DIMENSIONAL VARIATION ANALYSIS
OF DEFORMABLE ALUMINIUM INTENSIVE VEHICLE ASSEMBLIES

By

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ABSTRACT

The thesis concerns dimensional management and the provision of tools and techniques to assist designers and body engineers in the automotive industry with the tolerance specification and variation analysis of deformable aluminium-intensive-vehicle (AIV) assemblies.

This document includes a review of literature relevant to the main research goals of:-

- creating knowledge to enhance the tools and techniques available for the dimensional control of deformable automotive assemblies with a particular focus on the design and construction of aluminium body-in-white (BIW) structures.
- seeking ways of applying this knowledge in an expedient way during the early phases of the automotive product development cycle, and in the digital environment, to facilitate informed decision making where only limited and uncertain product and process data is available.

From the literature it has been determined that there is a lack of an efficient variation-modelling approach for deformable assemblies during the manufacture and assembly of lightweight aluminium vehicle body structures involving next generation alloys, manufacturing processes, and joining and assembly technologies. Existing tools for Computer-Aided Tolerancing (CAT) do not consider the non-rigid behaviour of deformable parts and this should not be ignored otherwise assembly process simulations using these tools can lead to predicted final assembly geometry which is considerably different from actual production assemblies.

CAT tools and techniques should have the capability to simulate assembly process variations for deformable assemblies. This should contribute to an improved and deeper understanding of the relationships between tolerance values and the physics of product functions and manufacturing processes.

An approach to modelling and analysing deformable assemblies, based on the method of influence coefficients and Finite Element Analysis (FEA), has been demonstrated using an industrial example of an aluminium vehicle assembly from the automotive industry. This shows that it is possible to consider the effects of part deformation in the variation analysis of automotive BIW assemblies.

The development and further enhancement of computer-aided tolerancing (CAT) tools with this capability will provide better support for tolerance specification and variation analysis during the early phases of the automotive product development cycle. The thesis concludes with a number of recommendations for areas of research warranting further investigation.

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1. INTRODUCTION

There is a lack of an efficient variation-modelling approach for flexible components during the manufacture and assembly of lightweight aluminium vehicle body structures involving next generation alloys, manufacturing processes, and joining and assembly technologies. This research aims to develop tools and techniques to assist the automotive industry in the production and assembly of compliant, non-ideal parts.

All manufactured parts and tooling have unavoidable variations from their nominal shapes. During assembly, relatively rigid assembly tooling further deforms compliant parts. A lack of knowledge regarding variations and deformations often results in expensive problems. Since most current computer-aided design systems and tolerance analysis software solutions are based on ideally located, and rigid geometry, they are unable to model or predict the effects of variations in parts or tooling to the required level of accuracy.

An approach to product modelling and variation analysis will be developed that accommodates the flexibility of parts and tooling to simulate the propagation of dimensional variations during assembly and joining processes; and to predict and manage these variations in the resulting assembly.

1.1 CONTEXT

Dimensional variation in today's automobile design and manufacturing development processes must be understood and managed. One of the key ways to successfully accomplish this is to use a tolerance analysis tool with the capabilities to encompass all types of known variations. Understanding and managing these variations as early as possible in the product development cycle allows engineers to produce a robust design solution which is both cost effective, and designed for manufacture to the optimum quality achievable.

In the automotive industry, controlling the assembly process for vehicle body shells is of critical importance. Managing variations is essential to retaining competitiveness in manufacturing because excessive variations directly affect product quality, time-to-market, and product development cost. For example, too-large or too-small gaps between the door and door aperture cause crucial problems such as high door closing effort, noise, and leaks as well as poor appearance of a vehicle. The required time and cost for resolving these problems increase exponentially as the product development process evolves. By the time parts and tooling are manufactured, the cost of scrapped, reworked or delayed assemblies becomes considerable. Therefore, methods to anticipate variations will have a major positive impact.

Typically, many concerns go unnoticed until early prototypes are built, measured, and tested. Many three-dimensional tools and techniques now have the technical capabilities to allow product designs to be optimised before problems occur in prototyping and production. With accelerated advancements in computing power and simulation tools not only helping to reduce vehicle engineering lead times but also increasing engineers confidence in getting the design right first time there is a growing trend for reducing the requirement for physical models and prototypes. This research will consider the development and design for dimensional control of vehicles in the digital environment or "digital factory", where zero or minimal prototypes are built and engineers not only determine that parts fit but can see how the vehicle functions, undertake full crash analyses and investigate such things as servicing needs. There is also growing importance given to the accuracy of computer models and whether these correlate with manufacturing processes in the real world.

A leading strategy in vehicle design and production is one that is based on reducing the mass of the car by the consistent use and optimum application of lightweight construction techniques. The aim of lightweight construction is to achieve a minimum construction weight, while simultaneously using all materials optimally. The growing use of aluminium in automotive engineering is rapidly increasing the experience base of the technologies involved, and hence the changes that will be integrated into assembly-production in the next few years will be concerned with the complete process concatenation of alloy production, via semi-finished product production and shaping through to mechanical processing and joint engineering in body shell construction. Joining technologies will have a decisive role to play in the competitiveness of aluminium body structures.

With the new generation of integrated CAD-CAE applications, there is an apparent lack of software tools that can simulate industrial processes such as part assembly by welding, bonding, riveting or bolting.

In particular for welded flexible parts, there is no efficient exhaustive computational aid for tolerancing and metrology available on the market. The assembly of structures consisting of parts that are subject to warping or distortion, in addition to dimensional variation, requires that assembly forces be considered. Finite Element Analysis (FEA) is a powerful numerical method used for deformation analysis of most engineering problems. By combining FEA with statistical tolerance analysis, the range of stress and distortion of assemblies can be estimated statistically and compared to design limits. However, there is still much needed research in this field and this research will examine the shortcomings of existing works. In particular, consideration will be given to the complex interactions among flexible parts, assembly tooling fixtures and joining processes to facilitate the increased awareness and understanding of the mechanics of variation in body construction.

1.2 AIMS & OBJECTIVES

The primary aim of this research is to create knowledge to enhance the tools and techniques available for the dimensional control of deformable automotive assemblies with a particular focus on the design and construction of aluminium body-in-white (BIW) structures.

Additionally this research will demonstrate an approach to applying appropriate knowledge in an expedient way during the early phases of the automotive product development cycle, and in the digital environment, to facilitate informed decision making where only limited and uncertain product and process data is available.

The above aims are addressed in the following objectives:-

- Determine and review the current state-of-the-art for dimensional management and variation analysis, to include analysis of deformable assemblies.
- Evaluate the application and utility of finite-element methods in the modelling and dimensional analysis of deformable assemblies.
- Utilise Dassault Systemes' CATIA Tolerance Analysis of Deformable Assemblies (TAA) to model the case of a suitable selection of aluminium vehicle components or a sub-set of an aluminium-intensive vehicle assembly; the objective of this work being to identify the limitations, if any, of assuming rigid body of motion in the analysis of dimensional variation in vehicle assembly processes; and highlight issues relating to the application of computer-aided tolerancing (CAT) tools in the automotive industry.
- Establish the capability requirements for tolerance analysis software and evaluate how CAT tools can be utilised in the early phases of the automotive product development cycle.
- Evaluate the use of the CATIA TAA software module as a tool for modelling the behaviours of steel and aluminium parts, assembly fixtures, and joining processes used in the production of state-of-the-art BIW structures.
- Propose, where necessary, additional functionality and enhanced performance for computer-aided tolerance analysis over and above that provided by software vendor solutions.
- Investigate the mechanics and the nature of product and process variations and their effect on the design, development, manufacture, assembly, and inspection of aluminium vehicle structures consisting of deformable parts.

2. LITERATURE REVIEW

The following chapter aims to give the reader an insight into the field of dimensional management and associated tools, and review the start-of-the-art for aluminium-intensive-vehicle production.

2.1 BODY ENGINEERING

Today's vehicle designers have to meet the needs of a market which is rapidly evolving on two fronts. Consumers expect and demand higher standards of safety, refinement, ride comfort, stability and handling, and comfort and convenience features. At the same time, new market segments have emerged and taken a significant share of sales, especially among higher-priced and more profitable vehicles: the MPV (multi-purpose vehicle), the RV (recreational vehicle) and the SUV (sport utility vehicle) being examples. The expanding markets of the developing world also demand that new product development meets their needs and aspirations, particularly in the realms of affordability and low-cost maintenance.

To achieve success, the vehicle engineer – and most of all, perhaps, the body design engineer – needs access to a wider range of technologies, and components with a higher technical content, than was previously considered normal. This trend is likely to continue. The proliferation of vehicle types, and the pressure they place on conventional production arrangements, has resulted in two highly significant trends: the evolution of more 'flexible' manufacturing facilities, and the adroit standardisation of large components in apparently dissimilar vehicles. The first of these trends has led to the serious study of off-line assembly of major 'modules' by first-tier suppliers, while the second has become the most evident in the 'platform' approach now adopted by all major manufacturers. Both of these trends are likely to continue, and to become 'standardised' in their pattern of application.

At the same time, the weight of legal requirements continues to increase. Beyond the established (and still evolving) imposition of passive safety and exhaust emission standards, likely new requirements include an insistence that a higher proportion of the vehicle mass shall be capable of life-end recycling.

2.1.1 CRAFTSMANSHIP

Craftsmanship practices are now underpinned in a number of vehicle engineering activities, through body engineering, integration, interior trim, seats and restraints, safety, body-in-white, and CAE disciplines, and their respective testing activities (Hazell, 2001).

Craftsmanship can be defined as perceived quality. Different customers have different wants and needs and so perceive things differently. Attributes of craftsmanship include: Appearance, Tactile, Auditory, Olfactory, and Function (precision and satisfaction). User-friendliness is underpinned by all these elements (Hazell, 2001). Additional elements of craftsmanship include ergonomics, surprise-delight features, trim size, colour matching, grain, and night-time illumination. In essence,

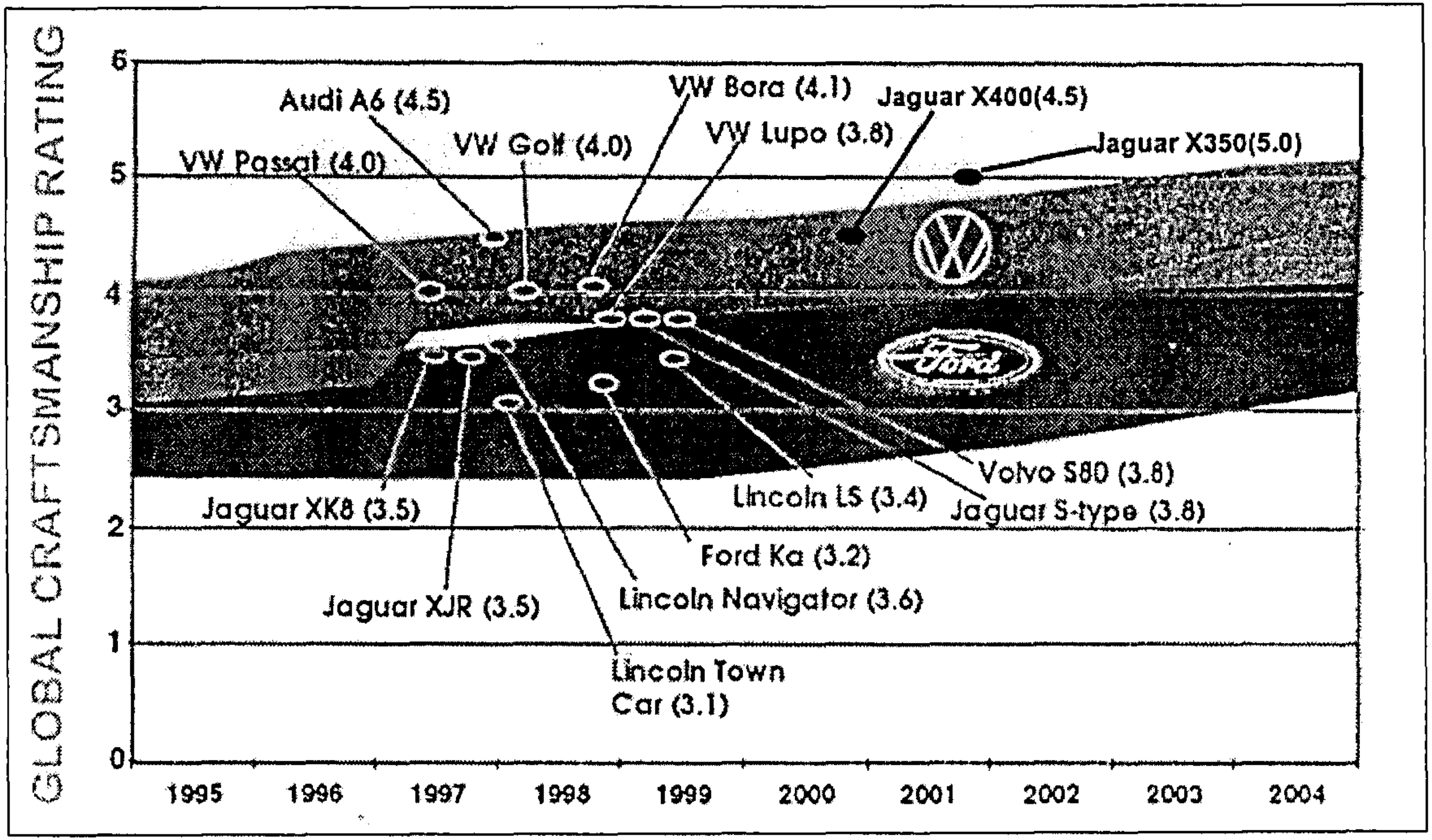


Figure 1: Market positions according to Global Craftsmanship Rating (Ford Intranet)

craftsmanship is really 'attention to detail in design and manufacture' in delivering these attributes into the product for customers.

Figure 1 shows the relative market positions of a number of vehicles derived from the Global Craftsmanship Rating System developed by Ford, and introduced in 2001.

At present, the new Skoda is perceived to have good craftsmanship. 'Best-in-class' is considered by many in the automotive industry to be Audi, Volvo, Seat and Skoda, although there are also Lexus, Mercedes and Porsche to consider.

Visual Quality	Sound Quality	Touch/Feel Quality	Smell Quality	Usability/ Ergonomics
Visual Expectation	Functional Sound Exp.	Touch Expectation	Smell Expectation	Findability
Visual Compatibility	Sound Compatibility	Functional Feel Exp.	Smell Compatibility	Accessibility
Fit		Touch / Feel Compatibility		Operability
Graphic Appearance				
Illumination Appearance				

Figure 2: Attributes of vehicle craftsmanship (Ford Intranet)

2.1.2 DIMENSIONAL MANAGEMENT

Dimensional management is a process by which the design, fabrication, and inspection of a product are systematically defined and monitored to meet predetermined dimensional quality goals. It is an engineering process that is combined with a set of tools that make it possible to understand and design for variation. Its purpose is to improve first-time quality, performance, service life, and associated costs. Dimensional management is sometimes called dimensional control, dimensional variation management or dimensional engineering (Hazell, 1998; Jeffreys, 1998; Leaney, 1996; and Moh, 1996).

2.1.2.1 Dimensional Management Systems

Inherent in the dimensional management process is the systematic implementation of dimensional management tools (Drake, 1999). A typical dimensional management system uses the following tools:

- Geometric dimensioning and tolerancing
- Key characteristics
- Statistical process control

- Variation measurement and reduction
- Variation simulation tolerance analysis

Geometric Dimensioning and Tolerancing (GD&T)

Geometric dimensioning and tolerancing is an international engineering drawing system that offers a practical method for specifying 3-D design dimensions and tolerances on an engineering drawing. Based on a universally accepted graphic language, as published in national and international standards, it improves communication, product design, and quality. Therefore, geometric dimensioning and tolerancing is accepted as the language of dimensional management and must be understood by all members of the product engineering group. Some of the advantages of using GD&T on engineering drawings and product data sheets are that it:

- Removes ambiguity by applying universally accepted symbols and syntax.
- Uses datums and datum systems to define dimensional requirements with respect to part interfaces.
- Specifies dimensions and related tolerances based on functional relationships.
- Expresses dimensional tolerance requirements using methods that decrease tolerance accumulation.
- Provides information that can be used to control tooling and assembly interfaces.

Key Characteristics

A key characteristic is a feature of an installation, assembly, or detail part with a dimensional variation having the greatest impact on fit, performance, or service life. The identification of key characteristics for a specific product is the responsibility of a product engineering group working very closely with the customer.

Key characteristic identification is a tool for facilitating assembly that will reduce variability within the specification limits. This can be accomplished by using key characteristics to identify features where variation from nominal is critical to fit and function between mating parts or assemblies. Those features identified as key characteristics are indicated on the product drawing and product data sheets using a unique symbol and some method of codification. Features designated as "key" undergo variation reduction efforts. However, key characteristic identification does not diminish the importance of other non-key features that still must comply with the quality requirements defined on the drawing.

The implementation of a key characteristic system has been shown to be most effective when the key characteristics are:

- Selected from interfacing control features and dimensions.
- Indicated on the drawings using a unique symbol.
- Established in a team environment.

- Few in number.
- Viewed as changeable over time.
- Measurable, preferably using variable data.
- Determined and documented using a standard method.

Statistical Process Control (SPC)

Statistical process control is a tool that uses statistical techniques and control charts to monitor a process output over time. Control charts are line graphs that are commonly used to identify sources of variation in a key characteristic or process. They can be used to reveal a problem, quantify the problem, help to solve the problem, and confirm that corrective action has eliminated the problem.

Variation Measurement and Reduction

After key characteristics have been defined and process and tooling plans have been developed, parts must be measured to verify conformance with their dimensional specifications. This measurement data must be collected and presented in a format that is concise and direct in order to identify actual part variation. Therefore, measurement plans and procedures must be able to meet the following criteria:

- The measurement system must provide real-time feedback.
- The measurement process should be simple, direct, and correct.
- Measurements must be consistent from part to part; detail to assembly, etc.
- Data must be taken from fixed measurement points.
- Measurements must be repeatable and reproducible.
- Measurement data display and storage must be readable, meaningful, and retrievable.

A continuous program of gauge and tooling verification and certification must also be integrated within the framework of the dimensional measurement plan. Gauge repeatability and reproducibility (GR&R) studies and reports must be a standard practice. Assembly tooling must be designed so that their locators are coordinated with the datums established on the product drawings and product data sheets. This will ensure that the proper fit and function between mating parts has been obtained. The actual location of these tooling points must then be periodically checked and validated to ensure that they have not moved and are not introducing errors into the product.

Variation Simulation Tolerance Analysis

Dimensional management tools have been successfully incorporated within commercial 3-D simulation software (Jeffreys, 1998; Leaney, 1996). The typical steps in performing a variation analysis using simulation software are listed below (see Figure 3):

Step 1: A conceptual design is created within an existing computer aided engineering (CAE) software program as a 3-D solid model.

Step 2: The functional features that are critical to fit and function for each component of an assembly are defined and relationships established using GD&T symbology and datum referencing.

Step 3: Dimensioning schemes are created in the CAE database and are verified and analysed by the simulation software for correctness to appropriate standards.

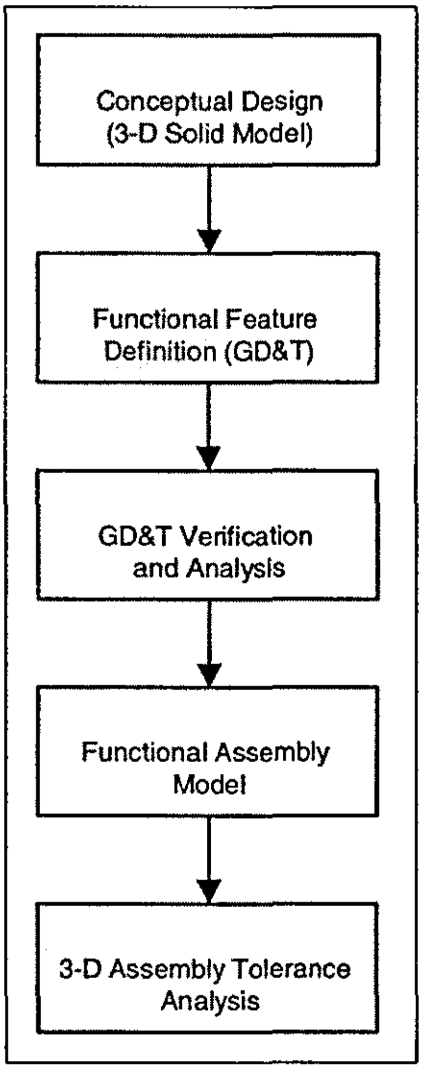


Figure 3: Variation analysis (Drake, 1999)

Step 4: Using information from the CAE database, a functional assembly model is mathematically defined and a definition of assembly sequence, methods, and measurements is created.

Step 5: Using the functional assembly model, a 3-D assembly tolerance analysis is statistically performed to identify, rank, and correct critical fit and functional relationships between the mating parts that make up the assembly.

The advantages of using simulation software are that it can be integrated directly with existing CAE software to provide a seamless communication tool from conceptual design to final assembly simulation without the expense of building traditional prototypes. The results also represent reality because the simulations are based on statistical concepts taking into account the relationship between functional requirements as well as the expected process and measurement capabilities.

2.1.2.2 The Dimensional Management Process

The dimensional management process can be divided into four general stages: concept, design, prototype, and production (Drake, 1999). These stages integrated with the various dimensional management tools can be represented by a flow diagram (see figure 4).

The key factor in the success of a dimensional management program is the commitment and support provided by upper management. Implementing and sustaining the dimensional management process requires a major investment in time, personnel, and money at the early stages of a design. If top management is not willing to make and sustain its commitment to the program throughout its life cycle, the program will fail. Therefore, no dimensional management program should begin until program directives from upper management clearly declare that sufficient personnel, budget, and other resources will be guaranteed throughout the duration of the project.

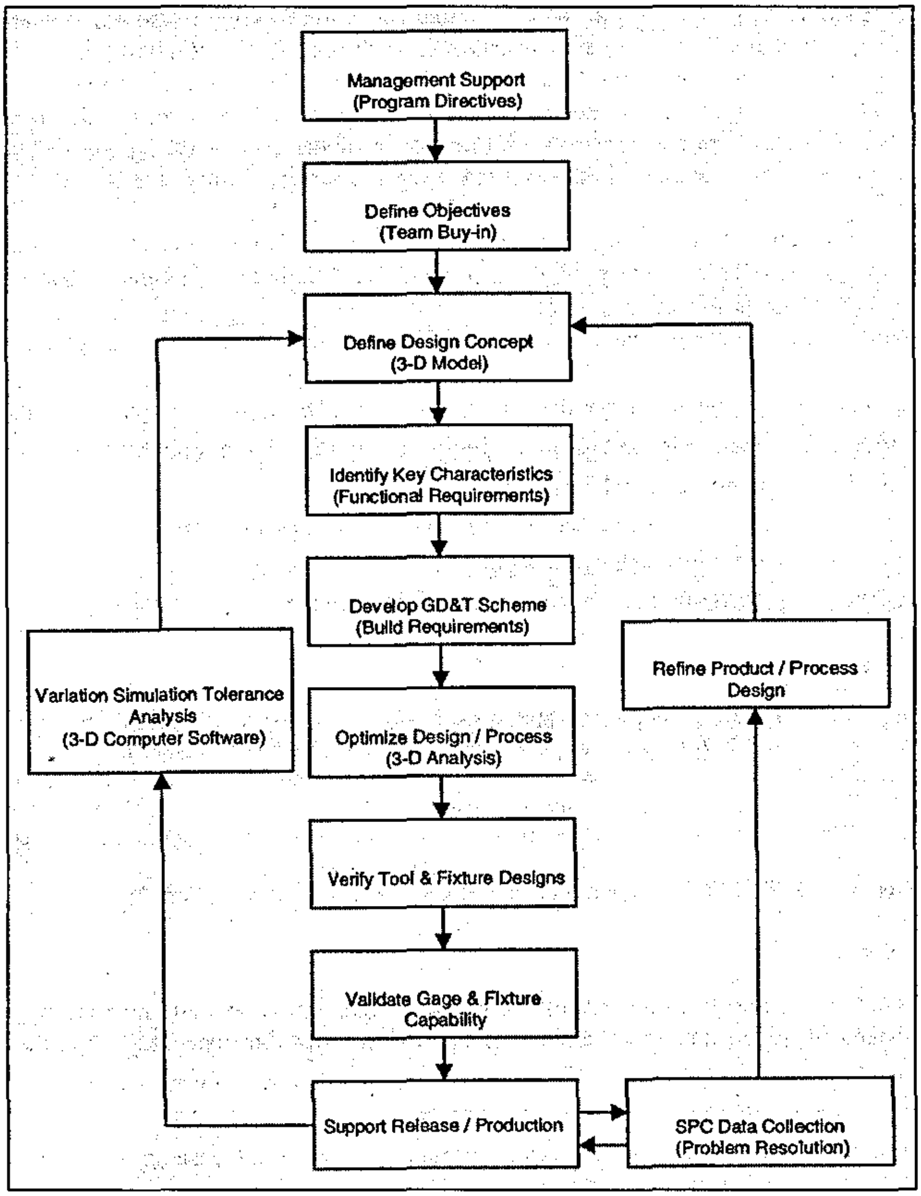


Figure 4: The dimensional management process (Drake, 1999)

It is imperative that the product dimensional requirements are clearly defined in written objectives by product engineering groups at the beginning of the design cycle. These written objectives must be based on the customer's requirements for the design and the process and measurement capabilities of the manufacturing system. If the objectives cannot be agreed upon by a consensus of the dimensional management team, the program cannot proceed to defining the design concept.

The design concept is defined by developing a 3-D solid model using a modern computer-aided engineering system. The 3-D model provides a product definition and is the basis for all future work.

Key characteristics are identified on individual features based on the functional requirements of the mating parts that make up assemblies and sub-assemblies. Features that are chosen as key characteristics will facilitate assembly and assist in reducing variability during processing and assembly.

Geometric dimensioning and tolerancing schemes are developed on the basis of the key characteristics that are chosen. Other requirements for correct fit and function between mating parts are also considered. A major objective for this GD&T activity is to establish datums and datum reference frames that will maintain correct interfaces between critical features during assembly. The datum system expressed by GD&T symbology also becomes the basis for determining build requirements that will influence processing, tooling, and inspection operations.

The product and process designs are optimised using variation simulation software that creates a functional assembly model. A mathematical definition of the assembly sequence, methods, and measurements that are based on the design concept, key characteristics, and GD&T scheme established in earlier stages of the program is created. This definition is used to statistically perform simulations based on known or assumed Cp and Cpk values, and to identify, rank, and correct critical fit and functional relationships between mating parts. These simulation tools are also used for the verification of the tools and fixtures. This is done so that datums are correctly coordinated among part features, and the surfaces of tool and fixture locators are correctly positioned to reduce variation.

Measurement data is collected from gauges and fixtures before production to verify their capability and compatibility with the product design. When the measurement data indicates that the tooling is not creating significant errors and meets the defined dimensional objectives, the product is released for production. If any problems are discovered that need a solution, further simulation and refinement is initiated.

During production statistical process control data is collected and analysed to continually refine and improve the process. This in turn produces a product that has dimensional limits that will continue to approach their nominal values.

The dimensional management process can substantially improve dimensional quality for the following reasons:

- The product dimensional requirements are defined at the beginning of the design cycle.
- The design, manufacturing, and assembly processes all meet the product requirements.
- Product documentation is maintained and correct.
- A measurement plan is implemented that validates product requirements.
- Manufacturing capabilities achieve design intent.
- A feedback loop exists that ensures continuous improvement.

2.1.3 VIRTUAL PRODUCT INTRODUCTION

The phrase "better-faster-cheaper" has become commonplace today, and perhaps a little tiresome. But nowhere is that phrase more applicable than in the design and development departments of automotive manufacturing companies. In fact, this imperative is becoming a basic price of admission for survival of vehicle manufacturers worldwide. Factors such as new regulations, emerging technologies, hybrid fuels, consumer demands, and competition have contributed to an evolution in the product development process. To remain successful and competitive, CAD/CAE groups have begun rethinking and redesigning their work processes and computing environments (Anon, 2000b).

The reality today is that design and development groups have been able to cut the turnaround time on new vehicles from three to five years to 12 to 24 months. At the same time – through efficient outsourcing, advanced simulations of prototypes, and new materials – vehicle manufacturers have been able to introduce more products, including hybrid vehicles.

With these improvements, however, comes a catch-22: how to speed time to market and improve product quality? This issue is one of the industry's most important challenges. Do you trade off 10% of your CAE verification cycles to get a new vehicle delivered weeks sooner, risking a recall later? Do you instead extend your simulation and testing process to assure that your new suspension system has been verified under all conditions, only to lose market enthusiasm when a competitor launches their vehicle ahead of yours?

The reality today is that the costs of research, development, testing, compliance, and quality are making the process of designing new vehicles very expensive and complicated. At the other end of the spectrum, the window of opportunity is shrinking as consumers want increasingly more for their money and are easily turned off by a vehicle that is slightly out of date. Manufacturers cannot afford to make a mistake in development, pricing, promotion, or delivery.

Technology is having a profound impact on the product development process today, allowing companies to do more work, faster than ever before, and at the same time giving them more control over their internal systems and resources.

The most significant impact computer technology has had on the design and development process is in the simulation and verification of the design-to-manufacturing process of new vehicle bodies, engines, suspensions, and electronics. Traditionally, stylists would sketch ideas for a new concept and then "dump" their creations over to CAD engineers, who would then take those ideas and build models on their drafting tables along with associated design criteria and documentation. CAE engineers would then take these blueprints and create physical models of the designs to be run through a barrage of live tests to assess flaws, structural defects, and manufacturing specifications. The process was long and error-prone.

Advanced software and hardware tools now allow the entire process to flow electronically from styling to design to analysis to manufacturing, as well as looping back to improve the process. The key to all of this is the electronic design model that carries with it all the specifications and tolerances necessary to test and ultimately manufacture the vehicle. Flowing these design models throughout the R&D process – with all the shared data – minimises errors, speeds development, and improves quality. This workflow process has allowed global design teams to collaborate around the clock on projects – sharing tools, workloads, and critical knowledge.

In addition, this electronic process permits manufacturers to minimise the amount of physical testing that is performed on new vehicles. Expensive, time-consuming, and limited physical testing simply cannot match the capability and quality of computer simulations. While tradition and the high cost of mistakes often make some people prefer real, hard data to "animated" pictures, it is just no longer possible to be competitive using traditional techniques. By using advanced computer simulations, validated against selective physical tests, engineers can perform more analyses in less time. The traditional approach to vehicle development requires extensive use of local and full-scale physical models. However, there are many detail design issues that get overlooked when using physical models. This is often due to extra time and cost involved in accurately modelling complex design details within the physical model and not fully appreciating manufacturing assembly and dimensional variation issues. Major differences between virtual modelling and the traditional approach are summarised in table 1:

Traditional Approach	Virtual Modelling Approach
Customer focus does not always prevail.	Process is customer driven with no functional barriers.
Manufacturing feasibility issues are expressed as individual opinion.	Mathematical product data is used to predict and visualise manufacturing outcomes.
Complex component interfacing areas are not optimised to eliminate see through gaps and rat holes.	High quality 3D visualisation helps the team to design out unacceptable see through gaps and rat holes.
Innovation is stifled due to lack of objective communication across different functions.	Interactive and collaborative environment exists to foster innovation and problem solving.
Potential cosmetic & dimensional variation problems are not predicted.	Potential cosmetic defects and worse case dimensional variation are visualised, including potential solutions.
Process does not reinforce concurrent engineering philosophy & discipline.	System quickly highlights data and information gaps.
No objective cosmetic quality acceptance standard & validation methods.	Quality acceptance criteria & validation process are based on objective data.
No intermediate component & process specific quality targets exist.	Component & process specific targets exists to meet end product quality standard.
Large number of late design changes to reduce quality problems.	Minimal or no late product design changes required to improve product quality.
Little scope to evaluate different options cheaply and quickly.	Ability to generate range of solutions based on objective data.

Table 1: Differences between virtual and traditional approach to vehicle development (Singh and D'Silva, 1998)

Traditionally the development of product quality standards early on in the product definition process has been very much the application of generic sets of tolerances along with an opinion of what the manufacturing process can achieve (Singh and D'Silva, 1998). Today VR tools can be used to display the impact of design tolerance stack-up on the aesthetic quality of the vehicle and this helps to create a more objective and customer centred process. It enables the vehicle project team to:

- set competitive customer focused quality targets.
- adopt a design approach that accounts for manufacturing process variation.
- get early agreement that the desired quality level can be achieved.

Applications of simulation and virtual reality tools in vehicle development provides significant new opportunities for manufacturers to develop more radical styles in shorter time frames with a high level of confidence in the product build quality. The total product development process must take less time, consume fewer resources, and be more responsive to changes in the economy, the market, regulation, and technology. This is the core challenge facing automotive executives, designers, and engineers. Key to meeting this challenge are the many trade-off decisions that must be made early in the concept development phase of the life cycle, and which are critical to the unfolding, and ultimate success of a vehicle program. The industry must make these decisions based on more, and more certain, knowledge and must employ that knowledge in shorter decision cycles. Better information and shorter cycle times will decrease the need for costly and time consuming revisions at later stages. Also, because unpredictable changes will always exist, shorter decision times are needed to assure powerful responses to unforeseeable events (Morell and Andrea, 2003).

