissolvable non-woven textile substrates may be used to form polymer structures. In combination with textile layers, a lace-like border may be applied to a textile selvedge.
- Design creation and development for this process may be facilitated with CAD allowing for flexibility and ease of development.
- Polymer powders are available in a variety of colours so multi-coloured designs may be produced offering an alternative to printed designs.

The operation of laser systems with textile materials is not well documented for textile designers and there is evidence that much design work is based on trial and error and 'happy accidents' that may not be able to be replicated. Indeed there are few formal opportunities for knowledge of a technology such as laser processing to be acquired at present in any other way. The subject specific language barriers that exist between designers, researchers and technicians from different disciplines exacerbate this situation. Through a practical demonstration of the methodology outlined in Chapter 3, a model for collaborative research for designers using technologies has been illustrated. This research has shown the advantage that may be gained from an iterative systematic approach that questions intelligently, records outcomes and accepts that 'not knowing' is an opportunity to be pursued.

More specifically, this research has documented a method for experimenting with materials and recording the outcomes. The method explains how to modify processing parameters for use on other laser systems and with other materials. It is hoped that through this, other designers may be in a position to move knowledge forward rather than constantly re-inventing the wheel.

It would also be advantageous to link the teaching of these methods to art and design technology curriculum in schools, where the equipment is available, and at undergraduate level. An understanding of laser processing and material behaviours would be beneficial.

This research has demonstrated that innovation that may be achieved through a thorough investigation of processes - traditional, contemporary and experimental – together with the application of a new technology in this case, pleating and lasers. It has shown that opportunity may be gained through breaking down a process into its component parts and intervening earlier in the process – here laser cutting and laser etching of woven cashmere. The research has highlighted the advantage that may be gained through revisiting a technology with traditional materials – additive manufacturing and traditional textile fabrics. These three approaches have resulted in the development of three new processes, which have application in several industries. In addition several opportunities have been identified to continue the research described in the following chapter.

10 Further Work

This chapter discusses opportunities areas for further research for each of the three novel processes.

10.1 Laser assisted template pleating

The laser assisted template pleating process has been developed to insert pleats and folds in textiles and other materials using paper of stiff card templates. The process has the potential to be developed further in the following areas:

10.1.1 Materials for templates

Paper or card templates are a low cost option and may be reused on a number of occasions. Research could be conducted into paper weight and composition, for example, coated papers that may extend the lifetime of the templates particularly on fold edges where repeated bending causes tearing. It was not possible to reuse the templates when resin pre-impregnated carbon fibre composites are pleated as the protective film covering the material bonded with the template during heat setting. Alternative template materials would offer advantage.

10.1.2 Designs

There is considerable scope for extending the range of designs for use with this process. To-date all designs investigated have employed parallel and straight-line folds. Research into design types that use curves and or folds at angles to each other would generate new three-dimensional surfaces and structures.

Experimenting with scale would also offer advantage. Designs at a very small scale would have application in the medical industry and those at a very large scale in architecture.

Another line of research would be to generate pleated designs where the two templates are matching but not identical. This would have application for generating three-dimensional structures or surfaces where one side is not the negative shape of the other.

The method employed here has been to generate designs manually with paper models and then to transfer the design modules into CAD (Adobe Illustrator) for development. A number of computer design systems exist for generating patterns for sheet metal folding, for example SolidEdge. These have the facility to visualise and move between the two-dimensional sheet and the three-dimensional folded object. An investigation showed these systems could not be applied here as the software restricts some types of fold designs, which are possible on paper and textile substrates due to the flexibility of the material but not on metal sheets. Research into modifying this type of software for designing templates would offer opportunity through the visualisation of the design and reverse engineering where a three-dimensional surface could be envisaged and the templates subsequently developed.

An investigation into the mathematics of folding, and folding in combination with cuts, may be able to promote new design research. The design families demonstrated to-date show that there are rules. As an example, some designs for three-dimensional surfaces are able to fold completely flat, whereas others will not. Some designs work on pliable surfaces but are less successful with rigid materials. A precise definition of the underlying mathematics may be able to be used in conjunction with CAD to model and reverse engineer three-dimensional surfaces as discussed above.

