12-2010

ANALYSIS OF PART CONSOLIDATION TECHNIQUES FOR AUTOMOTIVE BODY IN WHITE PANELS BASED ON ADVANCED SHEET METAL FORMING TECHNOLOGIES

Harish Thiruvengadam
Clemson University, hthiruv@clemson.edu

ANALYSIS OF PART CONSOLIDATION TECHNIQUES FOR AUTOMOTIVE BIW PANELS BASED ON ADVANCED SHEET METAL FORMING TECHNOLOGIES

A Thesis
Presented to
The Graduate School of
Clemson University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science
Mechanical Engineering

By
Harish Thiruvengadam
November 2010

Accepted by:
Dr. Mohammed Omar, Committee Chair
Dr. Imtiaz Haque
Dr. Yong Huang

ABSTRACT

The automotive industry is looking to move from mass production to mass customization in order to manufacture and sell a variety of products in different markets on a global scale. This requires a robust and cost effective manufacturing system which would help design new products in the shortest possible lead time. This thesis tries to investigate the current sheet metal forming process for body in white, identify the limitations and propose an alternative which would help the industry cut down product lead time and costs. Decision making tools are used to identify the hierarchy of technical attributes for a body in white manufacturing system and optimize the same. Part consolidation techniques are studied in detail and the various means to achieve them are investigated. Industrial origami® is proposed as an alternative to automotive stamping and a means to achieve part consolidation. Origami joints and their design features are modeled using cad tools and their load bearing, strength characteristics are compared to that of stamped joints using finite element analysis simulations. A bill of materials of a small sedan is constructed to identify the opportunities for part consolidation and process substitution of stamping using origami.

DEDICATION

I dedicate this thesis to my parents and my brother.

ACKNOWLEDGMENTS

I would like to extend my gratitude to my research advisor Dr. Mohammad Omar. His support and guidance throughout these years in graduate school has made it a very productive experience.

I would like to thank my committee members, Dr. Imtiaz Haque and Dr. Yong Huang for all their inputs and suggestions to help see this work to completion. I am indebted to my friends Arun Ganapathi and Srinath Vijayakumar for making graduate school a fun-filled experience. I would like to thank my fellow lab colleagues for all their thoughts, suggestions and discussions that kept the research work going.

I am indebted to my parents Mr. & Mrs. Thiruvengadam, the special people in my life who have provided me with unconditional love and support. Thank you. I would also like to thank my brother Aditya for all his encouragement through tough times.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER ONE– AUTOMOTIVE MANUFACTURING SYSTEMS

The automotive industry had been experiencing a steady growth on a global scale till the year 2007 when the production volume peaked at 73 million units. The economic recession in North America and Europe affected the industry and further decreased the profit margins of Original Equipment Manufacturers (OEM). The change encouraged the OEMs to look for innovative methods to decrease the production costs and find innovative means to optimize their manufacturing process. The industry started to cut down the number of product platforms and modularized the products by which they could quickly launch a variety of product in different markets. Shifting production facilities to cheaper locations, cutting down labor and adopting cost effective manufacturing technologies are some of the responses of the industry towards the changing industry paradigm. From the customer perspective there are three important factors which are driving a change in the automotive industry. The depletion of fossil fuels is encouraging lighter vehicles with compact engines in contrast to the past where heavy vehicles with large displacement engines were preferred [1-3]. Light weight and higher fuel efficiency are further encouraged by strict government regulations against automotive emissions and fuel efficiency [4-6].

This thesis investigates the current industry practices in mass production and identifies the optimal design strategy to minimize manufacturing costs and decrease product lead time of automotive body in whites (BIW). A majority of the cost involved in launching a new passenger vehicle is a function of the tooling, cost and the technology involved in manufacturing the BIW. The following section will study the typical manufacturing process of a BIW and will identify the current issues associated with it.

1.1 Body in white manufacturing process

The Body in white constitutes approximately 30% of the overall curb weight of the vehicle. Conventionally sheet metals of steel have been used to make monocoque structures of vehicle bodies which were later welded to the chassis eventually being fitted with the powertrain package. The current automotive industry have evolved are exploring newer options like hydroforming, superplastic forming to manufacture BIWs. Another field of advancement is the increasing usage of adhesive bonds in the joining process in place of welding. In spite of the above mentioned advances the following three manufacturing steps is the most prominently used manufacturing process involved in fabricating a body in white.

- Stamping
- Welding
- Painting

1.2 Stamping

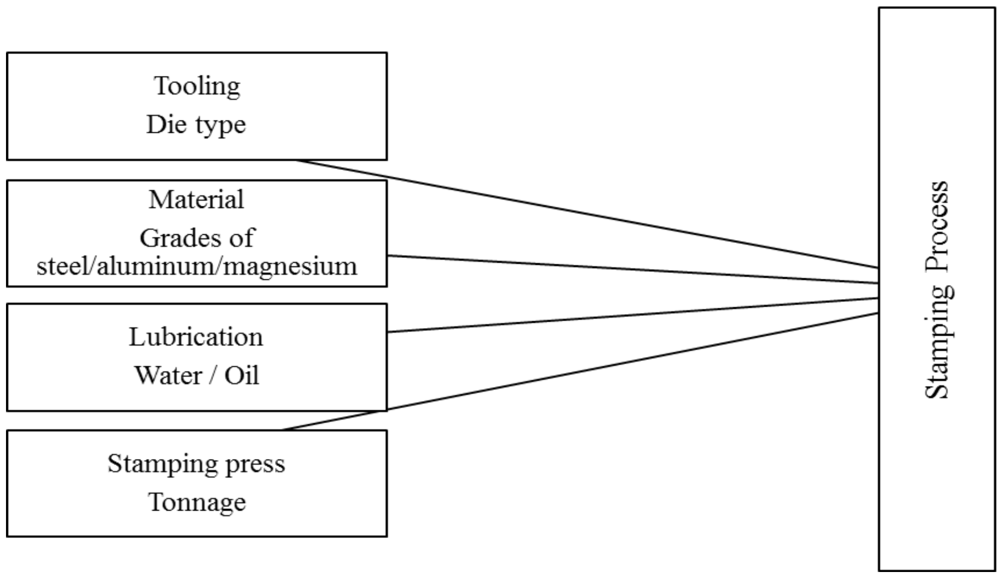


Figure 1-1: Stamping process inputs

Sheet metal working is the method of shaping thin sheets of metals into necessary shapes and sizes. The thickness varies between 0.1 mm to 6mm. Sheets thinner than 0.1 mm are called foils and thicker than 6mm are called plates. Stamping is one such sheet metal forming process which is widely used to make automotive BIW panels using metal sheets. Raw material is obtained in the form of rolled coils from steel suppliers. The thickness of the coils used is generally 0.75mm depending upon the grade and its applications. The coils are straightened and then cut into rectangular blanks for required dimensions. The blanks are then punched into necessary shapes and profiles using heavy stamping dies. Stamping is considered to be a net shaping process.

Stamping is a popular choice in the automotive industry due to high productivity, low assembly cost, ability to offer high strength panels and cost effective at high production volume[7]. The blanked coils are loaded into a deep drawing die where the binder holds the blank in place using a strong friction contact. The friction contact restrains the material flow from any movement during the punching operation. The punch deforms the metal panel into the shape of the cavity thereby imparting it the net shape required. The stamping process is very quick and typical transfer dies can process up to 300 parts per minute. In certain cases multiple drawings are necessary in order to stamp parts with intrinsic shapes and profiles. Here the spring back effect plays a major role in determining the number of shots required for each component. Trimming and piercing helps create additional profile features in the stamped sheet metal which might useful for secondary operations like welding and other assembly operations.

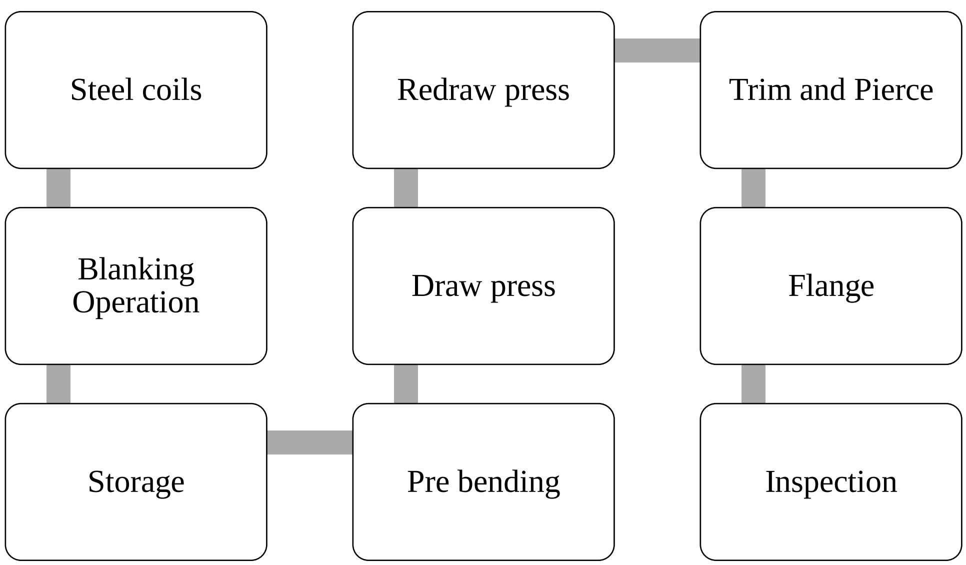


Figure 1-2 Stamping process flowchart

Stamped panels are classified based on their location, features and formability. The location helps determine the surface finish requirements and other aesthetic features. The presence of a weld lines and a surface defect is acceptable in interior panels but not on a class ‘A’ surface. This choice influences the stamping quality and material selection. Features are the presence of general shapes which help the designers associate certain properties or knowledge attributes. For example a hole cannot be placed very close to a bend in a stamped component as it would cause excessive stress concentration along the circumference. Stamped components are validated using three major criterion, appearance, strains and dimensions. While appearance and dimensions have a straight forward evaluation techniques, strains have to evaluated based on formability science which evaluates for strain values at critical places using Circle Grid Analysis (CGA).

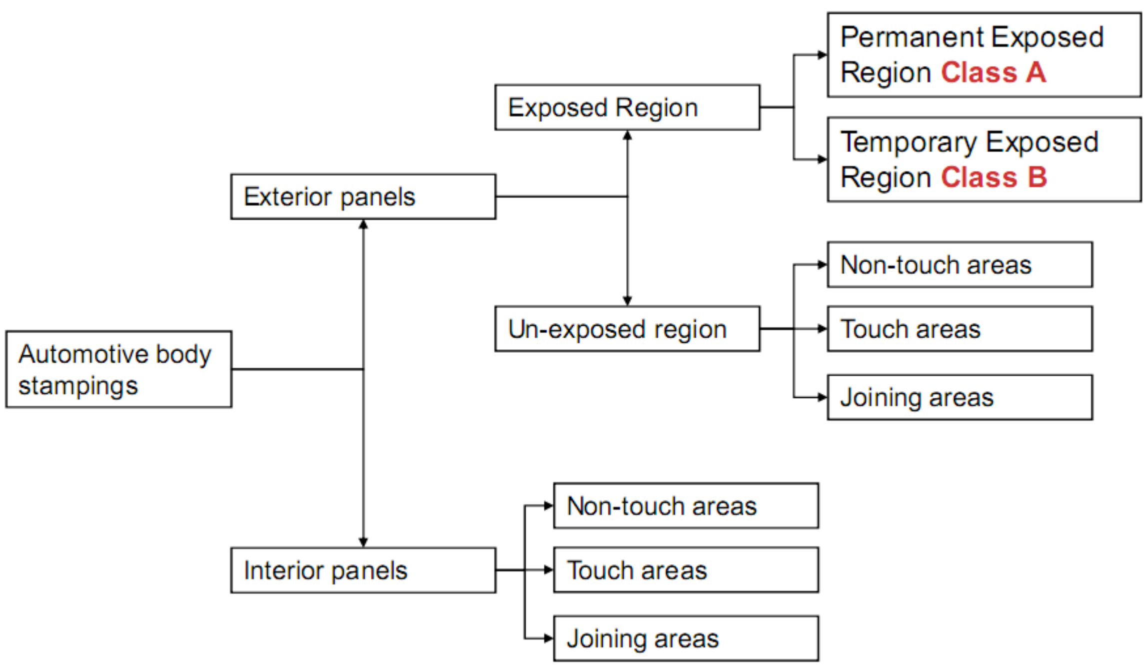


Figure 1-3 Classification of BIW panels based on location

1.3 Welding

The stamped body panels have to be joined together to impart strength to the BIW structure through welding. A majority of the automotive welding lines are completely automated except a few special cases of specialized sports cars where the product volume is very low and the cost is not an important factor. Recently adhesive bonds are finding increasing application by being used in combination with resistance spot welding. Thought the cost involved is low, the need for pre part treatment, specialized fixtures, environmental limitations and specialized equipment for automation discourage the OEMs from used adhesives for large volume production [8]. Hence a majority of OEMs still consider welding as the prime metal joining process. Two types of welding are widely used in the industry today, the fusion welding which takes place above the melting point of the metal and friction stir welding where welding occurs through plastic deformation.

The welding shop in a typical manufacturing facility consists of 250-300 welding robots armed with welding guns which perform 3000-4000 spot welds on a single body in white depending upon the size of the vehicle [9]. The absence of melting phase gives friction stir welding (FSW) the capability to join dissimilar metals making it an ideal process choice in the case of light weigh bodies. Research has shown that FSW has been successful in joining dissimilar alloys of aluminum 0.8mm thick without the loss of critical strength characteristics [10]. Laser welding using high power CO_2 and Nd:YAG lasers have been used to weld ultra-light weight body panels made of carbon steel, titanium alloys and aluminum alloys [11]. Patented hybrid laser welding technology is capable of welding thermoplastic components by combining the energy of a polychromatic light source and a welding laser [12].

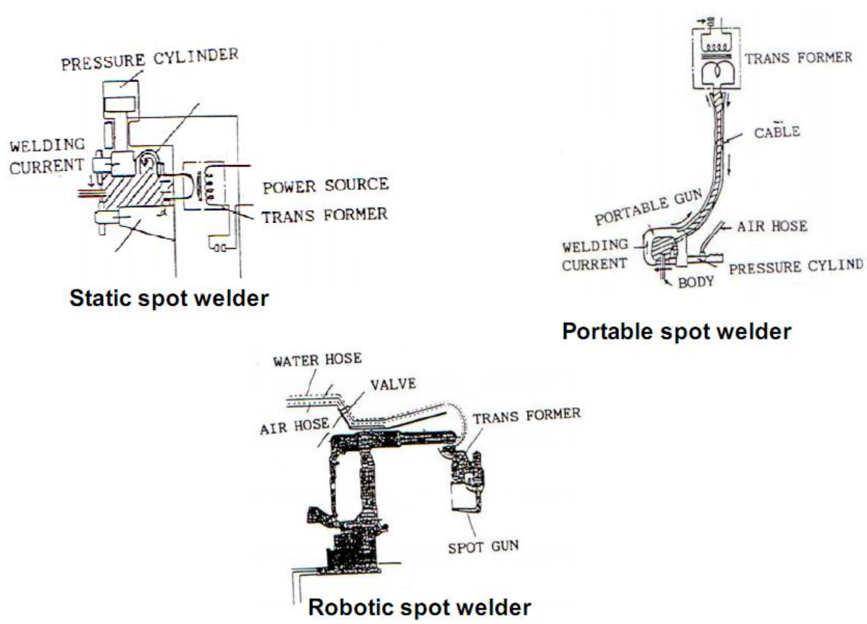


Figure 1-4 Spot welding robots [18]

Metal inert gas (MIG), tungsten inert gas (TIG) and manual metal arc (MMA) are some of the conventional welding methods which are popular due to their ability to access the vehicle body from one side only yet provide good strength to the joint. The tolerance on weld joints should be lesser than half the diameter of the welding electrode. Zinc coating is provided over steel panels to prevent them from corrosion and this requires specialized technique such as, fiber laser lap welding [13]. Welding aluminum is another challenge faced due to the presence of a thin oxide layer. Spot welding requires higher temperature to penetrate the oxide layer before the weld is actually formed. The presence of flux in the case of MIG can help flush away the aluminum oxide which might help in weld formation [14].

1.4 Painting

From a customer perspective painting fulfills two basic functions, to prevent the BIW from corrosion and to provide desired shape, style, texture and color. A majority of OEMs today employ flexible semi or fully automated painting robots for mass production. The change from hard automation to flexible robots was driven by shorter model life, flexibility to accommodate future models and painting multiple body styles on the same line [15]. The robots can be programmed offline to accommodate any of the above mentioned changes without any major delay in production planning schedules. Stop and go conveyor with vision systems are preferred over moving line painting booths due to their robustness, better interior painting quality and flexible process design.

A variety of paint choice can be made based on their medium (liquid/powder), suspension (solvent/water borne) and the numbers of coats (mono/multi) are available. Pretreatment process helps get rid of the dust and impurities which can lead to surface defects on the painted body. The electro coating (e coat) process deposits a layer of electrically charged particles to form a thin layer of uniform film thickness which prevents corrosion. The e coating is followed by a sealing process and then the primer coat. The high sludge output during pretreatment and e coating process is an issue when it comes to all aluminum body like that of jaguar XJ. In the event of a combination of aluminum and non-aluminum panels the later are pre coated before being fit into the car to prevent corrosion.