Implementation of simulation tools should also help to foster increased collaboration and communication across different functions and accelerate product and process innovations to meet rapidly changing consumer demands.

Vehicle leadtime is continuously being shortened by the utilisation of CAD/CAE/CAM (Szefi, 1997). Other means of shortening leadtime, such as the more intense use of virtual design tools for both interior and exterior applications, will become commonplace. Once defined, these virtual product models can be used over and over again to conceptualise rapidly and build new designs. Companies can create product definitions which incorporate the intuitive knowledge of designers and engineers about design and manufacturing processes thus reducing time spent on routine design work and freeing up designers for more creative thinking. Companies also view knowledge-based engineering (KBE) as a means of reducing their vulnerability to knowledge holders. KBE techniques have generated impressive savings, reducing design times from weeks to minutes, in some cases. In the example of a bonnet stiffener, design time was reduced from six to eight weeks to just 20 minutes (Kochan, 1999).

Virtual verification has become an important tool for cutting costs and shortening lead times, as the vehicle market becomes increasingly competitive and customers more demanding (Wickman, 2002). New tools and methods are used to support the development process in order to maintain market leadership. Today, when an industrial design concept is evaluated in an aesthetic manner no consideration is given to geometrical variation, i.e. the concept is evaluated with nominal models. If geometrical variation were to be considered as early as the concept phase, when industrial design concepts are evaluated, the possibility to discover aspects that can influence on the quality appearance would be enhanced. By using non-nominal models during the design process, important geometric aspects can be stressed and the need for physical test series can be reduced. In the automotive industry, especially in body design, the relationships between doors, bonnets, fenders and other panels are critical for the quality appearance. The level of variation in these relations is affected by part variation, assembly variation but also with the robustness of the design concept. The robustness, i.e. the ability to suppress variation, is dependent on the design and style configuration. The ability to evaluate and verify product design early in the design process has been an important activity to meet a modest development time. If virtual evaluation can be done early, the probability decreases of taking incorrect decisions that may result in expensive post-conceptual changes.

Wickman, Soderberg, and Lindkvist (Wickman, *et al*, 2001 and Wickman and Soderberg, 2003) present how virtual reality techniques can be used to visualise simulation results gained from tolerance analysis. Combining traditional CAT tools with modern VR tools has the potential to enhance concurrency between styling and design and provide more powerful support for the geometry process in early phases. Traditional non-nominal verification can then be performed already in the concept phase using digital models instead of physical. An example rear end of a vehicle (Volvo S60) is used to illustrate how integrated CAT/VR tools can be used to support decision making and virtual verification throughout this process.

In Maxfield, *et al*, (2000a, 2000b, 2001, and 2002) a comprehensive outline of a computer system for visualisation of cosmetic quality is presented. This is the result of a collaborative research project, known as VITAL (Visualisation of the Impact of Tolerance Allocation in Automotive Design), researching and developing prototype software to enable designers to easily assess cosmetic quality as components and assemblies deviate from nominal. It's most recent application is the aesthetic assessment of the glove box assembly within the instrument panel of the Jaguar S-Type. The assembly is composed of over 80 rigid and flexible components. The components are made from a wide range of materials from metal alloys and injection moulded plastics for the main shape and strengthening components to wood, leather and textiles for trim and upholstery. VITAL brings together a combination of interactive simulation technologies including tolerance variation, assembly, deformation, appearance and environment modelling. The case study illustrates how the tool can be used for setting, predicting and assessing aesthetic quality targets throughout the design process without the need to produce physical prototypes.

2.2 LIGHTWEIGHT VEHICLE CONSTRUCTION

The volume production of light-duty vehicle bodies continues to be organised almost entirely around the assembly of pressed sheet steel panels into 'unitary' (integrally stress-bearing) bodies by jigging and spot-welding. In practice, the unitary body can actually be considered as two parts, the platform and the upper body. The platform incorporates all the mounting points and attachments for the engine, transmission, suspension, fuel tank, exhaust system and other important elements. Its design is therefore more difficult and expensive to change than that of the upper body which acts fundamentally as protection for the vehicle occupants, and as a housing for the majority of body systems, while also providing hinged attachment points for the 'openings' – doors, bonnet, and rear hatch or boot lid. Modern vehicle design is therefore increasingly based around the combination of a number of upper body sections with a much smaller number of platforms. A fundamental of efficient modern design is to achieve this combination at low cost while also ensuring the efficient distribution of stresses (those of normal use, and also of impact loads) through both the platform and the upper body. If such efficiency is achieved, acceptable body stiffness in bending and torsion can be achieved at the lowest body weight.

The era of traditional mass-production of automobiles seems to have come to a halt. The incitement for cost-effectiveness, that urged on the introduction of the assembly line in the beginning of the previous century, seems to fade away in favour of other attributes like crashworthiness, driving performance, reduced fuel consumption, advanced driver's information etc. Also the sense of individuality that flows through the western society means that the customer demands a certain level of uniqueness of the products offered. Therefore the concept of the body structure, or body-in-white, is undergoing a paradigmatic shift in engineering and manufacturing, which calls for new technical solutions (Larsson, 2002). Customer demand and increasing competition is forcing car manufacturers to develop more models in a shorter leadtime measured from model or styling freeze until start of production (Schupp, 1998).

Traditional unibody construction calls for massive investment in three production areas; in the hydraulic presses needed to produce panels of large size and complex shape, in the jigs needed to locate them accurately in relationship with each other, and in the spot welding robots needed to perform the actual assembly. The essential virtue of unibodies is that of an eggshell. By distributing stresses more or less evenly in all directions, it achieves great stiffness in relation to its weight. Its biggest drawback is its fragility when subjected to an impact with a substantial component perpendicular to the shell. Therefore the ideal body structure has lately been developed to become an extremely stiff and strong compartment - the safety cell - protected in the worst impact cases by front and rear structures designed to absorb energy while crumpling. In truth, the average body structure has become more like a spaceframe, with box-section members running not only around the side openings but also transversely, while yet other members make sure that impact loads, which could not be absorbed, are transmitted into areas where they would do least harm. However this spaceframe could still be called unibody, because it is still spot welded to a skin which contributes to the body stiffness.

Spaceframe and unstressed body panels have been common practice among low-volume car manufacturers for many years, simply because they can not justify the expense of tooling up for unibody construction. One needs to be contemplating a run of at least 50,000 bodies before you can do so, and the economics get better the more bodies you make, up to around 500,000 after which the dies need to be refurbished or replaced.

Today, most spaceframe structures are based on aluminium, taking advantage of the favourable manufacturing technique of extruding this material into beams with closed or open sections, with or without internal stiffeners. The closed sections can then be given a more complex shape through hydroforming. Well-known examples of this spaceframe technology are the products coming out from the Audi Neckarsulm plant, the A8 and A2 models. However, steel spaceframes can also be cost-effective, using the rollforming technique to create cross-sections of very complex geometry, which also later on can be hydroformed to its final shape. Developing this "steel track" implies at least two other advantages over aluminium; lower material price and a more well-known material type for the body shop community.

2.2.1 MATERIALS TECHNOLOGY FOR BODY CONSTRUCTION

What follows is a brief summary of the main considerations relating to the choice of materials for body construction.

Steel

Rolled sheet steel remains overwhelmingly the material choice for the manufacture of light-duty vehicle bodies in significant volume – from 50,000 units/year upwards. At smaller volumes, the trade-off between the low cost of the material itself, and the high cost of the machinery used to handle it (and especially of the dies used to press-form it) becomes more problematic. No satisfactory 'middle way' has been devised between the high-cost, long-life die for volume production and the low-cost, short-life type which are extremely useful for prototyping and pilot builds having a typical life of 100 panel sets compared with the 500,000 panel sets that could be expected from long-life dies given proper maintenance and refurbishment.

The sheet steel itself has been technically developed, especially in the last 10-15 years, partly in response to the challenge of aluminium but mainly to meet the demands of body engineers in terms of weight reduction and passive safety performance. There have been parallel improvements in quality, especially in areas such as sheet thickness uniformity. The standard technique for steel body panel shaping remains the heavy-duty hydraulic press, now very highly developed into fully automated and enclosed sequential multi-station machines capable of very high throughputs.

An alternative technique which is quickly gaining acceptance is that of hydroforming, in which a tube is expanded against a mould by internal hydraulic pressure (Ahmetoglu, 2000; Feraille, 2002; Perarnau and Tondo, 2002; Nottrott, 2002; Dong, 1999). Hydroforming is especially suitable for complex beam shapes of the kind which often perform structurally important functions in modern car bodies. Tubular hydroforming and its cold working effect produces high dimensional stability and increases the effective yield strength in a component.

For example, figure 5 shows the UltraLight Steel Auto Body (ULSAB) being developed by a consortium of 35 steel manufacturers worldwide (ULSAB, 1998; Adam, 2002; Flaxa and Shaw, 2002). The hydroformed side roof rail is made from a welded, high strength steel tube of 1mm thickness and outside diameter of 96mm with a yield strength of 280 MPa. Hydroforming is used in the ULSAB project as a means of mass reduction by combining components that would normally be stamped or resistance welded together into one part.

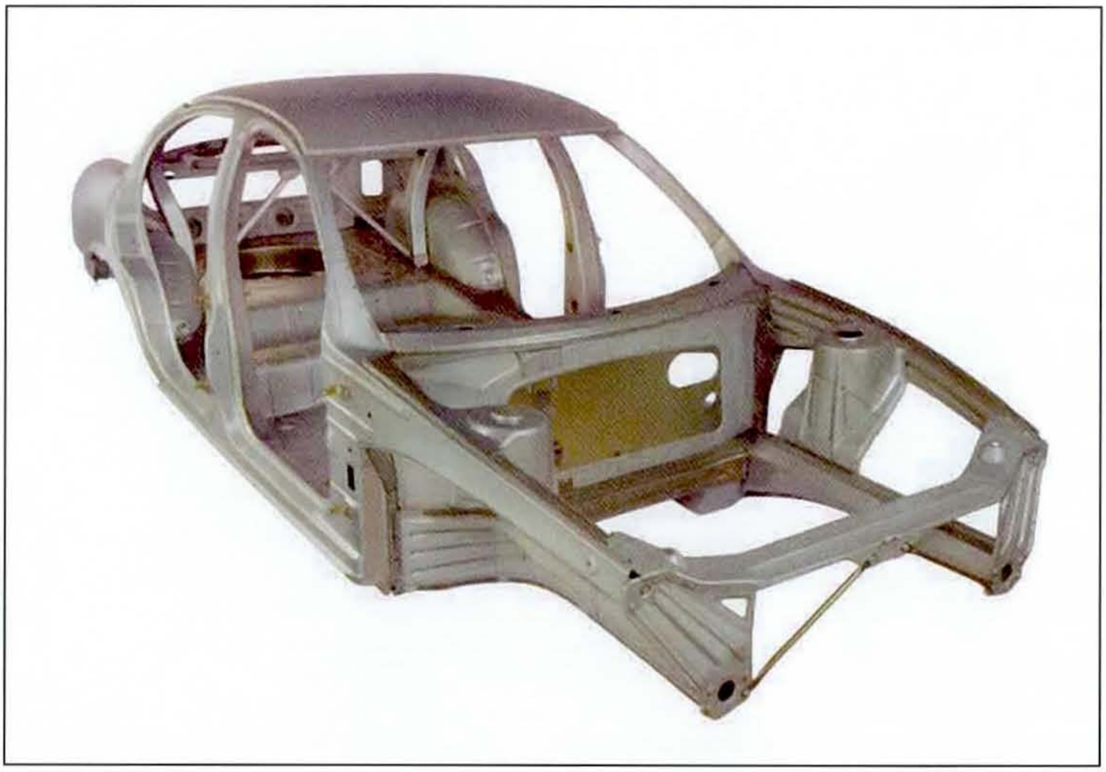


Figure 5: The UltraLight Steel Auto Body (ULSAB)

It is through the continued development of advanced manufacturing processes such as hydroforming, the production of tailored blanks, and steel/thermoplastic sandwich materials that steel is continuing to hold its own against a backdrop of increasingly stringent environmental requirements and growing competition from aluminium and composite plastics materials (Langerak and Kragtwijk, 1998; Larsson, *et al.*, 2003; Johnsonan and Mascarin, 2002; Plassart and Philip, 2002).

Aluminium

The main appeal of aluminium based-alloys for the vehicle body engineer is lightness, or more precisely its higher ratio of strength to weight compared with steel. This enables an aluminium alloy body to be made approximately half the weight of a conventionally engineered steel body with similar stiffness and passive safety performance. This advantage has been thrown into sharp focus by current anxieties about fuel consumption and the greenhouse effect. Also, aluminium does not rust; in fact it is protected by surface oxidation (which is not to say that it does not corrode, especially in the presence of salt – although sea water resistant alloys are available).

The principal drawback of aluminium is cost, which is not only substantially higher than that of high quality steel because the metal refining process is a prodigious energy consumer, but also subject to considerable fluctuation because existing demand and potential supply are more evenly balanced. In addition, aluminium is somewhat more difficult to spot-weld than sheet steel, demanding extremely accurate control of welding current and timing. This difficulty has itself been sufficient to discourage the idea of using aluminium sheet as a direct replacement for steel. Most research teams, including those who have put aluminium-bodied cars into limited-scale production have therefore developed alternative approaches to body structural design, generally seeking to carry the principal loads through a jointed framework of extruded aluminium tubes of complex section (it is virtually, certainly economically, impossible to extrude steel tubes in the same way).

The aluminium industry has suggested that eventually, most of the raw material needs of the motor industry could be met by recycling, since in contrast to the expense and difficulty of its extraction as a raw material, aluminium is easily and efficiently recycled. The problem remains of how to inject sufficient aluminium into the cycle in the first instance.

Although there has been a shortage of some kinds of aluminium scrap, there is not an overall shortage (Eurotrends Research, 2000). In the longer term the scrap stream will rise as cars with enhanced aluminium content reach the end of their life. Primary and recycled aluminium do not usually compete. Primary metal is used mainly in body panels (important for electric and hybrid cars).

It should also be noted that because a conventional steel body accounts for approximately 30% of the total weight of a passenger car, a switch to all aluminium construction would result in an overall saving of no more than 15% in the vehicle's kerb weight. This is still significant, but not sufficiently so to have persuaded the vast majority of vehicle body designers to abandon a material which they have known and trusted for so long, for which the necessary production machinery is in place, for which the technical solutions are so highly refined, and which is still being developed to offer better performance.

Aluminium alloy panels may be shaped by any of the methods used for steel, although more care is needed in deep-drawn pressing to avoid visible stretch-marking of cavity walls. Aluminium sheet is of course easier and less dangerous to handle than steel, but more susceptible to surface damage during handling. Its ready adaptability to skilled manual shaping by roller-press for prototyping purposes has become less relevant in a world where lightweight prototype dies can be cut directly using CAD/CAE digital inputs, and used to press sets of prototype panels (Miller *et al.*, 2000, and Furrer and Ruckstuhl, 2003). Aluminium may also be readily and extremely accurately formed by extrusion into thin-walled sections of considerable complexity and cross-sectional area. Many researchers into vehicle body structures have considered the potential of such extrusions as substitutes for the box-sections of steel bodies formed by the mating and welding of multiple pressings (Ahmetoglu, 2000; Feraille, 2002; Perarnau and Tondo, 2002; Nottrott, 2002; Dong, 1999; and Elkington, 2004).

Plastics and fibre-reinforced composites

Plastics are still, potentially, an alternative to aluminium as lightweight body materials. However, their challenge has been blunted throughout the last decade by anxieties about recycling. Plastics still continue to survive as a major material because for some purposes, their engineering advantages are overwhelming.

The so-called 'plastic' car bodies which have been made in small volume for many years are almost invariably made from plastic composites. However, the term 'composite' covers any combination of dissimilar but intimately associated materials, such as the steel/plastic sandwich panels being used by a growing number of manufacturers. The major problems of recycling, or even of safe and economic disposal, presented by fibre-reinforced composite components when they reach the ends of their useful lives has severely limited their use in the last decade. Car body engineers much prefer to use 'pure' materials which can be reliably and simply recycled.

2.2.2 UNITARY OR SPACEFRAME?

Unitary construction – in which the car body is assembled from a large number of press-formed panels, typically about 300 - is the standard production method of the major car manufacturers.

Although it is no trivial matter to replace steel with aluminium since the details of the pressing process -sheet gauges, bend radii etc - are different for the two materials, as are other aspects of their processing, essentially there is no reason why unitary construction in aluminium should not become the high-volume car production method of the future. Various unitary aluminium research cars such as BL Technology's ECV3 have already proved the point, as has Honda's NSX sports car. During 1994, Ford in the US built a fleet of 40 unitary bodied Aluminium Intensive Vehicles (AIVs), based on its Taurus/Sable model, for field-testing around the world (Aluminium Extruders Association, 1995).

Unitary construction has never been well suited to small and medium production volumes, however. Pressed panel piece costs are low but a high initial tooling investment is required. For this reason an alternative construction method has been developed for the aluminium primary structure, better suited to the limited production runs which early generations of aluminium-bodied cars will command.

Called spaceframe construction - although it involves none of the comprehensive triangulation many engineers will associate with the term -this method uses complex hollow extruded sections which are joined to form a rigid framework analogous to that of a frame tent. The body panels are then attached to this frame.

In addition to being inherently economic because of the low cost of extrusion dies, spaceframe construction has the advantage of being highly adaptable. Cast aluminium 'nodes' can be used to join the extruded sections together, as in the Audi A8, but direct welding is possible too.

The designer can also choose whether to stress the body panels or not, offering further adaptability in respect of cost and materials. Stressed aluminium panels offer the maximum body stiffness combined with minimum weight but are relatively expensive and may be judged to have insufficient dent resistance. Unstressed moulded thermoplastic body panels are a heavier but cheaper alternative with superior dent performance. Like aluminium panels, they are also recyclable.

Some disagreement exists within the motor industry regarding spaceframe construction's suitability to high production volumes. The general view is that spaceframe construction is economically viable up to volumes of approx 100,000 units per annum, above which unitary construction is favoured. But it has been suggested that spaceframe construction might be developed into a competitive technology for large-scale production also.

Alcan is convinced that the sheet stamped monocoque provides the maximum weight saving with the minimum requirement for new technology for medium to high volume production, where piece costs dominate (Scott, 1995). Existing stamped sheet production and assembly techniques, modified for aluminium, offer economic low weight car bodies. Alcan has invested many years and considerable resources in the development of the patented Aluminium Vehicle Technology (AVT), which continues to be refined and improved. The effectiveness of this technology has been successfully demonstrated by numerous programs with a variety of automotive manufacturers worldwide, resulting in aluminium prototypes engineered to the same exacting design standards as existing steel bodies, but with impressive weight savings of up to 50% of body weight without compromising performance or safety.

AVT comprises the aluminium sheet alloy, the factory applied surface pre-treatment for bonding and spotwelding, the factory applied press lubricant, and the special Ciba Geigy structural adhesive. All these components are compatible to allow the body parts to be stamped in the conventional manner from the pre-treated, pre-lubricated aluminium sheet or coil. The adhesive is applied without the need to clean off the press lubricant and the parts are held together with a reduced number of spotwelds through the uncured adhesive. The adhesive is then heat cured in a similar manner to that commonly used to cure the electrostatic primer or 'E-coat' on existing steel vehicles.

These basic processes are very familiar to the makers of sheet steel monocoque car bodies, and only differ in detail from the current steel practice. The application by robot of the adhesive is no different to the process currently used to install vehicle windscreens. Many automotive manufacturers already apply some underbody sealants prior to assembly and spotweld through these sealants before cure. The spotwelding of aluminium with a suitable surface pre-treatment is now a practical proposition for volume production of monocoque aluminium intensive vehicles.

The vast majority of parts now stamped in steel can be stamped in aluminium with minor modifications. Door panels and hoods are formed using conventional presses into their final shape. Some components are designed to have sharp creases (e.g., a "style line" of a hood) or deep recesses and small radii (e.g., curves like those found in door inner panels), which sometimes create problems for manufacturing engineers. These problems include splitting of the metal, wrinkling as material gathers in a corner, and springback when the part is removed from the die.

Because of these issues, a single aluminium part may require more stamping stages than a comparable steel part, or the part may have to be divided into two or more pieces that are joined together, adding time and cost to the manufacturing process. A less desirable alternative is to make compromises on either the choice of material or the shape of the part. Thus engineers have been trying to develop other methods to replace or complement the conventional mechanical stamping process to fully realise the potential mass savings of using aluminium components.

Researchers at the U.S. Council for Automotive Research (USCAR) and Ohio State University (Anon, 2000a) have experimented with a technique known as electromagnetic forming (EMF) to reduce or even eliminate the wrinkling and springback associated with conventional forming processes, as well as to increase the formability of aluminium sheet. The process works by passing a short-duration, high-current electric pulse through a coil, which is placed close to the part to be formed. This produces a brief but powerful magnetic field that generates an opposing magnetic field within the part to be formed. The coil and the part thus repel each other and the part is propelled into a forming die at high velocity, forming the part into its final shape.

Initial results indicate that EMF greatly improves aluminium forming based on trials with two aluminium parts. Using EMF, researchers could form the desired surface contour in a hood without wrinkling. A second trial demonstrated that EMF extends the forming limits of aluminium sheet by shaping a difficult-to-form door inner panel without wrinkling or splitting. While the researchers are encouraged by the preliminary results, much work remains to be done. One area of concern involves the coils used to create the magnetic filed. If EMF is to be employed on a large scale in the automotive industry, extremely robust coils will need to be developed.

The introduction of aluminium into the car body structure in the form of hang-on-parts and structural modules offers the potential for significant weight reduction. However, lightweighting with aluminium in a system-oriented approach also allows manufacturers to reach the envisaged ecological benefits under the prevailing economical conditions. Most important in this respect is the availability of a wide range of aluminium product forms (sheet stampings, formed extruded components, net-shaped parts produced by various technologies). Depending on the targeted production volume, this multi-product capability allows the realization of new, innovative aluminium design concepts in particular for different production volumes. Intensive alloy development and manufacturing process optimization activities during recent years will ensure that the applied material quality satisfies all the requirements of the automotive industry.

The use of aluminium for the primary structure of cars, while offering the highest weight saving potential, will still entail fundamental changes to current car production technology. Aluminium behaves differently to steel in most relevant respects, so choosing to use it in preference is not a simple matter of substitution – it cannot be treated as a lightweight form of steel.

It is this step change in design and production methodology and the issue of aluminium's price stability which represent the biggest hurdles to the widespread adoption of aluminium as a body material. They can be overcome by close cooperation between the aluminium industry and car producers. Through such partnerships, cost stability will be assured and the remaining technical issues resolved, thus improving the cost effectiveness of aluminium in this application.

Mascarina and Johnson (2002) explored the extended impact of advanced body technologies. Traditional cost model projections of direct manufacturing costs and mass are compared with the impact of functional system interrelationships and vehicle performance in order to assess the total vehicle costs and benefits of alternative systems. Both unibody and spaceframe designs consisting of steel, aluminium and composite constructed variants are evaluated. They conclude that at high volumes, cost benefits from primary and secondary weight savings, along with lifetime fuel usage outweigh the manufacturing premiums for aluminium unibodies, aluminium spaceframes, and lightweight steel spaceframes. Changes in powerplant technology and fuel prices will obvious alter these relative costs and savings. Up front purchase price is more important to consumers and OEMs than lifecycle costs, no matter how compelling. Whether this will change future legislation, vehicle life, and fuel prices remains to be seen.

The United States Steel corporation (USS, 2004) outline a number of disadvantages to aluminium unibody and spaceframe designs.

Disadvantages of unibody design:-

- Formability of aluminium is poor in conventional stamping methods (high scrap rate expectancy).
- Recycling problems associated with 5xxx and 6xxx series segregation, causing a wider variation in scrap revenues mixing alloys compared to steel grades.
- There is a cost penalty associated with using aluminium compared to steel of comparable strength and part performance characteristics.
- Insurance premiums increase along with costly repairability in the field.
- Questionable dynamic performance increase in vehicle handling and fuel economy by this intensive use of aluminium based on case studies of comparable steel intensive vehicles (see High Performance section).
- In most cases, little or no increase in fuel economy results from intensive use of aluminium.
- Currently, there are larger design lead times for tooling development with aluminium than for steel parts, including higher tooling development costs. This is mainly due to the knowledge and experience base available for steel design and utilization. Also, the difference in springback characteristics and less total elongation for aluminium make designing for manufacturability more difficult.

Disadvantages of spaceframe design:-

- An increased level of skilled labour is required for space frame construction, since the joining methods are more complicated that the conventional stamping method, based on data for the 2002 model year Audi A8. Most space frame vehicles on the market use fusion welding to join the extrusions to stampings or castings. Fusion welding requires specialized operators to ensure good welds are made. The new 2004 Audi A8 is said to have fixed some of these issues with use of laser welding and more automated processes.
- Due to part variability, the extrusions must be manually positioned in the assembly fixtures for the A8 through the 2002 model year. The newest generation A8 is said to have resolved some of these issues by use of hydroforming for improving dimensional tolerance, but this added procedure may prove cost prohibitive for Audi since it is a separate added process.
- Aluminium extrusion use requires secondary operations such as cutting, bending, and hydroforming, which can drive up assembly costs considerably, since these processes are separate. Steel also requires secondary operations but are performed in-line and in-sequence during the stamping operations.

2.2.3 THE BL ENERGY CONSERVATION VEHICLE (ECV 3)

Although not unique, and it is probable that other companies were seriously assessing aluminium-based lightweight structures at the same time, the BL Technology ECV 3 was a significant development programme exploring the feasibility of ultra-fuel efficient vehicles.

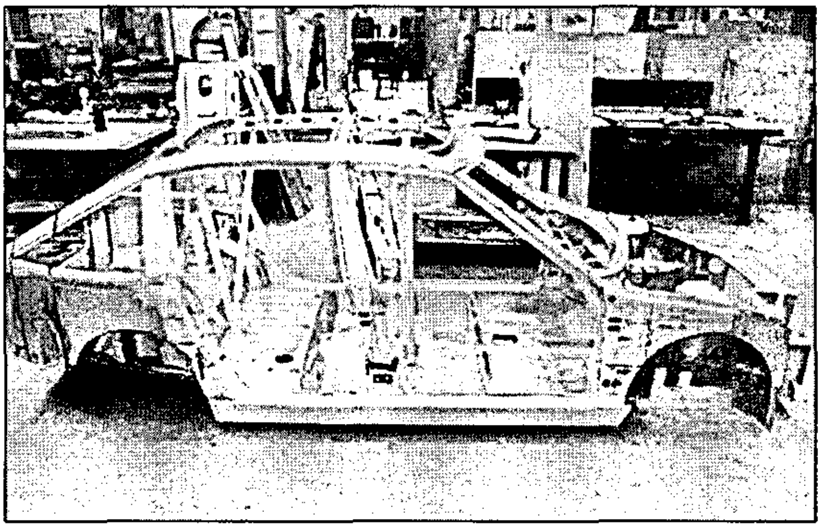


Figure 6: BL Technology's ECV3 unitary aluminium bodied research car developed in the early 1980s (Aluminium Extruders Association, 1995)

Rover had long been users of aluminium (being virtually the only material available in 1948 for the bodywork of the land rover) and it was natural that experience gained with this material made it a strong contender for a fuel efficient concept car. The ECV 3 was a totally new design but incorporated many of the ideas and processes from its predecessors, ECV1 and 2, and was first announced in 1982. A paper written on the car in (Kewley, 1985) commented that the concept stood up to examination after 3 years. The vehicle was planned with due regard to the total energy consumed in a vehicle life cycle and also total vehicle ownership costs.

The bodyweight of the ECV 3 was 138 kg compared with 247 kg for an equivalent steel structure and the vehicle weighed 664 kg or the same as an Austin Rover Mini, yet the internal space was the same as an average mid-range European car. This weight reduction assisted in achieving all aspects of the specification.

This technology was carried forward by Alcan who had been close collaborators on the programme, with the objective of building replicas of production cars and developing adhesive bonding technology for use at all volume levels.

2.2.4 HONDA NSX

When the Honda NSX was launched in 1990, it became the first modern car to use aluminium for its primary structure (Aluminium Extruders Association, 1995). Following a consideration of specific strength, specific rigidity and equivalent rigidity compared with sheet steel, the decision

Figure 7: The Honda NSX low volume sports car, with a unitary construction (Aluminium Extruders Association, 1995)

was made to manufacture the BIW in aluminium to reduce weight by about 140kg. The rigidity of a car is critical to maintain steering stability, and to help improve this, the sills were produced as extrusions with variable side wall thickness.

To satisfy different requirements for strength, formability, weldability and coating, detailed preparatory background studies showed that different alloys should be used for different panel applications.

By choosing to use unitary construction, Honda adapted a high-volume production process to the manufacture of what is a low-volume specialist car. The base structure and hang-on exterior panels are constructed from sheet pressings, 5000 series alloys being used for most of the inner stampings and stronger 6000 series alloys for the exterior body panels, to ensure adequate dent resistance. The only steel component in the structure is the dashboard mounting member.

As Alcan and BL Technology had already done for the ECV3, Honda found it necessary to develop special production processes for forming and pre- treating the NSX's panels. Specially polished pressing dies and 23-stage surface treatment ensure a high quality surface finish prior to the body being painted using a water-soluble primer.

It was found that wrinkling and shape control were the main problems on forming, attributed to lower modulus which resulted in more springback (compared to steel). Twice the overcrowning allowance was required than for steel in the forming of door outer panels. Together with proportionally lower forming limit curves, it was found that new disciplines in the form of die adjustments, crowning and lubrication were essential if the required shapes were to be mass produced.

Welding is the prime jointing method adopted although a limited amount of adhesive bonding is also used to attach some outer panels. Approximately 2500 spot welds, a third of which are made robotically, and 600 MIG welds in spots or short seams are used to join the body together including exterior panels the completed body weighs 21O kg, a saving of 140kg (40%) over a steel monocoque.

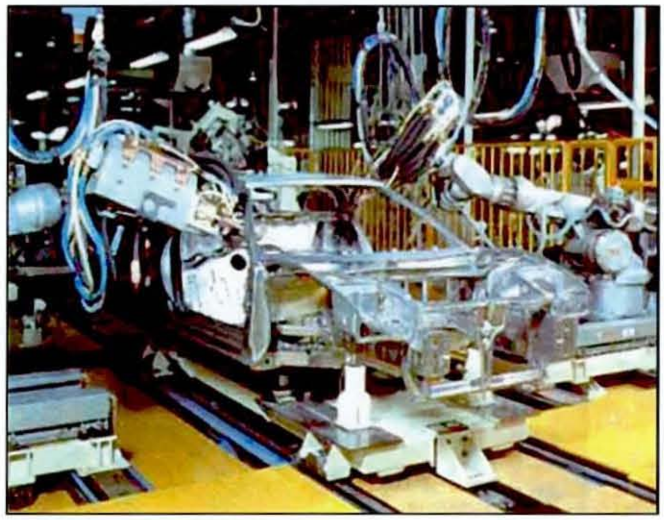


Figure 8: A third of the 2500 spot welds used to assemble the Honda NSX are made robotically (Aluminium Extruders Association, 1995)

A further 60kg is saved by the extensive use of aluminium castings and forgings for the suspension, reinforcing the message that, to retain its ride refinement and roadholding on bumpy roads, a lightweight car must also have lightweight suspension. Aluminium is used within the car interior as well, with the seat frames being constructed of cast aluminium and the seat runners from extrusions. Honda calculates the total aluminium content of the £60,000 NSX -which also has an aluminium engine block and head -to be about 34%, compared to an average of 8% for the remainder of its range.

The NSX production plant in Tochigi was always intended as a pilot project for future limited-production Honda vehicles also made in aluminium, although their exact nature is as yet unknown.

2.2.5 LOTUS ELISE

An innovative combination of adhesive and rivets is used to join the chassis of the Lotus Elise that is made primarily from aluminium extrusions (Kochan, 1996). The bonding technique was developed by the UK sports car company in partnership with Ciba Polymers of Switzerland and Hydro Aluminium, of Denmark.

When Lotus Group engineers set about developing the chassis of the new Elise sports car, the decision had already been taken that it should be made, as far as possible, from aluminium extrusions (see figure 9).