10.1.3 Mechanised folding

Templates used in this research have been manually folded. The process has been aided by the use of perforated fold lines, which are both easier to fold and indicate where and in which direction the fold should be made. An investigation into mechanised folding systems may offer advantage if multiple templates of the same design are required. If linked to software that enables designs to be visualised and templates to be produced, a considerable amount of time would be saved.

10.1.4 Printing and template pleating

This research has not conducted any investigations in to the use of dyeing or printing and template pleating. However in addition to pleating, the template offers potential as a vehicle for utilising transfer printing to apply colour to fabric. Research into printing directly onto paper or card to be used for templates before or after laser processing is necessary. Alternatively an investigation needs to be conducted into materials usually used for transfer printing to determine whether they are suitable for laser processing, folding and steaming to enable them to be used directly as templates.

10.1.5 Carbon fibre composites

This research has demonstrated that laser assisted template pleating may be used as a new process to form carbon fibre textiles without the use of traditional moulds which are expensive. Further research is necessary to determine optimum process parameters for the system to be used commercially.

Research here used resin pre-impregnated carbon fibre and the resin used in this research was cured by oven-baking. Other systems exist where curing occurs, for example, with UV light. Research into this if successful, would open up other opportunities. For example laser assisted template pleating could be used to form temporary structures, which would be cured by the sun and used for disaster relief.

10.2 Laser pre-processing of cashmere

Laser pre-processing of cashmere employs laser processing to cut or etch loom state woven cashmere. The finishing process generates a three-dimensional surface. Further research into this process would enable it to be developed commercially. The following areas are of interest:

10.2.1 Cloth

It has been shown that three-dimensional surface quality is affected by several factors - fabric structure, yarn, fibres, the way in which the fabric is laser pre-processed and the finishing treatments. Further research exploring fabric structures, fabric density, yarn types, yarn thickness, yarn twist, fibre length and fibre composition may yield other effects. Research here concentrated on cashmere fibres. Investigations into other natural fibres that shrink, particularly wool, would open up other possibilities as wool is sold in much higher volumes.

Research into double cloths demonstrated that the position of interlinking stitches affected the end result. Research into multi-cloth structures would enable layers to be removed from both sides revealing the inner structure and may provide another method for creating surface patterning through laser processing. Fabric integrity plays an important role so densely woven structures and or blends with manufactured fibres, are of interest for investigation.

All the research conducted here used woven fabric. Warp knitted fabrics are used extensively and due to their construction have little potential for three-dimensional surface patterning. Research into applying the results achieved here to warp knitted fabric offers huge potential.

10.2.2 Designs

This research demonstrated designs consisting of cut-out shape, dimension and spacing to generate three-dimensional surfaces. Advantage was gained from fabric structures and warp and weft yarn colour. Further research into other designs including scale and partially cutting yarn on both sides of the fabric is of interest.

10.2.3 Devoré

This research showed that laser etching of unbalanced twill structures may offer an alternative to devoré. The example demonstrated used a very finely woven silk. Further research into fabric structures and fibres that would enable this would be of great interest as it would offer a selective process that is ecologically more acceptable that one that employs chemicals.

10.3 Laser sintering of textiles

Laser sintering of textiles employed laser processing and additive manufacturing techniques to apply polymer powders to textile substrates. Further research into this process would focus on polymer selection. Opportunity arises if a flexible polymer may be used that is able to bend with the fabric substrate so that the textile retains its drape qualities, and alternatively the use of an appropriate material would selectively add rigidity to a textile, for example for body armour. Conductive polymers would enable the process to be used in conjunction with smart textiles.

Another area which would enable the application and development of this process, is an alternative method of powder deposition. A system that deposits the powder in front of the laser beam would not only facilitate the use of polymers of different types and colours within the same design but would reduce the quantity of powder used.