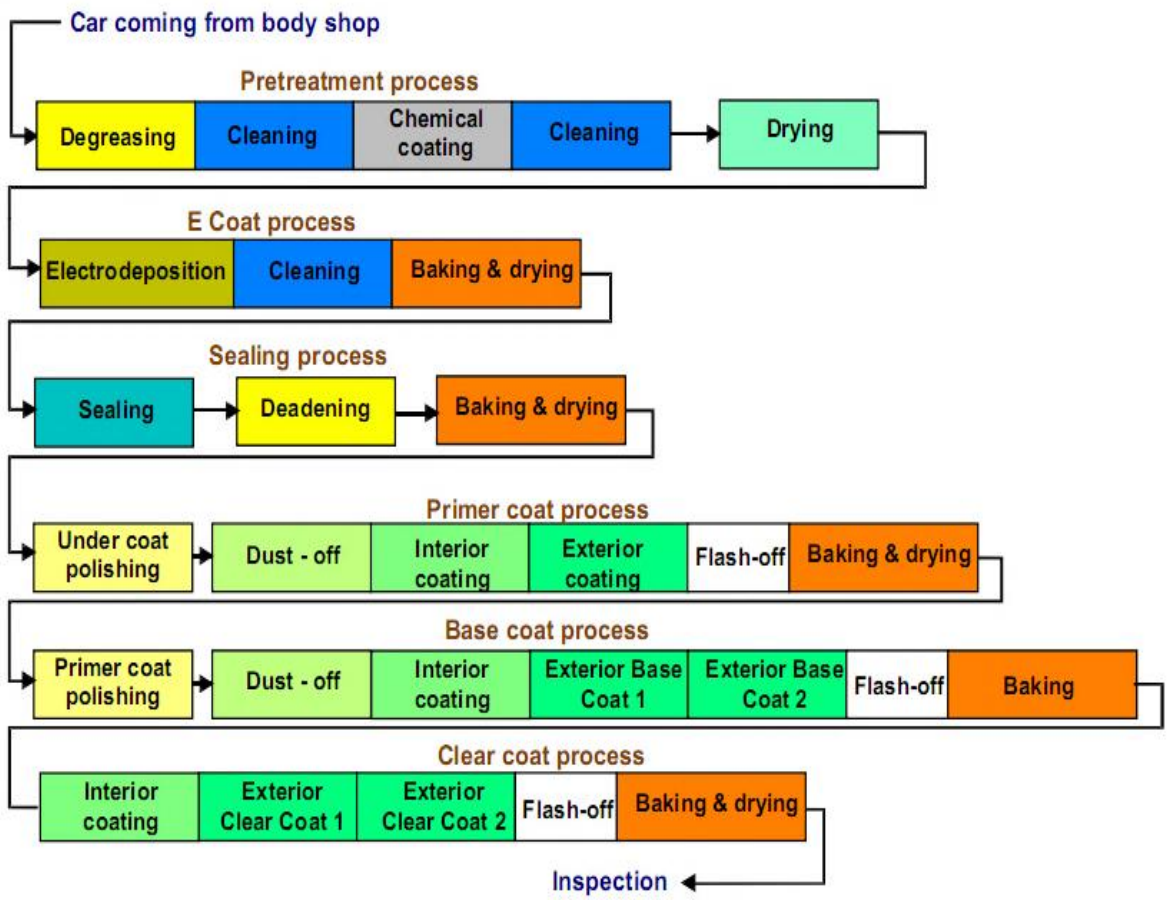


Figure 1-5 Painting process flow chart [19]

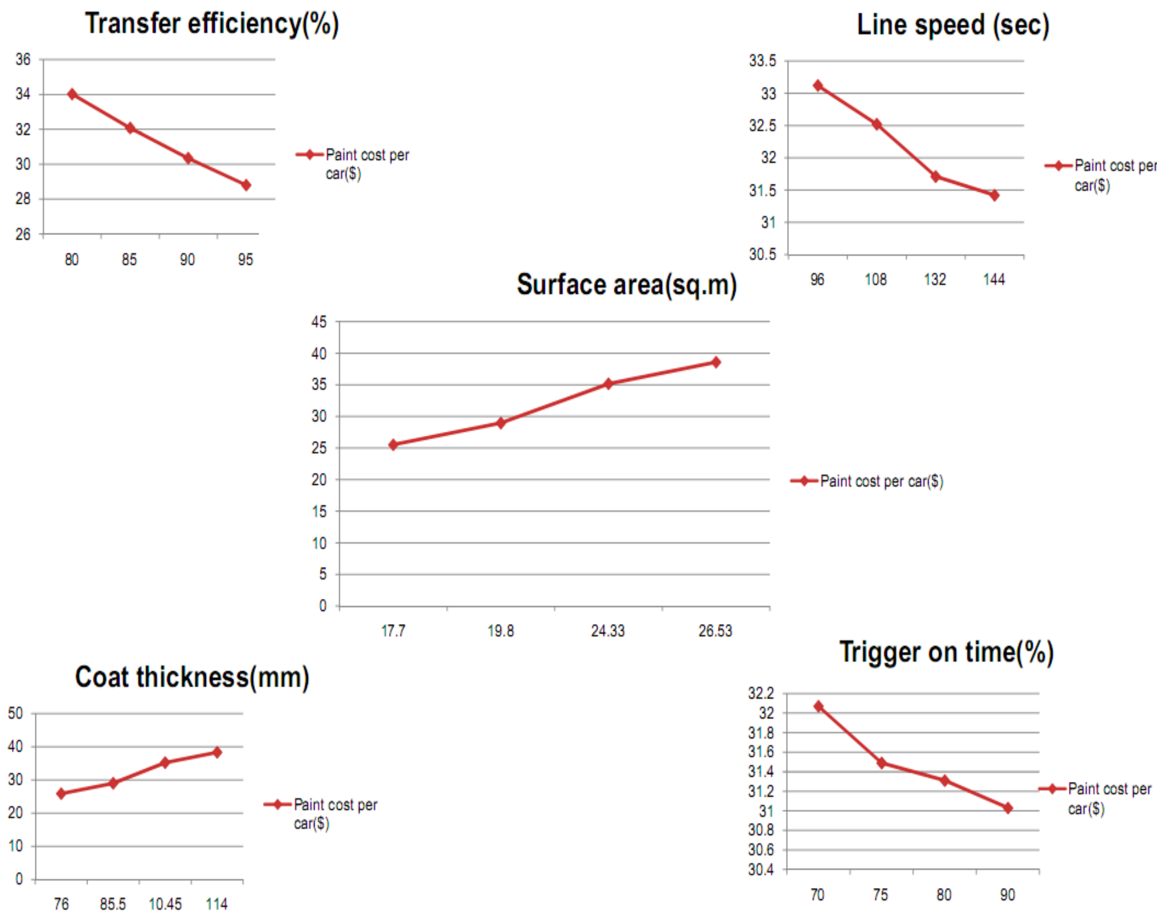


Figure 1-6 Effect on process parameters on painting cost

The usage of various coats, sealants and paint dispersing mediums lead to a high output of Volatile Organic Compounds which are an environmental hazard. The US council of automotive research (USCAR) envisions that the most ecofriendly painting process would be the combination of cathodic electro deposition primer, powder primer/surface, waterborne color coats and powder clear coat [16]. Currently BMW is the only OEM which uses the dry clear coating systems successfully, a system in which the VOC emissions are almost zero. The robotic painting stations have helped the automotive industry by providing good flexibility in product mix and variant. Though the cost of setting up a painting station is high, the cost of painting per car is considerable lower due to the long life and system robustness.

1.5 Current manufacturing process and its impact on vehicle lead time and production cost

The automotive industry is moving from mass production to mass customization due to an increasing need to manufacture a large variety of products in a short span of time with existing or limited resources [8]. The current manufacturing systems constrain the industry from being capable of supporting a wide variety of models due to process, technology and cost limitations. In order to work around the constraint, the major technological roadblock among stamping, welding and painting has to be determined. This thesis will do the same and suggest an alternative process based on the usage of decision making tools and analysis.

Let us understand the implication of launching a new product to be manufactured using the existing systems. The powertrain and the chassis have been modularized in the industry and development of these modules is concurrent to new product development. New engines, transmission, differentials continue to be researched upon and modifying them or customizing them to a particular model is feasible without major design changes. Increasing number of powertrain research are shared between OEMs in order to reduce the research lead time and cost. OEMs collaborate in research areas such as engines and transmission which are being shared across vehicle platforms of different markets. BIW design on the other hand is not shareable and requires in house design and development. Hence it is apparent that the most important roadblock towards mass customization is in fabrication of body in white panels. Only a small number of BIW panels can be shared between different models of the same platform which further strengthens the need for flexible manufacturing processes in fabricating them.

The above mentioned processes, stamping, welding and painting are analyzed for the maximum cost and time impact they create on a vehicle development process. There are two methods to determine the costing of manufacturing processes used in the automotive industry. The conventional method was to use labor cost, material cost, equipment cost, maintenance cost and other factory over heads to compute the unit cost of manufacturing a product or a component. Due to the changing manufacturing scenario and the inherent drawbacks of the system, activity based costing (ABC) was developed which calculated costs based on the activities and services which went into manufacturing a component/product. ABC can be applied to a variety of products and services both technical and administrative in nature. Specifically in the manufacturing industry technical cost modeling helps analyze the economic impact of alternate manufacturing process without actually performing a trial and error analysis.

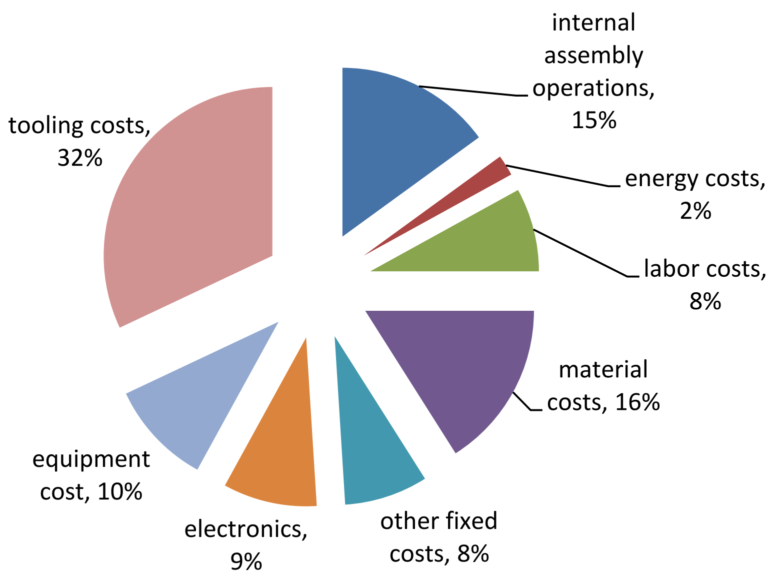


Figure 1-7 Driving factors in the manufacturing cost of a passenger car [20]

The welding process of joining different BIW panels is completely automated in mass production facilities using flexible and reprogrammable welding robots guided by vision systems. These robots provide the flexibility to accommodate newer models on their welding lines by just programming new motion sequence, position sensors and welding guns.

The painting stations in OEMs are semi/fully automated by the use of painting robots which can also be programmed to accommodate newer models just like the above mentioned welding robots. This makes painting process very flexible and cost efficient towards mass customization like that of welding.

Stamping process shapes BIW panels with the help of heavy stamping presses and tooling fixtures. A new product would require a majority of new tooling and fixtures in addition to the ones which can be modified from the existing process. As shown in the above figure tooling consumes the maximum cost and validation time thereby being a major investment from the OEM perspective. Tooling inventory control is another important aspect of using a variety of tools to accommodate a range of product variants [17]. Stamping process is a very fast, heavy tonnage and net shaping process due to which the tool wear and forces encountered is high. This calls for a robust tooling construction using high strength material which incurs and additional cost towards tool design and development. The following sections will discuss the current industry practices and challenges encountered in the stamping process and its impact on the BIW manufacturing process.

1.6 Stamping process and its challenges

The following sections will review the challenges in the stamping process from four different perspectives

1. Tooling design, cost and time involved
2. Material limitations in stamping
3. Customization issues with stamping

	Steel Unibody	Aluminium Unibody	Steel Spaceframe	Aluminium Spaceframe	Composite Monocoque
Geometry					
Overall vehicle mass (kg)	315	188	302	188	235
Mass as % of steel unibody	100%	60%	96%	60%	75%
Spot joints (#)	3250	3400		1000	n/a
Seam joints (cm)	n/a	n/a	4,000		6000
Piece count					
Total piece count (#)	204	224	137	137	41
Count as % of steel unibody	100%	110%	67%	67%	20%
Number of stampings	187	207	40	40	n/a
Number of castings	n/a	n/a	30	30	n/a
Number of roll/ hydroformings	n/a	n/a	50	n/a	n/a
Number of extrusions	n/a	n/a	n/a	50	n/a
Number of mouldings	n/a	n/a	n/a	n/a	7
Number of foam cores	n/a	n/a	n/a	n/a	34
Panels (inners/outers)	17	17	17	17	17
Materials					
Material prices ($/kg)	$0.77-$0.92	$3.00-$3.50	$0.77-$2.20	$2.00-$3.00	$3.13
Material density (g/cm^3)	7.85	2.70	7.85	2.70	1.59

Body-in-white cost analysis: key fabrication input for selected case study alternatives

	Stamping	Casting	Hydro-forming	Extrusion	Moulding
Range of cycle times (s)	8-12	50-60	30-40	3-10	600-1,200
Range of labourers/fab'n line	4-6	2	2	2	2
Range of machine costs ($M)	$1.3-$7.5	$0.8-$1.5	$1.0-$2.0	$1.0-$2.0	$0.5-$1.0
Range of tool set costs ($M)	$0.2-$6.0	$0.1-$0.2	$0.1-$0.5	$3k-$7k	$0.1-$1.2

Figure 1-8 Cost modeling of BIW manufacturing processes [36]

1.6.1 Stamping tooling design cost and time

Depending on their operations, stamping dies are classified as blanking, punching, bending and deep drawing. There are single and multi-operation dies based on the number of operations they perform per shot. Progressive dies are the most commonly used set up in body panels stamping owing to its high through put and low cycle time.

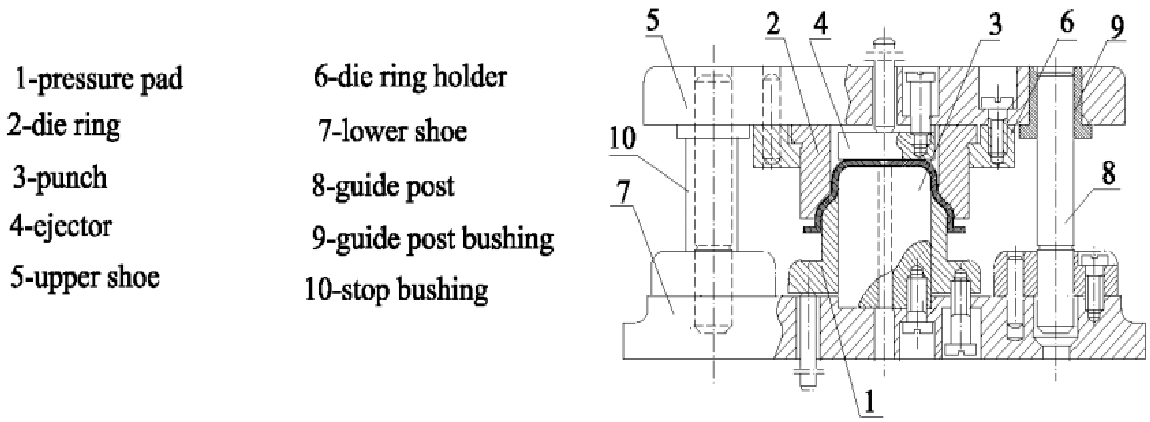


Figure 1-9 Drawing die used in stamping process [30]

Conventional high volume production tools are known as ‘hard tooling’ and low volume tools are referred to as ‘soft tooling’. Low cost tooling materials, such as low melting point alloys and plastics are used in the production of prototype panels which are used to validate and make trail runs before investing on hard tooling [18]. Lubricants are usually applied along the tool to perform two important functions, reduce sheet formability and ensure uniform distribution of contact stresses thereby reducing tool wear and increasing tool life [19].

Progressive dies are used to make small parts using multiple stations working in tandem with each other. They have high production speed and can be used for operations such as cutting and folding.

The following is a correlation developed by General Motors to calculate the tonnage and tooling investment during a stamping process [20].

Surface Area

Provides the surface area which is calculated based on weight of the part and its thickness. [Equation 1.1]

$$Surface\ Area = \frac{Weight}{Density * Thickness}$$

Tonnage

Helps calculate the tonnage of the stamping press in terms of surface area and part complexity. Complexity is a rating from 1 to 3 provided based on the shape and profile of the stamped part. [Equation 1.2]

$$Tonnage = 27.041 * Surface\ Area\ [0.01\ (complexity + 2)]^2$$

Tooling Investment

The equation below provides the total tooling investment required to manufacture the stamping tool. [Equation 1.3]

$$Tooling\ Cost = \$11950 + \$155888 * Complexity + \$\ 612322 * Surface\ Area$$

For example the maximum tooling investment to manufacture a stamped component which weighed 15kgs and a complexity rating of 3 would be 6 million.

The above equation provides an approximate estimate of the expenses incurred in manufacturing the tooling required for one component. A typical BIW of a sedan will consist of approximately 200-250 major panels which are made using stamping. Hence the overall cost would be hundreds of millions of dollars on a single model.

The high cost is mainly due to the use of specialized high strength material used during the construction of dies. The presses operate at about 24 strokes/minute, for slower applications like deep drawing and approximately 700 strokes/minute for high speed applications like blanking. This high speed combined with the heavy tonnage creates a lot of stress on the tooling materials and requires special material to withstand them. The tooling material requires high impact resistance, corrosion resistance and wear resistance over the course of its useful life. Mathematic models have been somewhat successful in simulating the relation between material choice and the type of tooling involved [21] [22]. High strength steel components are stamped using hot forming where the blanks are heated to a specific temperature, formed using presses and then quenched to room temperature [23].

The fabricated die is mounted on to the stamping presses and test runs are conducted to determine the dimensional and finishing accuracy of the finished components. This process is called validation and takes up a considerable time in the die fabrication process. The validation time can be marginally reduced by the usage of finite element method analysis and other simulation tools.

1.6.2 Springback

Due to the elastic nature of steel the stamped part will tend to retract its formed profile by a small angle immediately after stamping. In general it is about 3^0 for mild steel and about 6^0 in high strength steel. This change is compensated by modeling for spring back effect during the design stage of sheet metal itself. Spring back becomes a greater problem with the usage of aluminum and magnesium alloys as their elastic modulus is lower than steel. The amount of spring back is influenced by material thickness, mechanical properties and forming radii. This is a major reason limiting the profile complexities of aluminum and magnesium panels due to which they are limited to applications such as hoods, roofs and body side outers. Spring back in the case of aluminum has taken up to 6 months of tool validation time to correct [24]. Spring back can also be compensated by using multiple operations to create a particular profile but results in increased cycle time and manufacturing cost.

1.6.3 Feature constraints

Stamping process has some inherent design constraints in the form of bending angle and shapes. The control is due to a combination of the limitation of press forming tools and spring back effect. The location of holes, notches and their proximity to a bend is limited due to stress concentration that occurs during stamping. Secondary finishing operations or careful design choice would help in compensating for this limitation.

1.7 Thesis Objectives

The above sections have discussed in detail about the various drawbacks and challenges encountered in the stamping process. It is clear that stamping as a process and its associated tooling cost and time are a bottle neck when it comes to new product development. Hence there is a need for an alternate BIW manufacturing processes which would be able to fabricate body panels with low tooling cost and flexible designs. The new process should also have low product development time and reduced tool validation period which would help the automotive industry respond faster to changing market scenarios.

Decision making tool, Quality Function Deployment is used in the following chapter to determine the hierarchy of technical requirements of BIW manufacturing systems which would have the strongest impact towards decreasing production costs and product lead time.

CHAPTER TWO – DECISION MAKING TOOLS

2.1 Introduction

Quality Function Deployment QFD is a design tool which has been used to translate the customer requirements into appropriate design actions. Its role as a planning tools and its ability to accurately transform design requirements into technical requirements is the primary reason due to which it is extensively used by product development teams of OEMs like Toyota, General Motors, AT&T, IBM and Mitsubishi. As a quality system, QFD is successful in identifying the attributes of a product or a service as desired by the customer throughout all the appropriate functional components of an organization. QFD users benefit from one or more of the following advantages

- Reduces design cycle time and engineering changes
- Increases customer satisfaction
- Reduces lead time
- Reduces the cost involved in after launch design changes
- Fewer product rejects from customers
- Avoids or reduces product failure probability

Toyota Auto body plant claimed that usage of QFD over a period of seven years helped them reduce manufacturing start up and preproduction cost by nearly 60% and reduced the product development cycle time by 33% due to the reduction in the number of engineering changes.

2.2 House of Quality

HOQ is the structured relationship mapping between the WHATS and the HOWS. In a manufacturing house of quality the WHATS represent the process attributes and HOWS represent the production attributes. The mapping is basically a matrix which helps relate the rows and columns quantitatively based on scores provided by the designer. There are other supporting data provided in the HOQ which helps clearly communicate the importance and comparative ranking of the attributes specified in rows and columns. QFD is a combination of HOQs which are bound by a dependent relationship.