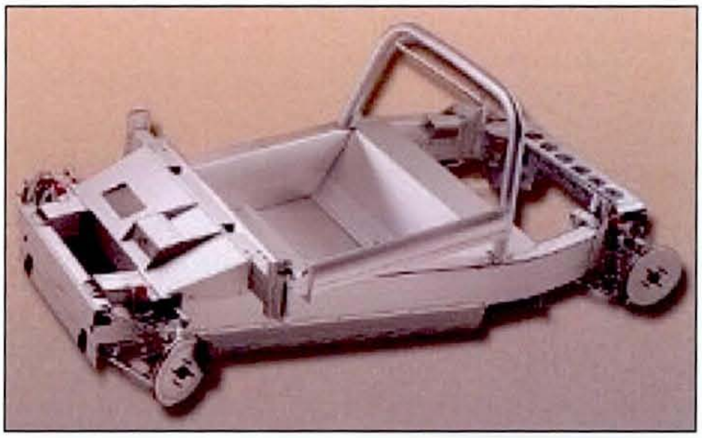


Figure 9: The Elise bonded aluminium chassis weighs half as much as the equivalent one of welded steel (Kochan, 1996)

The use of extrusions as opposed to sheet aluminium also gives cost savings. "The tooling to achieve complex-shaped extrusions costs only a few thousand pounds whereas tooling to press aluminium sheet costs hundreds of thousands of pounds" , says Richard Rackham, who managed the chassis design team. "Tooling cost is a significant factor considering that Lotus is a low-volume car producer. Currently only 750 Elises are produced each year.

Another benefit of an extrusion is that it can be made thick in some areas and thin in others to give components the strength required exactly where it is needed", he adds.

At the start of the project, Rackham's team was uncertain of which joining technology to use and developed two chassis designs, one of which was welded, the other bonded. When tests with a bonded prototype proved successful, the welded one was dropped.

"Bonding has many advantages over welding", says Rackham. First, it is more precise because it eliminates the distortion that comes with welding. "This is very important because in a high-performance car structure, the point where the suspension is joined to the structure has to be controlled to within 0.5mm or there is a great variation in handling between vehicles", he adds. Another factor in the decision was the negative effect of the heat of welding on the aluminium. Bonding enabled Lotus to take advantage of the strength-to-weight benefits offered by heat-sensitive aluminium alloys which could not be welded easily without losing properties. Bonding also spreads the loads across a greater area than welding, providing strength advantages.

Both the design of the extrusions and the design of the chassis are specially adapted to the bonding process. According to Rackham, the basic approach was to design the vehicle frame as if it were Lego. Many of the extrusions link to the neighbouring extrusion with a tongue-in-groove joint. Also, where parts have to come together, the design ensures wide flat areas for the bonded joint.

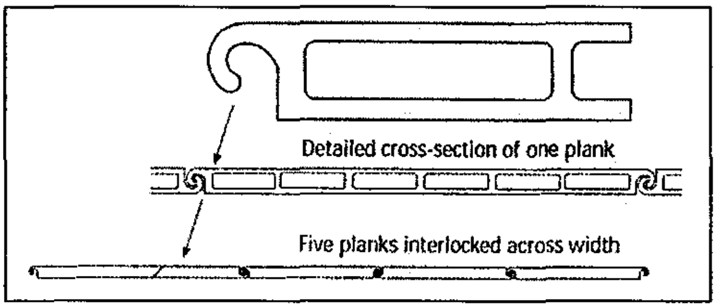


Figure 10: The interlinking structure of the aluminium extrusions used to create the Elise chassis (Kochan, 1996)

The form of the extrusion itself features 0.5mm-high ridges along all mating surfaces to control the gap width. "This ensures that all the adhesive is not squeezed out from between the joint and maintains the gap width at 0.5mm. The adhesive works up to a gap width of 4mm but, because it is expensive, we try to minimise use", says Rackham.

Finding the right adhesive and developing the optimum bonding process for an aluminium chassis was a complex exercise. According to Ken Sears, head of vehicle engineering at Lotus, "unlike the steel industry which shares information, the aluminium industry is very closed". Sears found no available data on aluminium bonding technology which meant Lotus had to develop its own. Swiss company Ciba Polymers was selected to supply the adhesive and collaborated on the bonding process together with Hydro which supplied the aluminium extrusions.

About 35 extruded components and three sheet metal components make up the angular box-shaped aluminium chassis for the Elise.

Hydro was able to develop extrusion tooling capable of a 2mm minimum wall thickness. However, it was not possible to reduce the wall thickness to 1mm which is all that is required in some areas.

Because adhesive-bonded joints are strong in shear but weaker in peel, each joint is reinforced by thread-forming rivets to prevent the onset of peel during a crash. The ejot rivets selected for the task are self-swaging and self-tapping drive screws. They are made from mild steel coated with a high-performance corrosion-resistant finish called Dacromet. This is a zinc aluminium coating that gives a significant 480 hours of salt-spray resistance.

Where a rivet is to be inserted, a hole of 8mm diameter is drilled in the top element, and one of 4mm diameter directly underneath. The 6mm diameter rivet is then rotated at high speed by the special insertion tool and introduced into the larger hole. As it is driven down into the smaller hole, it melts the aluminium around the sides, and the displaced material is drawn up into the larger hole. As a result, thread engagement along the length of the rivet is ensured.

A major exercise in corrosion prevention has led Lotus to adopt Xylan and Delta finishes on components where an aluminium element comes into contact with a steel element. In some places, a coated 0.5mm thick shim is inserted between the aluminium component and the steel component so that it protrudes from the joint by 5mm. This effectively provides a 10mm-long path between the two metals which is sufficient to prevent corrosion, says Rackham. A finish, however, cannot be applied in every case, he adds. For example, there is a circlip to hold in bearings, which cannot be coated. Here, the engineers have employed aerospace-grade grease.

The assembly of the complete Elise chassis is performed by Hydro in Denmark in a specially-constructed controlled-environment building. The clean atmosphere ensures that really nasty contaminants such as silicon cannot get anywhere near the bonding process, says Sears. The adhesive is manually applied to the extrusions, and the more than 130 rivets are inserted before the chassis is loaded into an oven for curing. The rivets also hold the chassis together so that it can be transferred to the oven without falling apart.

The completed aluminium chassis is delivered to the Elise assembly line which has been set up parallel to the Elan line at Lotus' Hethel factory. During the final assembly process, other elements to be bonded to the chassis are joined to it using a cold cure adhesive.

The technologies developed for the Elise have been selected on the basis that volume car manufacturers will be interested in adopting them, says Tony Shute, Elise programme manager. "If we thought that Ford or Opel might not be interested because it was too exotic, we didn't use it", he adds.

However, if the Elise chassis structure with bonded aluminium extrusions is to be adopted by volume car manufacturers, a number of developments will have to take place, says Rackham. "The curing oven is an expensive nuisance. Adhesives technology is evolving and within a few years cold-cure adhesives will become available for this type of application", he believes. Also, the Elise chassis structure is very simple. No complex joints are involved and only straightforward surfaces have to be bonded. "In most cars, complex joints would have to be tackled, and that would require some development", he adds.

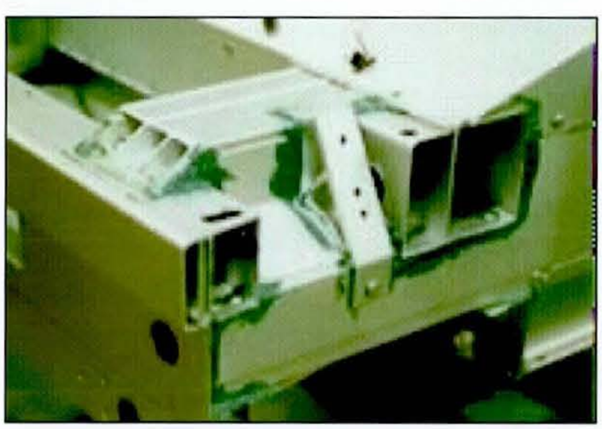


Figure 11: Adhesive and rivets are used to join the aluminium components (Kochan, 1996)

One disadvantage of the bonded design of an aluminium chassis still remains, however. Maintenance and repair is not quite as easy as with steel. Should such a chassis be damaged in an accident, it cannot be repaired by any back street garage. The bonding conditions are too exacting for that. However, the Elise chassis has been so designed that extra boltholes have been formed in those areas susceptible to damage. These holes are there so that a plate can be bolted on to the existing structure to compensate for the damage, should it occur. In the event of a serious collision, the body and the chassis can be separated and whichever is beyond repair can be replaced.

2.2.6 THE AUDI A8

Awareness of an ever-increasing weight spiral due to the high level of comfort and safety in cars was a decisive factor in the development of a new vehicle-body concept for the Audi A8 (Aluminium Extruders Association, 1995; Schretzenmayr, 1999; Kaiser, 1998; and Kaounides, 1995). After an extensive study of the advantages and disadvantages of lightweight materials, Audi came to the conclusion that the most favourable material was aluminium, in various forms. Hence, a completely new body structure, the Audi Space Frame (ASF) (see figure 12), was devised. This enables the design of vehicle bodies with superior characteristics in stiffness, rigidity and energy absorption, while at the same time reducing weight by approximately 40% and consequently fuel consumption and emissions. The fact that aluminium provides large potential in lightweighting

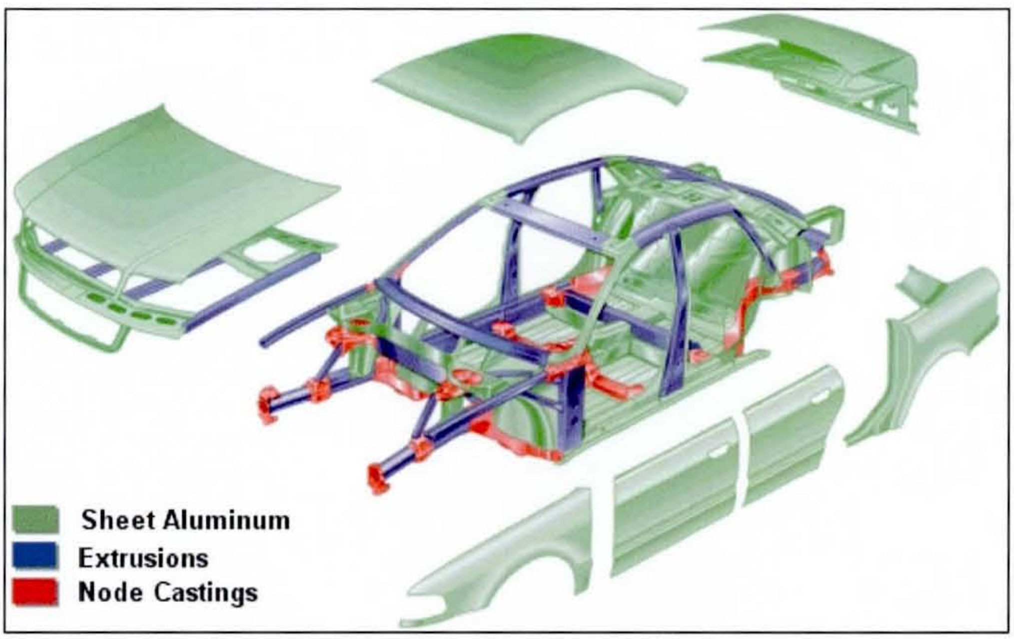


Figure 12: The Audi Aluminium Space Frame (ASF) with hang-on parts (Aluminium Extruders Association, 1995)

technology led to the R&D partnership between Audi and Alcoa, which possesses a vast expertise in the development of aluminium alloys, in processing capabilities, in manufacturing and in structural design.

In terms of process design the three major areas of development were vacuum die casting, extruding and part forming. All these processes require higher levels of process control and monitoring techniques and the development of new thermal methods, quenching systems and ageing practices. The ASF gave rise to a whole range of new manufacturing demands. These comprise, in the main, of five crucial issues, namely joining techniques, surface treatment, dimensional accuracy and tolerances, speed and cost of production.

The ASF structure is similar to a lattice framework, with vacural pressure die-cast parts as nodular elements linked with each other via hollow, straight or curved extruded profile sections acting as support beams. Moulded plates are integrated into this structure as surface-closing parts, which add to the total stiffness, on account of their shear-surface function.

Simply replacing sheet steel with aluminium sheet metal for the hood, tailboard, doors and other exterior shell parts represents, for the car manufacturer, the simplest, surest and cheapest option to reduce the total vehicle weight.

The vacural die-castings facilitate a high degree of geometrical and functional integration, and optimum rigidity, thereby allowing a potential 20% greater torsional stiffness to be exploited.

The use of extruded box-sections eliminates the rigidity losses of conventional spot-welded seams, and the variable distribution of wall thicknesses facilitates the efficient use of material. The windscreen cross-member (see figure 13) is an example of an extruded section having great complexity and demanding close tolerances.

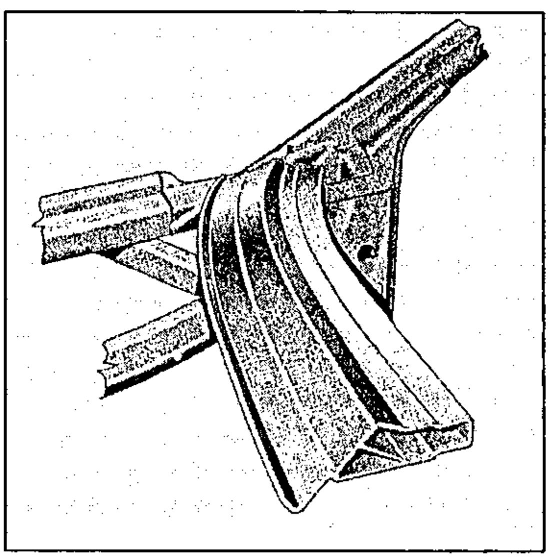


Figure 13: Extruded section windscreen cross-member (Kaiser, 1998)

Extruded, cast and sheet aluminium components offer the potential for revolutionary new construction methods if used with regard to the properties of aluminium.

Aluminium adds its complications to the joining techniques used in the body compared with the traditional steel. The main techniques used in the A8 body are pulsed MIG welding, self-pierce riveting, clinching, and adhesive bonding (for the windscreen and rear window) and resistance spot welding.

MIG welding as a shielded arc welding process is a familiar technique in the automotive industry, but required further development for joining the thinner aluminium sheet gauges used for the Audi A8. In the ASF, all the joints between the node castings and the extruded sections of the aluminium structure are made by shielded arc welding.

The skin panels are mainly joined by self-pierce riveting, the common substitute for resistance spot-welding, because the joint strength is relatively insensitive to surface quality at a comparable installation speed, and the joint has excellent fatigue. The half-tubular rivet pierces the upper sheet, then penetrates the lower sheet without piercing. The punch provides the force for the penetration and the piercing. The bottom die spreads the rivet shank and a form closure has been put into practice. This technology was specially developed for the aluminium space frame concept. For a given sheet metal thickness, punch riveting achieves 30% higher strength than spot-welding. Another advantage that Audi discovered is that it requires less energy than resistance spot-welding.

Most of all single-point joints are riveted. The method is used, for example, for the flanges around the windscreen and rear window, the complete doorframe, the B-pillars and the side flanges of the engine bonnet.

Mechanical clinching, which is achieved by local slitting and/or deformation, is used for lower strength joints because it is quick and simple. It gives a joint without a support joining element. The clinch process is applied in a combined hub- and intersperse action, as well as forming by upsetting to achieve a frictional, form-closed joint.

The Audi A8 ASF is a member of the first generation of aluminium spaceframe vehicles. Alcoa is already working on second-generation alloys which will facilitate cost reduction in manufacturing, on new processing and assembly paths to simplify the manufacture of the spaceframe and on new designs which will consolidate parts, eliminate steps in manufacturing and reduce costs to an even greater extent than at present (Kaounides, 1995). It is a result of these developments and others that led to the Audi A2 covered in the following section.

2.2.7 THE AUDI A2

The Audi A8 is largely a hand-built car and while the strategy adopted by Audi is fine for 15,000 cars a year, production levels of four times that number demand faster, automated systems. This section describes the production and assembly technologies developed by Audi for the A2, the smallest of the vehicles in its range, and like the larger A8, features an all-aluminium body and a space frame design (see figure 14).

Audi had long ago considered and abandoned the idea of developing aluminium monocoques on the basis of repairability problems, double walls and rigidity. The key challenge for Audi, according to programme manager Wulf Leitermann was to develop the proper joining technology

Figure 14: The all-aluminium Audi A2 (Kochan, 2000)

suitable for automated production (Kochan, 2000; Glover, 2000; Kimberley 2000; Anon, 2000c; Adcock, 2000; and Adcock, 2000a).

Advances made by Alusuisse in materials aided Leitermann and his colleagues at Audi's aluminium centre at Neckarsulm who were working on the continued development of joining techniques-self-piercing rivets and laser welding as well as CAD and CAE programmes.

"We have further developed some of the joining methods we used on the A8. And some we have abandoned for the high volume car, such as spot welding and clinching," explained Leitermann. MIG welding, for example, had been further refined for the A2 and other joining systems, such as bonding and riveting (as used by Hydro Raufoss for the Lotus Elise chassis) had been investigated but in Leitermann's opinion were insufficiently developed to suit Audi's current needs. Spot welding had been abandoned altogether.

The floor pan is laser welded to the spaceframe structure of extruded sections and pressure die-castings. The space frame structure is MIG-welded as access from one side is sufficient.

Compared with the A8, the use of various sizes of self-piercing rivets has been increased by 60 percent from 1100 to 1800 in the smaller A2 where they are primarily used to join sheet metal and extruded sections or a combination of both.

But for Leitermann and his colleagues it is the increase in laser welding to a total of 30m that is the big breakthrough in the A2's construction techniques. At the time of the A8's development laser welding was not considered a practical alternative but that certainly is not the case today, with Audi selecting Nd-YAG solid state laser.

There are a number of reasons behind Audi's decision to select this system, not the least of which is that its wavelength is better absorbed by aluminium than CO_2 and is more easily carried by the flexible fibre-optics needed for robotic welding.

Principally laser welding is used for joining the large sheet metal body panels to the skeletal framework of extrusions and castings where access to both sides is not possible (laser welding only requires access to one side of the assembly). The most difficult criterion to meet is the extreme accuracy needed. In the case of the A2's frame the specification is ±0.2mm and, according to Leitermann, should not present any undue challenges.

To reduce production time even further, all of the new car's principal extruded sections are calibrated in a hydroforming plant prior to assembly. This significantly cuts the need for bending and milling operations. It is the near-perfect dimensional accuracy achieved in this process that allows Audi to use laser welding.

In addition to being able to create a joint from just one side, laser welding offers high strength long linear connections instead of spot welds and, where there is an overlapping connection, a smaller flange width is sufficient. It is also considerably faster than MIG at 3 to 7m/min depending on the thickness of the material used.

However, its adoption was not without its problems. As the 6000 type high-silicon-content aluminium alloy, which can be case hardened, was selected for several parts to aid weight reduction even further, it meant that a special feed wire had to be used. Solutions had to be found for the fact that as a maximum gap width of only 0.1mm could be tolerated, the two parts being welded together had to be pushed by mechanical systems fitted alongside the robotically-held welding head. The end result, though, is a cheaper and more efficient process than either MIG welding or riveting.

The only joining technology to have been carried over wholesale from the A8 to the A2 is the folding and adhesive bonding technique used to join the inner and outer door panels.

The A2's all-aluminium space frame consists of 22 per cent castings, 18 per cent profiles and 60 per cent panels resulting in a structure that is 43 per cent lighter than had been assembled from steel. Most significantly, from a production standpoint, there has been a drastic reduction in the total number of components-from the A8's 320 to the A2's 235.

Dr Wolfgang Ruch, deputy head of Audi's aluminium centre cites the B-post as a typical example of the increased functionality of a single component. "In the A8 we have eight different parts and a combination of castings, sheet and extrusions. The A2's B-post is one single casting," he said.

These multi-functional castings represent a new concept in body components, according to Ruch. Not only is the B-pillar a large casting at 1220mm, but it also has to perform a variety of functions, locating the door hinges and latches and the upper seat belt mounting. Moreover, together with the A-post, it performs a vital role in side-impact protection. Because these and other pressure die-castings used in impact zones need to absorb energy, they are manufactured from heat treated GD-AISi10Mg with wall thicknesses varying from 1.6 in the flange area up to 6mm locally.

Ruch believes there is further considerable potential in these tailored castings as materials and manufacturing technologies continue to develop. By further developing vacuum high pressure die casting it will be possible to increase the size of the cast parts and include localised reinforcements where needed.

While castings are used in high strength areas, the A2 also incorporates a number of hollow extruded sections, such as the single-piece cant rails and other linear components (sills and energy absorbing sections like the longitudinal engine mounts). In these areas Audi has been able to reduce minimum wall thicknesses from about 1.4 to 1.5mm in the A8 to a minimum of 1.2mm for the A2 without impairing performance.

Perhaps the most impressive body component is the single-piece side panel that stretches from the A-post through to the rear lights. This has been made possible by a patented tooling concept that allows aluminium panels to be deep drawn like their steel counterparts.

Aluminium body panels, however, are notoriously susceptible to minor dents, whether caused by stones flung up by other traffic, hailstones or even over-enthusiastic polishing or closing a door with your knee. To avoid such blemishes, the sheet or rolled aluminium is age-hardened prior to forming which, in itself, tempers the alloy adding durability and strength.

Despite its space frame structure, the A2 body is constructed in a rather conventional manner. It is made as a series of sub-assemblies (floor pan, tailgate, side panels etc.) (shown in figure 15), each of which is constructed by its own group of equipment. The sub-assemblies are then brought together at a framing station, as in most body shops.

Framing involves the insertion of 232 self-piercing rivets by eight robots working simultaneously.

The body shop, in fact, features a degree of automation of more than 80 percent. It uses 220 Kuka robots, some mounted on rails to provide an additional axis of movement, for a range of operations. An innovative robotic application is flange rolling where the robot uses a roller to join an outer panel to an inner one by folding over a flange.

Unusually for a body shop, milling machines are involved in the assembly process. They "trim" the castings to size on modules such as the front-end and the rear-end assemblies to ensure that the required accuracy is provided for the framing operation. This reduces the accumulation of tolerances and the milling centre allows Audi to adjust the dimensions of sub-assemblies to within one tenth of a millimetre. This is aided by the use of Perceptron measuring heads to determine exactly how much material has to be removed from each casting.

Audi has employed a total of 273 lasers and sensors, consisting of both Perceptron measuring heads and Faro arms, at 19 measuring stations throughout the body-in-white assembly process to

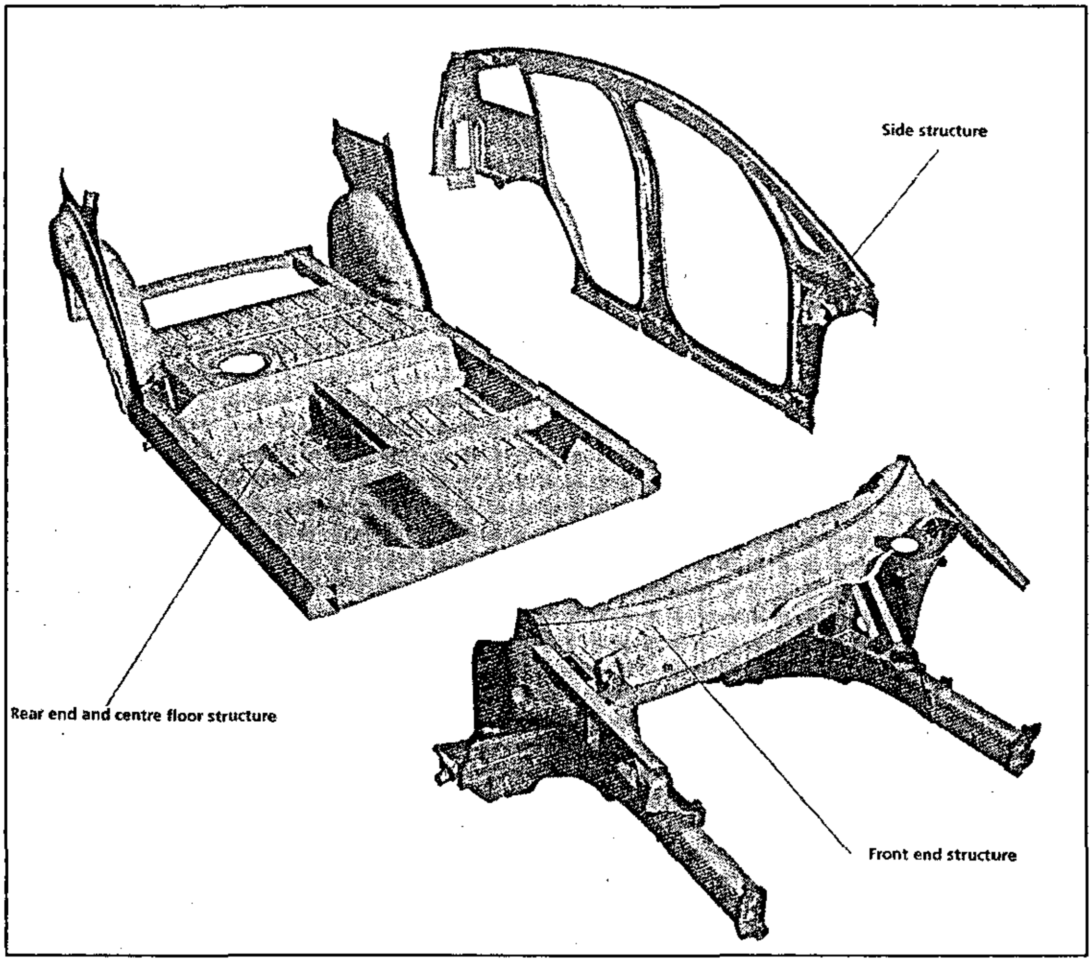


Figure 15: The Audi A2 consists of three major sub-assemblies (Kochan, 2000)

maintain accuracy. The short feedback loops ensure that manufacturing discrepancies are predicted at a very early stage and can be prevented before they have a cumulative effect on the assembly.

To define precise positioning and location of components throughout the assembly sequence Audi uses a Reference Point System (RPS) that establishes the BIW's precise dimensions and location points. The RPS is used throughout the assembly procedure and provides the template for the other checking and machining systems. Problems of aluminium components expanding during welding of the Audi A2 assembly – they can grow by as much as 0.2mm per metre for every 10°C increase in temperature – have been overcome by a novel (and patented) solution that allows the components to expand and contract during welding so that the optimum weld gap is maintained at minimal operating temperatures. This is shown in figure 16.

Before leaving the body shop, the assembled body has to go through a curing oven where it spends 30 minutes while the aluminium components reach the required strength and stiffness. It then proceeds to the pre-treatment and paint shop areas.

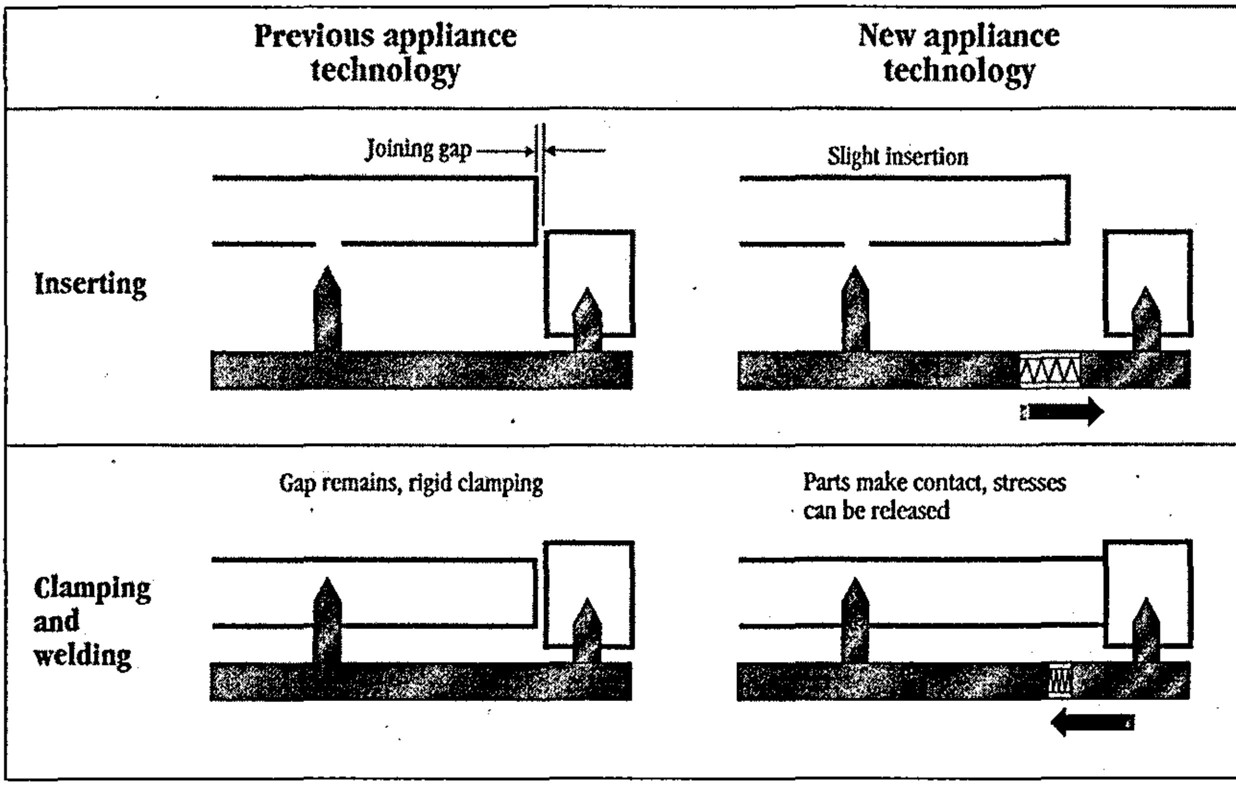


Figure 16: Audi's novel and patented solution for controlling weld gap variation (Kochan, 2000)

The Audi A2's assembly facility represents a significant step forward in the production of aluminium space frame technology and gives Audi a considerable head start over its rivals.

2.2.8 JOINING TECHNOLOGIES

A variety of joining methods are available whereby the components of an aluminium structure can be assembled with the required strength. Typically a mix of them will be used in any one structure, the choice being dictated by a combination of joint performance and practical constraints.

Issues such as capital and operating costs, cycle time, reliability, and quality are just a few of the many issues which must therefore be considered, in conjunction with each of a whole range of potential joining techniques available to the automotive industry.

This section outlines a number of joining techniques with due consideration to production issues pertinent to the automotive industry, in the context of their applicability to either aluminium monocoque or spaceframe structures.

Resistance spot-welding

Spot-welding is the conventional technology of BIW fabrication in the automotive industry, and as such it has the benefit of being a well known, extensively used technology with which the industry is highly familiar and has considerable experience. However, it is also a capital intensive process, and a process with which there are significant problems with regard to welding aluminium. Not least of these problems is the need for access to both sides of the joint, thus restricting it's use in spaceframe fabrication processes.

The primary difficulty experienced in spot-welding aluminium is that of breaking down its surface oxide layer. The substantially higher melting point of this oxide film requires sufficiently higher resistance heating to break it down and thus allow weld formation to take place. The only way this can be achieved in practice is by the introduction of an electrode cooling system to prevent rapid electrode wear as a result of overheating.

The need for such modifications to basic spotwelding equipment, is itself an indication of the extent to which a change in material can affect a manufacturing process. But this change is further compounded when the change from sheet monocoque to spaceframe construction is considered. Current automotive body framing stations employ spot-welders not merely in conjunction with highly versatile robot arms, but also as part of large multi-welders such as the "clamshell framing bucks" used in the production of vehicle bodies. Such equipment is capable of simultaneously applying some 240 welds from 70 guns, reducing fabrication time significantly. However, such equipment tends to be designed for use on specific parts and cannot therefore be readily adapted for use in fabricating spaceframes. Therefore, any argument supporting the retention of spot-welding for spaceframe fabrication, on the grounds that the automotive manufacturer could adapt existing equipment and therefore reduce costs, would not necessarily hold.

Nevertheless, the principal benefits of spot-welding are process speed and versatility, notwithstanding the restrictions on access. It is also a process with which the automotive industry is familiar and therefore has considerable experience in its application. Given the inherent risk involved in adopting new or previously little used joining techniques, such factors should not be ignored.

Arc-welding

Arc-welding techniques such as metal inert gas (MIG), tungsten inert gas (TIG) and manual metal arc (MMA), have the immediate advantage of being known and proven technologies. Of these, MIG and TIG are the most widely used production methods (Barnes and Pashby, 2000). Access to only one side of the joint is required and, provided that each joint is properly designed and suitable welding parameters have been established, joint integrity and quality is high.

There are however some notable limitations to the process so far as the welding of aluminium and the application to spaceframe fabrication is concerned:

Thermally induced distortion: The considerable heat input resulting from arc-welding generally gives rise to a significant degree of distortion. Such distortion is likely to lead to considerable problems in panel fit-up and the relative movement of engine mountings, for example, and is therefore highly undesirable. Lotus engineers cited distortion among the primary reasons for not using welding in the development of the Elise (Kochan, 1996). Such distortion would have required adding extra material to those sections of components where welding would take place. Since extrusions are, by the nature of the process, uniform in section, this would mean attaching discrete additional pieces of material to the components. Such a design could not be considered robust in terms of the quality issues it would raise, and the additional procedures involved would render the fabrication process inefficient. The additional material would also add weight to the tub structure.

Post-weld heat-treatment: Because the structure of the weld is effectively as-cast, and the structure of the surrounding metal, the heat affected zone (HAZ), is significantly changed by the welding process, the as-welded joint is weak. Strengths more closely approximating that of the parent metal can only be achieved by heat treatment, at additional cost. Alternatively, joint details can be designed to reduce stress in the region of the HAZ, thereby increasing the load-bearing capacity of the joint and ensuring a favourable mode of failure. Alternative weld details include tube and socket, post and tube, and staggered lap joints (figure 17).