10.4 Conclusion

This chapter has shown areas where each of the three processes may be developed. Clearly for any one of them to become commercially viable, a portfolio of successful designs and collection of samples that that demonstrate aspects that show the potential of the process is necessary. Further work would also develop these sets of designs.

11 Appendix

Table 5 : Warp 1

Warp 1 – 2/28 snow cashmere, 2/2 Twill		**Marker picks (beginning/end)**
Sample	**Fibre and yarn**	
1/01	Snow cashmere	Red/red
1/02	2/30 75% wool, 25% nylon	Mustard yellow/mustard yellow
1/03	1/32 Wool, Angora and Nylon (percentage not known)	-/Purple
1/04a	monofilament	-/-
1/04b	Cashmere and monofilament, separate shuttles	-/pink
1/04c	Cashmere and monofilament, same shuttle	Pink/orange
1/05a	2/60 spun silk	-/-
1/05b	2/30 spun silk	-/yellow
1/05c	1/10 silk noil	Yellow/blue
1/06	Kevlar	-/red
1/06b	Nylon/polyester	Red/red
1/06c	D/2 pink viscose/rayon	Red/-
1/06d	Kriss 4% nylon, 96% acrylic	-/-
1/06d	Waste yarn	-/red

Table 6 : Warp 2

Warp 2 – 2/28 snow cashmere			
Sample	**Weft**	**Construction**	**Marker picks**
2/01	Snow cashmere	plain	Red
2/02	Snow cashmere	2/2 twill	Yellow
2/03	Caramac cashmere	1/3 weft faced twill	purple
2/04	Caramac cashmere	3/1 warp faced twill	Moss green
2/05	Caramac cashmere	plain	Turquoise/brown
2/06	Caramac cashmere	2/2 twill	Bright pink
2/07	Caramac cashmere Narrow bands of : • 80 denier mono filament • Acrylic chenille • Nylon/polyester mix • Pink wrapped elastics • 180 denier mono filament • Fibrous polyester/nylon	2/2 twill	Salmon pink
2/08	Ground snow, floats caramac cashmere	2/2 twill, floats bound in with two warps	Turquoise blue
2/09	Ground snow, floats caramac cashmere	2/2 twill, floats not bound in	Berry loop
2/10	Ground 2/60 silk, floats caramac cashmere	2/2 twill, floats bound in with two warps	Moss green
2/11	Ground caramac cashmere, floats fantasy silk	2/2 twill, floats bound in with one warp	Mint green

Table 7 : Warp 3

Warp 3 – 2/28 snow cashmere			
Sample	**weft**	**Construction**	**Marker picks**
3/01a	Snow cashmere	Plain Weave	Royal blue
3/01b	Snow cashmere	2/2 twill	Turquoise blue
3/01c	Snow cashmere	1/3 twill	Navy blue
3/01a	2/30 spun silk	1/3 twill	Mid green
3/02b	1/10 silk noil	1/3 twill	Mint green
3/02c	1/10 silk noil	2/2 twill	Dark bottle green
3/02d	2/30 spun silk	2/2 twill	Sea green mohair
3/03a	Snow cashmere	2/2 twill	Strong pink
3/01b	Snow cashmere	Plain weave with borders	Baby pink
3/03c	Snow cashmere	1/3 twill with borders	Cerise pink
3/04a	Snow/heron cashmere	Full float, 2 ground to one float	Red
3/04b	Snow/heron cashmere	Full float, 1 ground to one float	Aubergine red
3/04c	Snow/heron cashmere	Pinned float, 2 ground to one float	Plum red
3/04d	Snow/heron cashmere	Pinned float, 1 ground to one float	Burnt orange
3/05a	Snow/heron cashmere	2/2 twill snow borders	Canary yellow
3/05b	Heron cashmere	Plain weave borders	Mustard yellow
3/05c	Heron cashmere	Twill borders	Orange mohair
3/06a	Heron cashmere	2/2 twill	Purple mohair
3/06b	Heron cashmere	1/3 twill with borders	Lilac
3/06c	Snow cashmere	2/2 twill	Purple/pink
3/07	Snow cashmere	2/2 twill	Chocolate brown

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