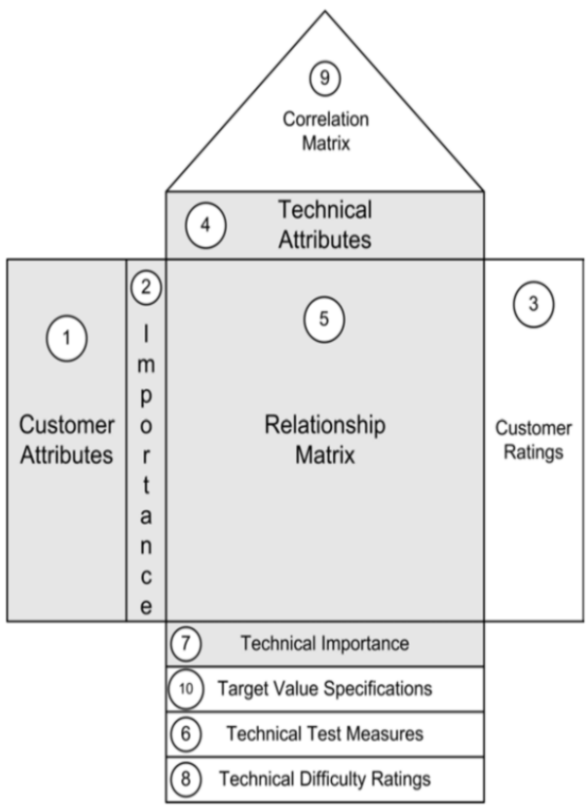


Figure 2-1 House of Quality

2.3 Interactions and Constraints

2.3.1 Customer Requirements (WHATs) are the important product attributes as perceived by the customer. It is obtained through Voice of Customer data (VOC) or through other means like market surveys or customer feedbacks. WHATs are very generic ideas in simple terms and seldom contain any kind of technical data in them. They are very expressive in nature like good looking, stylish, fast which cannot be absolutely quantified by an engineer.

2.3.2 Customer Importance is a score provided by the customer to express how much of an impact does the attribute make in the customer decision to purchase or use the product. This is important to find out which parameter when enhanced will bring greater customer satisfaction and thereby lead to greater sales or service. It is usually a number from 1 to 10. 3, 6 and 9 are the three normalized importance scores assigned in the QFD.

2.3.3 (HOWs) are the engineering characteristics which are determined by the product development team. For every customer requirement (WHAT), there is a corresponding technical attribute and a particular direction of improvement i.e. if it has to be increased, decreased or unchanged. Determining these attributes plays a critical role in the overall success of using QFD.

Table 2.1 Rating score

Strong	Θ	9
Moderate	O	3
Weak	▲	1

2.3.4 The relationship matrix forms the core of the QFD where the relationship between the customer requirements and the technical attributes are established. One customer attribute may affect multiple technical attributes and hence establishing their relationship can become difficult. The relationship is based on three different scores which are not quantitative in nature. They are to be considered as qualitative scores as a strong to moderate relationship does not mean that strong relationship is 3 times as strong as moderate relationship. These scores are provided by the cross functional team based on their experience and technical expertise in their respective fields.

2.3.5 Targets are a measure of the above relationship score in terms of a relative number which the design team will be able to utilize the most important technical attribute. They are the raw numbers which are located at the bottom of the HOQ. They consist of degree of difficulty, target values and the weights/importance. The degree of difficulty corresponds to how difficult it is to attain the customer attribute. The target value is a measure of values that must be obtained to achieve the technical attributes. It is an actual measure of what has to be done in the customer attribute in order to fulfill the customer requirements. The absolute weights a_j of the j^{th} engineering attribute is calculated by equation 2.1

$$a_j = \sum_{i=1}^{n} R_{ij}\, c_i \,, j = 1, \ldots\ldots, m \qquad \text{[Eqn 2.1]}$$

R_{ij} = weight assigned to relationship matrix (9,3 or1)

c_i = degree of importance to the customer

m = number of engineering characteristics

n = number of customer requirements

2.4 Different QFD models

There are two models of QFD, the four phase model developed by Hauser and Clausing and the Dr.Akao model called the matrix of the matrices. The latter is considered to be huge, time consuming and computationally intensive [Cohen 1995]. The four phase model is commonly used in the industry owing to its simple approach and quick results

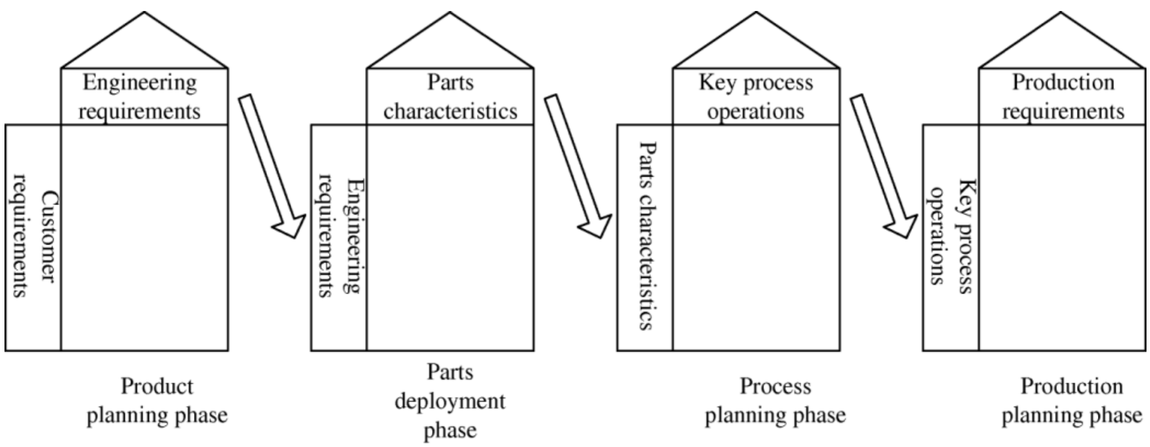


Figure 2-2 Cascading phases of QFD during product development

The four phase model involves four important modules which will help an organization completely deploy QFD techniques from the customer requirements stage to the process variables prioritization stage. The phases involve four different HOQs, which are customer requirements, parts deployment, process planning and production planning.

2.5 Decision making using QFD

The fourth and final phase of the above discussed QFD is considered for the decision making process. That is the phase where the design parameters are converted into the process variables. This helps us arrive at the prioritized variables which will help us divert adequate resources in order to optimize the complete manufacturing process. The WHATs in the fourth phase is the design parameters which are obtained from the shop floor requirements. The HOWs are the process variables which are key controlling parameters in the body in white manufacturing process. By mapping the relation between the WHATs and HOWs we will arrive at the hierarchy of the process variables which have to be optimized in order to achieve better lead times and lower costs.

The metrics behind arriving at the final scores of the production requirements starts with calculating the relative importance of the process attributes. The numerical values of the mapping matrix are obtained from the strength of the relationship between the rows and columns as provided by the designer. For every single column the maximum weight is identified and is used to normalize the total weights or the cumulative importance using the calculations shown below. The weights are divided by the maximum value in their respective column to get the specific weight or the relative weight. This process is repeated for all the production attributes and the attribute with the highest relative weight is ranked number one. Descending order of the relative weights relate to an ascending order of the ranks.

2.6 Process parameters

Process requirements are the important objectives or the production targets which when achieved would result in cost and time savings by the OEM. The can also be classified as the shop floor requirements which when optimized would enhance the overall efficiency of the production line.

1. Reduction in lead time

This refers to the time spent by the raw materials in the manufacturing facility when they are transformed from metal coils/sheets to completed body in white units. In addition to the time spend by the materials being processed, it also includes material handling time and material waiting time before being processes by the machinery. The decrease in production lead time results in a lower idle capital costs, lower operating costs and faster response to a change in the product mix or variety.

2. Fewer operations

This is the number of operations required to shape the raw material to its final usable product. Fewer operations leads to lower utilization of machinery, shorter lead time, reduced material handling and easier production planning.

3. Reduction in operational complexity

Operational complexity is a qualitative measure of the effort undertaken by the body shop personal to ensure that the required part is stamped to the final shape and dimensions as required by the BIW design. Usage of specialized stamping fixtures, multiple shots to form intricate shapes and special die construction to stamp aluminum are some of the common complexities encountered in body shop operations.

4. Ease of reconfiguration

A change in the process layout and the production machinery to accommodate a change in the product mix or the product variety is known as reconfiguration. Different models of passenger vehicles will require body panels of different dimensions, material, and shape. These changes have to be accommodated by changing stamping die designs, ejection mechanisms and varying tonnage. These changes can be accommodated easier by the usage of reconfigurable manufacturing systems, standardized parts and modularized body panel sub-assemblies.

5. Automation

Automating material handling and loading/offloading of blanks in stamping lines leads to improved process efficiency, reduces human fatigue and eliminates error due to human factors.

6. Scrap reduction

Necessary blank sizes cannot be accurately cut from the metal coils and this leads to some wastage. The scrap steel can be used to cut smaller parts or can be recycled and either way it leads to wastage of resources and time. This can be reduced by optimizing the nesting configuration, reducing binder scrap and consolidating smaller parts to better utilize the coil dimensions.

7. Decrease in rework

This is the wastage in resources caused due to defects in stamped parts. Stamped panels are evaluated based on dimensions, appearance and strains. Any nonconformance in these characteristics will lead to the stamped component being recycled or scraped.

2.7 Production requirements

1. Number of components

It is the total number of components which go into making the body in white. This includes major panels and sub assembles provided by the supplier. Reducing the part count helps lower costs, manufacturing lead time and material handling time.

2. Changeover time

A change in the product requires a change in tooling, and the time required to do so is the changeover time. This time decreased drastically after the introduction of SMED technique invented by the Japanese OEMs.

3. Uniformity in material selection

Different parts of an automotive body require different materials to satisfy its requirements of surface finish, strength and torsional strength. For example a door inner and outer would require different materials but specialized joining techniques would be required to spot weld them or adhesive bond them together. Hence reducing the variety in the choice of material selection would help save costs and time during joining process like welding or adhesive bonding.

4. Variability in dimensions

Thicker exterior panels help increase crash/ dent resistance and thinner interior panels help reduce weight. This is made possible by the usage of tailor welded blanks which can weld panels of different thickness and thickness. However TWBs have certain limitations which restricts their application and hence the variability in dimensions have to kept minimum.

5. Avoiding Intricate shapes

Fabricating panels with intricate shapes is not easily achieved due to the spring back effects experienced during press forming. Advanced processes like super plastic forming and hydroforming help manufacture complex shapes parts but with high cycle time. Intricate shaped parts help part consolidation but are in conflict with modularity.

6. Usage of common platform/Modularity

Common platforms in automotive structures help develop modular systems which facilitates interchangeability between vehicle models. This increases standardization, reduces rework but increases the lead time of fabricating modules. Due to globalization, OEMs are increasingly looking to consolidate their vehicle platforms to coordinate product launches and reduce vehicle lead time.

7. Open architecture control

Open architecture control of the software used in the manufacturing machinery helps reconfiguration principles. Open architecture facilitates easier configuration of machining equipment due to which parameters like capacity, operations, alignment and tonnage can be modified using remote production control units. This translates to faster response to change in product mix and combination.

8. Optimized nesting parameters

Nesting techniques during blanking help reduce scrap generation and ensures better material utilization. This saves product cost but increases the pre-production lead time which can be offset with better optimization techniques.

9. Consolidation of parts

Part consolidation helps reduce cost, achieve weight savings, decrease production lead time, standardize parts and leads to fewer product operation. These parameters have been discussed in detail in the literature survey section.

10. Reduce intra-cell and inter-cell distance

Reducing the above stated distance can be achieved by optimizing the process sequence and modifying the production floor layout. This helps achieve lower product lead time and material handling cost associated with operations such as welding and painting.

2.8 Determining the weights

1. The weights were calculated using the formula

$$a_j = \sum_{i=1}^{n} R_{ij}\, c_i\,, j = 1, \ldots\ldots, m \qquad \text{[Equation 2.1]}$$

Sample calculation

$a_j =$

$$\sum_{i=1}^{n} 14.3 * 9 + 14.3 * 9 + 11.1 * 3 + 12.7 * 3 + 12.7 * 3 + 12.7 * 9 + 11.1 * 3 + 11.1 * 3$$

= 547.6

Where R_{ij} are customer importance ratings

Ci is the score obtained in the decision matrix

2. Relative weights

Relative weights = $\frac{a_j}{\sum_i^n a_{ji}}$ [Equation 2.2]

Sample calculation

$$a_j = \frac{547.6}{547.6+265.1+484.1+512.7+446+506.3+430.2+407.9+582.5+398.4+239.7+417.5} = 9.6$$

Table 2.2 Mapping customer requirements to production requirements

Decrease in rework	Scrap reduction	Automation	Ease of reconfiguration	Standardization	Reduction in operational complexity	Fewer operations	Reduction in Lead time	Process Requirements ("Whats") / Production Requirements ("How s")	Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)
3.0	3.0	6.0	6.0	6.0	3.0	9.0	9.0	Weight / Importance	
○	○	⊙	○	▶	▶	⊙	⊙	Number of components	◀
▶	▶	▶	○	○	▶	⊙	⊙	Change over time	◀
▶	▶	○	○	⊙	⊙	⊙	○	Uniformity in material selection	▶
▶	▶	○	○	⊙	⊙	⊙	○	Variablity in dimensions	◀
○	○	▶	○	○	⊙	⊙	⊙	Avoiding intricate shapes	◀
▶	▶	⊙	○	⊙	⊙	▶	○	Number of process parameters	◀
▶	○	⊙	⊙	⊙	○	○	○	Usage of common platform	▶
▶	▶	⊙	⊙	▶	▶	▶	▶	Use of open architecture control	◀
⊙	⊙	▶	○	○	○	○	○	Optimized nesting patterns	▶
▶	○	○	⊙	⊙	○	▶	○	Use of modular structures	▶
○	○	○	○	⊙	▶	⊙	⊙	Consolidation of parts	▶
▶	▶	○	▶	▶	▶	▶	⊙	Concurrent operations	▶
▶	▶	⊙	⊙	▶	▶	▶	⊙	Reducing the intracell and inter cel distance	◀

2.9 Results and discussion of the decision making process

Table 2.3 Final ranking of technical requirements

Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▼	▲	▼	▼	▼	▲	▼	▲	▲	▲	▲	▼
Production Requirements ("How s") / Process Requirements ("Whats")	Number of components	Change over time	Uniformity in material selection	Variablity in dimensions	Avoiding intricate shapes	Number of process parameters	Usage of common platform	Use of open architecture control	Optimized nesting patterns	Use of modular structures	Consolidation of parts	Concurrent operations	Reducing the intracell and inter cel distance
Weight / Importance	580.0	473.3	513.3	513.3	553.3	433.3	526.7	313.3	353.3	406.7	606.7	286.7	473.3
Relative Weight	9.6	7.8	8.5	8.5	9.2	7.2	8.7	5.2	5.9	6.7	10.1	4.8	7.8

The Quality Function Deployment was performed to identify the order of production parameters which when improved will help achieve reduction in production cost and decrease in manufacturing lead time. The relative weight score was calculated and the table below gives the consolidated ranking of all the technical attributes. The attribute with the highest weight implies that improving this attribute in BIW manufacturing process would provide the best results in terms of cost and lead time. Reduction in the number of components is ranked second and this further strengthens the need to integrate the parts. The following section will address the application of part consolidation techniques to integrate the BIW design of a small sedan. A manufacturing bill of materials was prepared to identify the panels and the current manufacturing process used to fabricate them.

CHAPTER THREE– CURRENT PART CONSOLIDATION TECHNIQUES

Chapter three will investigate the manufacturing process based part consolidation techniques, used in the fabrication of body in white panels. The three processes being considered are hydroforming, superplastic forming and tailor welded blanks.

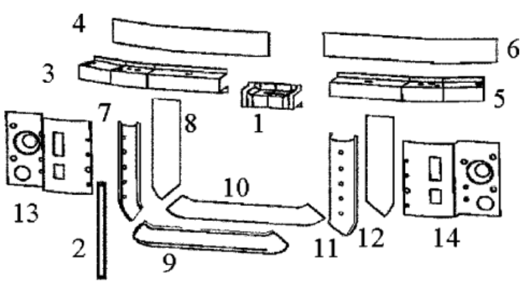
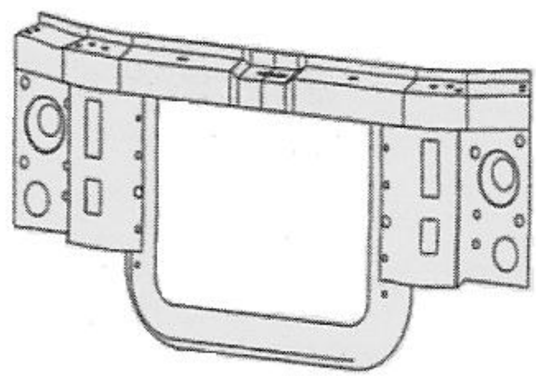
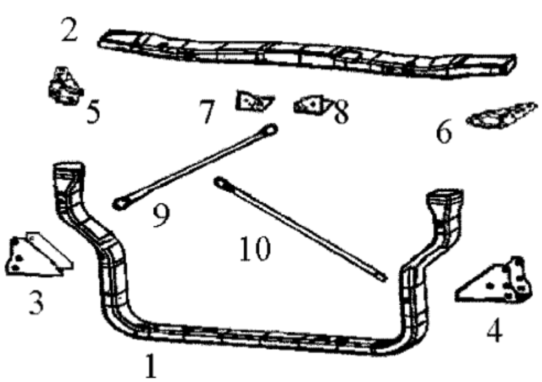
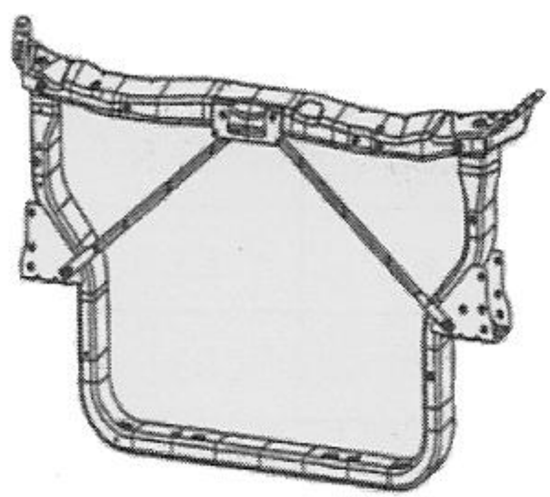
Part consolidation or part integration is the process of reduction in number of components by attaching multiple functions to a single component. In terms of BIW design, it is the consolidation of multiple smaller body panels into one single but larger panel without compromising the functionality, strength or the aesthetic requirements of the panel. Reduction in the number of panels will lead to a decrease in manufacturing costs and time, apart from the transportation, material handling and factory overheads of manufacturing them. Introduction of tailor welded blanks helped consolidate metallic panels of different material and thickness to provide better strength and rigidity when compared to individual panels. The trend of consolidating parts to reduce costs continued further with the introduction of superplastic forming and hydroforming. The following case studies will help understand the technique used and will help understand the advantages and challenges encountered in consolidation.

3.1 Part consolidation using hydroforming

Hydroforming is the usage of forces exerted by pressurized fluids to shape sheet metal or tubular parts into net shaped components. When compared to stamping hydroforming helps in the fabrication of complex shaped parts in addition to lowering costs, facilitating part consolidation and eliminating the need for secondary joining processes. Space frames and hybrid frame designs use a combination of sheet metal and tubular hydroformed components to achieve weight reduction and increased structural strength. Certain challenges in implementing hydroforming are the high cycle time, labor intensive and the usage of specialized joining/holding techniques to hold the hydroformed assemblies together. Welding of tubes may not be possible due to the thin cross section of tube designs.