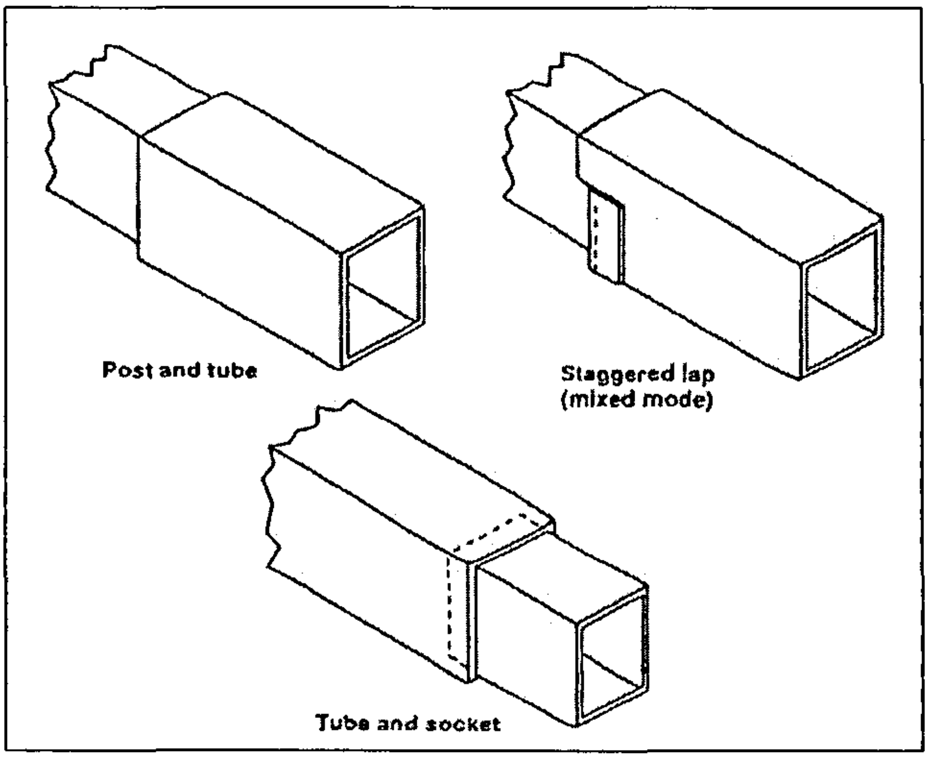


Figure 17: Examples of joints to improve the load-bearing capacity of an arc-welded joint (Barnes and Pashby, 2000)

Arc-welding has been adopted in the manufacture of the Audi A8 where the technique is employed in the joining of extruded components to die-cast nodes. Furthermore, the Audi A2 represents a continuation of the practices used in the manufacture of the A8. Optimisation of production methods as a result of Audi's experiences with the A8 has enabled the number of cast nodes in the A2 to be reduced (Barnes and Pashby, 2000). Many of the cast nodes have now been replaced by butt-welding, facilitating a further reduction in the weight of the spaceframe structure.

Arc-welding lends itself to automation extremely well and therefore remains subject to further development. The equipment though currently very bulky and heavy for aluminium welding can be linked to a robot thereby providing flexibility and process consistency. Alcoa, recognising that arc-welding, a proven technique, has considerable as a production process for spaceframe fabrication, have focused on improving production system reliability. Furthermore, Alcoa are addressing the issue of developing manufacturing guidelines in the areas of process parameters, joint design and fit-up requirements, and weld sequencing to manage assembly tolerances (Barnes and Pashby, 2000).

Laser welding

Commercially available CO_2 and Nd : YAG laser systems are increasingly broadening the scope of their industrial application in the automotive industry. In particular, they are widely being adopted in tailored blank fabrication, a technology that is enabling steel to achieve significant weight reductions.

Laser welding has a number of inherent advantages over arc-welding, which makes the process worthy of consideration for spaceframe applications:

Advantages:

1. The process introduces very little thermal distortion as a result of a lower overall heat input.
2. High processing speeds are possible.
3. Welds are generally of a high quality.
4. Laser systems are particularly conducive to automation, being highly programmable and highly versatile in the materials that can be processed, and the geometry's of joints that are possible.

Equally however, lasers have a number of significant limitations to consider:

Limitations:

1. The relative expensive of capital equipment remains prohibitive, particularly for the cost conscious automotive industry.
2. Limited penetration depths with aluminium, which means that a maximum of 2-6mm is achievable possibly limiting their application in reinforced areas.
3. The highly focused beam, i.e., small spot diameter, means that the process will not tolerate gaps greater than 10% of the material thickness between the abutted edges of the components being joined.

Developments have been made in the combining of the laser with a plasma-arc to create a process known as plasma-arc augmented laser welding (PALW). The advantages offered by this combined process include an increase in the already rapid welding speeds possible with laser systems, and a reduction in the level of joint preparation required. A larger weld-pool is produced by PALW that, whilst this is not always desirable, does not have the effect of relaxing otherwise demanding fit-up tolerances for butt-joint welding. A joint gap of no more than 10% of the thickness of the material being welded can be increased to 60% using PALW. Such a relaxation of fit-up tolerances could have significant cost-saving implications with regard to edge preparation procedures.

With regard to spaceframe structures, wider fit-up tolerances may well prove advantageous. However, the implication is that since this process produces a larger weld-pool, thermal distortion may also increase. The degree of thermal distortion induced in the vehicle structure and its effect on the fit-up of exterior panels, for example, may therefore be an issue.

Diffusion bonding

Diffusion bonding offers potential for further weight savings since the technique can be used to produce efficient structures, whilst eliminating the need for fasteners and associated joint flanges.

The main advantages include simple starting blank forms, high material utilisation, and processing times are insensitive to either component size, complexity of structural form, or the number of components manufactured in one operation.

The actual savings achieved through the use of diffusion bonding in vehicle manufacture would be dependent on the component being manufactured, the equivalent conventional method of manufacture, and the associated material. Clearly, in the case of spaceframes manufacture, the relative economies of this technique would need to be compared against all other candidates.

High frequency butt-welding

As with PALW, high frequency butt-welding was developed to overcome the high tolerances placed on edge preparation for the laser welding of tailored blanks. The technique is still in the early stages of development however, although there it has been demonstrated that there is no evidence of excess material or weld flash at weld sites, which would need to be removed in a separate process (Barnes and Pashby, 2000).

With further development the technique could prove as feasible for the joining of extrusion components for spaceframes, as for the tailored blanking applications for which it is primarily being developed.

Adhesive bonding

The benefits of adhesive binding have been demonstrated by a number of car manufacturers in concept cars and low volume niche products, e.g. Jaguar's XJ220, Ford's AIV, Rover's ECV3, the Lotus Elise, and to a limited extent in Honda's NSX. Not least of these benefits is that adhesive bonding does not distort the components being joined as arc-welding has been shown to do, and there are a number of other advantages:

Advantages:

1. Adhesive bonding offers improved joint stiffness compared to mechanical fasteners or spot welds because it provides a continuous bond rather than a localised point contact. This results in a more uniform stress distribution over a larger area.
2. It is possible to join dissimilar, and otherwise incompatible materials. The adhesive layer preventing intimate contact that could otherwise lead to galvanic corrosion.

The limitations of the process are:

Limitations:

1. Current high performance adhesives are epoxy or solvent-based systems, giving rise to considerable environmental concerns.
2. Structural adhesives require heat curing.
3. There are foreseeable problems with extensive utilisation of adhesive joints in volume production, with limited shelf-life being the prime concern.

Aside from these issues, the need for fixturing to support joints during adhesive curing presents another significant production problem. Such fixturing has tended to result in a process that is both time-consuming and expensive. The combined use of adhesive and mechanical fasteners provides a solution that obviates the need for much of the fixturing but introduces more consumable items, and weight, into the process. Mechanical fasteners will however, improve the peel strength of joints, an otherwise significant weakness. A more efficient solution was that adopted by Lotus, who in developing the Elise, replaced mechanical fasteners in a number of areas by incorporating interlocking details on the extruded parts, as outlined in section 2.2.4. The result was a reduction in the number of parts required, and therefore cost and weight (Kochan, 1996).

Mechanical fasteners

The range of mechanical fasteners currently available is numerous. Self-piercing rivets and clinch joints have been identified as two such types of fasteners with considerable potential for use in vehicle bodies. Both processes are essentially cold forming operations in which two or more pieces of material are mechanically fastened together. There is also no requirement, in either case, for the pre-drilling of holes in the components to be joined.

As the name suggests, the self-pierce rivet is designed to both pierce and form a permanent fastening within the materials being joined. Having pierced the upper sheet of material, the rivet expands in the lower sheet, usually without piercing it, to form a mechanical interlock. The actions of piercing and then forming the joint are carried out in a single operation (figure 18). Such is the

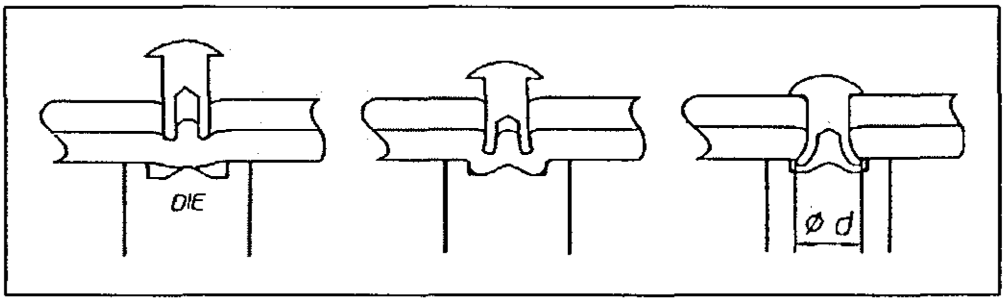


Figure 18: Schematic of the self-piercing rivet process (Barnes and Pashby, 2000).

nature of the process that quite large setting forces are required (typically 40 kN). For this reason, a C-frame structure is necessary in order to withstand the riveting force. As a result, the process requires access to both sides of the joint.

The clinch joint is very similar in that, it too involves the deformation of the material being joined to form a mechanical interlock. Clinching does not however use rivets, using instead a punch to force the material into a die (figure 19). The material is forced between the punch and die in such a way that mechanical interlocking of the sheets themselves occurs. For vehicle body applications the sheets of material are generally not pierced, thereby producing a joint which is sealed against moisture ingress.

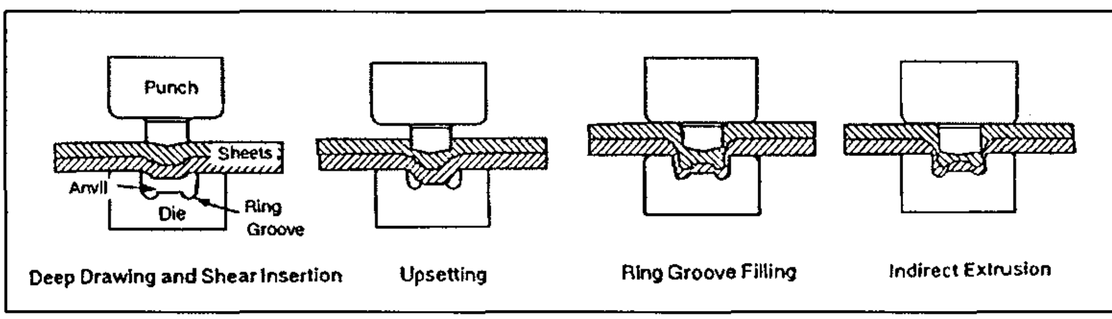


Figure 19: Schematic of the clinching process (Barnes and Pashby, 2000)

The advantages and limitations of these fasteners are summarised below:

Advantages: Both of the above fasteners compare favourably to spot-welding in terms of production criteria:

1. Equivalent speed of operation (~1s per operation). Furthermore, unlike spot-welding, the cycle time for clinching and self-pierce riveting does not increase as the thickness of the materials being joined increases.
2. Ease of automation - the equipment can be adapted for use with a robot, and can be easily integrated into fully automated, high-speed assembly lines. Such integration is made particularly easy by the elimination of the need to pre-drill (or punch) holes, and also therefore, the need to align the holes with the rivet setting equipment.

3. Good tool life (spot-welding - ~500-2000 operations (for aluminium), SP rivets and clinching - ~200,000 operations).
4. Low energy process.
5. Little or no part distortion.
6. Simple set-up.
7. Relatively low capital and operating costs, and equipment has a long service life.
8. It is possible to join dissimilar materials.

Limitations

1. Both techniques require access to both sides of the joint.
2. The size of the riveting gun restricts access to certain joint areas.
3. Bulges and indents associated with both techniques may not be aesthetically desirable.
4. Self-piercing rivets introduce additional consumable items, and therefore weight, into the process.
5. Despite the use of passive coatings to prevent corrosion, surface irregularities or crevices occur as a result of the deformation process that could allow corrosion to occur.

The use of blind rivets in lightweight structures is not obviated by the considerable benefits offered by self-piercing rivets and clinch joints, not least because blind rivets require access from one side of the joint only. The need for dual access is a significant disadvantage which may preclude the use of self-piercing rivets in some areas of a spaceframe construction.

Equally, blind rivets present significant problems by the necessity to pre-drill holes. This introduces an additional operation and requires considerable hole position accuracy and tight assembly tolerances in order to avoid significant assembly problems.

EJOT self-drilling rivets from Germany, are a notable exception which combine the benefits of single-sided access with an ability to produce their own hole by the incorporation of a drilling or forming head into the rivet's design. Where a forming rather than a drilling head can be applied, there is an added advantage that little or no swarf is produced, therefore minimising the risk of swarf entrapment leading to damage elsewhere.

Despite requiring access to both sides of the joint area, clinching and self-pierce riveting in particular, are nonetheless commanding considerable interest from the automotive industry. Such interest exists not least because these processes are extremely robust, relatively low cost, and greatly simplify production by eliminating the need for hole drilling and hole alignment.

Specific interest has been shown in self -pierce riveting by Alcoa and Audi, who tested out the technique in their ASF all-aluminium car body concept (Aluminium Extruders Association, 1995;

Schretzenmayr, 1999; Kaiser, 1998; and Kaounides, 1995). Their conclusions were that despite the consumable cost of the rivet, the technique appeared to be a low cost but more robust option than spot-welding. Lotus also used self-piercing rivets in the construction of a lightweight-chassis for the Elise. In joining the aluminium extrusions which make up the chassis structure, Lotus made extensive use of adhesive bonding, with rivets providing secondary protection against peel (Kochan, 1996).

Clearly, as a result of the automotive industry's increasing interest in, and the difficulties associated with joining aluminium, mechanical fasteners (probably in conjunction with adhesive bonding) are rapidly emerging as a feasible alternative to the conventional method of spot-welding. Self-piercing rivets in particular are attracting considerable interest within the industry and will certainly continue to feature in the further development of lightweight, aluminium-intensive vehicles.

Comparison of joining

The most significant technical difficulties with regard to welding aluminium are associated with its stable surface oxide layer. Whilst surface oxide also presents problems for adhesive bonding, necessitating pre-treatment to remove it, the need to design around the inherent weakness of adhesive bonds in peel is at least equally problematic.

The uncertainty regarding the long-term durability and weatherability of bonded joints, and the lack, at present, of a reliable method of NDT to test for defects are also significant areas of concern. Despite the substantial benefits of adhesive joints, such shortcomings mean that adhesive bonding does not compare favourably with welding, an area in which the industry has far greater experience and therefore confidence.

In contrast, mechanical fasteners show far greater promise given that self-piercing rivets and clinch joints, for example, have been shown to compare favourably with spot welding in terms of speed of operation, ease of automation and tool life, etc. Moreover, current mechanical fastener systems also offer a safe, low energy process, which is simple to set-up, and costs relatively little in terms of capital and operating costs. Here the benefits over predominantly energy intensive, hazardous and expensive welding techniques are clear. However, mechanical fasteners also share some common disadvantages with spot welding, such as the need to access both sides of the joint and restricted access to joint areas due to the size of the gun.

The combining of adhesive bonding with mechanical fasteners, generally termed riv-bonding, may provide a more robust solution and is being actively researched (Barnes and Pashby, 2000; Messler, 1997, 2000). Such a combination brings together the benefits of both techniques whilst minimising or removing some of the limitations. For example, the ability of adhesives to seal joints against moisture is a highly desirable one, as is the ability to damp noise. The addition of mechanical fasteners increases the otherwise poor peel strength of the joint, thus resulting in a joint which offers the best of both techniques.

However, from a production viewpoint the fabrication process now involves a second processing operation with its associated implications for process control and added cost. Also, the environmental hazards associated with adhesives are unaffected when combined with riveting, and would therefore continue to be a significant disadvantage of the process.

Despite the difficulties posed by surface oxide in welding aluminium, and generally high capital and running costs, the industry's long-standing experience with welding will almost certainly ensure that further development of the various techniques available will continue. Even high cost technologies such as lasers are gradually beginning to find applications in the automotive industry, as the technology develops to meet the industry's needs. In contrast, adhesives have been shown to have some significant way to go before, structural bonding in car bodies can be fully realised. Nevertheless, the not inconsiderable benefits of adhesives mean that they too are unlikely to be discounted at this stage.

Moreover, the ability to combine adhesive bonding with mechanical fastening techniques and the considerable benefits that ensue, markedly increase the viability of both techniques for the volume production of vehicle spaceframes.

There are some significant issues with regard to production capacity and process speed, as well as a lack in some areas, most notably adhesive bonding, of an adequate means of ensuring process consistency and product quality. Where such issues arise, a significant amount of further work will be necessary before automotive manufacturers can gain sufficient confidence in these processes to commit to the substantial investments required, and the associated business risk.

There is also great potential in the combining of processes to produce effective hybrids. Examples of these include riv-bonding, as discussed previously (combining riveting and adhesive bonding), or weld-bonding (combining spot- welding and adhesive bonding). It is evident that such combinations enable the benefits of both processes involved to be enjoyed, whilst some of the more significant shortcomings are minimised or eliminated.

2.3 MODELLING OF WELDED ALUMINIUM ASSEMBLIES

The assembly of aluminium castings and extrusions into a finished structural spaceframe most often requires close three-dimensional tolerances. Variability in the component parts or the assembly process can result in an inability to fabricate the final structure such that it meets the required dimensional tolerances. The actual variability, the factors affecting them and the impact of each variability, separately and combined, on the final assembly variability need to be understood to improve manufacturability and quality; and reduce costs.

The biggest problem facing engineers in welding fabrication of aluminium structures is predicting the residual stresses and distortion. This phenomenon is magnified even more so with aluminium than steel structures due to the higher heat conductivity, larger coefficient of thermal expansion and lower yield strength. The resulting distortion and residual stresses leads directly to variation in the assembled structure. To combat these problems, there has been a significant number of studies completed on methods to control distortion as well as improve analysis techniques (Masubuchi, 1980, 1991, Brumbaugh, 1973). Many of these resulted in general guidelines in welding (Masubuchi, 1980), though very few have concluded with a broad theoretical method to predict weld distortion or shrinkage. Most welding predictive models are directly related to empirical data.

By nature, welding is not a predetermined manufacturing process. Few mathematical models can accurately describe the internal stresses that result from welding. One approach is to run multiple experiments on specific types of materials across various geometric shapes, but this is time consuming and very specific. More often, it requires complex modelling techniques such as finite-element methods to understand such a process. Many believe that predicting weld distortion is a black art, a skill that is learned from years of experience in manual welding. Predicting the outcome of just two parts welded together is difficult enough. When this is extended to an entire assembly of parts, the task becomes a complex one.

Hu *et al.* (1997) modelled different kinds of joint configurations and variation characteristics in sheet metal assemblies (presumed to be steel). Daniel *et al.* (1986) modelled product variations based on rigid body assumptions implementing computer aided techniques. Takahashi *et al.* (1991) took variation simulation and tolerance analysis even further by applying it to rigid body assemblies by looking at part contact states.

Applying variation modelling to assemblies joined by welding is not an entirely new approach, yet there has been relatively limited research in this area completed to date. Hu (1996, 1997) developed a "Stream of Variation" theory to examine variation propagation in the spot welded assembly of flexible parts. The technique first looks at how variation propagates through the system, then tries to locate sources of variation where there might exist a quality problem. Hu made it clear that modelling of spot welded sheet metal assemblies differentiates from other structures since it is compliant. Many of the previous techniques are based on rigid body assumptions. In order to completely model the system Hu employed a combination of simple flexing models and statistical analysis.

Most of the work in the area of modelling welding distortion has been limited to very specific studies on particular weld joint types and materials. Some specific studies on various types of aluminium welds have resulted in some applicable techniques to capture both shrinkage and distortion.

A large contributor to the study of welding distortion, Masubuchi, provides a detailed discussion of all the effects produced by welding; as well as the development of methods for predicting and controlling distortion in welded aluminium structures (Masubuchi, 1980). In other studies, Masubuchi outlined methods for actual in-process reduction and control of residual stresses and distortion in weldments.

Dimensional variation and distortion in aluminium weldments can be due to a variety of effects: transverse shrinkage between parts, longitudinal shrinkage along the weld, angular distortion, and rotational distortion.

There are five common types of mating joints found in aluminium assemblies of extrusions and castings. Table 2 displays the common types of joints and the applicable welds associated with them.

Out of these joint types, there are three main types that are encountered in an aluminium welded frame: lap joint, T-joint, and butt joint. For structural applications the other types of joints, edge and corner, are usually avoided since they are harder to fit, weaker, and more prone to fatigue failure.

2.3.1 DISTORTION AND DIMENSIONAL VARIATION IN WELDMENTS

Residual stresses and distortion are closely related phenomena. During heating and cooling in the welding cycle, thermal strains occur in the weld metal and base-metal regions near the weld. The strains produced during heating are accompanied by plastic upsetting. The stresses resulting from these strains combine and react to produce internal forces that cause bending, buckling and rotation. It is these displacements that are called distortion (Masubuchi, 1980).

The dimensional changes that result from the welding process can be classified into the following categories:

1. Angular distortion: an angular change close to the weld line.
2. Rotational distortion: an angular change in the plane of the plate due to thermal expansion, most common in butt joints.
3. Transverse shrinkage: a shrinkage perpendicular to the weld line.
4. Longitudinal shrinkage: a shrinkage parallel to the weld line.

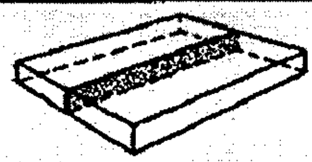
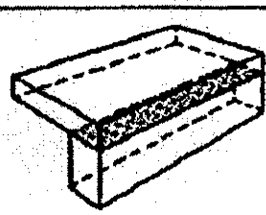
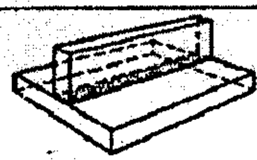
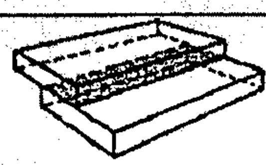
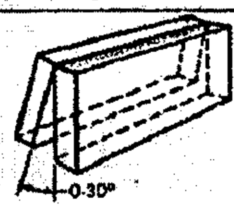
WELD JOINT TYPE	APPLICABLE WELDS
 Butt Joint	• Square-Groove • V-Groove • Bevel-Groove • U-Groove • J-Groove • Flare V-Groove • Flare Bevel-Groove • Edge-Flange
 Corner Joint	• Fillet • Square-Groove • V-Groove • Bevel-Groove • U-Groove • J-Groove • Flare V-Groove • Flare Bevel-Groove • Edge-Flange • Corner-Flange
 T-Joint	• Fillet • Square-Groove • Bevel-Groove • J-Groove • Flare Bevel-Groove
 Lap Joint	• Fillet • Bevel-Groove • J-Groove • Flare Bevel-Groove
 Edge Joint	• Square-Groove • Bevel-Groove • V-Groove • U-Groove • J-Groove • Edge-Flange • Corner-Flange • Edge

Table 2: Common weld joint types and associated welds (Masubuchi, 1980)

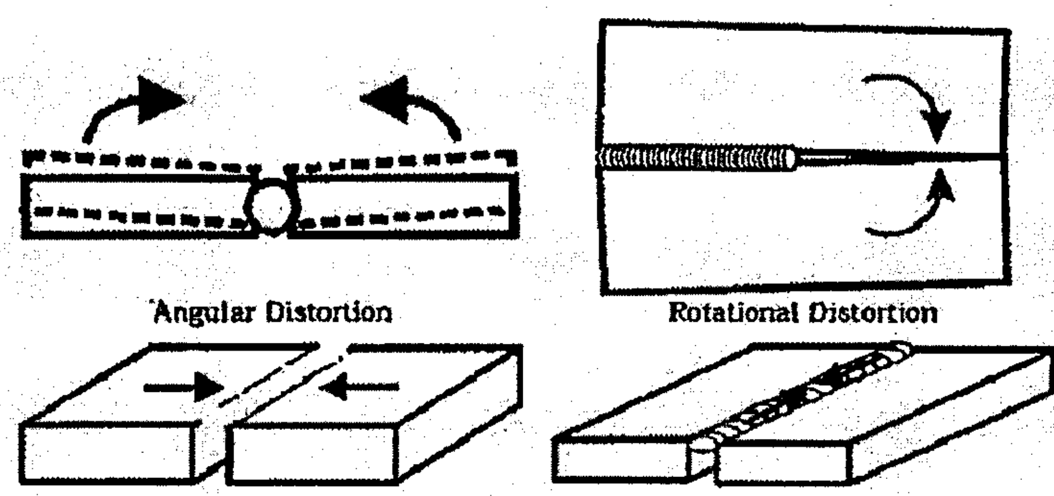


Figure 20: Various weld distortion effects (Masubuchi, 1980)

5. Longitudinal bending distortion: distortion in the plane through the weld line and perpendicular to the plate.
6. Buckling distortion.

Some examples of the different distortion effects, as seen for a butt type weld, are displayed in figure 20.

2.3.2 TYPICAL MIG WELDED ALUMINIUM AUTOMOTIVE STRUCTURE

Painter (1995) used a hypothetical MIG welded aluminium frame as an example to demonstrate and support the capability of methods proposed for variation propagation and tolerance analysis (figure 21). The frame was a simplification of an actual frame made in a real production environment. This consists of a combination of extrusions and castings joined together to make a complete assembly.

First piece parts are manufactured by either an extrusion or casting operation. The extrusions are then subsequently bent either by a rotary bend method or by a stretch bending operation. At the same time, castings undergo an additional heat treatment and sometimes a subsequent

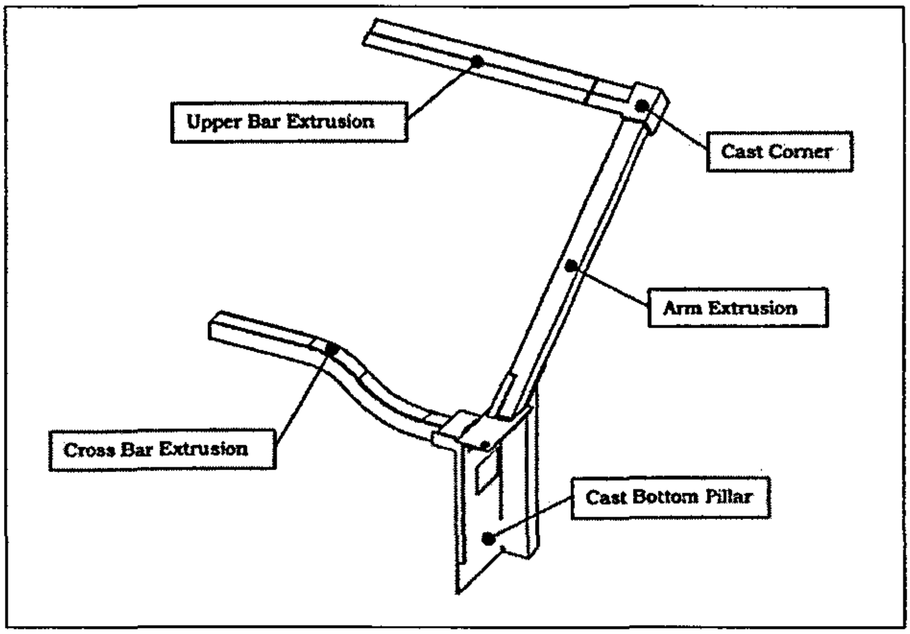


Figure 21: Hypothetical MIG welded aluminium frame (Painter, 1995)

straightening process. This is often followed by machining and/or grinding in order to maintain the required tolerances and remove any rough part variations.

A common method with welded aluminium structures is to first join certain components believed to have sensitive welds, into a sub-assembly prior to final joining. The smaller sub-assembly offers to maintain greater control of the welds. Then the sub-assembly and the remaining parts are loaded into a final weld fixture and joined together. The joining process itself almost always consists of a predetermined sequence in which the welds are made.

Part shape errors enter the system at the weld fixture locations, causing variations in the gaps between the parts at weld locations. Gap variation then becomes an input to the welding process, which also introduces uncertainty due to material and process variations. Finally, the welding uncertainty leads to variation in the final assembly state.

Painter (1995) models the entire system of manufacturing operations which allows key sources of variation and output quality characteristics to be identified. Back propagation is used to determine intermediate tolerances in relation to the final required output tolerances.

2.4 COMPUTER-AIDED VARIATION ANALYSIS

For a long time, tolerancing has been one of the most difficult and least understood activities in design. Every designer knows that the proper functioning of an assembled product depends on the size of the clearances in the joints between the parts. However, it appears to be problematic to assign clearances in complex assemblies such that all functional and assemblability requirements are guaranteed simultaneously. Clearances, which essentially are attributes belonging to pairs of parts, have to be converted into tolerances, which are attributes of single parts. This process has to be carried out with manufacturability, interchangeability and maintainability considerations in mind.

The relations between the tightness of tolerances and the manufacturing cost are usually non-linear and do show discontinuities when the limits of process capabilities are exceeded. Moreover, the relations between tightness of tolerances and the quality of the functioning are not always clear. Because of this, it is quite impossible for a human being to define fully consistent interrelated sets of requirements for distance, concentricity, straightness etc. Usually, tolerances are specified for every functional requirement without much attention for the side effects. This leads to inconsistent tolerancing schemes, which contain excessively tight tolerance values. As a result, the parts become expensive and the proper functioning of the assembly is still not guaranteed.

The consistency of tolerancing schemes is becoming a topic of concern now computer-based geometric modelling is getting mature. Presently it is possible to build virtual product models with thousands of parts, which can have very complex shapes and geometric relationships. However, the specification of allowable deviations from the nominal geometry is still a big problem. Until now, the CADCAM systems used in industry have provided inadequate support in the definition, analysis and synthesis of tolerances. A number of systems are not capable of representing them properly.

Tolerancing has become an important issue for CADCAM vendors. The latest generation of CADCAM systems use advanced geometric modelling and constraint satisfaction kernels. The technology used in these kernels can be applied to macro geometric aspects as well as micro geometric aspects.

The creation of virtual product models only for visualisation and marketing purposes does not pay off. The real profit can be made if the data can be used for the subsequent downstream processes. For instance, the process planning function can be automated to a high degree, if consistent micro geometry specifications are available.

A number of research groups have been working on tolerancing issues for a number of years now. They are trying to bridge the gap between the mathematical formulation of problems and the practical aspects in terms of computer representation, automatic or computer assisted specification, consistency and completeness analysis and tolerance set optimisation.

Some efforts have already resulted in commercially available tolerancing software packages which are being used in industry. Most of them focus on tolerance analysis and optimisation. Also efforts are being undertaken to bring the tolerancing standards up to the present requirements.

Many companies do not have a clear methodology for tolerance specification. Most designers use intuition and experience. Sometimes they follow general guidelines. As a consequence, most product designs do not contain all functionally relevant tolerances while some tolerance values are too tight. A clear and reliable method for tolerance specification is required as part of an overall tolerance management strategy. Tolerance management includes all design, manufacturing and inspection activities, striving to control and optimise the effect of geometrical variation. In this way computer-aided tolerancing tools should be used to increase geometric robustness during concept design and to assign tolerances on the basis of sensitivity, manufacturability and cost during the detailing phase.

Within the context of robust design and life cycle engineering, education about consistent tolerancing becomes a very important item. With a consistent tolerancing theory at hand it becomes to teach robust design as a science.

Reviews on representing and processing tolerances can be found in the work by Roy *et al.* (1991). Juster (1992) reviews modelling and representation of dimensions and tolerances. Another review on tolerance analysis and – to a lesser extent – tolerance specification can be found in Chase and Parkinson (1991). A more philosophical approach perspective is provided by Voelcker (1993). In previous work a number of authors make the distinction in the following main fields within computer-aided tolerancing:

- tolerance representation
- tolerance specification
- tolerance analysis, and
- tolerance synthesis.

Tolerance representation refers to how tolerances are represented within a geometric model, which is important for applications processing these tolerances. Tolerance specification is the activity of specifying tolerances; defining the tolerance types and tolerance values as well as datum systems. Tolerance representation is important together with tolerance specification as the way in which tolerances are represented often influences the way in which they can be specified and vice versa. An adequate tolerance representation enables computerisation of applications following tolerance specification such as tolerance analysis and synthesis. Tolerance analysis is a method to verify the proper functioning of the assembly after tolerances have been specified. A distinction can be made into worst case, statistical and sampled tolerance analysis. Tolerance specification and tolerance analysis are often iteratively applied. Tolerance synthesis is sometimes referred to as tolerance allocation.

Assigning tolerances is considered to be one of the most important and difficult tasks in trying to achieve vehicle specifications. It involves an agreement or commitment between part manufacturers and assembly plants on the achievable tolerances based on what they believe are their respective process capabilities. One can imagine that if the part tolerances are too big, vehicle requirements might not be obtained. For example, suppose a gap of 5 mm ± 0.5 mm is specified for the complete vehicle. Tolerances need to be assigned to the various subassemblies, such as body-in-white, doors, and the door hanging process. In turn, tolerances need to be broken down and assigned to the parts of these subassemblies, such as door-inner panel, and door-outer panel for a door assembly. However, questions like how the tolerances are accumulated need to be answered first, since it is an integrated part of tolerance synthesis.

2.4.1 TOLERANCE ANALYSIS

A metric for the overall product is the amount of variation of the whole from the nominal dimensions, as caused by the variation in the parts. A typical method for determining the overall variation is *stack-up*: by adding the variations in the parts to arrive at the variation of the whole.

Engineers are often faced with the necessity of predicting the tolerance of an assembly. Tolerance analysis is the procedure that evaluates the effect of part tolerances (independent variables) on the assembly tolerance (design function). Usually it is necessary to find the tolerance analysis model between the design function and the independent variables.

Since tolerance is defined as the permissible level of variation, techniques used for variation simulation analysis are the same as those used for tolerance analysis. There are presently three primary methods available for the analysis of assembly tolerance variation. These methods are: worst case analysis, statistical analysis (root sum square), and Monte Carlo simulation (Variation Simulation Analysis / Modelling).

The worst case method was the first version of variation stack-up for one-dimensional assemblies. It evaluates the assembly under the assumption that all parts are built to their extreme values. It generally requires very tight and unrealistic tolerances for the parts in order for the final assembly tolerance to meet the design specifications.

The probability of each part in the assembly having the "worst case" dimensions simultaneously is usually very small. This tolerancing technique generally requires very tight and unrealistic tolerances for the parts in order for the final assembly tolerance to meet the design specifications.

In statistical analysis, the variation of the parts is specified as statistical distributions. Calculating the distribution of the design function based on the part distributions is the task. Statistical analysis yields a more realistic estimate and looser part tolerances than the worst case method. It is also more practical for modeling interchangeability of mass production processes, because part distributions are taken into consideration.

A sub-case of statistical analysis, root sum squares (RSS), is based on the assumptions that the variance of the dependent variable can be expressed by a first order Taylor's series expansion of the independent variables. It is common practice to take the part variability as normal distributions with mean at the tolerance midpoint, and the natural tolerance limits at plus and minus three standard deviations. The statistical distributions of part dimensions are taken into consideration. This allows the assembly tolerance to be looser than based on the worst case. Results are therefore closer to real assembly situations. The method is simply to add the sums of the squared tolerances and take the square root of the total. The assumption of the normal distribution is needed.

For mass production, Monte-Carlo simulation is used to create a statistical distribution of an assembly by randomly selecting many values from the known distribution of parts. The procedure is as follows:

- Generate random numbers (deviations) for each part dimension based on the probability distribution.
- Create a mathematical description of how the parts are assembled.
- Repeat 1000-2000 times and create a histogram of the results. The resulting histogram will have a mean, and a standard deviation.
- Study the results and revise the part tolerances if necessary and re-simulate the procedure until the desired assembly tolerance is achieved.

A number of computer-aided tolerancing (CAT) software systems combine Monte-Carlo simulation and statistical techniques to predict the percentage of nonconformance for any dimensional assembly characteristics and determines the factors that cause the nonconformance, such as variation in part properties, assembly methods, and assembly sequence. With this information, it is possible to optimize tolerance values, dimensions, or assembly methods.

The model also represents assembly methods and sequences including bolt-to-hole clearance, and three-dimensional locating schemes. Attachments to locating fixtures that contribute to overall assembly variation are also included in the model.

Random number generators are used to select values for each dimension associated to each part, based on the distributions of part dimensions. Output variables (assembly dimensional distributions) are displayed graphically. Based on assigned functional specifications, the predicted nonconformance is obtained for each output variable.

However, all these techniques do not consider the non-rigid behaviour of deformable parts. In deformable assemblies, part variations do not stack up as these conventional models predict. Takezawa (1980) applied linear regression models to real production data for automotive body panel subassemblies in modeling variation, and concluded that for deformable sheet metal assembly, "the conventional addition theorem of variance is no longer valid for determining the permissible limits (tolerances) for the automotive body assembly." In addition, his regression models showed that the dispersion for the assembly was closer to the variance of the stiffer part, and tooling was quite effective to control dispersions of an assembly. He concluded that analysing the variation of deformable parts assembly, parts deformation had to be considered.

2.4.2 COMPUTER-AIDED TOLERANCING (CAT) SYSTEMS

CAT systems have evolved considerably since their initial creation. This evolution has been made possible by advances in both computer hardware and software, which have brought about improvements in areas of software visualisation, accuracy, speed and ease of use. This improvement in computational power has given the user access to statistical data not previously available and therefore given them the ability to solve new, more complex, numerical problems. This has been especially beneficial in customer driven fields such as the automotive sector. The latest types of software are integrated within CAE packages and allow the user to obtain geometric data straight from CAD sources thus removing the need for complex programming to describe assemblies

There are various different companies offering software and consulting to aid dimensional management programs; the three main players are:-

- Unigraphics (Owners of Engineering Animations Inc. and Variation Systems Analysis – VSA)
- Dimensional Control Systems (DCS)
- Catia V5 Release 13 – Tolerance Analysis of Deformable Assemblies (TAA)

VSA and DCS can trace their roots back to General Motors and their push for dimensional management in the '70's.

Variation Systems Analysis (VSA)

VSA defines a 6-step process for implementing DM into a company, which goes far beyond the software analysis of an assembly:-

Step 1 – *Clearly define product dimensional requirements.*

The first step ensures that you know what you are aiming towards so that any measurements can be measured against this specification. These requirements may concern assembly tolerances, which have been determined from an actual need for the function or appearance of the assembly, and should be customer driven (e.g. gap and flush requirements). Sometimes the specification can be functional such as for suspension assemblies where limits for toe and camber angles can be defined as requirements.

Step 2 – *Determine if the design, manufacturing and assembly process optimally meets the product requirements.*

This stage is a capability study to determine if your design can fulfil the criteria set out in step 1. This can be done in one of three ways:

1. Guess.

2. Build many thousand prototypes to prove the capability.

3. Simulate the building of the product in 3-D with full variation of dimensions as per the engineering drawings.

Obviously only the third method offers an accurate, speedy and cost effective capability study.

Step 3 – *Ensure that dimensional management product documentation is correct.*

This step ensures that your product will be manufactured and assembled correctly and using the most up to date information. This is essential if the information gained from step three is to be the same as what will be made.

Step 4 – *Measurement plan validates product requirements.*

The measurements taken for the product should reflect the specification in step 1 and documentation in step 3. Features must be measured with respect to the same datums and targets used in both the documentation and of course the simulation. If there is any discrepancy between the method of measurement in the simulation and real life, then the results will be meaningless and the simulation must be corrected and re-run.

Step 5 – *Manufacturing capabilities achieve design intent.*

The capability study should verify the findings from the simulated study, which should (ideally) show that all measurements meet the specification.

Step 6 – *Production to design feedback loop.*

Where any areas are found not to meet design intent a solution must be found, provided the cost can be justified in terms of the impact on the final product. Once the solution is implemented the 3-D model and documentation must be updated and the process rerun.

The VSA software tools have changed considerably over the years and especially after VSA was sold to Engineering Animation (EAI) in 1999 and then acquired by Unigraphics in 2001. Unigraphics have inherited the expertise of EAI in product visualisation and concurrent engineering tools and this emphasis has led to the integration of VSA into their standard visualisation tools with a view to removing the specialist understanding currently required to use the software. The change in the VSA software can be followed through its various guises released over the years:

VSA 3-D release 12.5 – This is often referred to as the 'stand-alone' software since it runs on a desktop PC without the need for CAD data. It is marketed as a design verification tool to be used as part of the design process. Component part geometry and tolerance information must be entered manually using VSA's own variation simulation language (VSL), which is similar to the 'C' programming language. The user must also code assembly information and where the software should take measurements during the analysis. The VSL file is then compiled and the statistical analysis carried out. The end result is a set of charts for each measurement output showing both graphically and numerically the range and central tendency of the variation. Values are also given for conformance to specification so the user can see how many parts that are built are expected to be scrapped.

CAD Integrated VSA – The integrated VSA product is in essence just a translator to take CAD geometry and tolerances and turn them into VSL code to be used in the statistical analysis. The statistical analysis and reporting options remain unchanged from the previous version. There is no need to hand code geometry and tolerance information in a separate step making the CAD based version of VSA easier to use and faster than version 12.5. However, due to some tolerances and assembly types not being supported by the software some manual coding is still required.

VisVSA – This product is a direct result of a VSA/EAI software development team collaboration, which has married the VSA software analysis core with EAI's visualisation tools to create an add-in component to run seamlessly within EAI's VisView/VisMockUp software packages. The aim of the new software is to remove the need for specialist knowledge usually needed to operate such software and to make tolerance analysis a one-click solution.

VisMockUp – EAI created VisMockUp as a digital prototyping software tool to allow the viewing and verification of CAD data on an ordinary office PC. This can be used to aid concurrent engineering practices during product development to verify assemblies for collision and annotate the CAD data with comments about corrective action. Where different areas of design may be based great distance apart VisMockUp can be used for online data collaboration and product data management. VisMockUp provides further functionality such as the ability to animate assembly processes and to take measurements from the CAD geometry which can be useful in assembly line situations to replace engineering drawings as a means of communication.

Dimensional Control Systems (DCS)

DCS is a Michigan based US dimensional engineering firm specialising in software tools for variation analysis and DM engineering consultancy. Their track record spans over 15 years includes many academic collaborations as well as supplying DM solutions to many original equipment manufacturers (OEM). DCS' tools for variation analysis are similar to those used by VSA in that they rely on geometric part information coupled with tolerance/GD&T data to create a 3-D tolerance model. This 3-D model is then subject to two statistical tests; a Monte Carlo variation analysis and a HLM sensitivity study. This software study forms an integral part of DCS' ten-step dimensional control procedure, which is defined as:

1. Identify and document dimensional quality goals.
2. Team consensus and signatures.
3. Develop strategic plans to achieve all dimensional quality goals.
4. Determine global tolerance and major datums for major sub-assemblies.
5. Generate tolerances and datums for all parts and assemblies, statistical simulation, work towards buy-in from all team members – this is the key engineering phase.
6. Optimise the design/process through 3-D analysis.
7. Verify prototype tool and fixture designs – validate gauge and fixture capability.
8. Evaluate prototype results.
9. Verify production tool and fixture designs – validate gauge and fixture capability.
10. Support during pilot, launch and production.

Information gathered from steps 8 and 10 acts as feedback to be put back in at step 6 to allow optimisation of the product for dimensional robustness.

The software tools used operate on a standard PC workstation platform easing accessibility to non-CAD operators. The 3-D geometry is imported from CAD data via an IGES file converter and there is also the option to manually build simple geometry. Because of this CAD-like operation there is no manual programming language accessible to the user, which does mean that the ability to develop custom code is lost. The 3-D geometry can be visualised within the dynamic tolerance simulation package (3D-DTS).

CATIA V5 Release 13 – Tolerance Analysis of Deformable Assemblies (TAA)

TAA is the advanced module released with the introduction of the first P3 (Platform 3) configuration of Catia V5. The module has been developed for the Tolerance Analysis of Deformable Assemblies (TAA). Its function is to 'assess the impact of the assembly process on flexible components.' In real-world terms this will allow users to create a digital simulation that follows the assembly of a particular set of components (such as a car body panel) and gauge the effects that the various production processes have on the tolerance of that assembled product. Whereas this type of work may be possible within other high-end systems at a basic level, what will make this most interesting will be the ability to use the Catia knowledgeware functions to experiment with different manufacturing processes (such as variation in welding positions and timing) and accurately gauge the effects they have on the tolerance of the final product. All of this allows users to optimise, not only the form of the part, but also the production of the part.

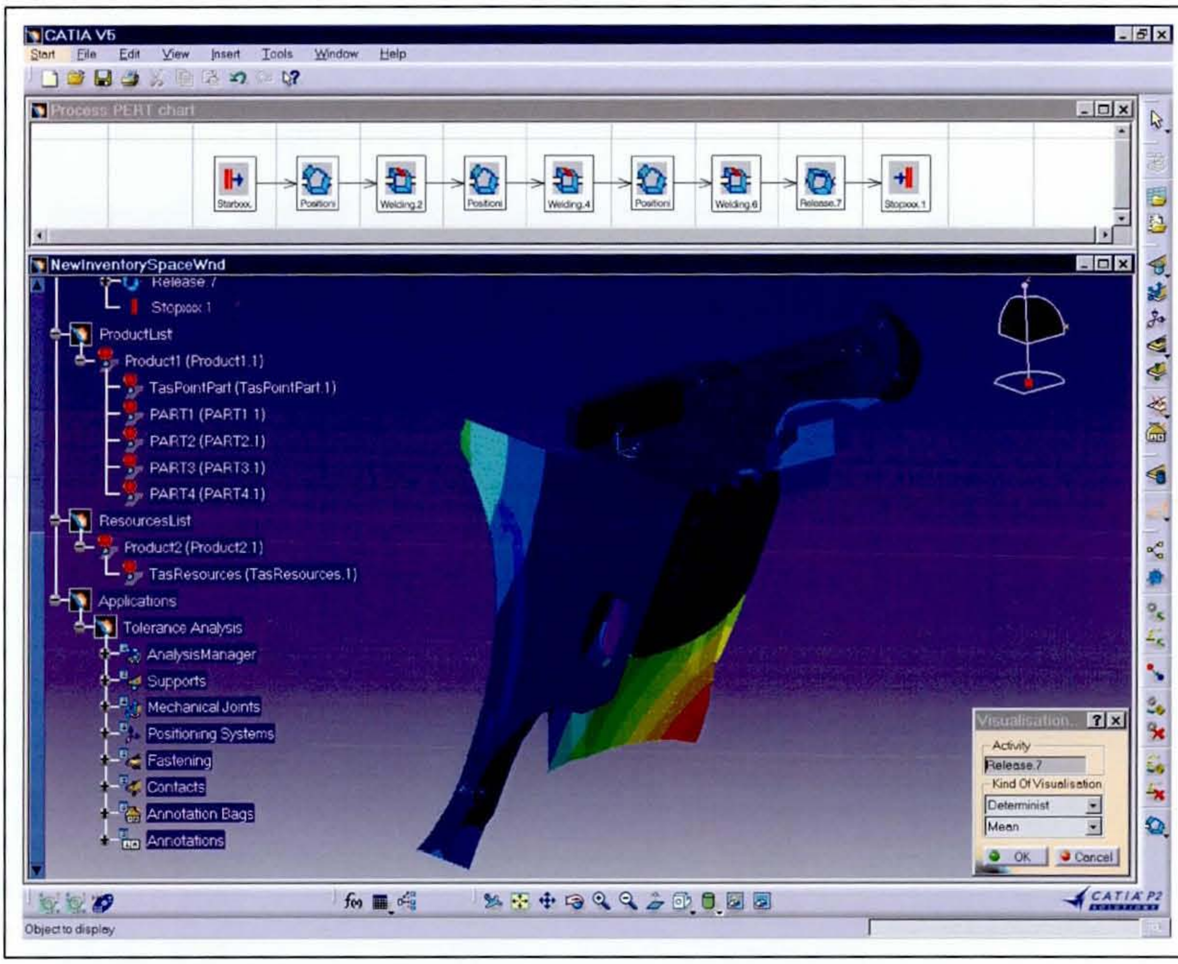


Figure 22: Tolerance analysis of a deformable assembly in CATIA V5 (IBM)

Key product features include:

(1.) Deformation and assembly process approaches — This product is based on a mechanical approach that takes both deformation and the assembly process into account to predict the tolerances for welded (riveted, bolted, or glued) assemblies of sheet metal parts.

(2.) Easy creation of data and assembly process specifications

(3.) Process verification before simulation — This function avoids simulation deficiencies by allowing the user to make sure the specified process does not contain faults. For instance, it can detect if there are two spot weld operations for one point.

(4.) Simulation of the assembly to perform a set of tolerancing analyses — The product provides sensitivity analysis, determinist analysis, and statistical analysis that are based on the same common computation. Integration of Finite Element Analysis models the elastic "deformability" in the assembly process and results in a finer and more realistic simulation. The user can get a sensitivity analysis to identify the key characteristics of the assembly.

(5.) Easy re-computation of the simulation — This product avoids the use of time-consuming Monte Carlo simulation. Additionally, there is no need to re-compute the simulation if only the input variations are modified. The type of simulation used allows the user to do a quick update simulation when the assembly process or few attributes need to be modified, added, or removed.

(6.) Multi-display of the simulation

- Graphical display of statistical and determinist analysis results are provided through displacement presentation (using FEA representation) and point deviation (using arrow and ellipsoidal representation).
- Graphical display of sensitivity analysis results is provided through the representation of input deviation contributions (in percentage) of output deviation.
- Statistical and determinist analysis results are also available through numerical display.

The module has the potential for serious in-depth analysis of not only the behaviour of a product during its use, but during the manufacturing and production process.

2.4.3 REVIEW OF EDS/UNIGRAPHICS VISVSA

This section presents a brief overview of the capabilities of VisVSA and highlights a number of it's limitations when applied to the variation analysis of assemblies.

VisVSA facilitates statistical analysis of dimensional variations in parts and assemblies, based on Monte Carlo simulation. Tolerance specific entities and attributes are interactively extracted from CAD models. Feature attributes are varied within the specified tolerance range, and user-defined statistical distributions are used in simulation runs to determine the contributors, the extent of contributions, sensitivities, and statistical distribution of the analysed part dimension or assembly clearance/interference.

Interfacing with CAD

VisVSA imports geometry from CAD systems via its own proprietary file format *.jt. Translators are available for most CAD systems, but the translators only translate geometric information and geometric location information. Neither GD&T information nor mating conditions can be transferred from CAD files into *.jt files. So, each part in an assembly must be imported separately; assembly information in the original CAD files is lost and assemblies need to be re-built. Also, constraint information in the original CAD model is not imported. However, if the assembly is already in a *.jt file, VisVSA can import it without losing any data.

Building the Model

VisVSA uses an abstraction of the geometry and selected dimensions and tolerances for analysis. These abstract objects can be created independently or congruently with actual CAD geometry. The features supported in VisVSA are plane, pin, hole, point, tab, and slot.

For analysis of the assemblies, constraints are defined by selecting the appropriate features from the part models. Then the measurements on the assembly are defined. These definitions include Point Coordinate, Point-to-point, Point-to-line, Point-to-plane, Gap/flush, Angle, Maximum or minimum virtual clearance. Multiple measurements can be defined in the assembly.

Tolerance Analysis

Tolerance modelling in VisVSA includes modelling of part variation, assembly process and measurement (definition of dimensions to analyse). The types of results that VisVSA can give include statistical distribution, contributors, and corresponding contribution percentage. For the amounts of variation, all of the toleranced dimensions are assigned a statistical distribution. Monte Carlo simulation then chooses one value from each distribution to create a unique sample for each component. The way VisVSA handles geometric tolerances is actually moving/deforming a feature according to tolerances specified with the help of a geometric solver. So if a point is defined on a pin surface and that pin has a size and location tolerance, then VisVSA will actually vary size and location of the pin (within the bounds of tolerances), and determine where the user-defined point lies in model space for that particular Monte Carlo simulation. It will do this for all user-defined points and then calculate distances between them for each simulation.

Since VisVSA uses point-based analysis, it might not guarantee that the relative position of the simulated points satisfies the tolerance specification enforced on the feature to which these sample points belong. It is not clear to outside parties how VisVSA deals with tolerance refinement relation during tolerance analysis. For example, it is unknown how to represent a floating form tolerance zone inside an orientation or location tolerance zone. The geometric solver is used to determine values of dependent geometric parameters from other parameters. An instance of an assembly is a series of features and relationships between features are passed to the solver to find the value of the dimension under analysis. Thus, the capability and accuracy of the solver becomes an issue as every solver has its own capabilities and limitations. VisVSA uses an inhouse constraint solver called Conjoin.

Monte Carlo analysis lends itself well to the case where the component parameters have distributions other than normal, since only the random number generator needs to be modified to represent any other kind of distribution. It also handles both linear and nonlinear response functions, since the values of the response function are computed by simulation. The main drawback of the method is that to get accurate estimates, it is necessary to generate very large samples and this is computationally intensive. If the tolerance analysis is carried out within an iterative loop of a large tolerance synthesis problem, this could make the solution process extremely time consuming and computationally expensive. On the other hand, if the Monte Carlo analysis is not run with enough samples, the results may be quite inaccurate. Also, if the distributions of the independent variables change or shift, the whole analysis must be redone, as there is no way of adjusting the existing results.

Level of Expertise Needed to Build and Analyse Models

Using VisVSA requires not only knowledge of GD&T, but also an understanding of VisVSA's solution logic. Considerable skill and experience is needed to get valid results. Besides, the documentation available in the user manual and online help is not as detailed as it should be for self-learning. Also, there is not much information on how to interpret results. For a specific dimension of interest, it is not obvious which type of measurement to choose of all the types of measurement. For example, if one wants to analyse the distance between two parallel planar features, then one can choose point-to-point or point-to-plane measurement. The results are found to be sensitive to the locations of the points on the target plane; then comes the question of which location to choose and how to interpret the three different sets of results for the same dimension of interest – the distance between two parallel planar surfaces, evaluated by three measurements.

The graphic user interface could also use some improvements. For example, point picking during defining measurement points on features can be made easier if the mouse pointer can automatically focus or snap to special points like corner points, centre points and so on.

Type of Analyses Supported

VisVSA does statistical tolerance analysis based upon Monte Carlo simulations. The statistical distribution parameters (mean, standard deviation etc) are extracted from all the results of the simulations. Worst-case limits can be estimated when the sample size of simulations is big enough. Strictly speaking, however, it does not do worst case analysis.

Overall VisVSA, despite its shortcomings, is one of the best commercial tools currently available for variation analysis, and it represents state of the art. Better mathematical understanding of geometric variations is required to improve the state of this art.

2.5 VARIATION ANALYSIS OF DEFORMABLE ASSEMBLIES

Sheet metal, both steel and aluminium, or plastic assemblies are subject to misalignment between mating parts due to warped or distorted parts, deflections under gravity or handling loads, and residual stresses from welding or bonding processes. They are also subject to the tolerance stack-up of dimensional variations inherent in stamping, forming and moulding processes.

The analysis of dimensional variations generally assumes rigid parts (Bihlmaier, 1999). This does not account for deformations of individual parts during assembly. Rigid body analysis tends to over-estimate assembly variation in an assembly of flexible parts and cannot predict resulting stresses and deformations. Thin and easily deformable parts, such as sheet metal or composite laminates, cannot be accurately modelled using these methods.

Sheet metal and composite laminate parts are often used in the aerospace and automotive manufacturing sectors, and many others. For example, the skin of an aircraft wing typically is assembled from many smaller sheets of pre-formed sheet metal riveted together. Variation in the sheet metal parts results in residual assembly stresses which could cause the wing to fail prematurely. Also, shape deformations due to assembly could also affect the aerodynamic properties of the wing. Automotive bodies are another common example of deformable assemblies. Aesthetics, among other considerations, could be affected by deformations due to part variation. Vibrational noise is also affected by assembly stresses. A method for accurately modelling assemblies of deformable parts is clearly needed in these areas.

Since all manufacturing processes are afflicted by variation the nominal value of a key characteristic or critical dimension may not be expected at all times. Variation in a geometrical key characteristic of an assembly typically results from a number of different sources. There is variation in the individual component geometry, which results from machine precision itself, but there is also process variation over time. Similarly, the assembly process will contribute variation related to the way in which parts are assembled, which may also vary over a period of time. The geometrical robustness of an assembly concept can be evaluated by its ability to minimise the effect of geometric variation in the final assembly product. Low robustness means that our assembly concept (the components and processes used) adds variation to the final assembly. High robustness on the other hand means that the system is able to suppress the variation in individual components and processes so that they do not affect the quality of the end product to any great extent.

The industrial need for geometrically robust concepts increases rapidly as the development and production ramp-up time decreases. Since a concept change during pre-production is often very costly, geometry-related production problems must be avoided in early design stages. This is highlighted in figure 23, a generalised automotive product design cycle.

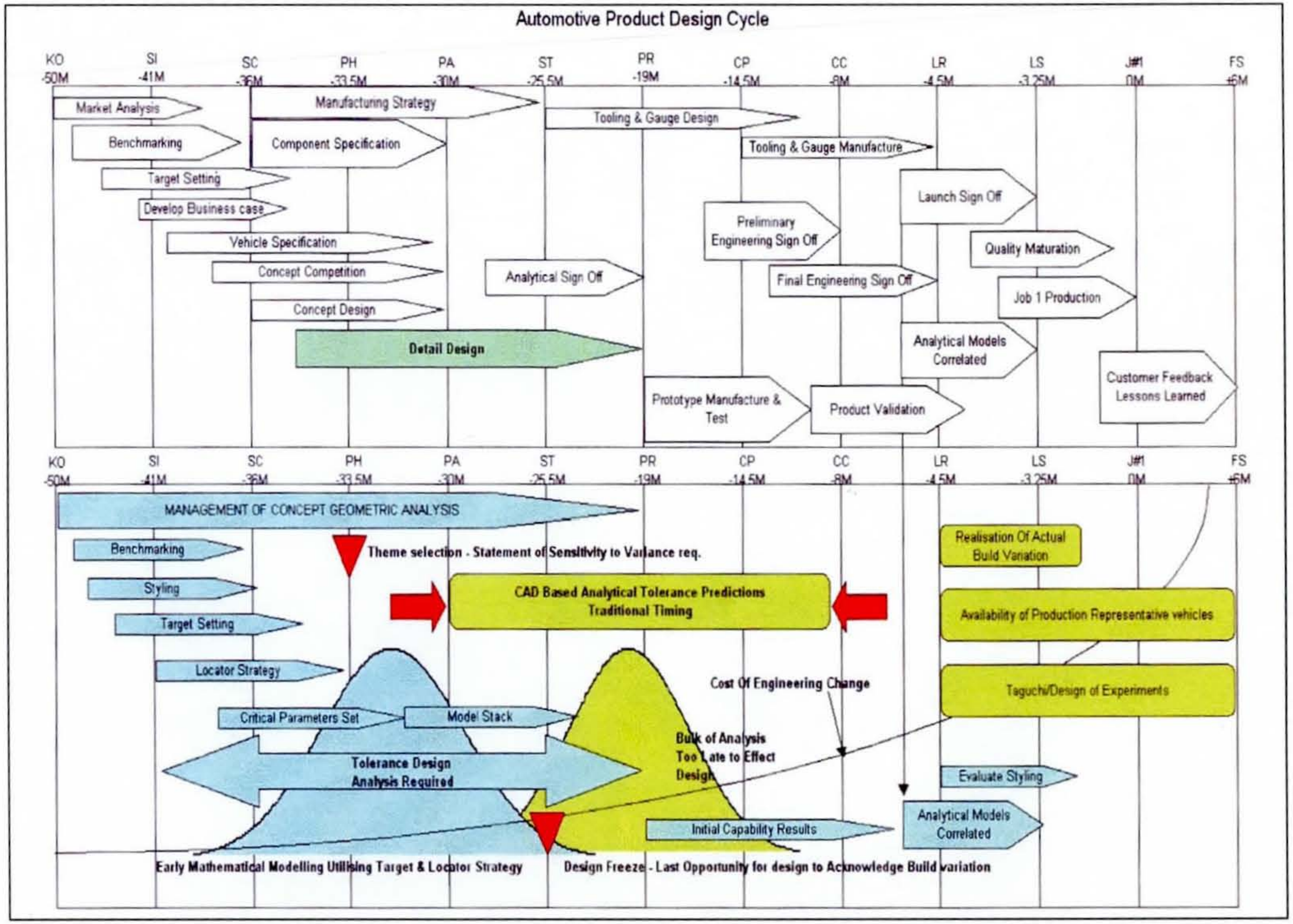


Figure 23: A Generalised Automotive Product Design Cycle (Richmond, 2001)

Sheet steel and aluminium automotive assemblies often use the material as their supporting and functional structure, so it is a key issue to control or predict the final geometry and variation of the assembly. The assembly process for sheet metal assemblies is often conducted in three steps (Dahlstrom and Soderberg, 2001):-

- positioning and clamping the parts in a fixture;
- welding or joining the parts and;
- finally releasing the parts from the fixture.

During assembly, parts and process variations will influence the final geometry of the assembly proportional to the robustness of the assembly concept. Normally, the information needed to make a realistic analysis of the final geometric variation is extensive and in the early stages of the development process still relatively unknown. In the early phases of the product development process, a prediction or evaluation of the final geometry of the assembly is necessary to ensure the final geometrical requirements for the assembly are fulfilled.

The variations introduced during the assembly process can be divided into two main sources:-

- *part variation,* mainly shape, size defects and material property variations;
- *process variation,* introduced to the assembly by clamping, welding and joining forces or by variation in the fixtures used.

These variations lead to different effects in the resulting sheet assembly. The difficulty in analysing a sheet metal assembly is when the variation listed above, forces the sheet metal parts to bend in order to fix them in their nominal position. In order for the above listed variation sources to influence a critical dimension of the assembly, two aspects of the assembly concept (both design and production) are critical:-

- whether the concept allows variation to propagate through the assembly structure, which is an aspect that is determined in the early design stages and;
- whether the assembly sequence allows for spring-back, which is an aspect that is mainly determined during production preparation.

In deformable sheet metal assemblies, part and process variations do not stack-up as the conventional models (worst case methods, RSS methods, and Monte Carlo simulations) predict. Takezawa (1980) applied linear regression models to real production data for automotive body panel subassemblies in modelling variation, and concluded that for deformable sheet metal assembly, "the conventional addition theorem of variance is no longer valid for determining the permissible limits (tolerances) for the automotive body assembly." In addition, his regression models showed that dispersion for the assembly was closer to the variance of the stiffer part, and tooling was quite effective to control dispersions of an assembly. He concluded that in analysing the variation of deformable parts assembly, parts deformation had to be considered.

An offset beam element model was developed by Liu and Hu (1995) for predicting the assembly variation of deformable sheet metal parts joined by resistance spot welding. The purpose of using the offset beam element is to include the shear effect provided by resistance spot weld nuggets that cannot be captured by the conventional beam element. The offset element is applied to predict sheet metal assembly variation for one-dimensional (1D) models. The first example used evaluates the effects of sheet metal thicknesses on assembly variation. The second example shows how the assembly sequence affects assembly variation. The material used is presumed to be steel and the known difficulties associated with the spotwelding of aluminium would support this. In concluding their work, some general guidelines are provided for the design and production of sheet metal assemblies:-

- choose sheet metal thicknesses as equal as possible when tooling variation is small;
- choose opposing sheet metal thickness when tooling variation is large and;
- control the variation of the thicker part because it plays a dominant role to assembly.

The three piece welding example highlights the advantage of sequential assembly since it was shown that sequential welding results in smaller variation than simultaneous welding.

Liu, Lee and Hu (1995) and Liu and Hu (1995 and 1995a) proposed an approach, Mechanistic Variation Simulation, for analysing the variation of deformable part assemblies by combining engineering structural models with statistical methods. The mechanistic variation models can be obtained analytically, numerically, or empirically. These models provide an improved understanding of deformable sheet metal assembly processes.

Liu and Hu (1996, 1997, 1997a, and 1998) also proposed the use of finite element analysis (FEA) in Mechanistic Variation Simulation for two-dimensional and three-dimensional free-form parts. A direct computer simulation is provided by the combined use of finite element modelling (FEM) and Monte Carlo simulation. The analyses performed highlight how part variation is transmitted through a number of different joint types. This method is very time consuming if many types of variations are to be simulated. Furthermore, the random numbers generated must be correlated to make realistic distributions, and in many cases this is difficult to achieve. The method assumes small deformation for each component so that linear mechanics can be applied. The assumption of linear mechanics (small deformation and the linear Hooke's Law) guarantees the uniqueness of the assembly configuration for an occurrence of a set of sources of variation. All nonlinear effects are ignored.

A faster way of doing the simulation is to establish a linear relationship between the parts deviation and the assembly spring-back deviations by using the *method of influence coefficients* (Liu and Hu, 1997, 1997a and 1998). Defining the sensitivity matrix, which describes how the assembly spring-back is influenced by initial geometric variations, achieves this.

Lately, a robustness evaluation method for compliant assembly systems has been presented (Lee *et al.*, 2000).