The following case study by a hydroforming supplier investigates the successful part consolidation of a radiator assembly for an American OEM using tube hydroforming. The conventional assembly was a combination of 14 stamped parts weighing 14.1kgs. The supplier helped modify the design to facilitate the usage of tube bending hydroforming which effectively reduced the part count by 28%. The center console 4 and 6 could be formed into one large tube instead of three separate stamping parts. The central tie bar could be easily accessed during service or repairs due to the ease of removing one long tube compared to 3 stamped parts. This resulted in weight savings of nearly 3.7kgs in addition to facilitating a 40% increase in cooling air flow [25]. The hydroformed structure also provided better stiffness when compared to the original stamping design.

Table 3.1 Part consolidation of a Dodge radiator assembly[25][26]

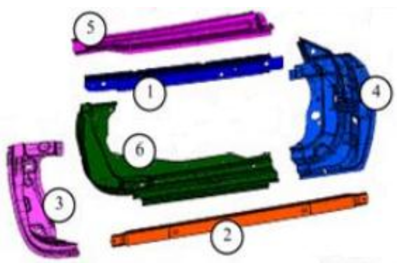
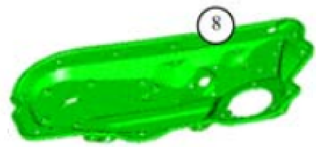
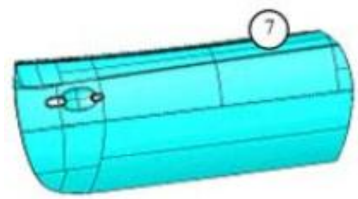
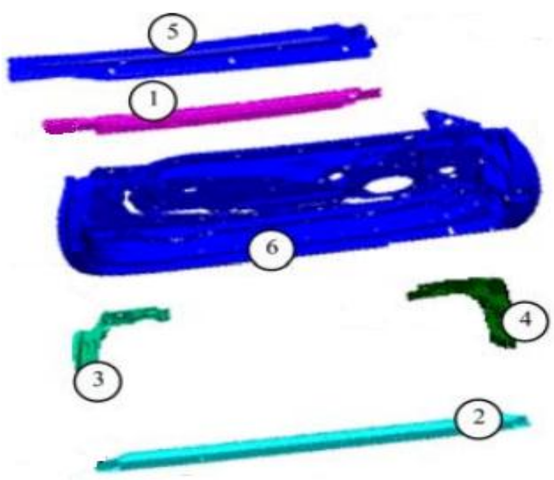
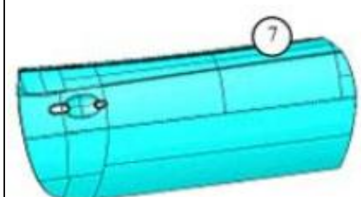
<table>
<tr><td colspan="2">Comparison of hydroformed and a stamped components</td></tr>
<tr><td colspan="2">Stamped Radiator assembly, part count : 14</td></tr>
<tr><td>
</td><td></td></tr>
<tr><td colspan="2">Hydroformed radiator assembly, part count : 8</td></tr>
<tr><td>
</td><td></td></tr>
</table>

3.2 Part consolidation using superplastic forming (SPF)

Superplastic forming is the process of fabricating class ‘A’ surfaces of BIW panels by exploiting the super plasticity property of certain metals like aluminum and magnesium. Pressurized gas is used to force preheated metal panels into one sided die cavity to obtain net shaped metal panel with good surface finish. It is easier to form sheet metal panels with intricate shapes using SPF when compared to stamping due to the elimination of spring back effect. This helps consolidate smaller parts to form a single complex shaped sheet metal panel using materials like aluminum and magnesium which is not possible in stamping. High cycle time and specialized raw material requirements are some of the limitations of this process

The following section reviews the successful implementation of superplastic forming by an OEM to fabricate a door module made of aluminum [27]. The inner assembly consists of 2 stamped parts (5,6), 2 extrusions(2,1) and 2 castings(3,4) as shown in the figure below. The inner structural component and the outer panel are made of stamping. The inner structural component was combined with the two extrusion parts to form one single panel by using superplastic forming. This eliminated the need to stamp a separate inner module made of aluminum thereby reducing the part count from 8 to 7. The weight reduction of the overall door structure was estimated to be 11.4% by using CAE simulations. This consolidation helped achieve a cost reduction of 5% per piece and more importantly the tooling cost of SPF is just 20% of the tooling cost of stamping the panels. The only limiting factor in this case is the cycle time which is nearly 5 minutes per piece. Hence the production has to be limited to low volume specialized batch production.

Table 3.2 Part consolidation of a door module using super plastic forming [27]

<table>
<tr><td colspan="3">Part consolidation in fabricating a passenger car door</td></tr>
<tr><td colspan="3">Current aluminum door structure</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Inner assembly</td><td>Structural component</td><td>Outer panel</td></tr>
<tr><td colspan="2">
</td><td>
</td></tr>
<tr><td colspan="2">Super plastic formed inner assembly</td><td>Outer panel</td></tr>
</table>

3.3 Part consolidation through tailor welded blanks

Tailor welded blanks (TWBs) are fabricated by welding two or more panels of different thickness or material to form a single structure which can be stamped into desired net shaped body panels. TWBs help consolidate thinner panels for non-load bearing applications along with thicker panels for load bearing into one component thereby eliminating the need for specialized stamped panels. Apart from decreasing the number of components they also help in reducing the number of spot welds, decreasing scrap rate, improving structural integrity and lowering manufacturing costs. The consolidation also provides a design flexibility which reduces development time and improves the dimensional accuracy. Case studies have indicated that the use of tailor welded blanks to integrate parts also leads to weight savings [28].

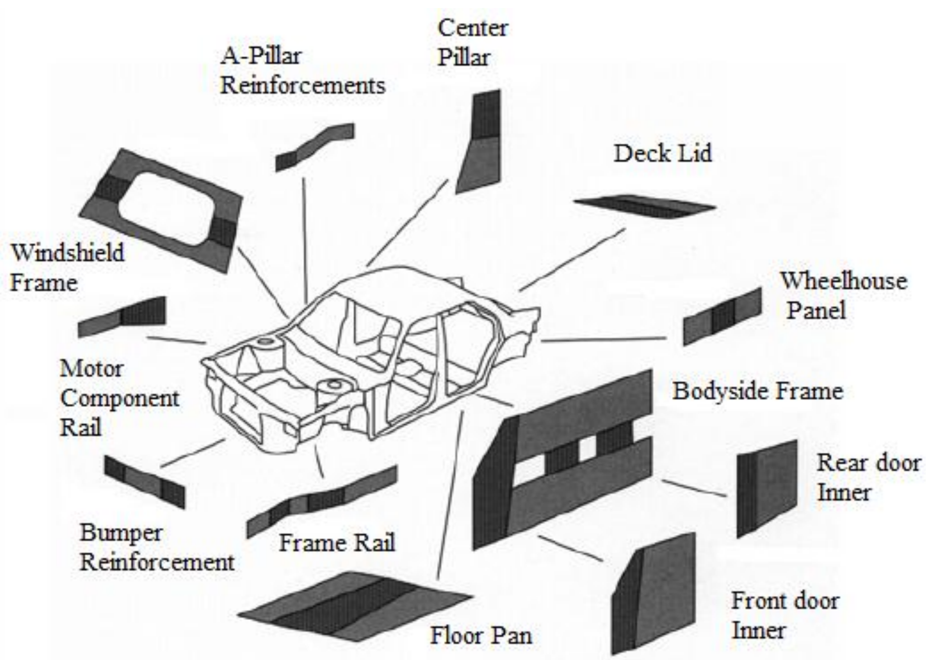


Figure 3-1 TWB application in automotive BIW [7]

3.3.1 TWB process types, applications and selection criterion

Tailor welded blanks (TWB) refers to the welding of two or more blanks which have different material and geometrical properties prior to the stamping operation. Some of the reasons for implementing tailor welded blanks are [AS]

- Cost reduction
- Structural improvement
- Mass reduction

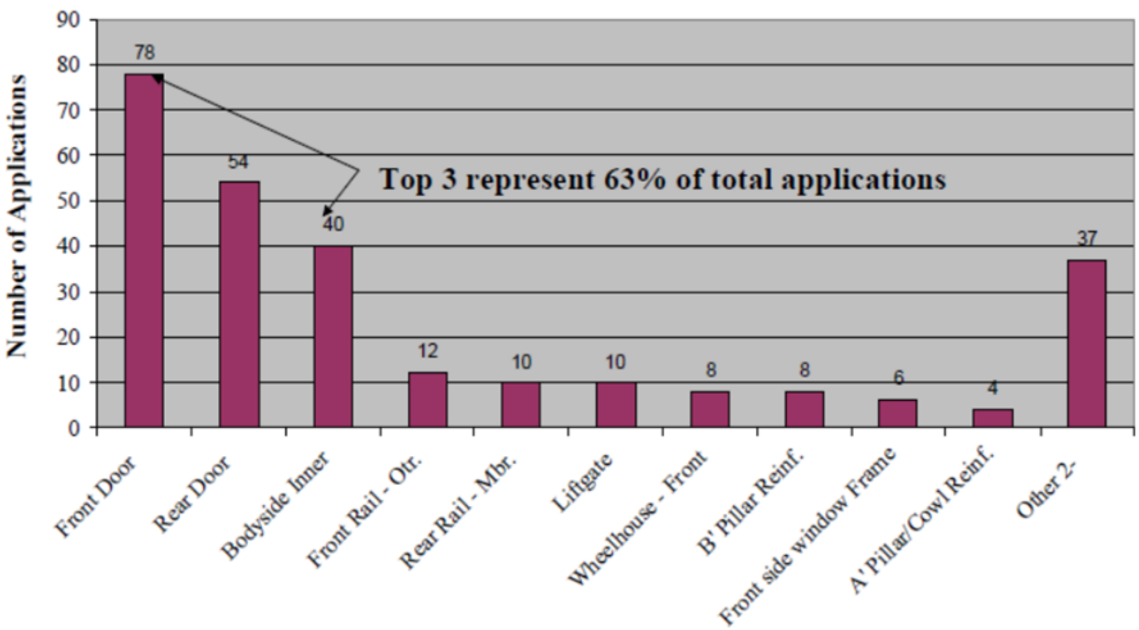


Figure 3-2 Part wise TWB application in USA [29]

The TWB process is classified into five major types based on their applications as follows

- Single straight line
- Multiple straight line and angular
- Non linear
- Patch
- Tubes

3.3.1.1 Single straight line

Single straight lines of weld are used in conditions wherein the length of the required weld is not greater than 1.3 meters and consist of one straight line. They are generally used in manufacturing of front and rear door inners, longitudinal rails, floor plans and rocker panels etc. The figure below shows a typical single line tailor welded blank. The figure (a) depicts a typical B pillar consisting of a 400mm straight line weld joining two sheet metals of different thickness. Here the use of straight line weld is mainly for the purpose of mass reduction without compromising on the required structural strength of the part. Figure (b) represents the usage of single weld on a door inner panel. TWB combines the high strength requirement of the hinge region (light colored) with the thinner section (dark colored) required for dent resistance. This TWB process is the most simplest and cost effective of all of them due to low weld length and simplicity in weld line placing.

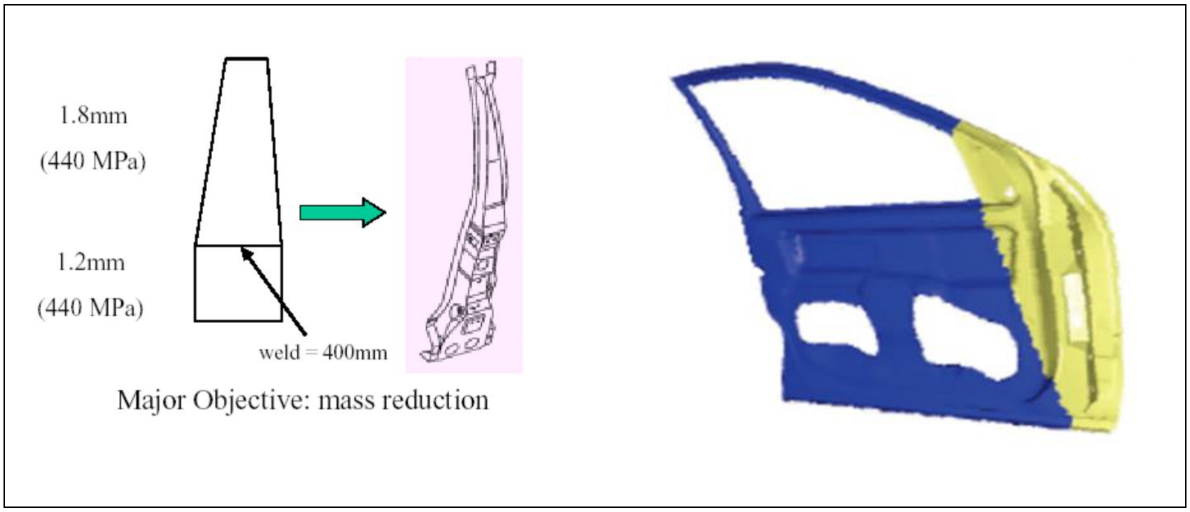


Figure 3-3 (Left) A B-pillar made of TWB (Right) A door application of TWB[29]

3.3.1.2 Multi Straight Line or Angular Tailor Welded Blanks

When the tailor welded blanks consists of two or more straight welds which could be either in axis, or parallel or weld in different axis. It's mainly used in the fabrication of body side panels and engine rails. The different types of multi straight line welds are shown in the following figure.

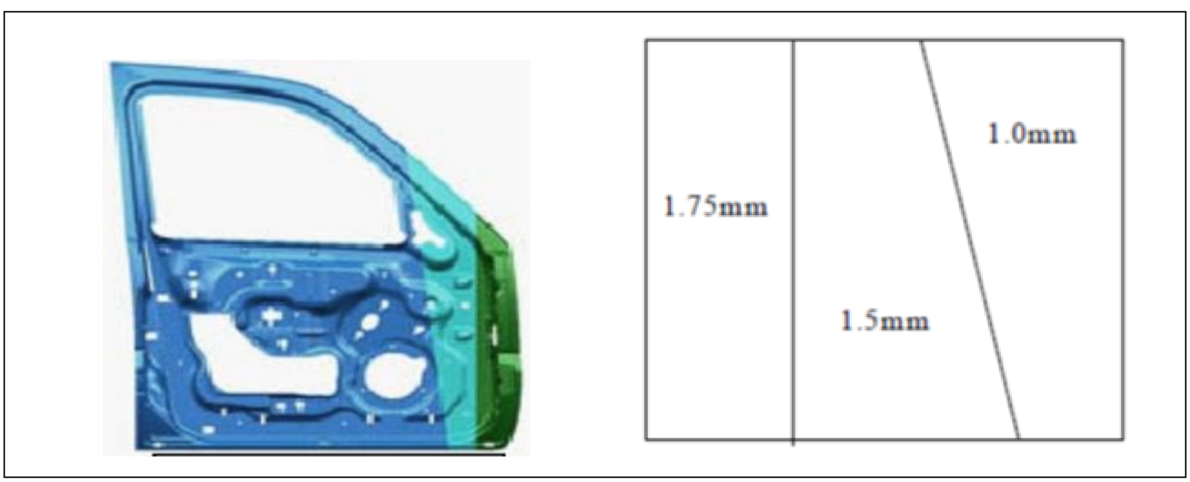


Figure 3-4 Multi Straight line tailor welds inside inner panel of the door

The above figure shows a multi straight line welds from VW Golf door inner. Here the hinge region has a greater thickness of 1.75 mm as compared with the rest of the area for the purpose of structural strength. Use of tailor welded blanks enables the use of thinner materials on the other portions of the door inner where structural stiffness required is much lower and thereby it brings about a reduction total cost.

3.3.1.3 Non Linear Tailor Welded Blanks

These types of blanks are used in situations where there is a need for increased formability which might be affected if other types of tailor welded blanks are used. The application of this type of TWB is limited due to the high cost involved which offsets the marginal advantages. The major advantage of this type of TWB is that it possesses superior surface finish as it is devoid of defects like blowhole which occur quite often in multi straight line welds. A typical Nonlinear TWB is shown in the figure below.

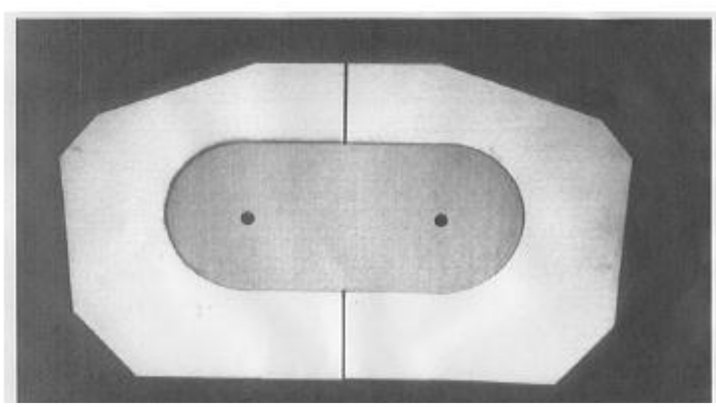


Figure 3-5 A Non Linear TWB [29]

3.3.1.4 Patch Welded Blanks

In a typical patch welding operation one blank of material is overlaid on the top of another blank of material for the purpose of additional strength. A thicker panel is placed over a thin section and welded together using spot weld before being formed to achieve net shape. These are mostly used in making door inners. The primary advantage of this type of welding is that it possesses superior fit up as multiple pieces are formed in the same die as can be seen in the case of welding of reinforcement to a larger blank. Other advantages are that it is easier to weld and greater flexibility in design. Also it has been proved that patch welding costs lesser than other conventional types of TWB. An example of a patch welded part is shown in the figure below. The below figure is a part of floor bar consisting of two spot welds each. The cases before and after stamping are represented here.