A method developed by Sellem and Riviere (1998, 1999, and 1999a) takes into account three different kinds of variation in the simulation: positioning, conformity and shape variabilities. The output of the simulation produces the influence of these variabilities on: distributions at control points, the force required for the clamping process and the residual stresses near the fastening points. The theoretical basis for this method is based on the influence matrices.

The use of beam-based modelling to describe a sheet metal assembly has been presented by Ceglarek and Shi (1998). The method identifies different joint types and beam elements to achieve a simplified model of the assembly.

The use of transformation vectors to describe variations and displacement of features has been presented by Chang and Gossard (1997). The method represents the interaction between parts and tooling by contact chains which are later used in vector equations.

Suri, Painter, and Otto (1998) developed a strategy for setting tolerances on operations within a manufacturing system. Back-propagation methods are used to predict the end-of-line variation and to demonstrate that the final product meets the target specifications. The approach is demonstrated with a model of the manufacturing process for a flexible MIG welded automotive structure, where the required tolerances at weld fixture locations are established to ensure the final frame distortion is within acceptable limits.

Frutiger and Rastogi (1995) describe the application of the finite element method to a class of variation problems induced by assembly build distortion. Two case studies are presented to illustrate the use of FEM to predict car body build distortion. The first example is the mounting of a sheet metal wing on a car body, and the second example is the door assembly process for a coupe door on a midsize vehicle. The individual parts of the assemblies are modelled and the processes simulated using appropriate boundary conditions, constraints and a special element for the spotwelding operations. The method is then used to consider the process sensitivities of various process conditions. Correlation with measured coordinate measuring machine (CMM) data on several prototype door builds from the assembly process is also shown.

Merkley (1998) proposed a new method for tolerance analysis of flexible assemblies. He uses the assumptions of Francavilla and Zienkiewicz (1975) to linearise the elastic contact problem between mating flexible parts. Merkley derived a method for predicting the mean and variance of assembly forces and deformations due to assembling two flexible parts having surface variations. He describes the need for a covariance matrix representing the interrelation of variations at neighbouring nodes in the finite element model. The interrelation is due to both surface continuity, which he calls geometric covariance, and elastic coupling, which he calls material covariance. Merkley uses random Bezier curves to describe surface variations and to calculate geometric covariance. He also showed that material covariance effects are described by the finite element stiffness matrix. Stout (unpublished) followed Merkley's work by using polynomial fits to produce the geometric covariance matrix. Merkley described surface variation in terms of a tolerance band specified about the nominal surface. Stout investigated the effect of different wavelength surface variations on assembly results.

Bihlmaier (1999) proposes a method for modelling flexible assemblies, called the Flexible Assembly Spectral Tolerance Analysis (FASTA) method, which uses an autocorrelation function from frequency spectrum analysis to model random surface variations. Finite element models are used to predict assembly forces and stresses from known surface variations.

3. INDUSTRIAL LINKS

This chapter identifies the industrial relations that have been established during the course of this research. It also aims to highlight for the reader those issues considered timely in relation to the design, development, and production of aluminium intensive vehicles in the current commercial climate.

3.1 MSX INTERNATIONAL (MSXI) LTD.

This research is sponsored and supported by MSX International (MSXi) Ltd. They provide collaborative enterprise services for automotive manufacturers on a global scale. Their list of capabilities encompasses a full range of engineering, staffing, and business and technology solutions. In the UK, particularly their base in the East Midlands, they provide engineering support and deliver products and services for a number of vehicle manufacturers, including Jaguar Cars, Ford Motor Company, Lotus Engineering, Bentley and many others.

They consider their approach to tolerance analysis to be somewhat traditional in the sense that only recently software tools such as VSA and Valisys have been adopted in the work they undertake. Previously, traditional tolerance stack-up methods including the worst case and RSS methods were used in product and process development.

Their approach to product development consists of four phases:-

- Pre-programme
- Concept Competition
- Concept Development, and
- Implementation Phase.

The use of tolerance analysis software relies on the provision of CAD data for vehicle geometry. This is a problem in the earliest phases of a vehicle development program when such data is generally unavailable. Ideally, MSXi would like to be able to identify a design or vehicle concept's sensitivities to dimensional variation at the earliest available opportunity in the development programme. They are looking for an approach to tolerance analysis that can be applied consistently to all four phases and in particular would like to make use of software tools using Monte-Carlo simulation in not only Concept Development but also in Concept Competition where a vehicle theme is selected and significant costs and engineering resources are committed.

There are a number of areas for research that have been highlighted resulting from the identification of common ground of Loughborough University and MSXi to enhance and further develop competencies in the field of dimensional management:-

(1.) The accuracy of tolerance analysis models – do they really correlate with real-life processes? Can we better understand the science of dimensional variation?

(2.) Flexible components – how do we handle them and in particular, how do we model location processes, clamping forces etc.?

(3.) The characterisation of processes for their geometric capabilities – the production of a benchmarking guide to identify the processe(s) required to deliver required geometric requirements.

(4.) How do we link cost into the tolerance allocation process?

MSXi is also beginning to develop its own Craftsmanship methods. The company hope to market their craftsmanship methods to other industries. For this reason, they are planning extensive research into the current use of craftsmanship in non-automotive industries.

MSXi have become highly integrated into Ford Motor Company with work carried out on the Ford Ka and the Jaguar X400 vehicle programmes. They are currently in the process of developing for Jaguar Cars a manageable craftsmanship evaluation and rating system that can be used throughout the vehicle design, development and manufacturing processes, with common targets identified throughout.

MSXi are presently heavily involved in Jaguars' X600 vehicle development programme and are using this work as an enabler to drive new systems into place in the craftsmanship process. For example, the use of virtual product design tools in the digital environment as craftsmanship evaluators.

MSXi have a rich tradition for supplying excellent engineering solutions in steel (Roberts, 2001). The future is considered to lie in building up the equivalent skill sets in the use and knowledge of aluminium. MSXi have been involved in a number of aluminium-intensive vehicle projects over the years and have worked with a number of leading players in the aluminium industry including Alcan Alusuisse, Alcoa, and Hydro.

They are currently in the process of developing a strategy to take advantage of the opportunities that aluminium has to offer and "as manufacturers strive to remain competitive, and weight becomes a critical factor, MSXi needs to be at the forefront of intelligent, innovative engineering solutions, working with and using aluminium" (Roberts, 2001).

In light of Audi's decision to manufacture the new A4 body from steel because they have not reached a manufacturing solution for production volumes of 70,000 units in aluminium per year or greater, it is considered a timely issue to develop approaches to AIV construction based on Audi's model of 60% sheet aluminium, 20% diecastings, and 20% extrusions.

Another topical issue and area of concern is the use of exposed vehicle structures as exterior trim on vehicles. This is of significant importance to the motor industry with the increasing application of magnesium and aluminium in vehicle bodies.

3.2 JAGUAR CARS LTD.

Jaguar Cars, a Ford Motor Company Trust Mark brand – like Aston Martin and Land Rover, is a company undergoing a great many changes. The introduction of the highly successful S-Type sedan expanded its range and took it toward new status as a medium-volume producer. This transition is now almost complete following the introduction of the smaller all-wheel-drive sedan, code-named X400, or X-Type. These changes – coming at a time when pressure on all vehicle producers to reduce design time and costs while enhancing quality has never been greater – bring particular challenges to Jaguar whose strength lies in products that combine performance, style, and quality.

At Jaguar's Product Engineering Centre, in Whitley near Coventry in the UK, they employ the latest design tools, including the C3P (CAD/CAM/CAE/Product Information management) system. This reduces the number of design iterations and the time-to-market for new products. Thus, Jaguar has the capability for true concurrent engineering involving all of their suppliers.

"The introduction of the C3P system means that our design process now only caters for one type of prototype called a confirmation prototype", says Jonathan Browning, Jaguar Managing Director. "As the name suggests, these vehicles are used to confirm that the advanced CAE and manufacturing feasibility work have indeed produced a vehicle which will satisfy the customer" (Anon, 2000b).

Browning states that there is a need to develop such computer simulation techniques to bring further reductions in design and development time for new models, but he is aware of the potential dangers of cutting too far, with possible impact on quality. The typical time from design approval to Job One remains around 30-36 months, although this depends on a range of factors including the size of the project, the number of body derivatives, and in how many markets the car will be sold.

The next vehicle from Jaguar Cars will be the X350 - an all-aluminium car. It will be made at the company's Castle Bromwich plant and will be the first Jaguar to make extensive use of technology developed from Ford's North America Aluminium Intensive Vehicle (AIV) programme, carried out in conjunction with Alcan Aluminium. Jaguar's Castle Bromwich works will become "a centre of excellence" for aluminium technology, assisted by input from engineers from Ford in America and Alcan Aluminium, the material supplier.

Aluminium is also likely to be at the heart of two more new Jaguar cars - the X150, a replacement for the XK8, and the X600 - Jaguar's reply to the Porsche Boxster. Production of these two cars, now merged under a single car programme, is expected to be in the region of 30,000 to 40,000 a year, in the same ball park as the X350. All three cars form part of a new product offensive which will see production exceed 200,000 units a year.

A particular focus of interest in all three cars will be the manner in which body designers will come to terms with aluminium. Car stylists tend to think in terms of steel for the detailed shape that a car takes. But aluminium - requires a different approach; what can be achieved in steel frequently is not always possible in aluminium. And, because aluminium is being used in the X350 in place of steel for the main structure as well as the closure panels, new methods of joining are being developed and honed by Jaguar engineers. Three joining processes will be used widely in production of the aluminium body: self-piercing rivets, adhesive bonding and clinching/hemming.

Particular care has to be taken with clinching to avoid cracking of the aluminium.

Both self-piercing rivets and adhesive bonding will feature strongly too in the combined X150 and X600 programme. A feature of all three cars is likely to be the British-developed system of self-piercing rivets designed and developed by Henrob of Flint, Clwyd. Self-piercing rivets have proved invaluable as a cost-effective means of joining aluminium panels together. The conventional alternative for steel is spot welding which is associated with high start-up costs, but this process is not the optimum joining technique for aluminium because of the high currents required during welding.

Henrob has already gained considerable experience with its self-piercing rivets at Audi in Germany with its aluminium-intensive A8 (now much improved over the first cars to appear), at Daimler Chrysler with the Plymouth Prowler, at Volvo in Sweden and at Porsche in Germany. To this reference list can be added the experience gained with Ford on its AIV programme.

Production of the body for X350 will require some 350 "guns" to apply rivets to the joints.

In the Henrob system a joint is made between two or more materials using a rivet to pierce and clinch in a single operation. The rivet is squeezed at high force into the material to be joined, piercing the top sheets of material and spreading outwards into the bottom sheet against an upsetting die. The technique is virtually noiseless and without fumes or sparks, according to Henrob. There is no need for pre-drilling or hole alignment and the technique can be applied to join dissimilar materials.

A compact automatic feeding device on the "gun" provides high-speed continuous riveting in any plane. Typical cycle time for a gun is between 0.25 and 1s. The joint offers high strength, can be visibly checkable is and water tight. The X350 bodyshop is being designed and built by Comau-PICO, part of the Fiat Group. The body shop will use Z-Series robots from Kawasaki which has also supplied the robots for the X400 bodyshop at Halewood and the X200 (Jaguar S-Type) bodyshop at Castle Bromwich.

The X350 bodyshop will require 100 robots, many of which will be used to apply self- piercing rivets. Among other companies taking part in the X350 programme are Premier Sheet Metal and Abbey Panels, both of Coventry. Premier is a prototype and production sheet metal specialist supplying both prototypes and parts to the likes of Rolls-Royce Motor Cars and Jaguar Cars. Some 10 car sets of prototypes are being put together under this part of the programme.

A big item of the X600 expenditure will be the body-in-white. But key questions surrounding the body include where it will be made, who will manufacture it and in what material, and how it will be made. How the body is manufactured and from what material depends, to some extent, on the level of success achieved with the X350. By the time the X600 moves to production, some three years from now, laser welding technology may have advanced to the point where it can be successfully used as another joining technique.

Digital mock-up at Jaguar

Prior to the purchase by Ford and the introduction of the automotive giant's high-volume design and product technology and processes, Jaguar used in-house tools to conceptualise and produce design details, primarily wire-frame and partial surface-based product definitions. One of the greatest disadvantages of this approach is the ambiguity of the product models. The interpretation of wire-frame models is a practised art and often does not allow the design team to validate the final concept correctly. Additionally, sharing this mission critical data to any great effect beyond the design department is practically impossible. Obviously, any system that allows engineers and designers to conceptualise, simulate and analyse a product prior to the manufacture of costly physical prototypes (and also allows the communication of that design throughout the enterprise) will provide immediate and tangible benefits.

EAI's solutions in use at Jaguar operate on many different levels. Within the engineering and design departments, VisView and VisMockup allow the visualisation, simulation and analysis of function and fit, manufacturability and assembly using a single geometry source and user interface. Other EAI products assisting in the development process include Virtual Jack, an anthropometrically correct human simulator assisting in the development of the 'cock-pit' and EAI's VisVSA tolerance analysis tools which allow engineers to analyse the variation of components within tolerances during manufacture.

Beyond the engineering department, VisProducts allow any department access to the wealth of engineering and manufacturing data generated during car development projects. Due to its ease of use, and the scalability of the solutions, a common interface can be deployed across the entire enterprise. This allows those that need to view and evaluate up-to-date information, and perhaps, just as critically, in a controlled and secure manner.

Initially deployed purely as engineering tools during previous projects, EAI's system are now in extensive use by both management and production departments. The ultimate goal is implementation throughout the enterprise, moving into the manufacturing facilities to allow collaboration between all parties involved during the life cycle of a vehicle.

4. ASSESSING CURRENT STATE-OF-THE-ART IN DIMENSIONAL MANAGEMENT

In this section a number of issues are highlighted pertaining to the application of dimensional management methods and CAT systems for industrial application.

Most CAT systems are advertised as "one press button" applications. However, this does not hold for many of the systems outlined in Chapter 2. In tolerance specification for example, users most often have to select the surfaces to be toleranced, sometimes come up with the appropriate tolerance type(s) and determine a tolerance value as well. In tolerance analysis often the kinematic loops on which the analysis is to be performed as well as equivalent joint types have to be selected. Thus current CAT systems cannot be called "one press button" applications.

Training and more importantly frequent usage of the CAT systems seems to be necessary to be able to effectively operate a CAT system. Ordinary CAD users, although trained in the use of the CAT systems, use the CAT functionality not frequently enough to effectively use the CAT system. Because of this, they often abandon the use of the CAT system. Therefore, it seems that current CAT systems can be employed most effectively either in large organisations which can afford one or more support departments which are specialised in the use of CAT systems or in highly specialised consultancy agencies that offer their CAT or dimensional management services to other organisations. It is expected however, that in the near future CAT systems will tend to develop more towards the "one press button" paradigm, allowing ordinary CAD users to take advantage of their functionality.

Most current CAT systems assume a rigid body for which the tolerances describe small allowable variations from the nominal geometry. Small displacements (relative to the component's dimensions) are assumed. Tolerances related to non-rigid, deformable bodies are not dealt with however. Another assumption that is often made in tolerance analysis, is that the influence of form tolerances is negligible. Other assumptions made in tolerance analysis are:

- when constructing solid assembly models, assembly sequence is implicitly assumed to be equal to modelling sequence.
- only dimensional, geometric and kinematic sources of variation are considered.
- analysis of final assembled configuration is good enough to predict assembly problems.
- same analysis procedures applied to all kinds of assemblies.

Most tolerance synthesis systems suffer from some drawbacks as well. The most important one of these is that statistical tolerance synthesis models often assume that manufacturing variations follow normal distributions. However, this is not valid in general.

There is a lack of understanding of the relation between the tolerance values and the physics involved in the functioning of the assembly. Although some general rules can be identified, direct relationship of tolerances to functioning and performance is not yet fully understood.

There is also a lack of understanding for the relation between the physics of the manufacturing process and the tolerances of the component made by that particular manufacturing process. Often statistical distributions are used for this. However in the best case these are based on measurements of other components than the ones currently under study. In other cases normal distributions are assumed that may not reflect actual process characteristics. As a result, most CAT systems offer insufficient tolerance value specification/allocation support.

Unresolved issues for CAD-based tolerance analysis

1. The relationship to GD&T must be resolved

   There are many misconceptions about the application of GD&T standards to assembly tolerance analysis. How do Maximum Material Condition (MMC) or Regardless of Feature Size (RFS) apply to a tolerance stackup? What happens with bonus tolerances? Are geometric variations applied differently in a statistical analysis versus worst case? If a form tolerance is applied to a feature of size, should two variation sources be included in the tolerance stackup? Do the size variations include the surface variations, or do they represent two independent sources of variation?

   Most of the misconceptions arise from a lack of understanding of the fundamental principles upon which the GD&T standards and assembly tolerance analysis are based. We also need to get a clear concept of the difference between a specified tolerance and a measured or prediction variation.

2. New standards for assembly variation are needed

   There are no standards for computing tolerance stackup and variation propagation in assemblies. ASME Y14.5 has only recently acknowledged the existence of statistical stackup analysis. How this is to be done is still open-ended.

3. Better data on process variations is needed

   The assembly variations predicted by tolerance analysis are only as accurate as the process variation data entered into the analysis model. However, there is very little published data describing process variations and the cost associated with specified tolerance limits. If you wait until the parts are made, so measured variations can be used in the model, you will lose one of the major benefits of tolerance analysis. In the design stage of a new product, tolerance analysis serves as a virtual prototype for predicting the effects of manufacturing variations before the parts are made. To fully realise this benefit, we simply must have an extensive database, which characterises process variations over a wide range of conditions and materials.

4. Ease of use and application

One problem with current analysis software has been the amount of effort required to become proficient in its use. Inexperienced users can output results that look accurate but may be filled with errors. Reviewers having less experience than the person who made the errors are not able to catch the mistakes. Efforts are being made to make the software more user friendly, and this should reduce the learning curve.

Attempts to produce a software package that speeds up the modelling process are introducing risks that may be easily overlooked. The software is permitted to select points on surfaces that later get used for determining part locations in an assembly. The automated point selections are made on the basis of routines written in the program code. If the user does not understand how the software makes the point selections, then a needed decision to override the program might not be made. The result will be an inaccurate analysis.

The future will eventually include CAD systems and the associated manufacturing equipment where only a 3-D product model will exist with all requirements attached to part features in such a way that either engineers or software can read and interpret this data.

Caution is recommended in using emerging software tools to ensure they are properly used, and that any outputs are accurate. Many of the new products available today are of very high quality, but the results obtained by inexperienced people can be extremely misleading. A well educated and experienced mind is still superior to the best available computer and software package.

5. DIMENSIONAL VARIATION ANALYSIS USING CATIA TAA

This section presents the approach based on the finite element method developed for TAA and a summary of research undertaken by Dassault Systemes to evaluate the application of TAA to industrial problems.

In automotive and aerospace companies, inspecting the sheet metal assembly process is a subject of critical importance. Due to the propagation of part defects or process imperfections, this inspection becomes necessary in order to predict the variations. The variations are those of the final shape of an assembly resulting from known error distributions at the pre-assembly level.

Dassault Systemes have developed a mechanical system simulation method, taking geometric faults and deformation of parts and mechanical sets into account (Sellem and Riviere, 1998).

Since simulation methods take the geometric definition of parts and mechanical systems into account, they can be separated into two categories:-

1) Mechanism-oriented analysis or tolerancing synthesis methods: if we know the tolerancing of each part, we can verify that the mechanism's functional conditions have been met or, vice versa, if we know the mechanism's functional conditions, we can deduce the tolerancing of each part.
2) Production process-oriented analysis or tolerancing synthesis methods: if we know the tolerancing of each part before it is subject to a process activity and the dispersion of the production process used, we can compute the tolerancing of each part when production is finished or, vice versa, if we know the tolerancing required when production is finished, we can seek out a process capable of achieving this production quality.

The FEA-based approach uses as input the nominal CAD geometries of the different parts and the distribution of variabilities both at the geometry and process level, to predict the distribution of shape variability at any number of specified inspection points in the final assembly.

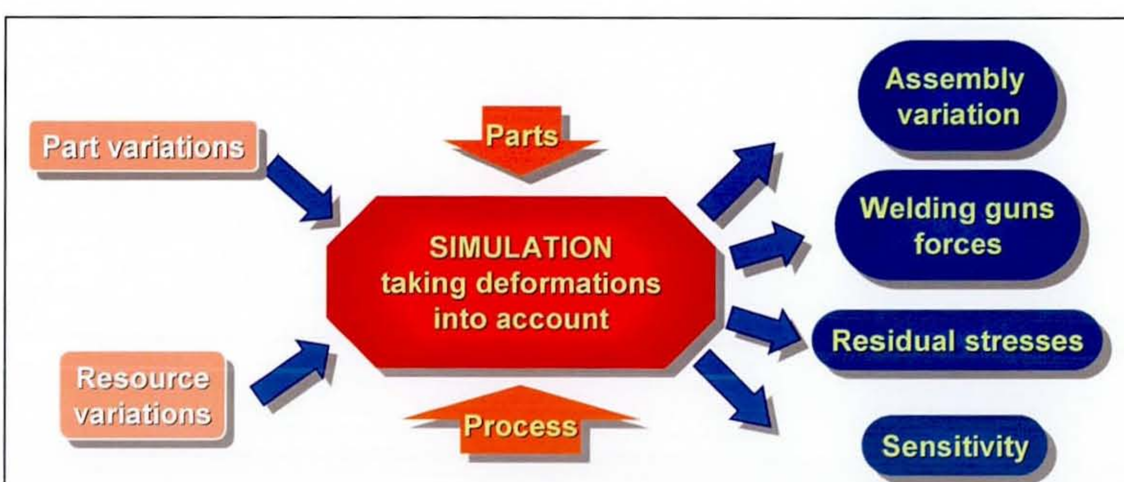


Figure 24: TAA Simulation (Sellem and Riviere, 1998)

The process for fastening two sheet metal parts can be described as follows:-

1) each part is positioned in a free state on statistically determined "isostatic" supports (see figure 25).
2) each part is brought into conformity with additional supports.
3) the parts are brought in contact by the fastening robot, at the fastening points.
4) the parts are welded by attaching together the couples of corresponding points.
5) the robots are released.
6) the assembly is released (aside from one arbitrary set of "isostatic" supports).

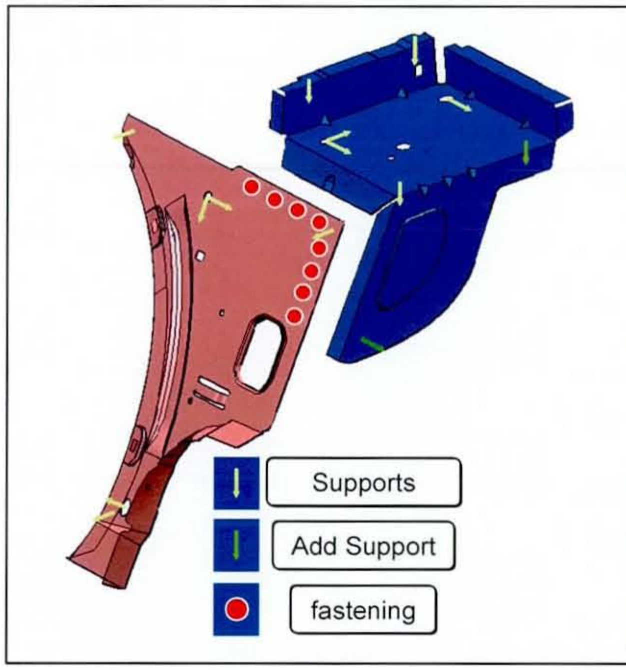


Figure 25: Definitions of points (Sellem and Riviere, 1998)

The simulation attempts to model the assembly process as clearly as possible. The first step corresponds to the positioning of each part to assemble. One method consists of locating each part relative to an absolute reference frame by using fixtures (see figure 26). Another method consists of positioning a part relative to another one by using the so called "Hole to Hole" method.

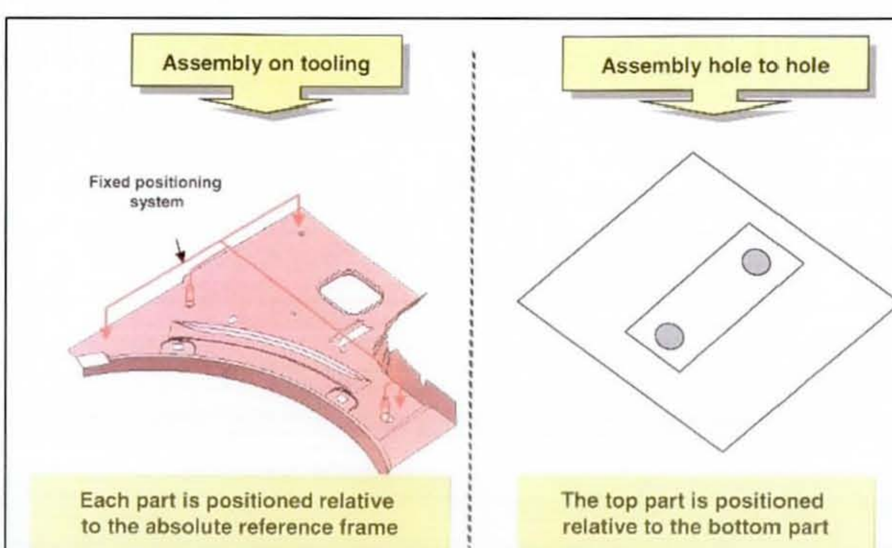


Figure 26: Positioning methods (Sellem and Riviere, 1998)

The parts are brought into contact:-

- either by applying equal and opposite loads on each side of the assembly (in the case of a light flexible robot). If the robot is considered perfect, the parts are assembled in the deformed configuration.
- or by applying a load which forces the parts in the nominal configuration (the case of a massive, rigid robot). Fastening will occur at a fixed location relative to an absolute reference frame). In this case, the parts are assembled in the nominal configuration.

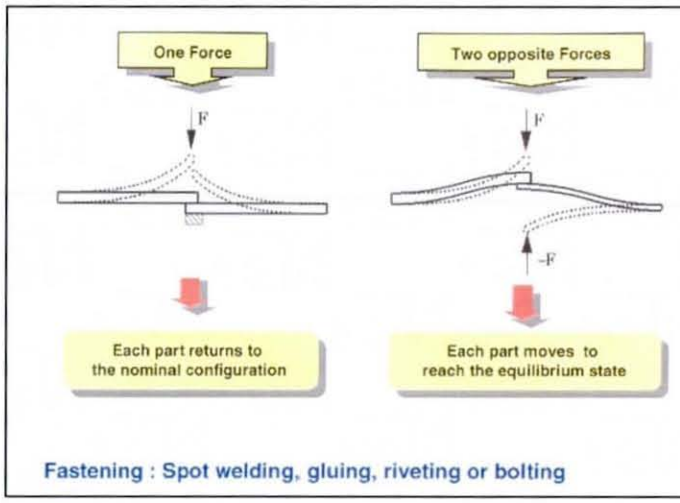


Figure 27: Fastening methods (Sellem and Riviere, 1998)

As opposed to rigid parts, which are measured while in a free, unconstrained state, flexible parts are constrained prior to inspection (that means additional supports are used). The constrained state corresponds to the one which will be used for the positioning of the assembly for the next assembly process.

The following set of hypotheses are applied in the process of creating a TAA simulation:-

- all fastening operations take place simultaneously.
- all phases of the process (and hence the computation also) are considered to be linear (small displacements, no friction, linear material behaviour).
- contact between parts is assumed to occur at nodes of the FEM mesh.
- geometric defects are assumed to be linear combinations of static deformation shapes corresponding to unit displacements.
- all types of variability can be modelled using a discrete set of points (positioning points, additional points, and fastening points).

The method simulates a fastening process by taking into account:-

1) the positioning variabilities: these variations represent either a geometric defect of the part localised at the positioning points or a positioning defect of the isostatic supports (3-2-1). Such a variability generates a rigid body motion of the corresponding part.

2) the conformity variabilities: these are due to the positioning defect of the robot which fastens the parts, or possibly a positioning defect of the additional support (3-N).

3) the shape variabilities: these correspond to all profile defects (except those related to rigid body motions).

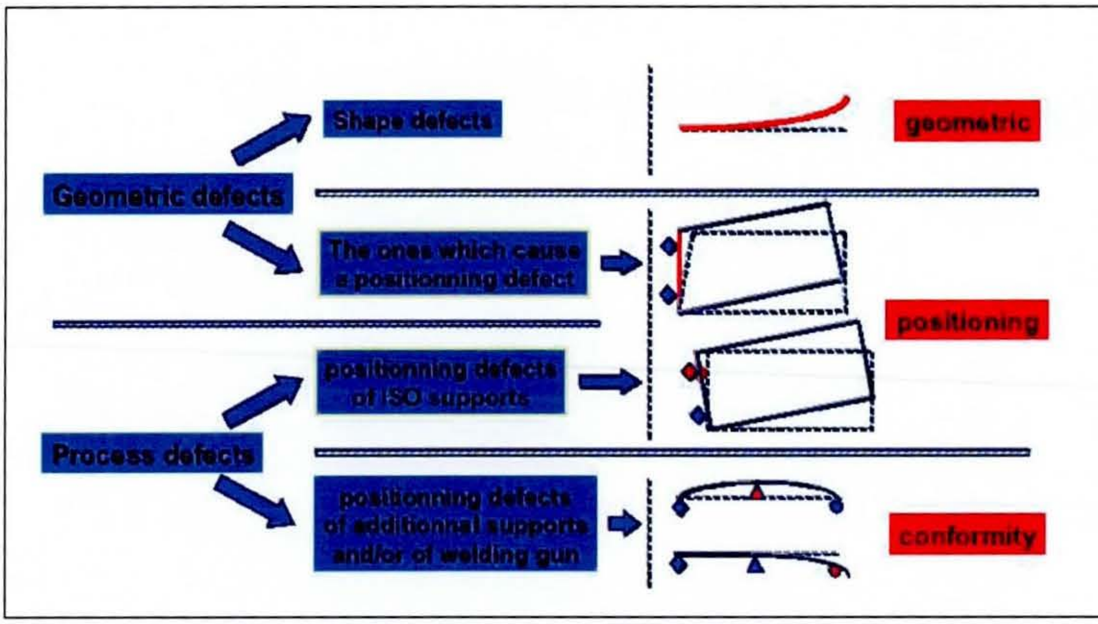


Figure 28: Variation types (Sellem and Riviere, 1998)

The positioning and conformity variabilities are defined by statistical distributions at the various points (positioning, additional, and fastening) whereas the shape variability is defined by Gaussian statistical distributions for each shape tolerance. Let these distributions be represented by:-

$\{x_P\}_{RB}, \{x_{A,F}\}_C, \{x\}_S$ where $\{x\} = \{\mu, \sigma\}$.

μ, σ mean and standard deviation of a statistical distribution

$\{D_A\}_B^C$ D is the type of data, B the type of variability analysed, C is the set of points where unit displacements are applied. A is the set of points where D is given. If A is not mentioned, D is given at all nodes.

$\{w\}$ nodal displacement vector

Types of variability

RB Rigid-body-related variability (isostatic positioning)

C Process-related variability (conformity defect)

S Geometry-related variability (shape defect)

Types of point sets

P Isostatic (positioning) points/supports

A Additional points/supports

F Fastening points (welding spot, riveting, bolted or gluing)

S Shape points (used to describe the shape defects)

The method produces the influence of these variabilities:-

- on the statistical distributions at control points,
- on the forces required from the robot (welding electrodes for the welding process) during the fastening operation,
- on the residual stresses in the neighbourhood of fastening points.

The linear behaviour and Gaussian distribution assumptions avoid the expensive use of the Monte-Carlo simulation. Therefore, the approach is based on the finite elements method (FEM) which models the deformation effect of given displacements and loads applied to elastic structures. Each sheetmetal part is considered as an elastic structure. The nominal geometry is meshed using thin shell elements, by making sure that to each of the above-mentioned points there corresponds a mesh node.

The simulation of the process can be carried out in two different ways.

The first approach would be to introduce simultaneously all variables and to obtain directly the corresponding solution vector. This method requires a full simulation for each new set of (part or process) tolerances, and can become quite expensive for what-if type studies.

The second approach consists of splitting the computations in two distinct sections.

In the first section, the program performs computations corresponding to « unit displacements » at the various points. This gives rise to a number of solution vectors equal to the number of simulations. These vectors grouped together form three matrices of influence coefficients $[W]^{P}_{RS}$, $[W]^{A,F}_{C}$, $[W]^{S}_{S}$, corresponding to the three types of variability.

In the second section, these matrices are linearly combined with any set of actual input distributions at the relevant points, to produce the final configuration. The global solution vector (geometric distribution) is then given by:-

$$\{\mu\} = [W]^{P}_{RS}\{\mu_{PI}\}_{RS} + [W]^{A,F}_{C}\{\mu_{A,F}\}_{C} + [W']^{S}_{S}\{\mu\}_{S} \qquad (1)$$

$$\{\sigma^2\} = [W^2]^{P}_{RS}\{\sigma^2_P\}_{RS} + [W^2]^{A,F}_{C}\{\sigma^2_{A,F}\}_{C} + [W'^2]^{S}_{S}\{\sigma^2\}_{S} \qquad (2)$$

Where each column of $[W']^{S}_{SI}$ equal to: $\{W'\}^{S}_{SI} = [W]^{S}_{SI}\{r\}^{MAX}_{II}$ (3)

The index i of the Equation (3) corresponds to the shape tolerance index.