Figure 3-6 A panel made using Patch TWB and Stamping [29]

3.3.1.5 Tailor Welded Tubes

Tailor welded tubes (TWT) find increasing application in the construction of BIW with increasing importance attached to the light weighting. Tubes also known as tubular welded tubes are finding increasing application with the application of hydroforming to construct space frame designs. Tubes come in different shapes like cylinders, conical, oval and find their application in exhaust manifolds, A-pillars, Engine compartment rails, roll bars and side rails. Hydroformed tubular structures are used in construction of various automobile parts. Tailor welded tubes are used in such hydroforming application to bring a further reduction in cost of the product. As in patch welding in tailor welded tubes sleeves are used in the area where reinforcements are needed. The application of TWT includes the following area

- Exhaust manifold
- A pillar
- Engine compartment rails
- Light truck side rails and roll bars

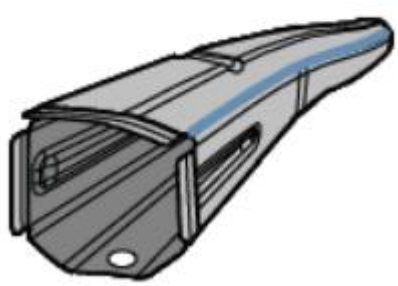


Figure 3-7 Tailor welded tubes used in hydroforming

3.3.1.6 Welding

Welding refers to the joining of two materials under the application of heat for melting and fusing of material which may or may not be accompanied with use of pressure. The different welding techniques used in tailor welding are

- Electron Beam welding
- Mash welding
- Induction welding
- Co_2 laser welding
- YAG – laser welding

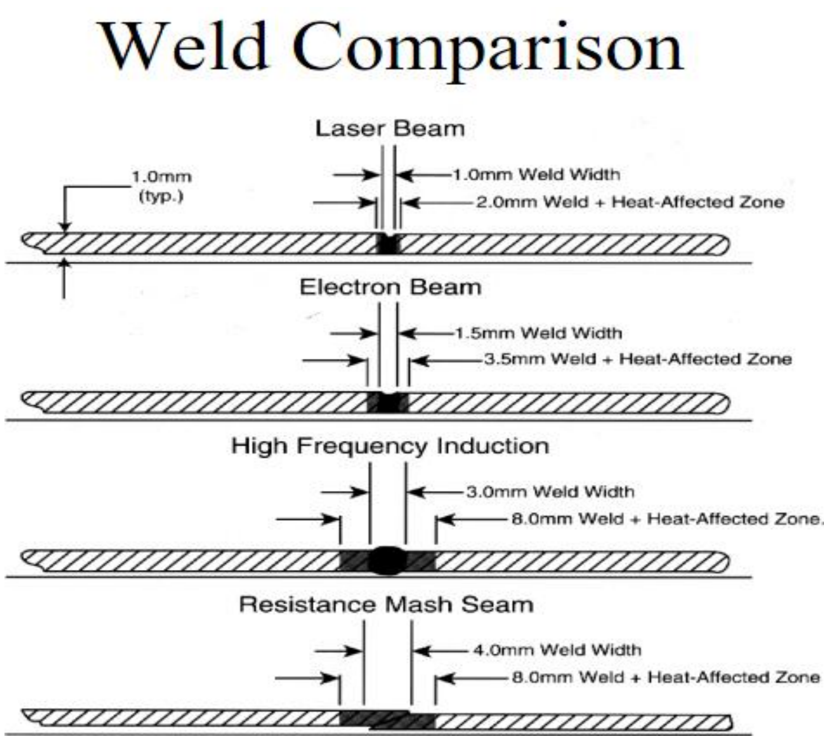


Figure 3-8 Comparison of different welding methods

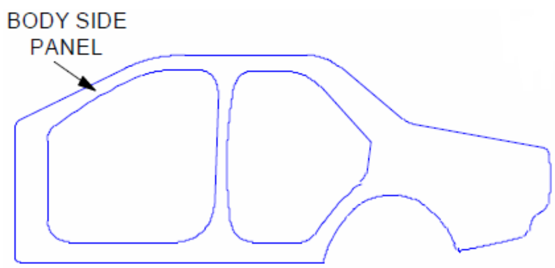
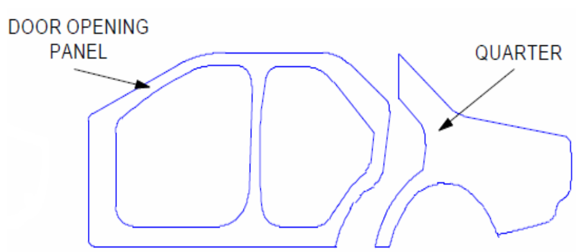
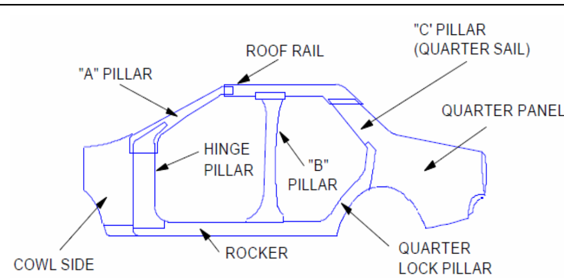
Laser welding is preferred over other types of welding due to its high weld speed and ease of automate. Here the Co_2 welding technique is preferred over the YAG when there is a need for high precision weld while in case of poor edge preparation YAG is the preferred choice of welding. The table below gives a comparison of the various welding process.

The main disadvantage of the laser welding process has been that it reduces the ductility of the material due to its high peak hardness whereas the mash welding has lower peak hardness thus increasing the formability of materials.

Edge preparation and weld speed play an important role in the properties of tailor welded blank. Removal of burr from the edges to be welded and having a minimum gap between the two materials results in good quality weld in addition to increasing the weld speed. Since tailor welded blanks reduce the number of components, it also reduces the number of stamping dies and hence eliminates the tooling and validation cost for these dies. This leads to savings in investment capital and product lead time. The following section analyses specific part consolidation techniques adopted by OEMs using tailor welded blanks.

3.3.2 Study of part consolidation techniques to fabricate body side panel using TWB

Table 3.3 Different body side panel fabrication techniques [30]

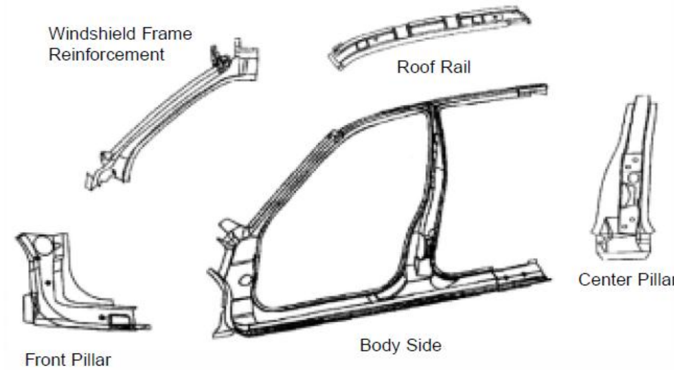
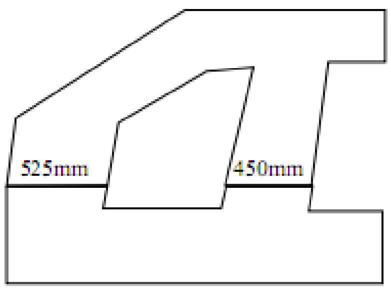
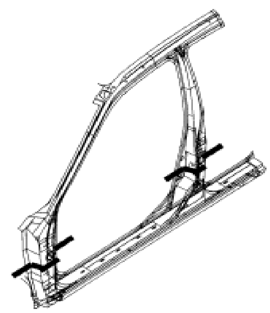
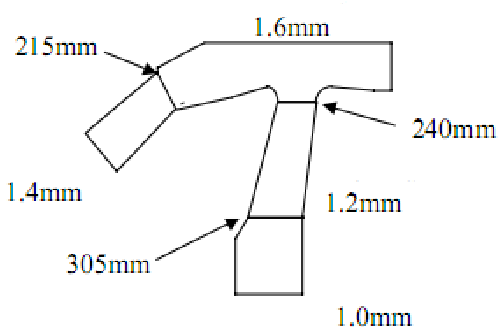
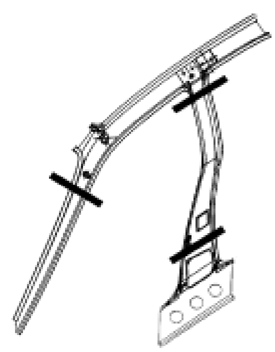
VW Golf, Mazda RX7,Honda Odyssey	Benefits	Challenges
 Single piece stamped component	Good finishing No welding	Heavy scrap rate Material Handling issues Reconstruction issue Complex tooling
VW Passat, Renault R5, R9		
 Double piece stamped component	Moderate welding	Reduced scrap rate High scrap rate for door opening panel
Mitsubishi Galant, Audi 100, Mazda		
 Multiple components using TWB	Minimal scrap Easier material handling Cost effective	Visible weld lines Labor Intensive Higher material cost

Conventional body side panels were made of stampings. It was usually a combination of different smaller stamped components which were welded together using spot welds. The table below shows the five stamped panels constituting a body side outer of a sedan. It generated large blanking scraps and required the fabrication of complex stamping die with heavy tonnage to stamp the side panel parts. Lower dimensional accuracy, expensive tooling and long tooling validation time encouraged the OEMs to shift to usage of TWB for body side panels.

By employing TWBs, the inner panels were fabricated using multiple straight line/angular welding of thick high strength steel to provide crash worthiness and high strength. The different smaller panels are welded together to form a single inner structure. The presence of weld lines is acceptable because the inner acts as a class C surface. The inner panel could also be modularized to be used in different product variants manufactured by the OEM.

The outer panel is made by multiple straight line welding of uniform gauged thin sheets to achieve good surface finish. The outer constitutes a class-A surface and hence they need to have minimal visible weld lines and should also be provided with corrosion resistant coating. The usage of tailor welded blanks provided flexibility in body side design, easier material handling and storage when compared to conventional stamping. It also increased the overall structural rigidity of the side panels due to selective strengthening of load bearing panels.

Table 3.4 Substitution of a stamped body side panel using TWB[29][31]

<table>
<tr><td colspan="2">A body side consisting of 5major stamped panels</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td colspan="2">Body side outer consisting of 2 panels made using TWB</td></tr>
<tr><td>
</td><td></td></tr>
<tr><td colspan="2">Modularized Body side inner consisting of 4 parts made using TWB</td></tr>
<tr><td>
</td><td></td></tr>
</table>

3.3.3 Costing implications of consolidating parts using TWB

As discussed in the previous section, TWBs are widely used to consolidate BIW panels with various benefits in design and application. The following literature will conduct a detailed cost benefit analysis of using TWBs with the help of a technical cost model developed by Camanoe Associates/MIT [32]. Technical cost models are detailed estimates of manufacturing cost which is obtained by modeling the interaction between the various parameters affecting the final cost such as material, equipment, labor, tooling, factory overheads and scrap rate. The costing analysis has been performed for a body side inner and a rail case by comparing the manufacturing cost of the above mentioned components by stamping and laser welded blanks.

3.3.3.1 Rail Case Study

A rail case consisting of 13 stamped pieces was studied and the feasibility of manufacturing it using tailor welded blanks was evaluated. The study was conducted by an organization Camanoe Associates in partnership with Tailored Steel Product Alliance which was a combination of tailored steel blank manufactures, equipment supplier and steel companies [33]. Rail case consists of multiple rail reinforcements, rail control and rail inner and outer components. This study was significant from a designer perspective due to the load bearing characteristics of the considered sub assembly. Tailor Welded Blanks had to match the strength and torsion requirements of the structure in addition to consolidating the parts to be a successful alternative to the current stamped assembly.

The stamping cost and the material cost contributed to nearly 51% and 45% respectively of the overall cost of the assembly. As the number of panels increases, the tooling required and the associated cost and time play a major role in the cost breakdown. Part consolidation using TWB helps to reduce the number of panels therefore bringing down the initial capital investment required.

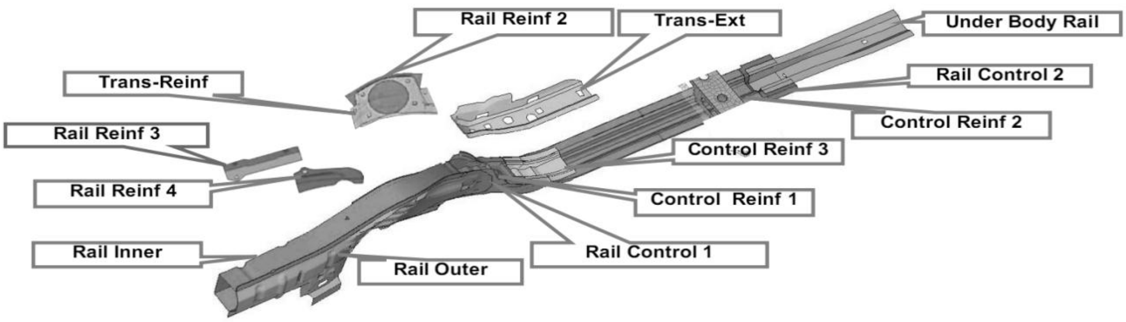


Figure 1.6 Current stamped rail

Table 1.5 Stamping cost analysis of rail case

Part	Vehicle	Blanking		Stamping		Material		Total
		Cost/Part	%	Cost/Part	%	Cost/Part	%	Cost/Part
Rail Control 2 - R/L	RAIL BASE	$0.16	8%	$1.47	73%	$0.39	19%	$2.02
Rail Outer - R	RAIL BASE	$0.16	2%	$3.02	35%	$5.51	63%	$8.69
Rail Outer - L	RAIL BASE	$0.16	2%	$3.02	35%	$5.51	63%	$8.69
Rail Inner - R	RAIL BASE	$0.16	2%	$2.71	43%	$3.46	55%	$6.33
Rail Inner - L	RAIL BASE	$0.16	2%	$2.71	43%	$3.46	55%	$6.33
Trans-Reinf - R/L	RAIL BASE	$0.16	6%	$1.54	56%	$1.03	38%	$2.74
Rail Reinf 2 - R/L	RAIL BASE	$0.16	6%	$1.45	55%	$1.04	39%	$2.64
Rail Reinf 3 - R/L	RAIL BASE	$0.16	8%	$1.42	76%	$0.29	16%	$1.87
Rail Reinf 4 - R/L	RAIL BASE	$0.16	8%	$1.36	74%	$0.33	18%	$1.84
Trans-Ext - R	RAIL BASE	$0.16	5%	$1.76	54%	$1.32	41%	$3.24
Trans-Ext - L	RAIL BASE	$0.16	5%	$1.76	54%	$1.32	41%	$3.24
Control Reinf 1 - R	RAIL BASE	$0.16	8%	$1.39	68%	$0.49	24%	$2.04
Control Reinf 1 - L	RAIL BASE	$0.16	8%	$1.39	68%	$0.49	24%	$2.04
Control Reinf 2 - R	RAIL BASE	$0.16	3%	$2.47	47%	$2.61	50%	$5.23
Control Reinf 2 - L	RAIL BASE	$0.16	3%	$2.47	47%	$2.61	50%	$5.23
Control Reinf 3 - R	RAIL BASE	$0.16	6%	$1.70	69%	$0.60	24%	$2.45
Control Reinf 3 - L	RAIL BASE	$0.16	6%	$1.70	69%	$0.60	24%	$2.45
Under Body Rail - R	RAIL BASE	$0.16	7%	$1.62	68%	$0.62	26%	$2.39
Under Body Rail - L	RAIL BASE	$0.16	7%	$1.62	68%	$0.62	26%	$2.39
Frt. Rail Inner Reinf. L/R	RAIL LWB	$0.16	4%	$1.98	55%	$1.47	41%	$3.60
Rail Extention Reinf. - R	RAIL LWB	$0.16	3%	$2.98	53%	$2.46	44%	$5.60
Rail Extention Reinf. - L	RAIL LWB	$0.16	3%	$2.98	53%	$2.46	44%	$5.60
Total Cost		$3.44	4%	$44.51	51%	$38.69	45%	$86.64

The consolidated TWB structure is less expensive than the stamped structure in terms of overall cost of making the assembly. Also it reduces the assembly cost associated with joining the stamped panels. Welding in TWB provides better joints and imparts strength to the assembly. The material cost is the highest contributing factor due to the usage of high strength steel which serves the dual purpose of reducing weight and increasing strength.

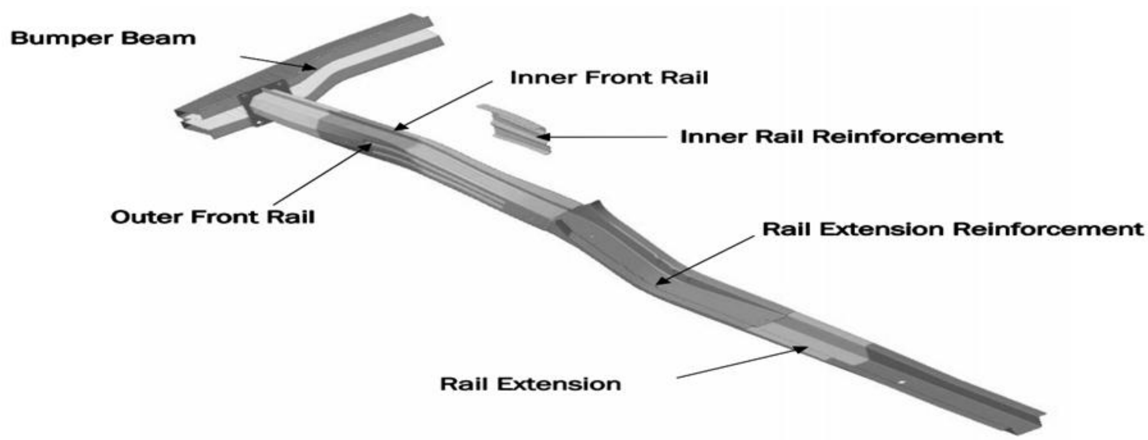


Figure 1.7 Proposed TWB part consolidated rail

Table 1.6 Tailor welded blanking cost analysis of rail case

Part	Vehicle	Blanking		Welding		Stamping		Material		Total
		Cost/Part	%	Cost/Part	%	Cost/Part	%	Cost/Part	%	Cost/Part
Rail Control 1 - R	RAIL BASE	$0.31	4%	$0.39	5%	$3.56	48%	$3.16	43%	$7.42
Rail Control 1 - L	RAIL BASE	$0.31	4%	$0.39	5%	$3.56	48%	$3.16	43%	$7.42
Rail Extension - R	RAIL LWB	$0.32	2%	$1.01	6%	$5.24	30%	$11.08	63%	$17.64
Rail Extension - L	RAIL LWB	$0.32	2%	$1.01	6%	$5.24	30%	$11.08	63%	$17.64
Front Rail Outer - R	RAIL LWB	$0.48	6%	$1.47	18%	$3.12	38%	$3.24	39%	$8.32
Front Rail Outer - L	RAIL LWB	$0.48	6%	$1.47	18%	$3.12	38%	$3.24	39%	$8.32
Front Rail Inner - R	RAIL LWB	$0.48	6%	$1.47	17%	$3.12	37%	$3.38	40%	$8.45
Front Rail Inner - L	RAIL LWB	$0.48	6%	$1.47	17%	$3.12	37%	$3.38	40%	$8.45
Total Cost		$3.17	4%	$8.68	10%	$30.09	36%	$41.71	50%	$83.65

3.3.3.2 Body side inner case study

The following is a specific case study of consolidating of stamped components of body side base using tailor welded blanks conducted by a partnership between Camanoe Associates/MIT and TSPA.

Table 1.7 Stamping cost analysis of body side panels

Part	Vehicle	Blanking		Stamping		Material		Total
		Cost/Part	%	Cost/Part	%	Cost/Part	%	Cost/Part
FBHP - Base - R	BODY SIDE BASE	$0.16	1%	$3.62	19%	$15.21	80%	$18.99
FBHP - Base - L	BODY SIDE BASE	$0.16	1%	$3.62	19%	$15.21	80%	$18.99
Centar Pillar - Base - R	BODY SIDE BASE	$0.16	2%	$3.20	33%	$6.48	66%	$9.84
Centar Pillar - Base - L	BODY SIDE BASE	$0.16	2%	$3.20	33%	$6.48	66%	$9.84
Wheelhouse - Base - R	BODY SIDE BASE	$0.16	1%	$3.36	28%	$8.54	71%	$12.05
Wheelhouse - Base - L	BODY SIDE BASE	$0.16	1%	$3.36	28%	$8.54	71%	$12.05
Roof Rail - Base - R	BODY SIDE BASE	$0.16	2%	$2.50	38%	$3.85	59%	$6.51
Roof Rail - Base - L	BODY SIDE BASE	$0.16	2%	$2.50	38%	$3.85	59%	$6.51
							Total cost	$94.78

The costing indicates that the overall cost gains due to the introduction of TWB is marginally negated by the use of expensive high strength steel and the extensive usage of welding. However the tooling cost and validation time saved in reducing the number of stamping components is a significant reason to consider TWBs. In addition to saving tooling cost, the usage of laser welded blanks helps reduce weight, the forming time and the assembly sequence followed in fabricating the stamped panels.

Table 1.8 Tailor welded blanking cost analysis of body side panels

Part	Vehicle	Blanking		Welding		Stamping		Material		Total
		Cost/Part	%	Cost/Part	%	Cost/Part	%	Cost/Part	%	Cost/Part
Body Side Inner - LWB - R	BODY SIDE LWB	$0.96	2%	$8.36	18%	$7.44	16%	$30.69	65%	$47.46
Body Side Inner - LWB - L	BODY SIDE LWB	$0.96	2%	$8.36	18%	$7.44	16%	$30.69	65%	$47.46
									Total Cost	$94.91

CHAPTER FOUR – INDUSTRIAL ORIGAMI

4.1 Industrial Origami®

Industrial origami® is the art of laser cutting and then bending sheet metals with the help of design features called smileys in order to achieve the desired profile and shapes. This process has been successful in fabricating small scale sheet metal components like shipping boxes, cooking tops, electrical boxes, motor modules and specific automotive sheet metal parts. The unique smiley shaped designs help in accurate folding of the joints and also creates a strong contact edge. Based on the information provided in the industrial origami company website, the process seems to have the potential to solve the limitations of stamping [34].

Some of the important aspect of industrial origami is that it encourages part consolidation due to its ability to mass produce parts with complex shapes and features. By integrating multiple simple profiled parts into one complex part we eliminate the time and labor involved in its manufacturing and assembly. The tooling and time required to develop it is comparatively lesser in industrial origami when compared to stamping. Past industrial origami projects have achieved up to 50% reduction in the material usage compared to conventional tooling process. Due to its inherent simplicity in design and assembly the amount of labor and time involved in the operations also reduces by nearly 40%. The biggest advantage which origami offers specifically to automotive industries is the ability to enter new markets with new designs faster and with much lesser capital investment.

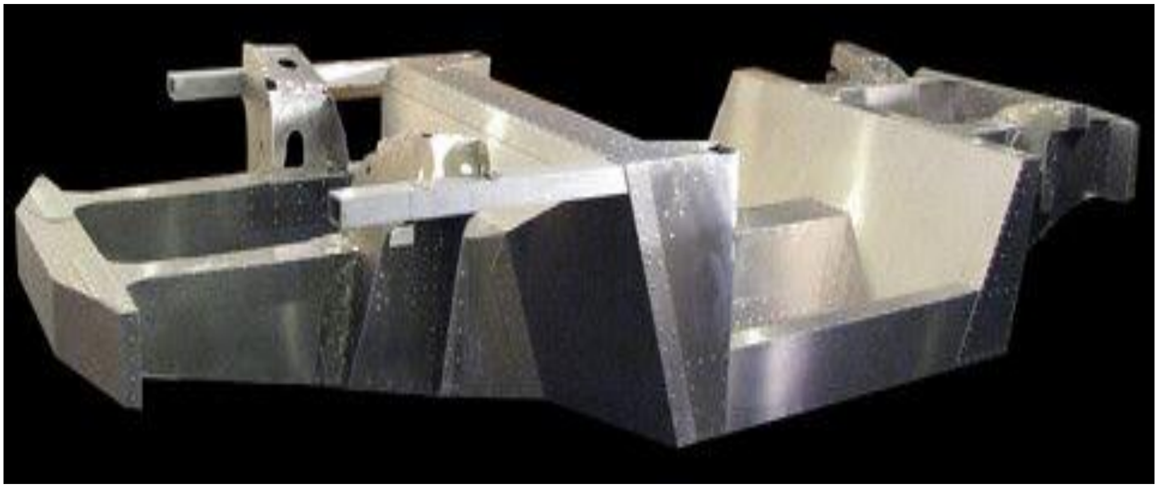


Figure 4-1 A prototype body chassis fabricated using origami

4.2 Industrial Origami process

The raw materials, steel coils of required dimension are purchased and cut to necessary blank sizes using blanking presses. Optimized nesting during blanking will save considerable space and reduce the scrap rate. The design feature which controls the folding line and strength characteristics of the folded joint is called ‘smiles’. They can be cut using high powered laser cutters which will precisely locate the position and shape of the smiles. The sheet metal is then folded using low tonnage bending presses. When folding occurs, the materials on either side of the smiles are pulled to create an edge-face contact. This contact also helps uniformly dissipate the compressive stresses experienced by the structure. In addition to load bearing, the smiles also help in accurately locating the bending line which reduces tolerance errors, scrap rate and the associated rework cost. The folding process can be automated using hydraulic or pneumatic equipment.

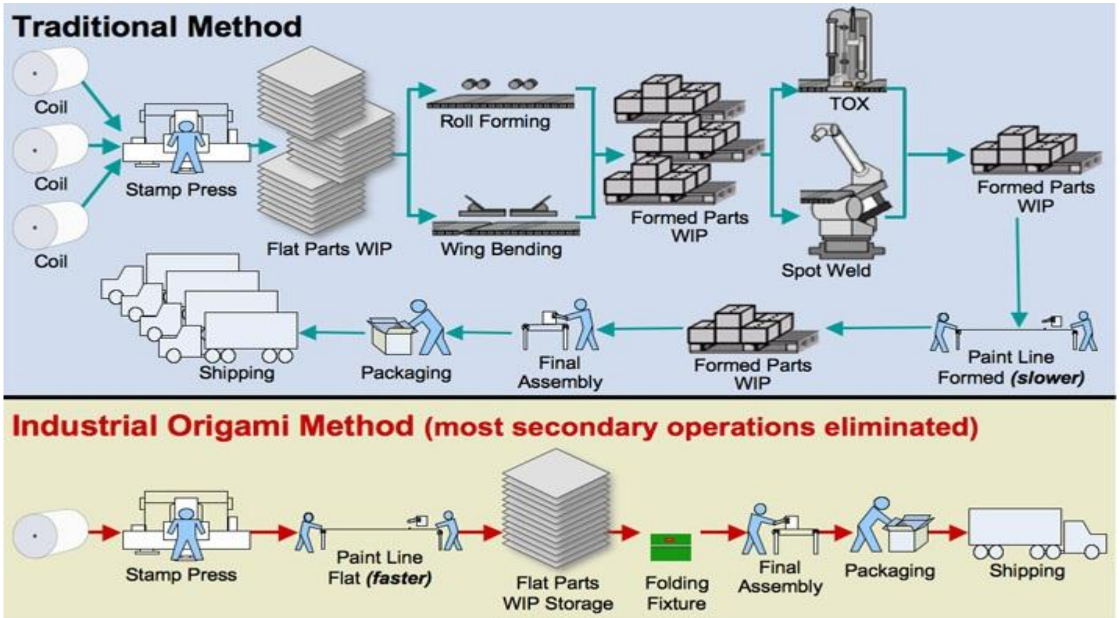


Figure 4-2 Industrial origami method vs. conventional method for sheet metal components

4.3 Potential benefits of using origami to manufacture BIW panels

4.3.1 Low tooling cost

Stamping body panels requires heavy machinery in the form of blanking, bending or drawing presses which are bulky and expensive. The stamping presses are made of specialized high strength alloys to endure the forces, stresses involved and increase durability during stamping operation. Comparatively industrial origami will require high precision laser cutters which are simple, quick and very precise. Further the bending presses can be of lower tonnage as the bending is localized and further assisted by the involvement of ‘smiles’.

4.3.2 Part consolidation

Industrial origami has the ability to fabricate complex and intricate shapes easier compared to stamping. This is a major benefit which can be exploited by the body in white design teams by consolidating smaller components into bigger panels of complex shapes. Multiple bending profiles can be easily accommodated in industrial origami by multi folding a single component in different folding fixtures compared to conventional stamping where a single shot decides the end profile. Spring back effect is another issue which will be easier to tackle using industrial origami compared to stamping. Industrial origami has been successfully used to manufacture functional components like center tunnels, dashboard panels and instrument clusters in certain automotive prototypes with very low lead time and very low investment in specialized tooling.

4.3.3 Material selection

Industrial origami has been currently developed for metals and further research is underway to extend its application to plastics, ceramics and composites which are finding increasing application in an automotive body in white. Stamping aluminum panels has been a major challenge faced by automotive OEMs due to its very low yield strength and high spring back effect. However this can be overcome by the using industrial origami.

4.3.4 High accuracy

The bending line in industrial origami runs in between the smiles which are uniformly spaced on the opposite directions to it. These smiles are in turn precision cut using laser cutters. Hence the process inherently produces highly accurate bending profiles when compared to stamping where the bending tolerance is a function of the tool profile, machinery involved, and the calculated spring back allowances.

4.3.5 Retrofitting existing stamping and bending tools

Existing stamping presses can be retrofitted to stamp the lancing and blanking presses can be modified to cut the smiles thereby preventing the need to make investment in additional equipment. This helps easy transition from stamping to industrial origami with low capital cost from an OEM perspective. Further no expensive trial runs or tool validations are necessary thereby reducing the changeover time and product lead time.

Industrial origami offers the above advantages over conventional stamping process and hence it becomes of interest to find out if it actually can provide the same quality and type of stamped components like that of stamping. Industrial origami fabricated components have to match conventional stamped components in terms of joint strength and performance characteristics for the OEMs to consider their application in their manufacturing process. It is important to determine the strength of industrial origami joints which are held together by the smiles and the lancing profiles as their will determine their area of application in a BIW panel.

4.4 Comparison of load bearing characteristics of industrial origami component and a stamped component

The following finite element analysis was conducted to study the feasibility of consolidation of parts using industrial origami. The study intends to sample different thickness of industrial origami joints and compare them with similar profiles of stamped components. The comparison is based on three important load bearing components, bending, shearing and tensile stresses. The testing also aims to determine the appropriate thickness at which an origami component will exhibit similar or better strength characteristics when compared to stamped component. The impact of the number of smiles on the strength of the joint and the effect of the spacing between the smiles is determined.

4.4.1 Modeling origami component using CAD tools

A sheet metal panel of dimension 150mm in length and 100 mm in breath was created using sheet metal tool bar in solid works, CAD modeling software. A sketch of the necessary part was drawn and a sheet metal was created using the base flange feature. Sketched bend was used to bend the modeled sheet metal at its rectangular center line forming an L shaped 90 degree part to replicate a stamped joint. The base flange thickness was modified and the same profile in thickness of 0.75mm, 1.00mm, 1.25mm, 1.50mm. 1.75mm and 2.00mm were saved in .step 203 format. A similar sheet metal feature was created using Solidworks® and the smiles feature was added. These smiles were modeled based on origami samples and its dimensions. The dimensions of the smiles, its position with respect to the sheet metal and its profile were modeled by measuring actual samples of industrial origami joints.

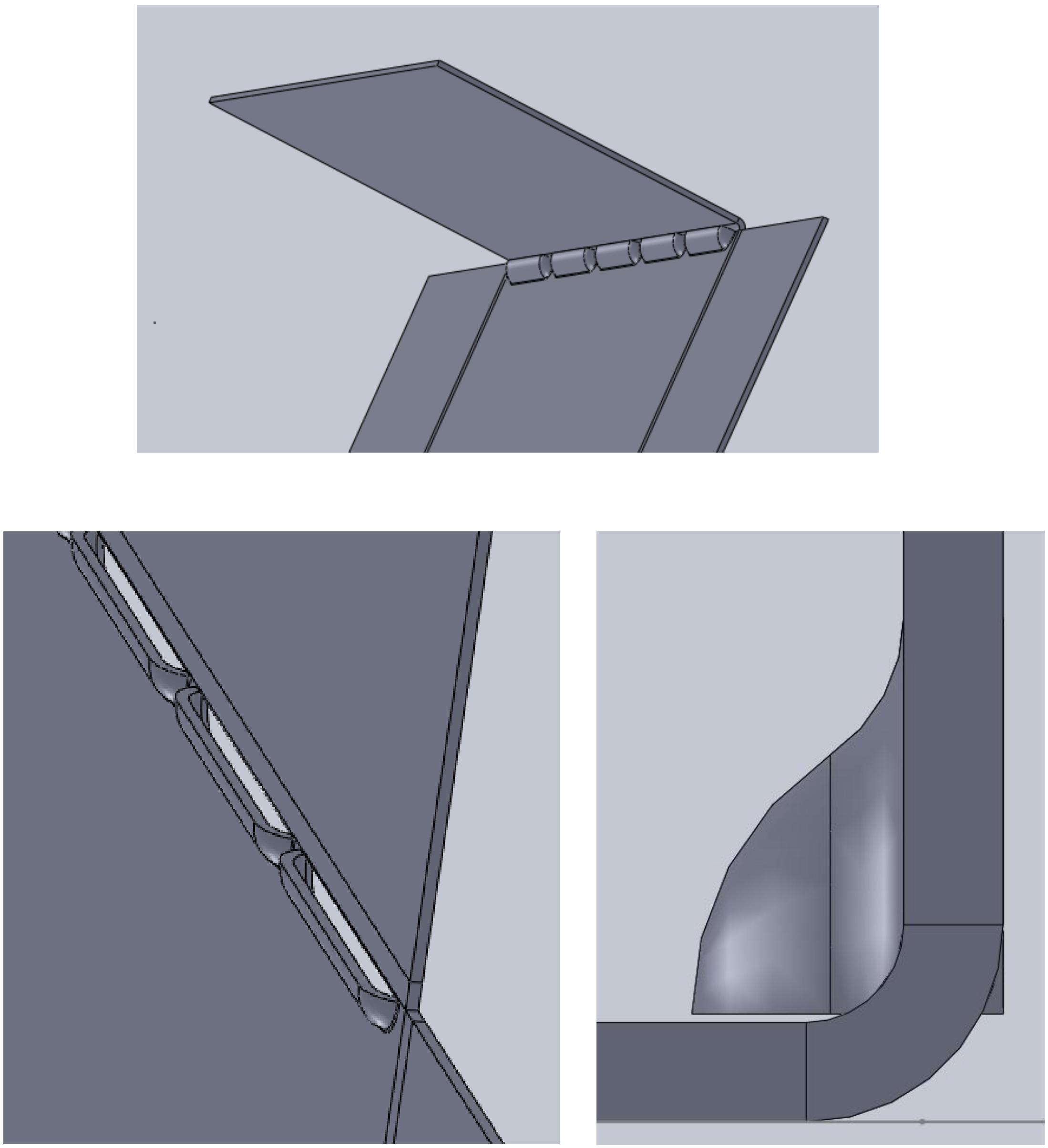


Figure 4-3 CAD modeling of Industrial origami component

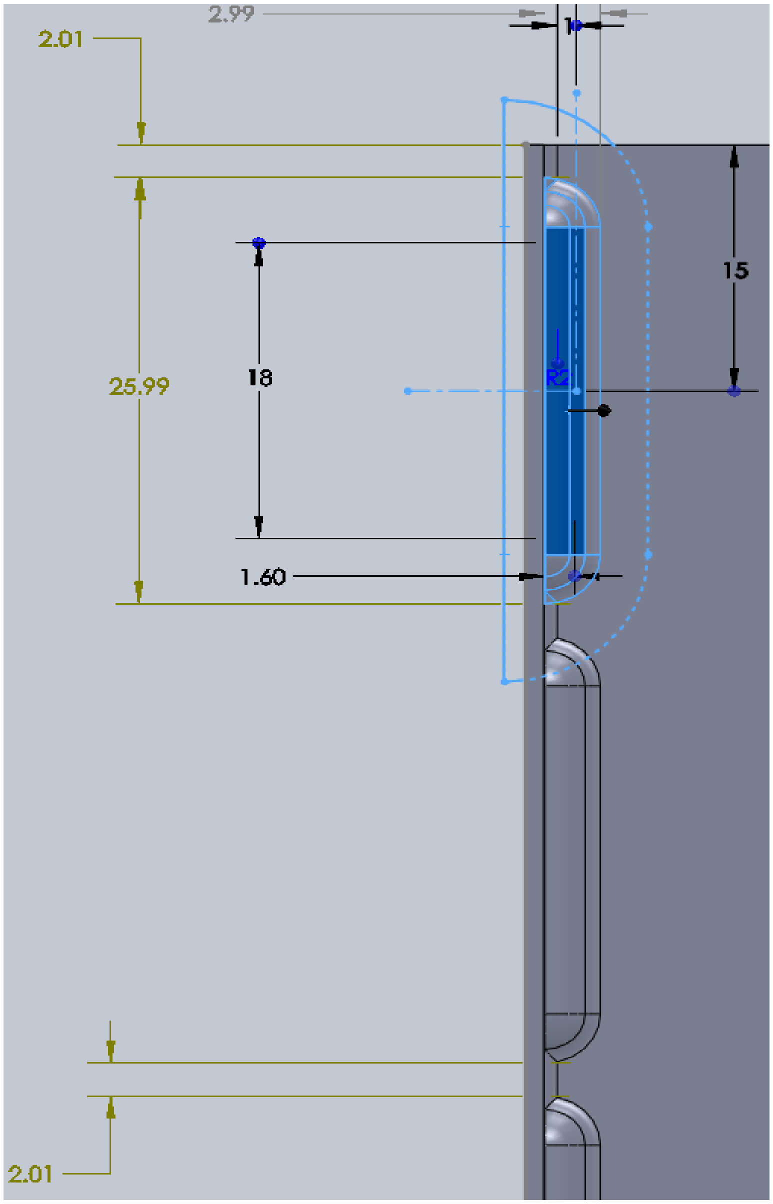


Figure 4-4 Dimensions of the origami design feature ‘smiles’

The sheet metals with smiles were also saved as separate part files for different dimensions in .step format. Step formats were used to import the cad geometry into finite element analysis software, ABAQUS®. The k value used during the modeling and bending of the sheet metal is 0.5. The k value is usually experimentally determined. However for this particular analysis it was based on industrial standards, thickness and material used.

4.4.2 Use of analysis tool to validate

The modeled stamping and origami parts are meshed and are subjected to various loading conditions using ABAQUS analysis tool. The following tests were conducted to compare the physical properties of an L shaped sheet metal component manufactured using conventional stamping and industrial origami. The material selected is steel, elastic in nature with a Young's modulus of 210Mpa and a poisons ration of 0.33. An independent meshing sequence is created on a part instance and the global node element size is 4. The selection of nodal element size was based on the tradeoff between the accuracy of the results and the computational time required to run the simulation. The meshing generated approximately 6000 elements for each model. The field output requested in strain as it is the primary reason for the failure of a component.

4.4.3 Tensile Loading

A tensile displacement is applied on the top surface of the L shaped plate. The bottom end of the component is constrained and hence applied displacement subjects the join to tensile loading. Changing the values of displacements helps change the magnitude of the loading and stress values are obtained for displacements starting at 0.2mm up to 3mm. The results of this analysis show that the stamping component is able to withstand almost twice the load when compared to origami for thickness up to 1.00mm.