The computation of the contribution of the positioning variations and of the conformity variations are directly obtained by a linear combination of the input data weighted by the influence coefficients of the corresponding matrices (see Eq. (1) and (2)). The reason is that there is one-to-one correspondence between unit displacements and statistical distributions.

For the shape variations, the statistical distribution are given for each shape tolerance generally represented graphically as ⌓ | A .

Here A represents the tolerance value with an optional symbol which imposes the tolerance to be one-sided. Each shape tolerance is represented by a set of point (termed shape points set) and a set of displacement vector $\{r\}_i$ (where $0 \leq r_{ij} \leq 1$ and each r_{ij} is applied to each point) corresponding to the possible profiles of the shape defect studied. Here the contribution of the shape variations is also obtained by a linear combination of the input data, but weighted by the influence coefficients of the $[w']_S^s$ matrix. Each column of this matrix is the influence coefficients vector of each shape tolerance (see Eq. (3)).

Matrices $[w]_{RB}^{p}$, $[w]_{C}^{AF}$, $[w']_S^s$ are independent of the input data, hence $\{x\}$ is directly obtained by the above equation, and can be used to evaluate the position distribution at any point (in particular, at the location of the control points).

The second method has been retained for its advantages. The solution is thus based on the computation of influence matrices. Each column of these matrices defines a vector of influence coefficients at a base point.

These displacement modes are obtained in two steps:-

1) Computation of the internal displacements (« static liaison modes ») and reaction forces corresponding to a unit (normal)ᵢ displacement at a basis point, all other (normal) displacements at basis points being kept equal to zero. The type of point where the unit displacement is applied depends on the type of variability being considered. This computation generates all data relative to the state of the assembly system just prior to the fastening operation (a state corresponding to the end of phase 3 of the assembly process).

2) Computation of the internal displacements corresponding to the numerical simulation of phases 4, 5 and 6, starting from the previous state. This time, parts are welded and all external actions on the assembly are relaxed.

The two steps are adapted for each type of variability considered.

The statistical distribution of the loads is obtained by replacing in the above relations the displacement vectors by the reaction force vectors obtained in step 1.

5.1 VOLVO BODY-IN-WHITE ASSEMBLY

The simulation method was first implemented in CATIA as a prototype in order to validate the modelling approach (Sellem and Riviere, 1999). The industrial example corresponds to an actual assembly composed of four complex stamped sheet-metal parts. The assembly is part of a Volvo body-in-white assembly. From the CAD model each part is meshed so that for each point (ISO supports, additional supports, fastening points, geometric points, etc) required to specify the process and assembly, a node is created. The welding guns apply two opposite forces to the assembly. The geometric points correspond to the points where the measurement is to be performed before the assembly of each part relative to its reference frame.

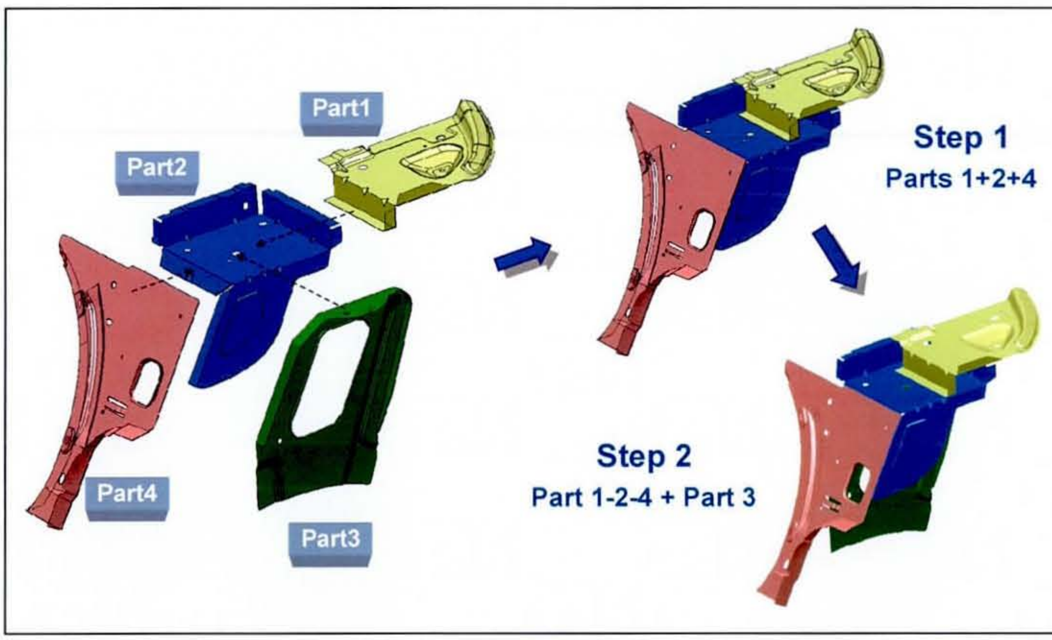


Figure 29: Volvo BIW assembly sequence (Sellem and Riviere, 1999)

The industrial partner, Volvo, extracted sample parts in the production phase, measured them before reintroducing them into the production line, welded them and then measured them after the welded assembly was produced.

Only shape variability was simulated. In fact, no information about the positioning and conformity variabilities was provided.

From the geometric model the parts were meshed. The mesh is constrained to have a node on each point necessary for the simulation. The following assumptions were made throughout the work:-

- the displacements and material have linear behaviour
- FEM mesh, from the geometric CAD model, is the same during all phases of computation (the stiffness of the parts is constant).

The first step was to calculate the matrix of influence coefficients. Figure 30 shows the interpolation of the deviations made from the measurements performed on the four parts separately before the assembly process. This deformation shown represents $\mu + 3\sigma$.

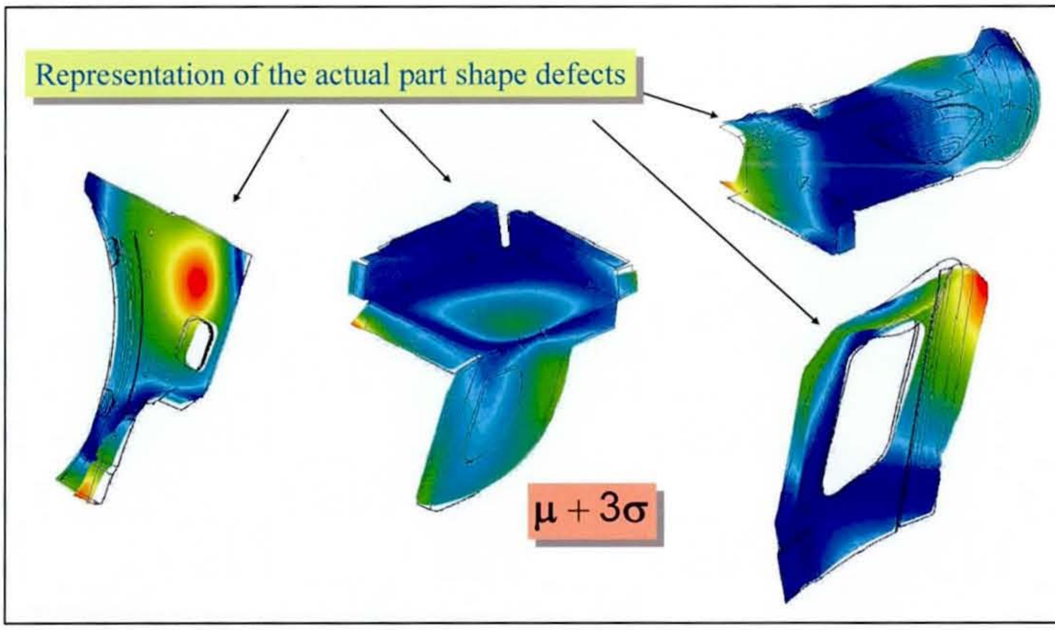


Figure 30: Interpolation of the deformation from measurement (Sellem and Riviere, 1999)

The predicted means exhibit the same behaviour as the measured ones with values of the same order (see figure 31). The difference obtained at the inspection points of the third part seems to reveal a positioning variability during the measurement. Although this last defect cannot be evaluated with respect to the measurement data, a strong correlation is still obtained with a correlation coefficient of 0.90.

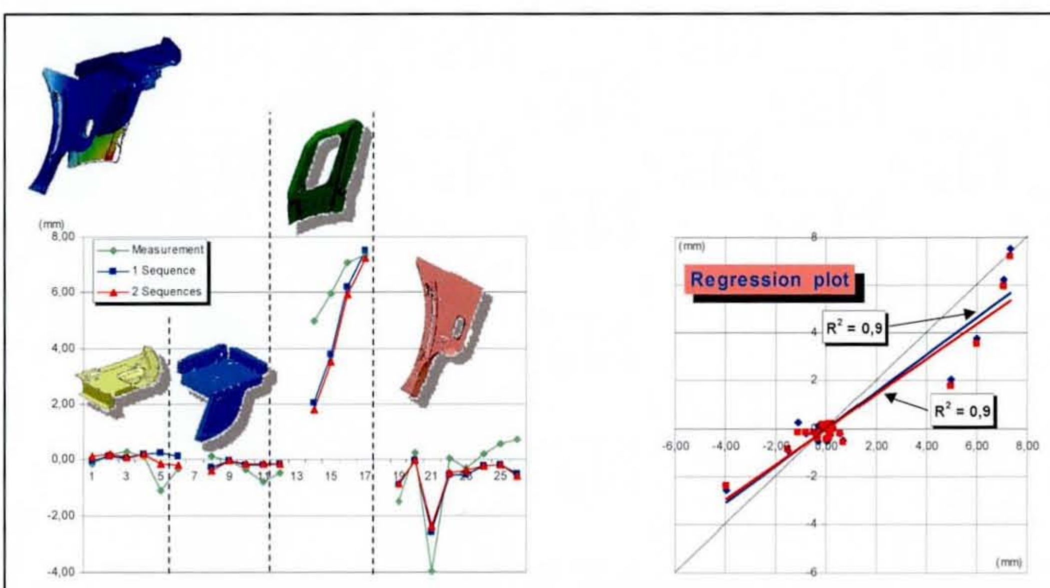


Figure 31: Mean comparison between measurement and simulation – R^2=0.9 (Sellem and Riviere, 1999)

The predicted ranges exhibit a behaviour similar to the one obtained by measurement (see figure 32). The correlation coefficient is equal to 0.80.

The inspection made on the assembly has been performed in a constrained state. The corresponding state provided by the computation is represented in $\mu - 3\sigma$ (figure 34).

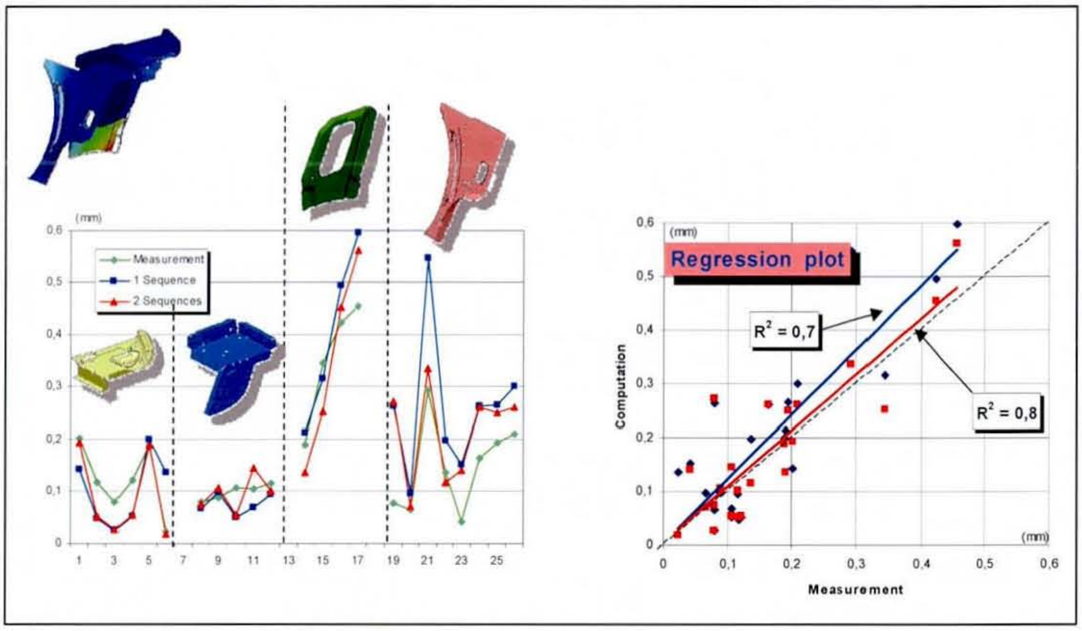


Figure 32: Standard deviation comparison between measurement and simulation – R^2=0.8 (Sellem and Riviere, 1999)

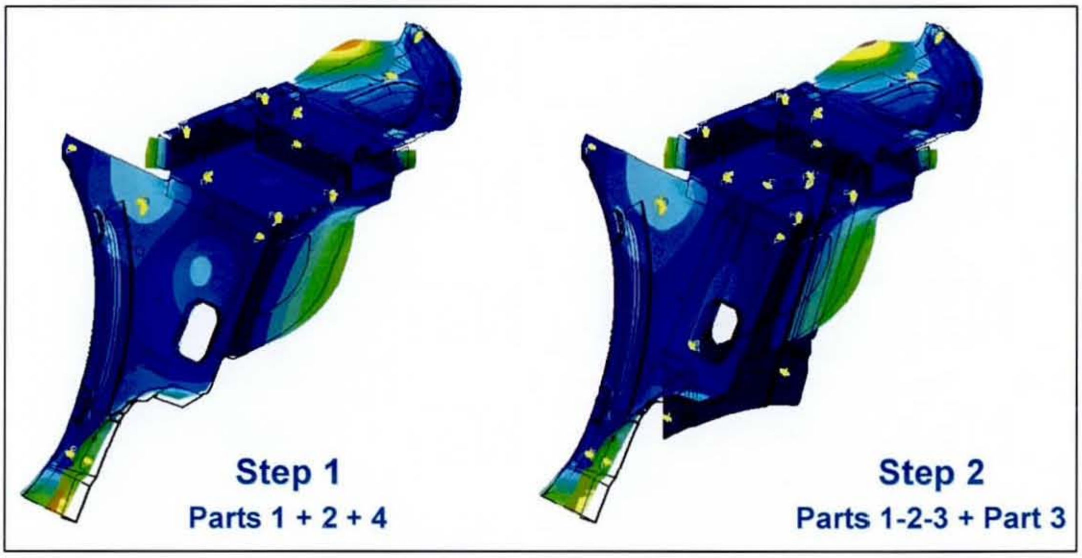


Figure 33: Intermediate calculation (Sellem and Riviere, 1999)

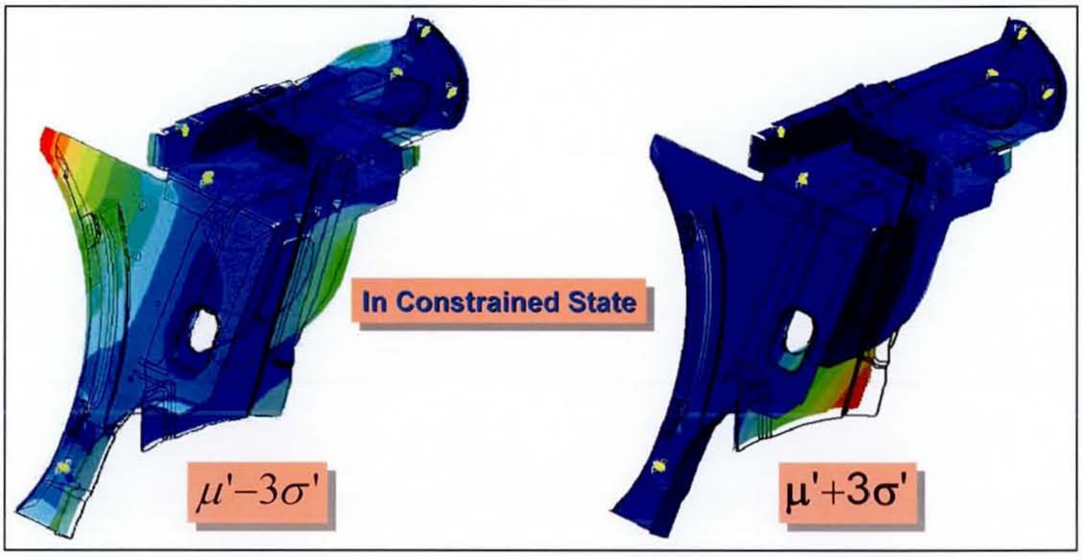


Figure 34: Prediction of the assembly variations in a constrained state (Sellem and Riviere, 1999)

This first case study provides encouraging results relative to the given inputs. In fact, even though only shape variability measurements were available, the simulation shows the same global behaviour for the mean and the range of the inspection points deviations.

Sensitivity analysis is also used to identify the root cause of variations at a given inspection point in the assembly. Figure 35 shows the root causes of the deviation of one point of the green part (Part3).

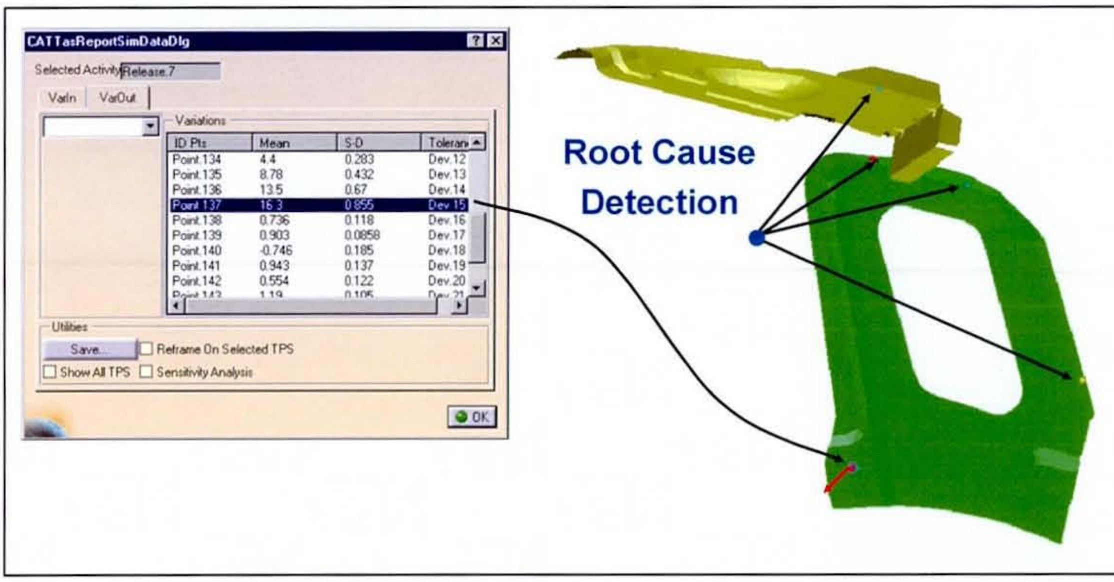


Figure 35: Sensitivity analysis for a given inspection point (Sellem and Riviere, 1999)

The results show that the welding sequence does not have a major influence. In fact, the influent parameters on the assembly process appear only by means of support variations and the type of reference or positioning systems used. In this case study, the reference systems defined, reflect the measurement of the parts and resulting assembly, and is assumed to be the same as the reference system used for the welding process. Therefore, this assumption cannot be applied generally to all processes in other simulations.

For the simulation, parts were meshed using geometric CAD models and discrete shell elements (Sellem and Riviere, 1999). But in some cases, this model may be unsuitable, particularly where this concerns the reduction of the degrees of freedom of the resultant meshes. In this instance, meshing with beam elements would be more suitable. Therefore, it is recommended that a validation of compatible meshing is carried out for each application.

For accurate modelling of the measurement process, position defects of the supports must be evaluated to identify their influence on variations between the measurements and the computed results. However, variations are tributary to the number of control points and in order to respect a balance between cost and execution time these were neglected in this instance. It will, however, be necessary to define position defects of supports if this simplification is to remain valid in other cases.

5.2 SPOTWELDED SHEET-METAL ASSEMBLY

As an example, consider the process of welding two simple sheetmetal parts with planar and cylindrical geometry (see figure 36). Suppose that 3 positioning points, 3 additional points and 3 welding points are associated to each part (the couples of welding points are coincident in the nominal models). In this application the weld gun forces bring the parts into contact in the nominal configuration.

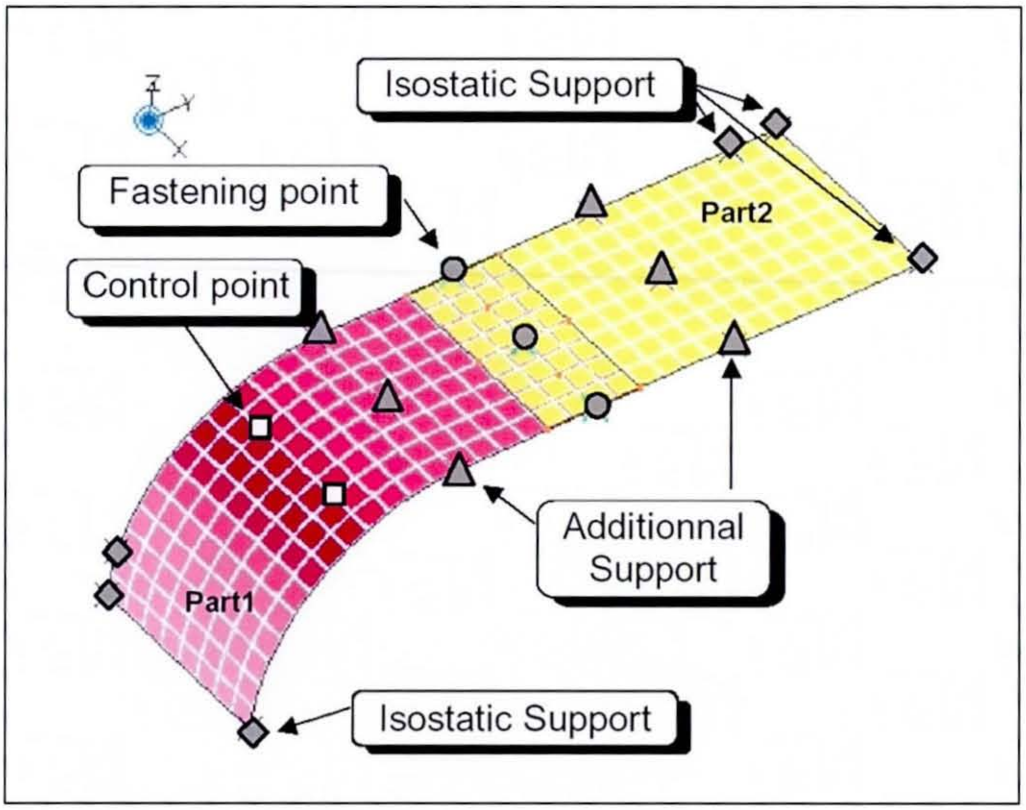


Figure 36: Spotwelded sheetmetal assembly with modelled constraints (Sellem and Riviere, 1999)

Figure 37(a) illustrates the simulation of a positioning error of part 1 (here a rotation about the Z axis of the part reference frame). Note that the requirement of enforcing conformity with additional supports and with the absolute welding point locations prior to welding induces deformation of both parts (due to the contact between parts). Welding is thus performed when the two parts are deformed. Figure 37(b) shows the final configuration of the free assembly (all external loads released), that is, a sliding of part 2 relative to part1.

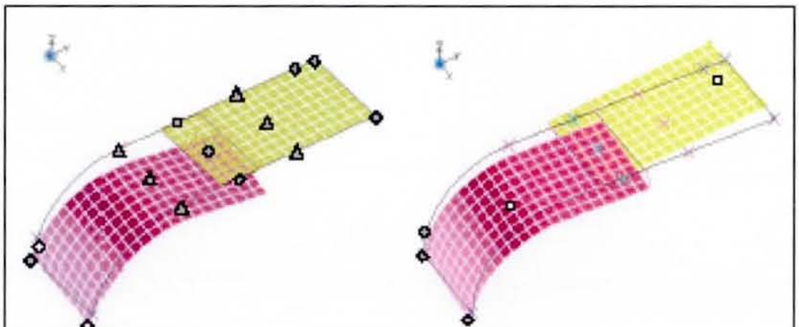


Figure 37: (a) Positioning defect of part 1. A rotation around the z axis of part 1 reference frame, (b) Effect of this variability on assembly (Sellem and Riviere, 1999)

Figure 38(a) illustrates the simulation of an error during the clamping operation of part 1 (a position error of one of the supports). The welding operations are again performed while the two parts are deformed. Figure 38(b) shows the final state of the free assembly, again with a sliding displacement.

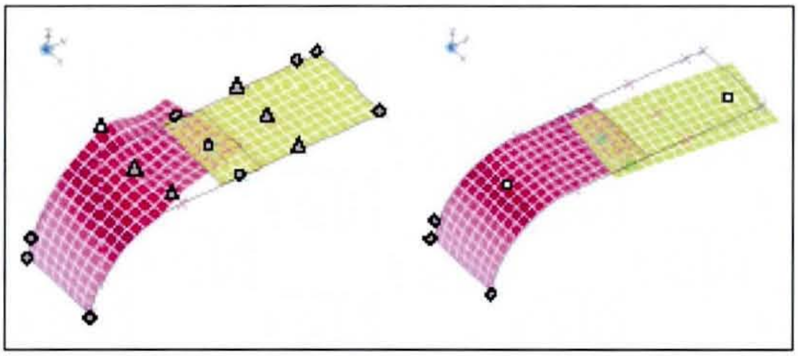


Figure 38: (a) Defect of positioning of an additional point, (b) Effect of this variability on the assembly (Sellem and Riviere, 1999)

Figure 39(a) illustrates the simulation of a shape defect of part 1, with only one unit displacement used. This time, the welding operations are performed while the two parts are in their nominal configuration (the additional supports and the welding electrodes bring the parts into the nominal configuration prior to welding. Figure 39(b) shows the final state of the free assembly.

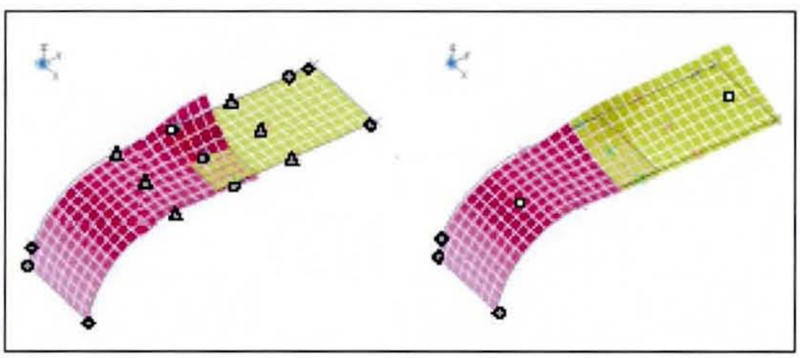


Figure 39: (a) Part 1 variation with a unit displacement to one welding point, (b) Effect of this variability on the assembly (Sellem and Riviere, 1999)

To illustrate the simulation of a shape defect we can apply a shape tolerance to part 2. Figure 40(a) and (b) shows two examples of a profile tolerance and the result after the welding process and the propagation of the defect of the second part on the first one.

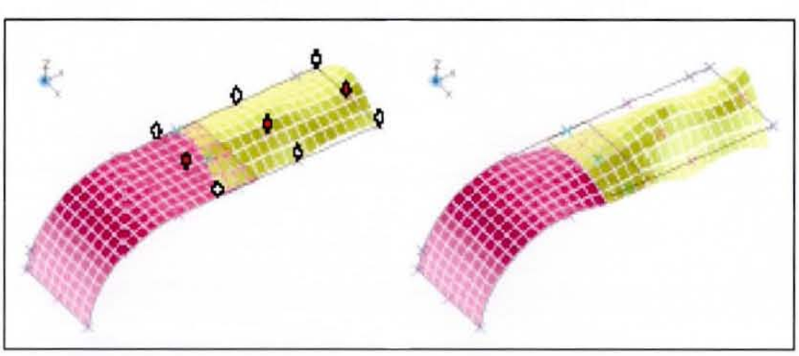


Figure 40(a): (a) Shape tolerance applied to part 2, (b) Effect of this variability on the assembly (Sellem and Riviere, 1999)

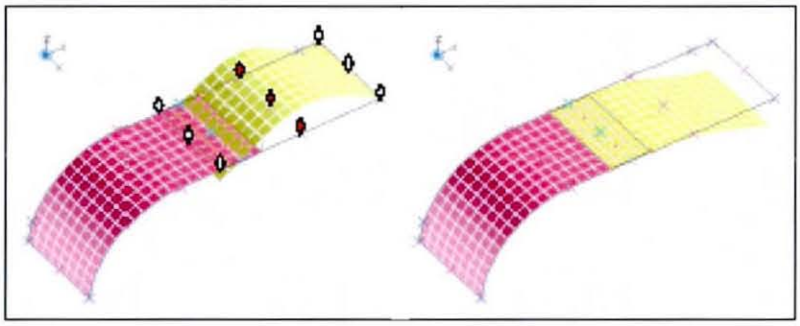


Figure 40(b): (a) Shape tolerance applied to part 2, (b) Effect of this variability on the assembly (Sellem and Riviere, 1999)

Absorption of the variations

The simulation approach which consists of taking the different steps of the assembly process into account but also the flexibility of the parts by a set of FE analyses shows it is possible to obtain a smaller variation for the assembly than the variation of the individual parts. The single part assembly shown below illustrates this. In fact, the single part partially comes back to the deformed configuration because of the process (which before the welding operation pushes the part back into its' nominal configuration).

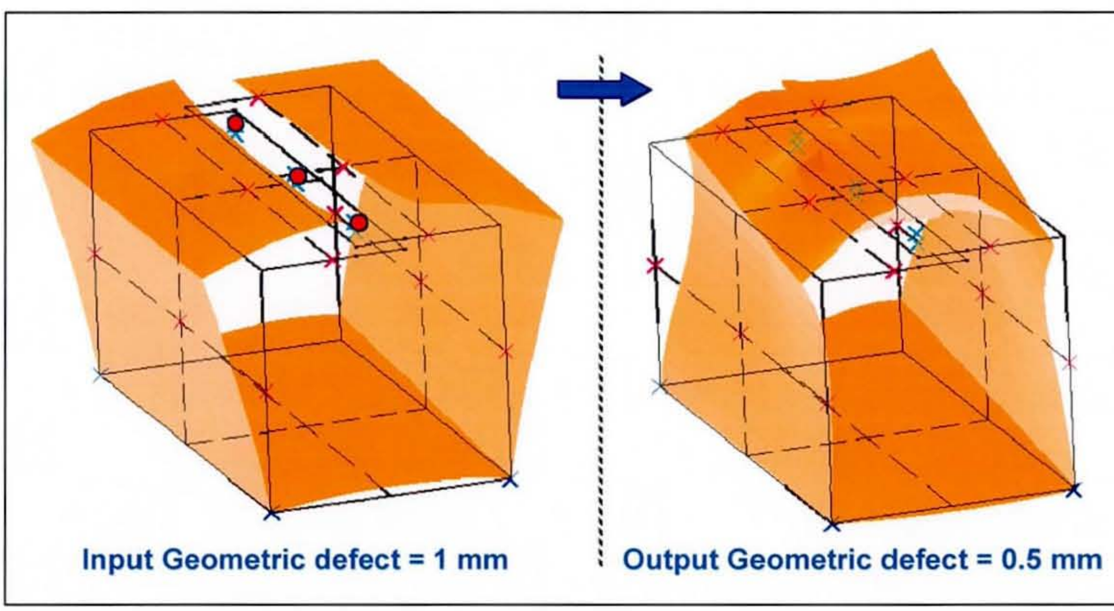


Figure 41: Absorption of the variation due to assembly process and flexibility of a part (IBM)

6. DIMENSIONAL VARIATION ANALYSIS OF INDUSTRIAL DEFORMABLE ASSEMBLIES

In this chapter the application of Catia TAA to an assembly of deformable stamped aluminium BIW components is presented in detail. The method developed by Dassault Systemes is applied to demonstrate that the tool can be used to predict the influence of geometry or process-related tolerances on the variation of an assembly consisting of flexible parts.

6.1 STAMPED ALUMINIUM BIW ASSEMBLY

The assembly consists of an aluminium crossmember and two aluminium side rails that make up the rear floorpan of a vehicle. The crossmember is the first part to be located in the assembly tooling fixture. Subsequently the two side rails are loaded into the fixture and all three parts are clamped into position using toggle clamps. The parts are then spotwelded together. The resulting assembly is then released from the assembly fixture.