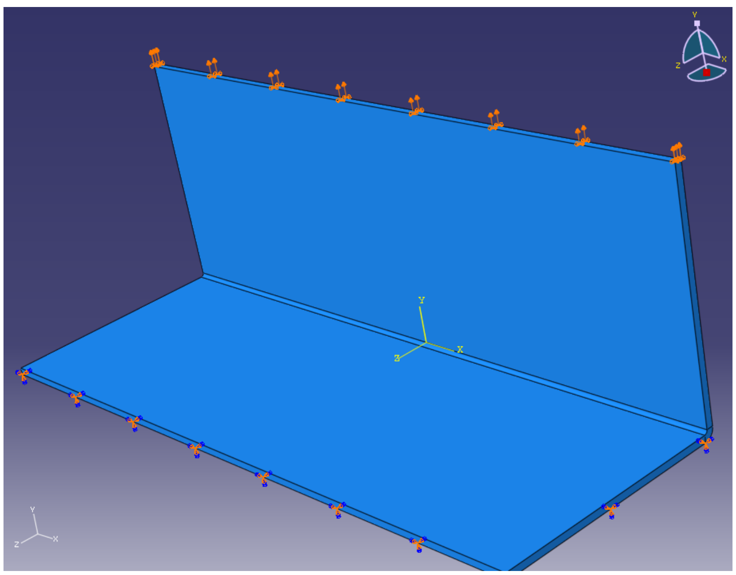


Figure 4-5 Figure 3.4 Tensile loading boundary condition

However the ratio continues to drop for thickness greater than 1mm up to 2mm. The normalization ratio saturates at approximately 1.7, which implies that the load bearing capacity of a stamped joint in general is 1.7 times that of origami under the test conditions. This trend can be attributed to the fact that the area of distribution of load in stamped component is higher and hence for the stress concentration is lower. However due to the presence of the smiley in origami component the stress concentration is extremely high in the edges of the smiley and hence they are not able to withstand higher stress levels. This limitation can be overcome by the use of specialized high strength steel at the presence of the smiley area.

Table 4.1 Maximum tensile stress experienced for different loads

Displacement in mm	Stress in Mpa											
	stamping						origami					
	0.75	1.00	1.25	1.50	1.75	2.00	0.75	1.00	1.25	1.50	1.75	2.00
0.2	2521	2669	2492	2665	2713	2947	5655	8979	4720	4862	4914	4798
0.4	5042	5338	4986	5332	5428	5896	11310	17959	9440	9728	9831	9601
0.6	7563	8008	7478	7997	8140	8842	17005	26938	14160	14586	14590	14400
0.8	10086	16017	9975	10667	10853	11790	22623	53876	18945	19456	19656	19193
1	12986	13346	12463	13328	13560	14729	28570	44897	23600	24310	24304	23990
2	18912	26692	24926	26657	27120	29458	42417	89795	48452	48620	48625	47984
3	37822	40040	37390	39986	40701	44212	84839	134693	70801	72932	73710	71976

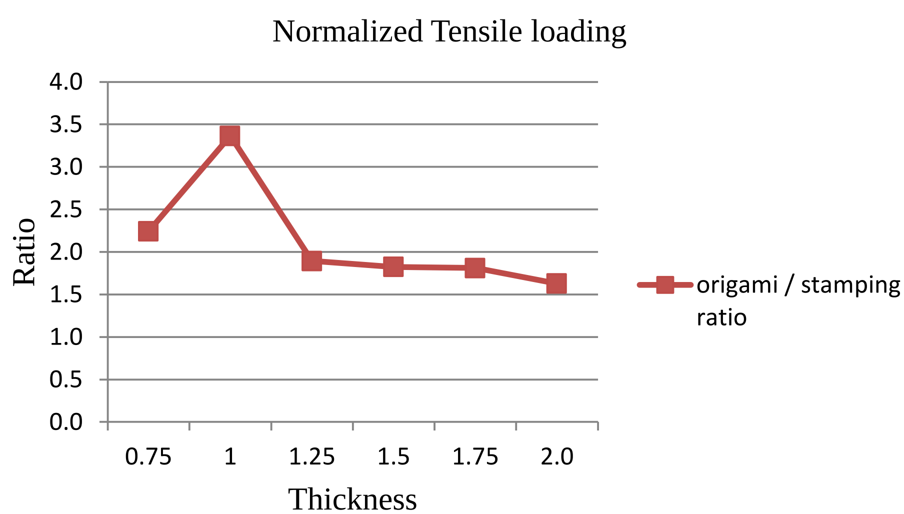


Figure 4-6 Normalized behavior of an origami and stamped joint

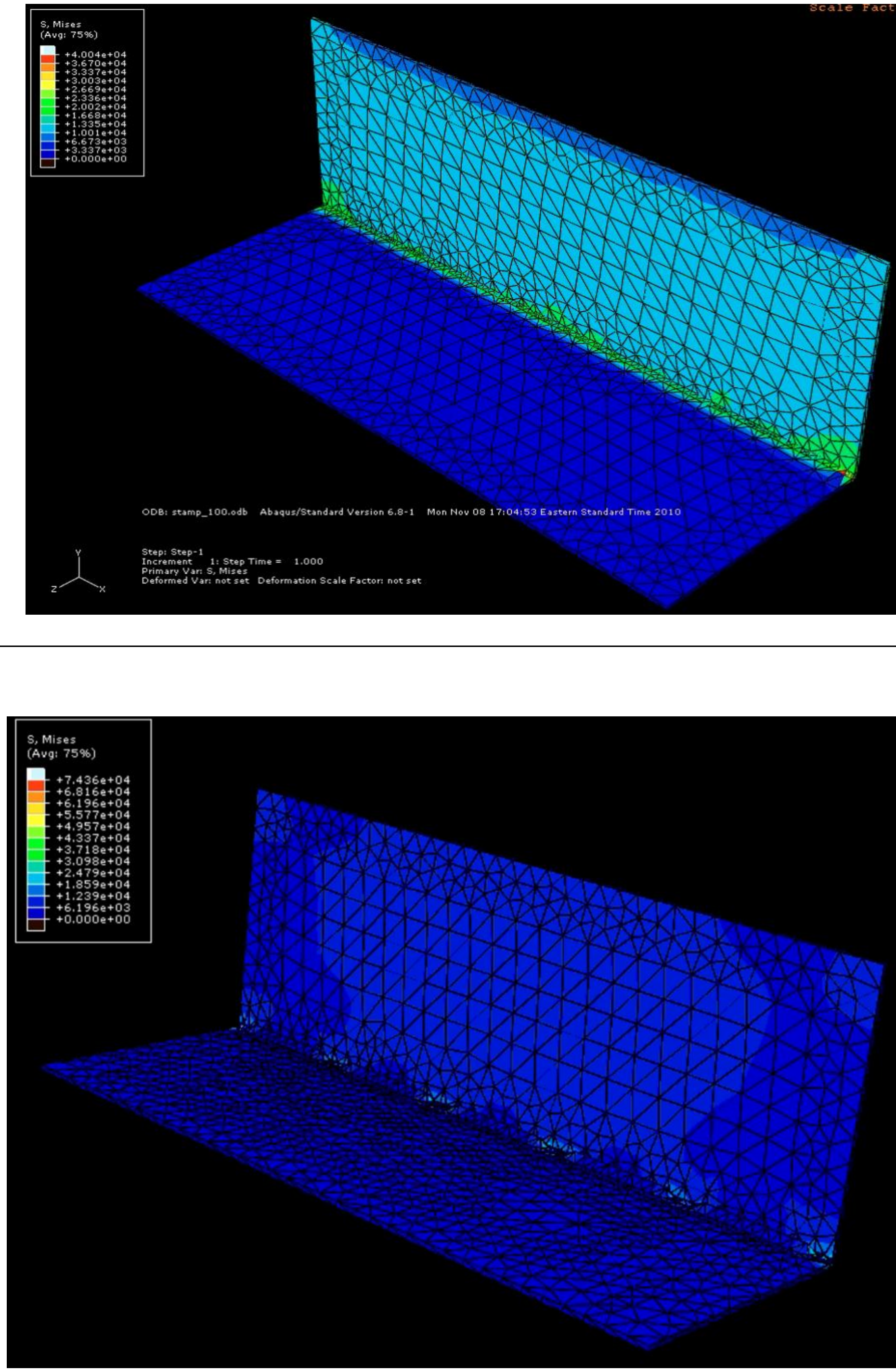


Figure 4-7 (Top) Failure mode of a stamped joint, (Below) Failure mode of an origami joint

4.4.4 Bending loading

Bending loading when repeatedly applied on a joint for a particular number of cycles leads to fatigue at the fold line which leads to part failure. Hence it is important to ensure that the bending force is uniformly distributed along the line of action of the load. Due to the nature of the joint, the loading applied inward and outward would lead to the same deflection in terms of magnitude but opposite in direction. Hence an inward bending displacement applied to the unconstrained face of the L shaped part simulates a uniformly distributed bending load. The load is non-linear and the part is allowed to come back to non-deformed state before reapplying load of a different magnitude.

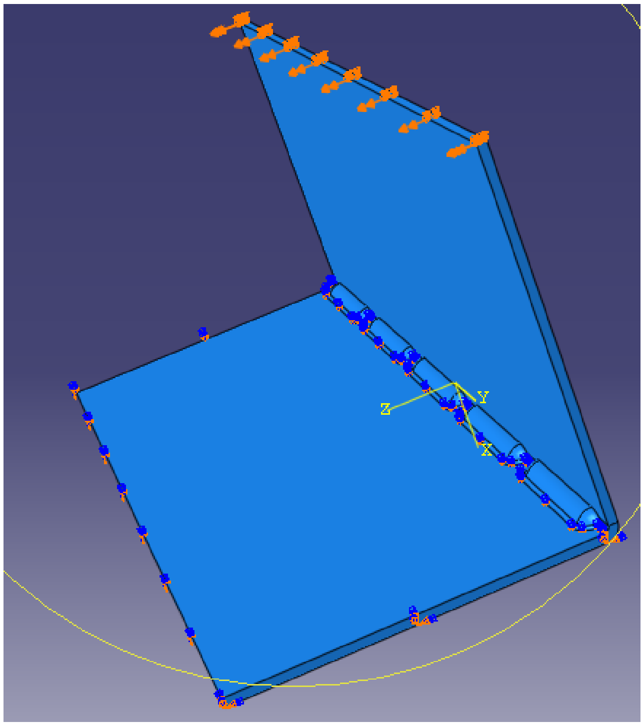


Figure 4-8 Boundary condition for bending load

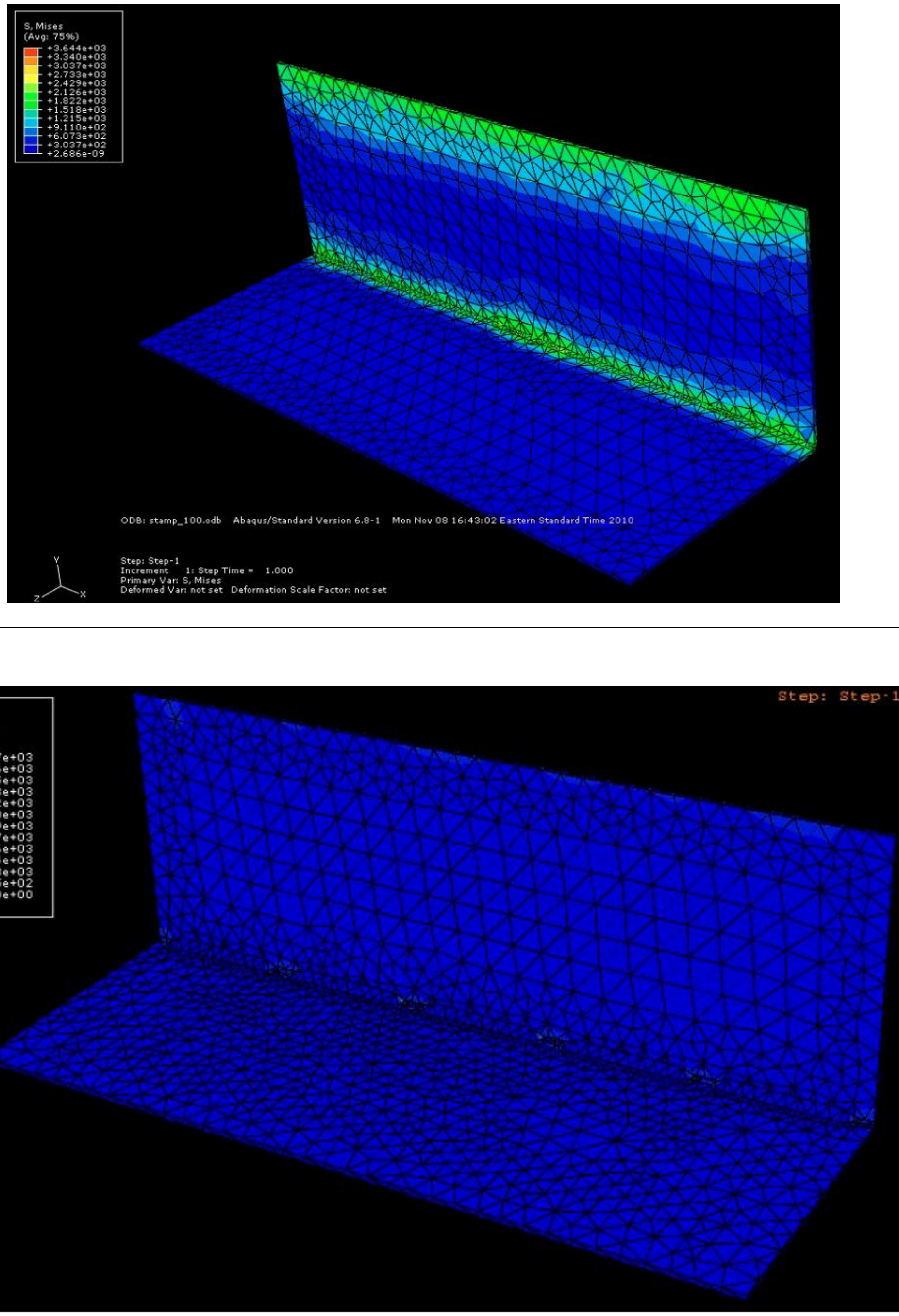


Figure 4-9 (Top) Comparison of failure mode of an stamped joint and (below) an origami joint

Table 4.2 Maximum bending stress experienced for different loads

Displacement in mm	Stress in Mpa											
	stamping						origami					
	0.75	1.00	1.25	1.50	1.75	2.00	0.75	1.00	1.25	1.50	1.75	2.00
0.2	329	242	295	321	352	375	354	1108	545	376	297	284
0.4	658	485	590	644	705	750	710	2216	1090	752	594	570
0.6	988	728	885	967	1057	1132	1066	3324	1636	1128	891	860
0.8	1317	971	1163	1287	1408	1501	1415	4432	2124	1469	1188	1138
1	1587	1214	1478	1608	1760	1876	1768	5540	2726	1838	1481	1422
2	3145	2430	2946	3218	3522	3755	3539	11089	5356	3678	2984	2846
3	5012	3687	4425	4826	5282	5630	5309	17058	8180	5509	4455	4267

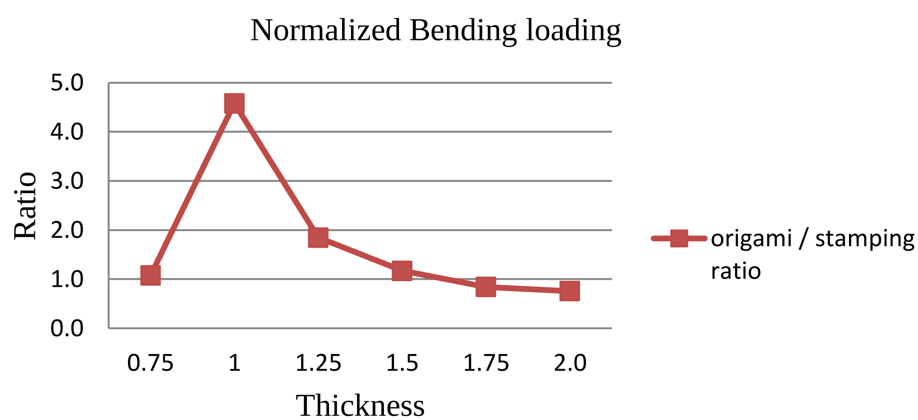


Figure 4-10 Normalized ratio of origami to stamping joint

The simulation results indicate that for thin panels the origami joint experience nearly 3 times greater stress values when compared to stamping. However as the thickness of the material increases, the smiles act as hinge thereby effectively absorbing the bending loads without failure. The load is also dissipated at the area of contact between the wall of the plate and the top of the smiles due to contact during deflection. The above mentioned factors make origami a better option for thicker sections of steel panels as the normalization graph indicates. Hence origami can be the used to make sections which experience a repetitive bending force without leading to failure due to fatigue.

4.4.5 Shearing loading

A shearing displacement is applied on the entire length of top edge, restraining the base of the component to simulate a panel tear mode of failure. Shearing testing is important during crash simulation, as the panels tend to tear away during the application of large deformation applied in opposite directions.

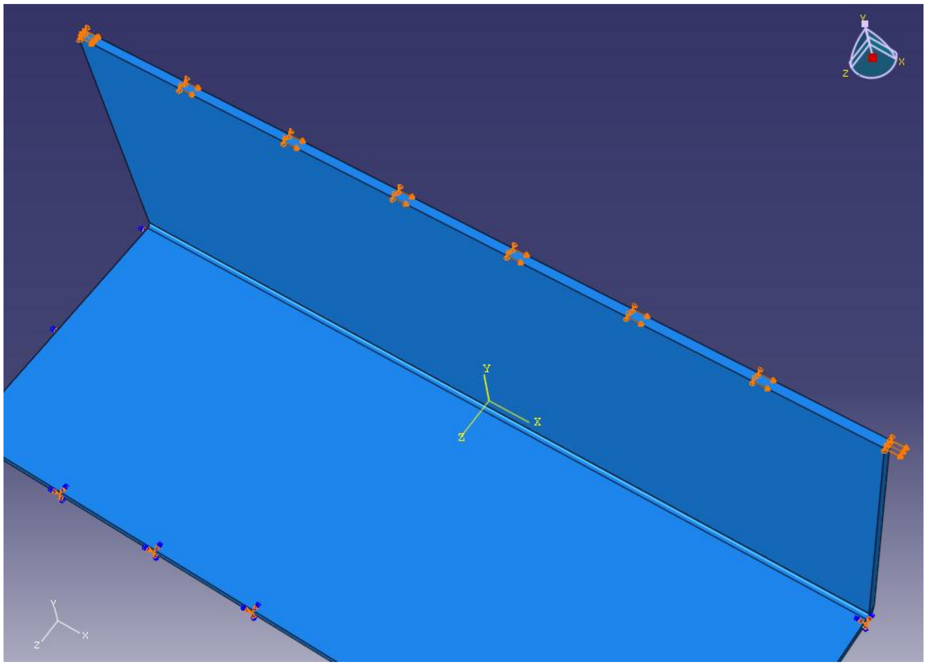


Figure 4-11 Boundary conditions of shearing load application

The simulation results are similar to the tensile loading conditions where stamping has better load endurance characteristics for lower panel thickness and as the thickness increases the performance of the origami joints improve. We also observe that maximum shearing force acts along the top of the plate and gradually decreases as we move down towards the center. This is due to the increase in the distance from the point of application of shearing load.

In case of stamping we note that the shearing force acts along the line of bending. Due to this the area over which force is applied increases. However the maximum stress concentration is found on the edges perpendicular to the shearing plain. Another interesting aspect to note is that in the case of stamping the maximum stress concentration denoted by the red area is along both the bending edge in comparison to the n number of edges of the origami component where n is the number of smileys on the joining edge. If this n is increased there will be more edges and hence it will be able to withstand higher stress values during shear.