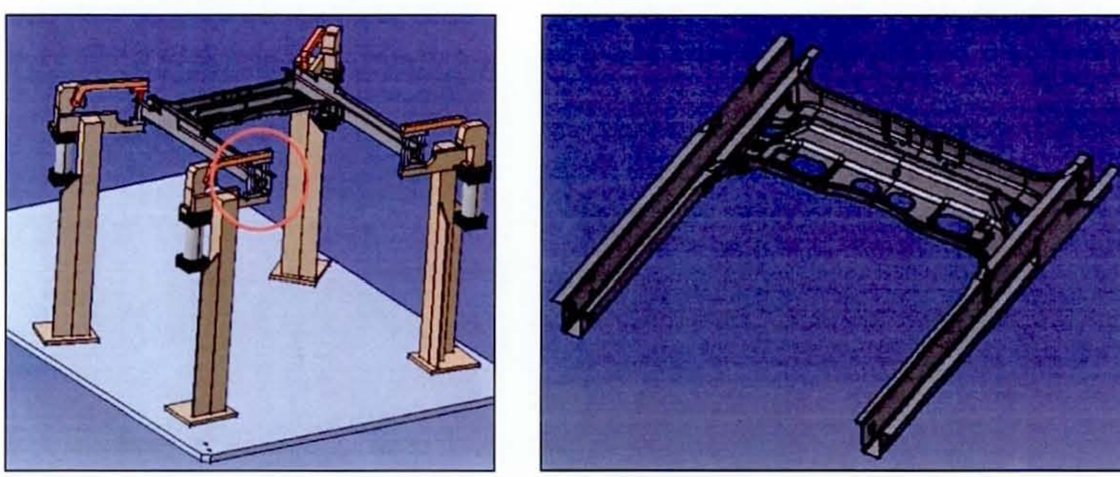


Figure 42: Deformable aluminium floorpan assembly and assembly fixture

The assembly is subsequently mated and welded to the rear floorpan as shown below:-

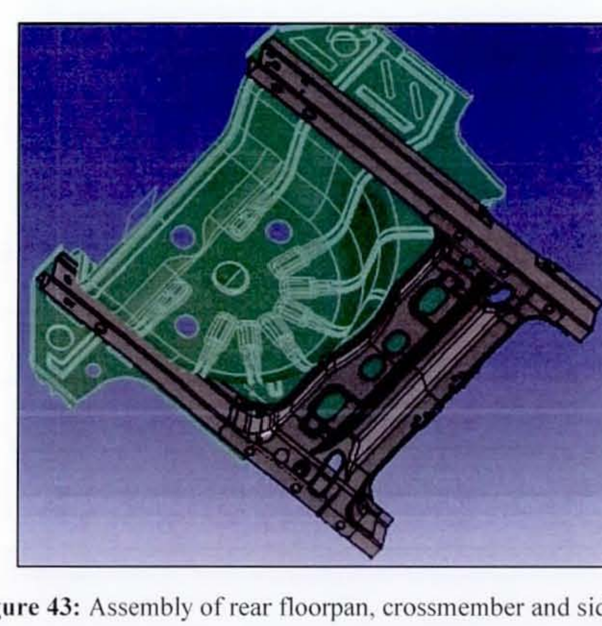


Figure 43: Assembly of rear floorpan, crossmember and siderails

The assembly was modelled in Catia TAA and a number of unit displacements were applied to the crossmember at various locations where corresponding measurements are to be taken. The unit displacements represent the variation input for the simulation and describe the shape and/or positional variation of the crossmember as it is located and constrained in the assembly tooling.

An initial simulation was then performed to visualise the assembly variation between each of the activities in the assembly process, shown in figure 44.

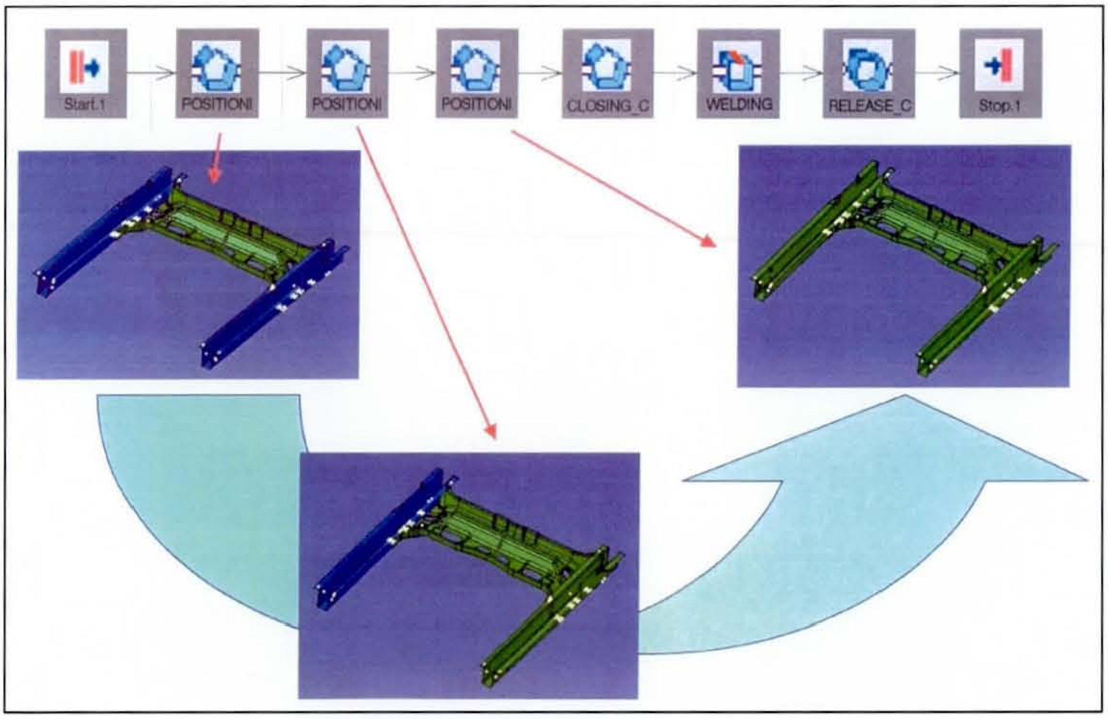


Figure 44: Assembly sequence and process activities

Figure 46 shows the measured displacement at each step of the assembly process corresponding to input variations of 1mm at 8 discrete points on the crossmember (figure 45).

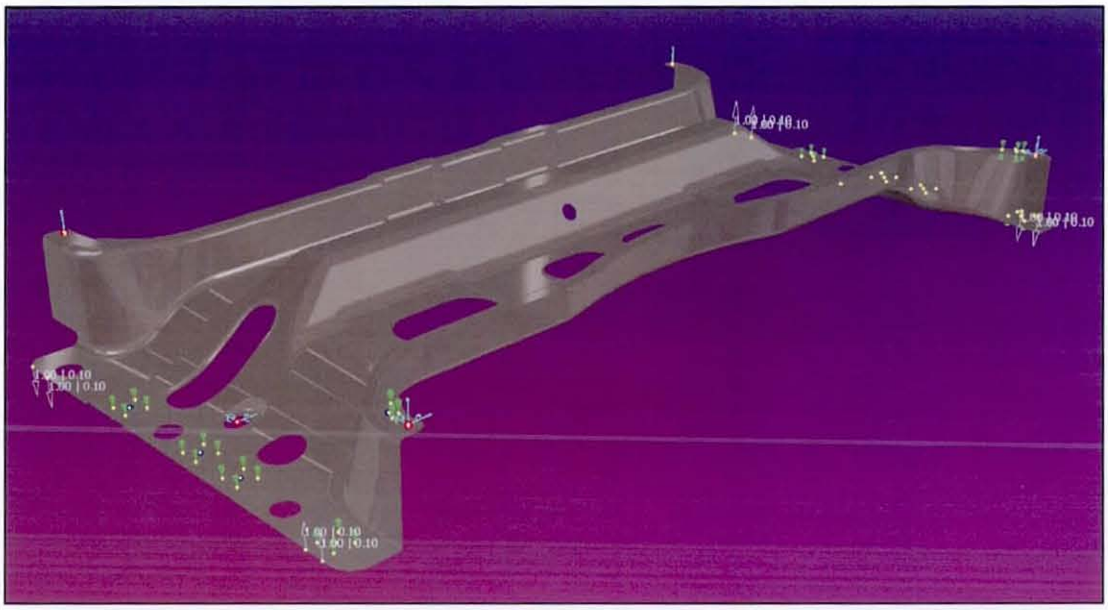


Figure 45: Crossmember with input deviations represented by white arrows

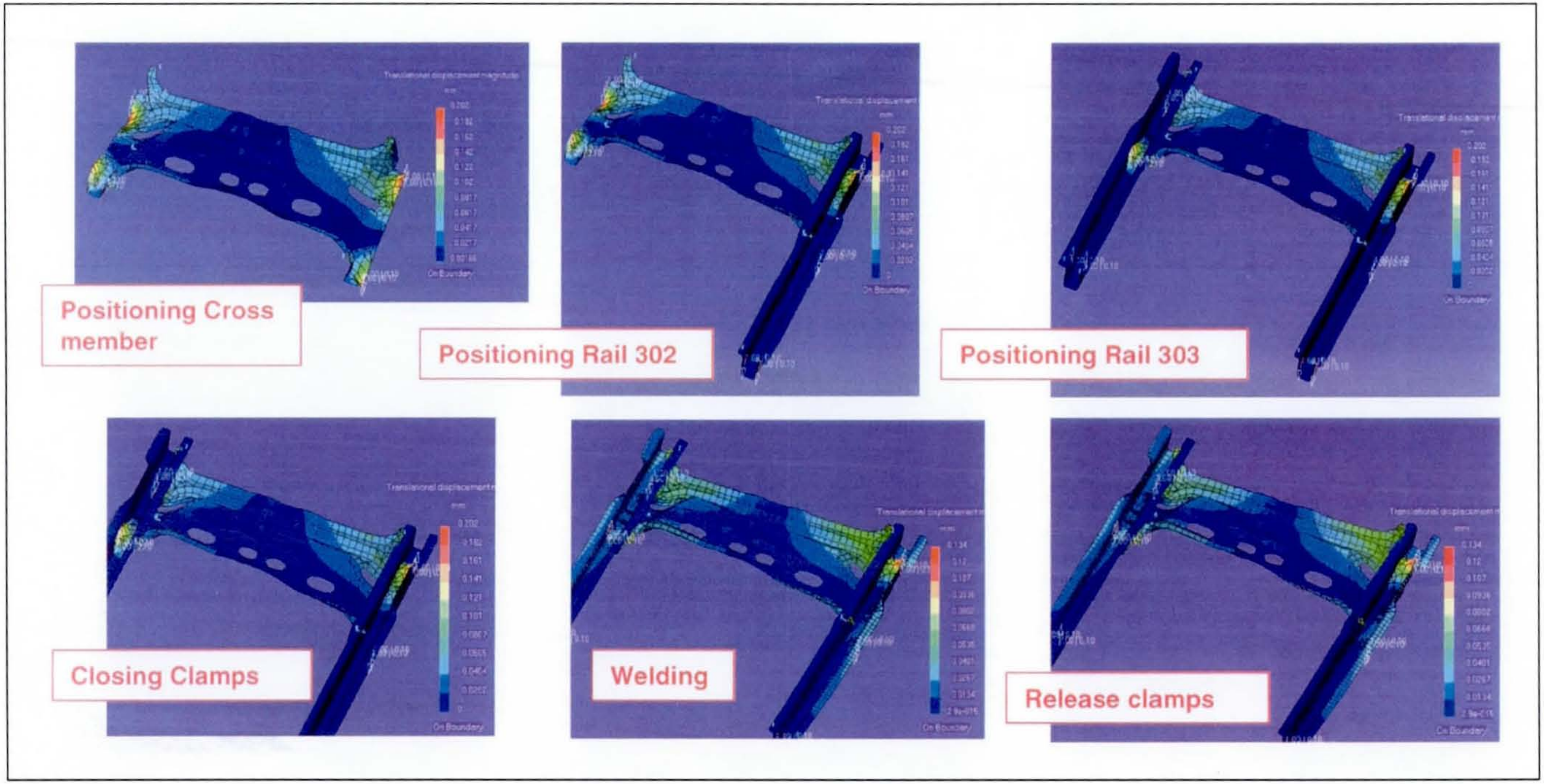


Figure 46: Visualising displacements for each process activity

The statistical analysis of the final release activity showed that there is a significant amount of twist imparted into the side rails when the spotwelded assembly is released from the tooling fixture. Further examination of the assembly constraints highlighted a need to revisit the method by which the crossmember is constrained. It was determined that additional mechanical joints were required to eliminate the twist observed in the simulation.

To control the variation of the assembly process prior to the subsequent assembly and welding of the floorpan, two additional clamps, defined by "revolute" type joints, are added to the model and the positioning system for the crossmember is modified accordingly to include these joints.

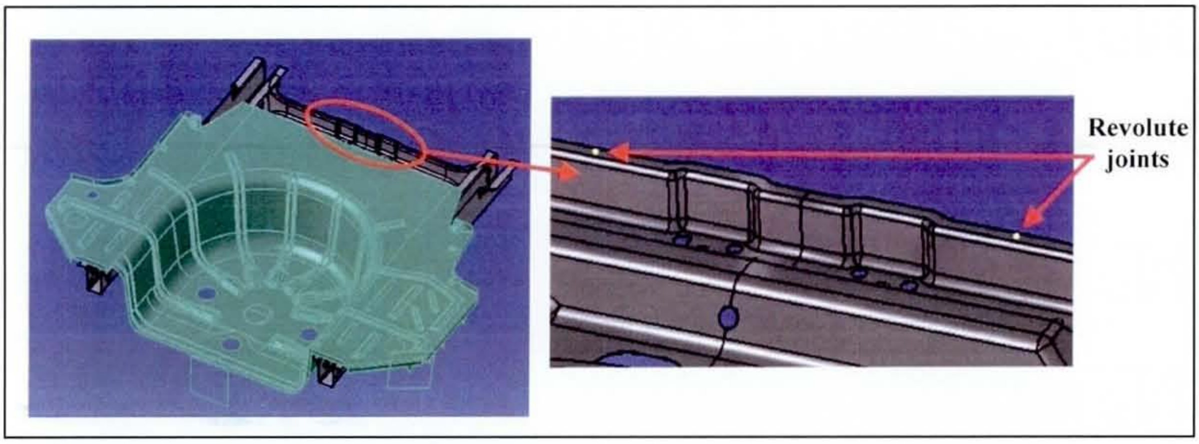


Figure 47: Revolute joints added to crossmember positioning system

The modified positioning system consists of the two revolute joints and the two existing cylindrical joints (figure 48).

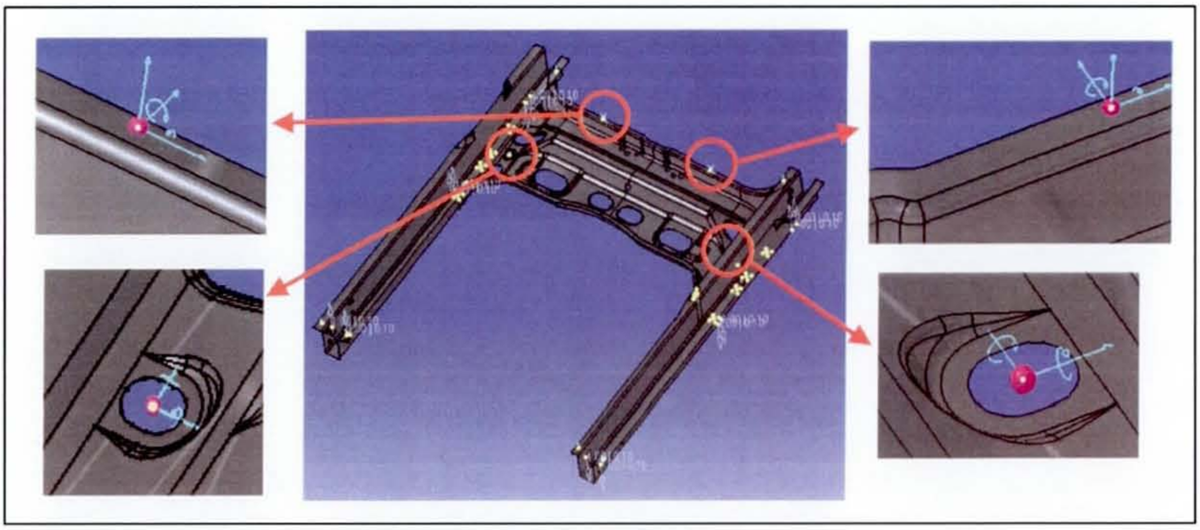


Figure 48: Modified positioning system for Crossmember

Running the simulation with the additional revolute joints produced the following results (shown in figure 49). The torsion imparted on the crossmember by the siderails translational displacements is now significantly reduced when the spotwelded assembly is released from the tooling fixture.

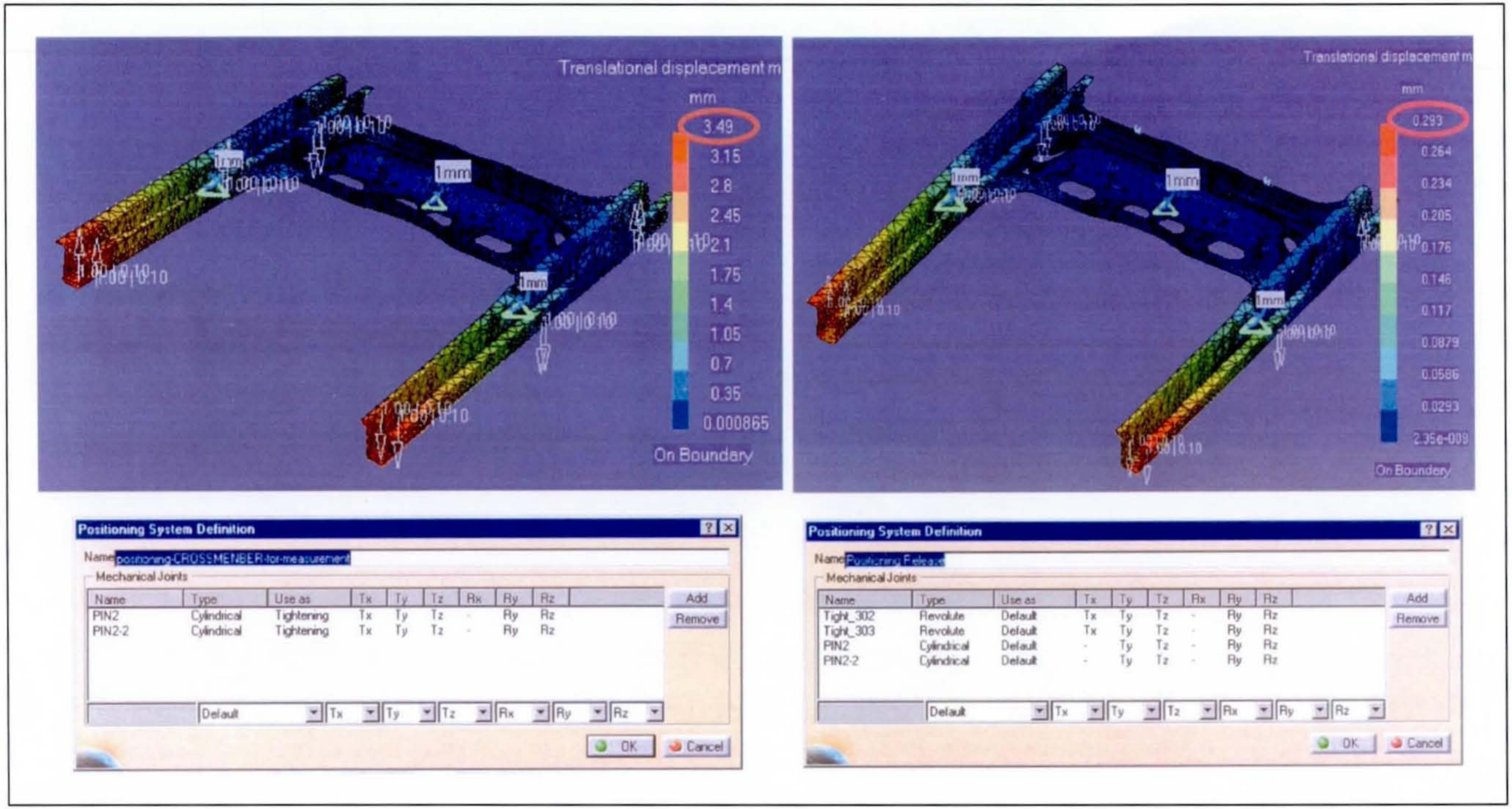


Figure 49: Comparison of translational displacement for original and modified crossmember positioning systems

7. DISCUSSION & CONCLUSIONS

This chapter draws together the issues presented within the thesis prior to the drawing of final conclusions.

7.1 DISCUSSION

Geometrical variations are inherent in any manufacturing and assembly process and cause small deviations in parts from the nominal geometry. The deviations affect position, orientation, and other behaviours of parts in an assembly. Moreover, these deviations propagate and accumulate as parts are assembled and can quickly drive assembly geometry out of specification. In order to put under control the effects of part variations it is possible to use dedicated software tools which are capable of performing tolerance analysis both for a single part and for a complete assembly. There are many commercial software tools dedicated to statistical tolerance analysis, as reviewed earlier in this thesis, however a great many of them are based on the assumption of perfectly rigid parts. It is evident that such an assumption is not acceptable in many industrial cases. Consequently, assembly process simulations carried out using these tools can lead to predicted final assembly geometry which is considerably different from actual production assemblies. The assembling procedure itself causes a degree of deformation in the parts themselves that make up an assembly which should not be neglected.

In this research it has been shown that it is possible to consider the effects of part deformation in the variation analysis of automotive BIW assemblies. A technique for variation analysis has been demonstrated that uses the method of influence of coefficients, available in the form of the commercially available tool, Catia TAA. This method takes into account three major types of dispersion: positioning, conformation and geometric dispersion of parts in an assembly. The output of the simulation produces the influence of these variations on the displacements of control points, forces imparted on assembly by the clamping process and on residual stresses near the fastening points. Catia TAA has the capability to model spotwelded, bonded, riveted, and bolted assemblies. It does not, however, have the capability to consider joining techniques like laser welding and simulates the assembly process on the basis of part measurements and not on the specifications of GD&T.

TAA is capable of predicting values of assembly tolerances during the early phase of the development process for a vehicle programme. Although part measurements may not be available at this early stage, rigid body analysis tools such as VisVSA could be used to generate measurements from virtual assembly builds of initial geometry at the earliest stage of a vehicles development. This could be fed into a Catia TAA simulation and could prove invaluable for the evaluation and selection of initial tooling locator strategies for new vehicles.

Catia TAA could be used as an analysis tool, to validate a set of preliminary (upstream) specifications, based on a set of subsequent (downstream) specifications, or as a synthesis tool, to directly determine all specifications.

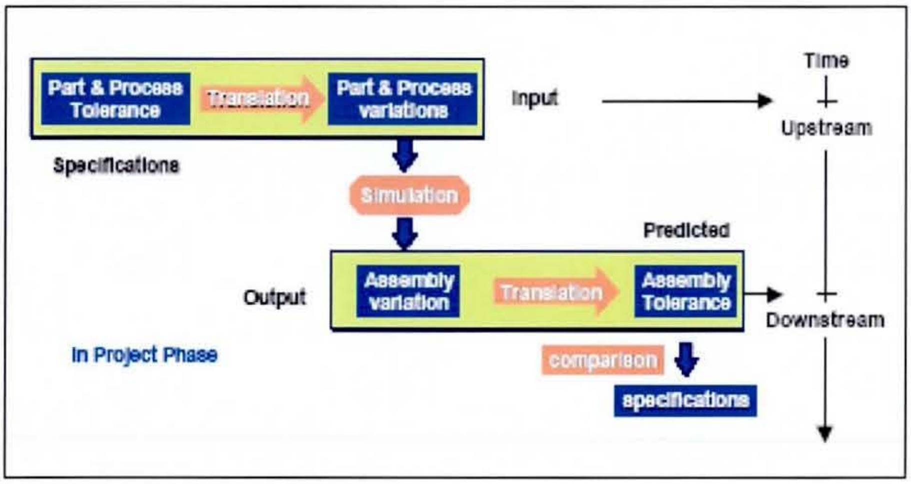


Figure 50: Application of CATIA TAA for validating process specifications (IBM)

The software could also be applied to the determination of optimum assembly sequence for fastening processes, based on the requirements of minimum position deviation at specific points such as fastening locations or the extremes of geometry, or alternatively be based upon obtaining minimum residual stresses in deformable assemblies.

7.2 CONCLUSIONS

The design, development and production of advanced aluminium-intensive-vehicles is a complex task. This research has been focused around a number of themes pertaining to the development of tools and techniques to assist designers and body engineers in the automotive industry.

Aluminium offers the automotive industry significant advantages over steel, and its adoption presents a number of opportunities and challenges in demonstrating the feasibility of deploying the material in structural BIW applications.

For the next few years the automotive industry will be concerned with the complete process concatenation of alloy production, via semi-finished product production and shaping through to mechanical processing and joint engineering in BIW construction.

With the new generation of integrated CAD-CAE applications, there is an apparent lack of software tools that can accurately simulate industrial processes such as part assembly by welding, bonding, riveting or bolting.

Recently some very powerful CAT systems have become commercially available and adopted within the automotive industry. Although they in general have solid mathematical backgrounds able to deal with 2D and 3D situations, with size and geometric tolerances, and are not in conflict with current international tolerancing standards, they have some drawbacks. One important drawback is the rigid body assumption. Another is a lack of understanding between the relation of the tolerance values and the physics involved in functioning and in manufacturing. As a result, tolerance specification and variation analysis functionality in most currently available CAT systems is insufficient.

An approach to variation analysis of deformable assemblies has been presented which will facilitate:-

- predicting closure forces in assemblies of misaligned parts
- predicting the final location of mating surfaces
- predicting distortion due to internal assembly stresses
- predicting internal residual stress and forces due to assembly of off-nominal parts
- predicting the percentage of assemblies which will not meet design limits/targets
- performing "what-if" studies and assigning tolerances throughout an assembly to ensure that both geometric and functional requirements are satisfied
- performing sensitivity studies to identify critical sources of variation

CAT tools and techniques should have the capability to simulate assembly process variations for deformable assemblies. This should contribute to an improved and deeper understanding of the relationships between tolerance values and the physics of product functions and manufacturing processes.

The variation analysis of deformable assemblies, as demonstrated in this thesis, highlights the need for better support to be provided for tolerance specification and variation analysis during the early phases of the automotive product development cycle, and in the digital environment, where only limited and uncertain product and process data is available. It is here where the greatest benefit stands to be gained.

A number of areas warranting further attention have been identified from both the literature reviewed and the modelling work undertaken and these are outlined in the following chapter, Recommendations for Further Work.

8. RECOMMENDATIONS FOR FURTHER WORK

This section outlines a number of areas for research that have been derived from the reviewed literature and the deformable assembly simulations:-

8.1 EARLIEST USE OF TOLERANCE ANALYSIS

During sheet metal assembly, part and process variations influence the final geometry of the assembly. Normally, the information needed to make realistic analysis of the final geometric variation is extensive and in the early stages of the development process still unknown.

There is a perceived general requirement to be able to do preliminary design purely on the basis of abstract schemes, or skeletal, with little or no nominal geometry attached. As a specific example, world-class practice in the area of design for minimum variation now seems to begin with conceptual top-down designs that establish chains of datum reference frames and key measurement points and characteristics far in advance of detailed geometric design.

The links in such a skeleton need to tie down 6 degrees of freedom for rigid parts, and generally many more for flexible parts. In practice, some of these are likely to be under-constrained. It is generally understood that maintaining and propagating under-constrained systems is difficult.

Methods and tools need to be developed for early evaluation of potential flexibility-related geometry problems in vehicle assembly processes. When necessary, FEA could be used to define the part and joint types for analysis of the direction and magnitude of propagation of dimensional variations. The time limitations imposed upon product development and production start-up processes, often dictate that concepts with the minimum associated risks will be chosen. Thus, the best concept with regard to other design criteria is not always chosen, due to lack of information or difficulties in conducting a realistic simulation. An area of research warranting significant attention should be the mapping of key parameters that control final assembly variation and the evaluation criteria used to determine that geometric and functional requirements will be satisfied.

8.2 TOLERANCE SYNTHESIS

Designers often view tolerance synthesis as either a "black art" that they don't understand or as a trivial part of the total design. With the increasing emphasis on design for assembly and design for manufacture, these views become untenable. To overcome this kind of thinking, engineers must be provided with tools that will allow them to understand the consequences of tolerance assignment and their relationship to product performance.

Tolerance synthesis refers to finding part tolerances that satisfy the requirements (specifications) of assembly tolerances. Part tolerance is closely related to the cost of manufacturing the part. The trend is that the tighter the tolerance, the more costly the part. Thus a cost vs. tolerance model needs to be established for optimal tolerance design (a least cost model). The mechanistic models derived in previous research could be used as constraints in the optimisation problem, while the cost function serves as the objective function to be minimised.

8.3 FINITE ELEMENT METHODS

Research should be conducted to verify the assumptions of compliant tolerance analysis. This would require building and measuring test specimens and comparing the assembly results with compliant tolerance analysis results. A possible test assembly could be to build and test pairs of flanged plates. Closure forces and displacements could be measured for a single assembly and compared to the output from a compliant tolerance analysis incorporating FEA routines. By comparing the results of a random sample of assemblies with a Monte Carlo simulation of the same problem it should be possible to validate the statistical compliant solution as well.

Little work has been carried out with FEA to investigate how deformations occurring at one joint in a flexible assembly affect other mating surfaces.

The effect that the order of assembly has on an assembly of flexible parts could be studied but with the inclusion of surface variations. This would require the modelling of the combined stiffness of two or more joined parts when fastened to another part in an assembly.

Previous work has only considered assembly gaps at fastener locations. There may be residual gaps or interferences that occur in-between the fasteners. This could be important for applications including gaskets, seals, aerodynamic surfaces, aesthetic appearance, etc.

Merkley (1998) assumed that small variations in geometry had little effect on the part stiffness. However, small variations in thickness can have a significant effect on shell type problems. Methods should be developed to include the effect of material and section properties on the stiffness-matrix itself and their consequences on compliant assembly variations.

8.4 PROPAGATION AND ACCUMULATION OF RESIDUAL STRESSES

As components are assembled, residual stresses develop at mating surfaces. Multiple components cause the residual stress to accumulate and propagate through the assembly. This propagation and accumulation is similar to the geometric variation in rigid body assemblies which can only be transmitted through the joints where mating parts contact. The nature of the propagation depends on the joint type. It may be possible to develop a library of compliant joint definitions, similar to the kinematic joints in rigid body assemblies.

The influences of distortions and residual stresses (in the local area around a weld nugget) due to welding heat, dynamics, vibration and nonlinearity of the assembly systems are not included in the majority of existing research. In some circumstances, these factors may be important to the dimensional quality of a sheet metal assembly.

8.5 SEQUENCE OF ASSEMBLY

Previous research indicates that assembly order can affect the required assembly forces. It appears possible to minimise the assembly stresses by determining the optimal order of component assembly.

A number of investigations have been carried out for assembly and spot weld sequences for simple one-dimensional sheet metal assemblies. There is the potential for extending research to assemblies with more complex two or three-dimensional free-form surfaces. Also clamping sequence needs to be addressed in the future.

There are certain structures that will assemble easily in a specific order, but will not assemble at all if the order is changed. Current research indicates that this may be similar to assembling springs in parallel or in series (Liu et al., 1995), where structures that act like parallel springs will be stiffer and more difficult to assemble. Based on the compliant tolerance analysis techniques proposed in research completed to date, assembly order may be optimised to reduce residual stress and assembly force. From this optimisation, methods could be developed for creating a rational process plan. This process plan would then have to be evaluated for efficiency and cost. It could also be used to verify process plans developed using traditional methods. This could help reduce tooling, redesign, and labour costs, as well as increasing part lifetimes.

8.6 UNDERSTANDING THE EFFECTS OF PART GEOMETRY

Stiffness of sheet metal parts plays a universal role in the final assembly dimensional variation. The shapes and cross-sections will contribute to the stiffness of the parts. Various shapes and cross-sections are widely used in sheet metal assemblies in the automotive industry. A comparison study of assemblies with various shapes or cross-sections will lead to a better understanding of design for shapes and cross-sections.

8.7 EFFECTS OF FIXTURING

Fixtures play an important role in the assembly process. The effects of fixtures could be included in the compliant tolerance analysis. The compliance of the fixture and its interaction with a compliant assembly could be studied along with the effect of dimensional errors. This could lead to the design of fixtures that reduce the residual stress in a finished assembly.

Fixture elements (locators or clamps) are assigned at given locations in this research. However, different schemes for fixture elements will result in different assembly variation. It will be useful to further study the effect of locations of locators and clamps. An optimisation technique could be developed to obtain the optimal solution to the location of fixture elements, so that the assembly dimensional variation is minimised.

Previous work assumes that the fixture elements consist of point contacts. In fact there is a small contact area between the fixture elements and parts during the assembly process. The fixture elements may constrain not only the displacements, but also the rotations of the parts.

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