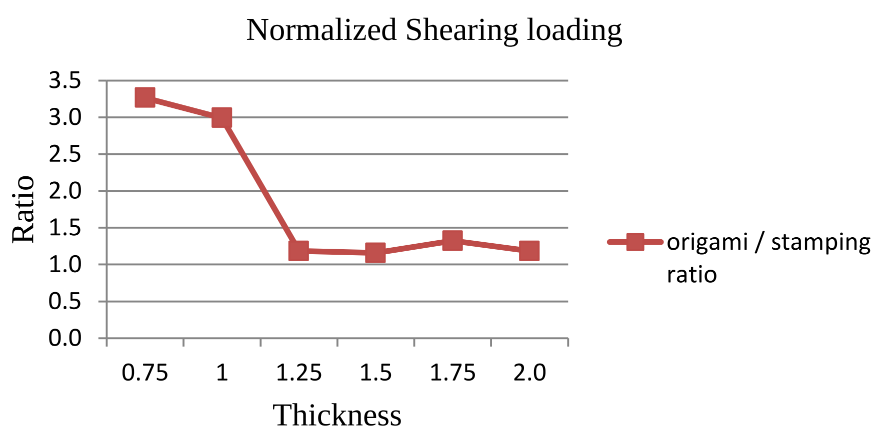


Figure 4-12 Stamping to origami performance comparison

Table 4.3 Maximum shearing stress experienced for different loads.

Displacement in mm	Stress in Mpa											
	stamping						origami					
	0.75	1.00	1.25	1.50	1.75	2.00	0.75	1.00	1.25	1.50	1.75	2.00
0.2	1732	1657	1903	2009	2041	2175	5655	4957	2251	2324	2697	2572
0.4	3464	3314	3806	4018	4082	4352	11310	9914	4502	4648	5395	5144
0.6	5197	4972	5710	6038	6125	6530	16966	14871	6755	6975	8093	7717
0.8	6928	6712	7709	8083	8167	8815	22905	19942	9125	9299	10789	10418
1	7016	8286	9518	9980	10082	10884	23157	24785	11259	11474	13320	12862
2	14034	16572	19037	19997	20164	21771	46315	49570	22587	22949	26648	25725
3	25980	24860	28554	30143	30628	32660	84839	74356	33777	34874	40458	38582

It is interesting to note that when the industrial origami component fails, all the hinges do not fail simultaneously. They fail independently. The simulation shows that when the outer hinges have high concentration of stress the inner hinges are still intact.

4.4.6 Effect of number of smiles on the different loading conditions

The number of smiles is an important parameter which determines the accuracy of the bending lines. Studying their impact on the strength of the joint is necessary to determine their application. Under the current simulation conditions varying the number of smile for a fixed dimension of panel would also affect the gap between each smile. The gap between each 'smile' when the joint has five smiles was 2.00mm. This gap increased as the number of smiles decreased. The panel thickness for the following test was 1.00mm. Tests were conducted for a panel of same dimension but different number of smiles 5, 4 and 3.

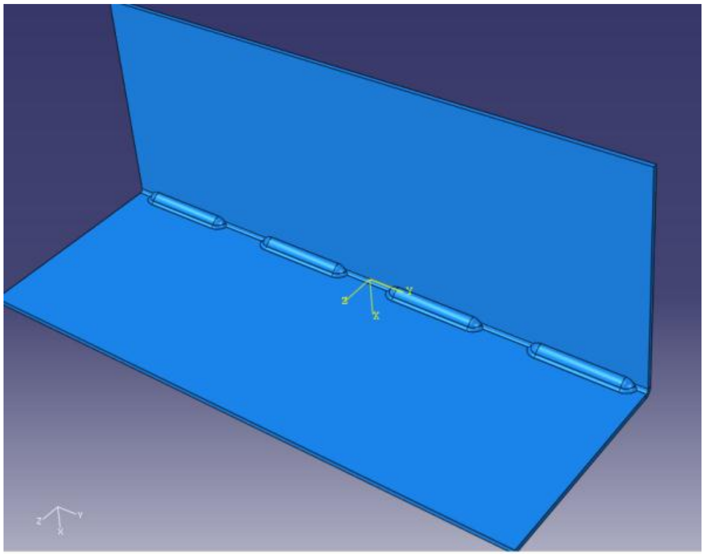


Figure 4-13 Origami joint with 4 'smile'

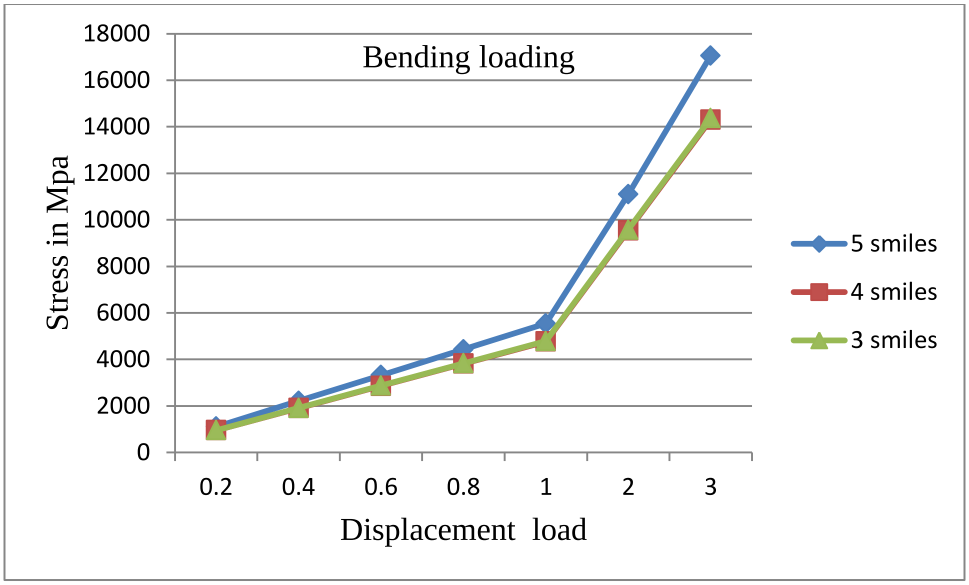


Figure 4-14 Bending load variation of origami joints with the number of design feature

In the case of bending, increase in the number of smiles resulted in higher stress in the panel. The stress difference is small in magnitude and widens with the increase in the value of load applied. The hinge action of the smile feature opposes the loading action of the part and hence as the number of hinges reduces the stress in the part also decreases.

Table 4.4 Maximum stress experienced by the joint for varying number of design feature

Displacement in mm	Stress in Mpa			Stress in Mpa			Stress in Mpa		
	Tensile loading			Shearing loading			Bending loading		
	5 smiles	4 smiles	3 smiles	5 smiles	4 smiles	3 smiles	5 smiles	4 smiles	3 smiles
0.2	8979	10218	9967	4957	5415	5733	1108	953	957
0.4	17959	20437	19935	9914	10830	11467	2216	1907	1915
0.6	26938	30655	29903	14871	16246	17201	3324	2860	2872
0.8	53876	40874	39871	29742	21661	22935	4432	3814	3830
1	44897	51093	49839	24785	27076	28669	5540	4768	4788
2	89795	102186	99678	49570	54153	57338	11089	9536	9576
3	134693	153279	149517	74356	81230	86007	17058	14304	14364

In the case of tensile loading, the relationship between the number of smiles and the stress value were not linear in nature. The highest stress was experienced by the part with 4 smiles and the lowest was experienced by the part with 3 smiles. Research is still underway to explain the non-linear behavior of the part under the above conditions.

In the case of shearing load, the increase in the number of smiles led to lower stress concentrations in the part. During hearing action, the displacement is resisted by the smile feature thereby lowering the stress concentrations in the gap between them. As a result an increase in the smile number resulted in higher stress dissipating capacity of the joint which can be seen from the graphs below.

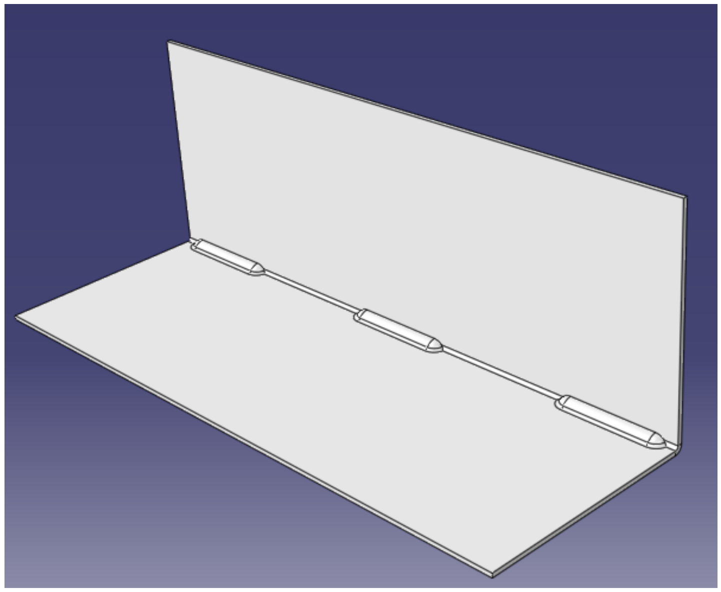


Figure 4-15 Origami joint with 3 ‘smile’ feature

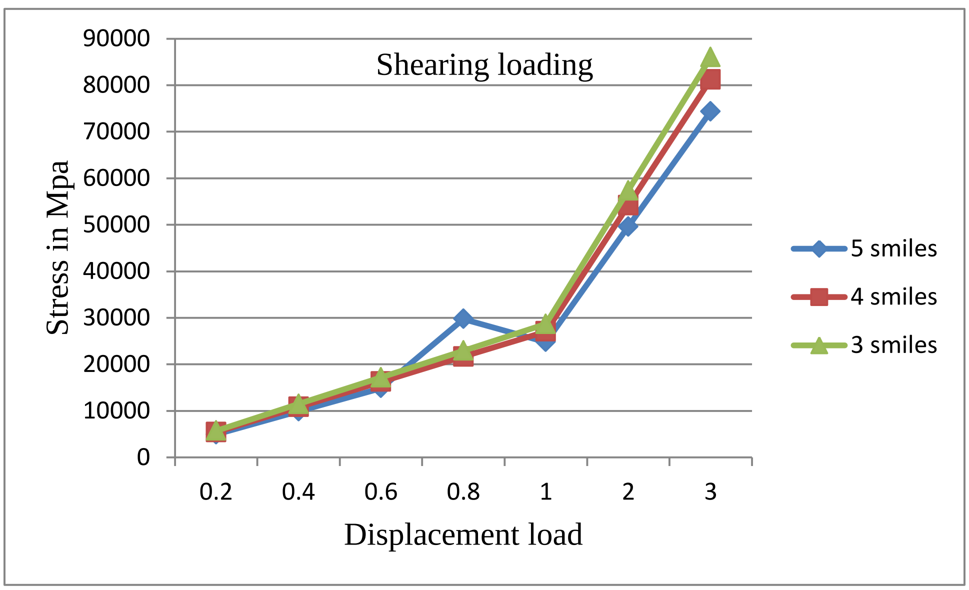


Figure 4-16 Variation of shearing load characteristics with the number of design feature

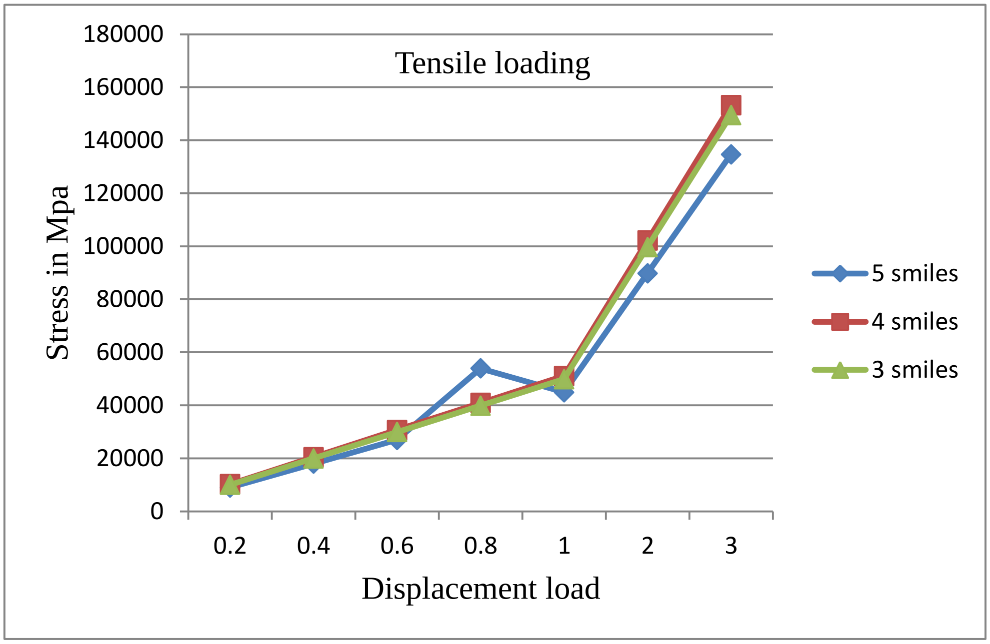


Figure 4-17 Variation of tensile load characteristics with the number of design feature

4.5 Conclusion

Based on the above simulation results we can infer that conventional stamping displays better tensile and shearing characteristics when compared to industrial origami. The difference in stress dissipation is high during lower thickness and decreases as the thickness increases. Bending tests prove to be the most promising application of origami joints as the normalization values goes below 1. In the case of a 0.75mm of steel sheet metal we can safely conclude that parts manufactured with conventional stamping are better suited for tensile and shearing applications when compared to industrial origami. Origami is better suited for bending applications when compared to stamping particularly for panel thickness of 0.75, 1.50, 1.75 and 2.00mm.

CHAPTER FIVE – APPLICATION OF INDUSTRIAL ORIGAMI

Bill of materials (BOM) is a list of assemblies, sub-assemblies and individual components with their respective quantity of the above required in manufacturing the end product. There are different classifications of bill of materials like Engineering bill of materials (EBOM), Manufacturing bill of materials (MBOM), service bill of materials (SBOM) and other types depending on their purpose and construction. In this research the manufacturing bill of materials for a passenger car with body type hatchback is constructed using the list of components obtained from an online service manual [35]. The construction type is indented, that is the highest component (complete assembly) starts from the left and later subdivides into sub-assemblies, part assembly and finally into part sub assembly.

The major sheet metal panels, support structures and major clamping structures are included in the BOM along with the list of components, their quantity, part number and their manufacturing process. The pictorial representations of the components and their corresponding part assembly are also provided to visualize their layout in the complete assembly. This also helps in part consolidation which will be discussed in detail later. There are a total of 149 components in the bill of materials and they constitute 14 major part assemblies. These part assemblies are assembled into 5 major sub-assemblies which make up the construction of the body in white of the mid-size hatchback. It is to be noted that there may be other smaller components like nuts, bolts, washers, bushings, and springs etc. which are purchased from the suppliers and are not considered due to increased complexity.

5.1 Construction of Bill of materials

The bill of materials constructed lists the parts, quantity and part identification number. The manufacturing processes to manufacture each part sub-assembly component have been added by the researcher based on theoretical knowledge of automotive manufacturing processes and the conventional manufacturing strategies deployed by OEMs. Visual inspection of identical BIW structures has been conducted to understand the components, their functional and aesthetic requirements, joining techniques and the production methods. The joining methods during assembly like welding or hemming are not included to avoid conflicts with secondary operations and finishing methods.

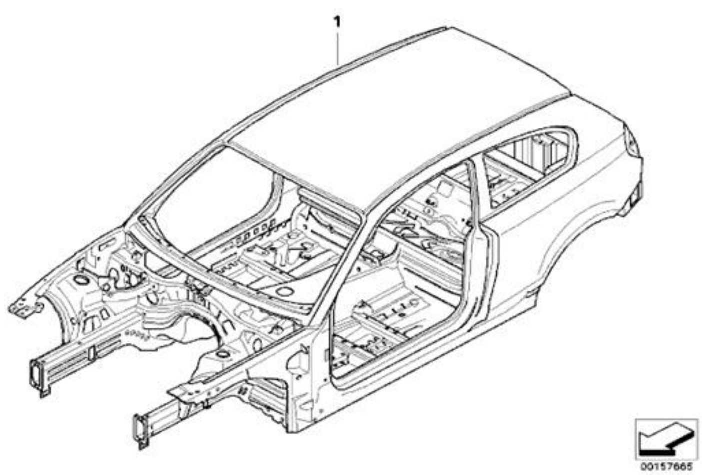


Figure 5-1 Small sedan BOM construction

The manufacturing processes being listed are

Stamping

Machining

Casting

TWB

The major BIW panels are stamped using heavy stamping presses from sheet metal coils in-house at the body shop. The smaller supporting parts are machined using CNC machines or other hard tooling machining techniques and are mostly procured from suppliers. Major components of the front module and other load bearing structures are casted due to their thick wall sections and high gauge requirements. Tailor welded blanks are preferred for increased structural integrity, fewer spot welds, high flexibility in material selection, weight reduction and lower manufacturing costs.

Table 5.1 Bill of Materials of Partition trunk/floor panels

Left front seat console	1	1	Stamping	LB	Left front seat console	Stamping
Right front seat console	1	1	Stamping	LB	Right front seat console	Stamping
Left rear seat console	2	1	Stamping	LB	Left rear seat console	Stamping
Right rear seat console	2	1	Stamping	LB	Right rear seat console	Stamping
Reinforcement tunnel	3	1	Stamping	NLB	Reinforcement tunnel	Origami
Support belt reel,left	4	1	Machining	LB	Support belt reel,left	Machining
Support belt reel,right	4	1	Machining	LB	Support belt reel,right	Machining
Support, wheelhouse left	5	1	Stamping	LB	Support, wheelhouse left	Origami
Support, wheelhouse right	5	1	Stamping	LB	Support, wheelhouse right	Origami
Bracket backrest outer left	6	1	Machining	LB	Bracket backrest outer left	Machining
Bracket backrest outer right	6	1	Machining	LB	Bracket backrest outer right	Machining
Centre backrest bearing bracket	7	1	Machining	LB	Centre backrest bearing bracket	Machining
Bracket f shifting arm bearing	8	1	Stamping	LB	Bracket f shifting arm bearing	Origami
Holder, backrest left	9	1	Machining	NLB	Holder, backrest left	Origami
Holder, backrest Right	9	1	Machining	NLB	Holder, backrest Right	Origami
Floor pan cross member, rear	13	1	Machining	LB	Floor pan cross member, rear	Machining

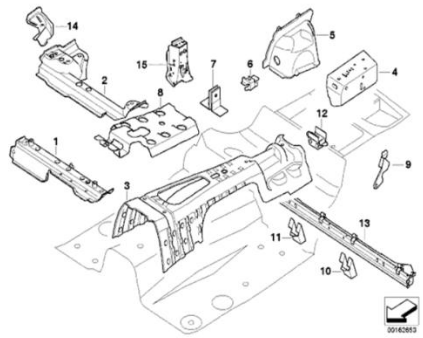


Figure 5-2 Partition trunk/Floor panels layout

5.2 Part Consolidation and alternate manufacturing methods

The first step was to classify the panels as load bearing (LB) and non-load bearing (NLB) based on their functional requirement in a BiW. This is important to study the feasibility of substituting stamped panels with industrial origami based on loading conditions. Origami has a limited load bearing potential and cannot be used to substitute panels where dent resistant or torsional stiffness are important requirements. The load bearing capability and strength comparison between stamping and industrial origami has been discussed in detail in chapter3. Since considerable research is still underway to determine the strength characters of an industrial origami joint, only the non-load bearing structures in the BOM have been considered for part consolidation.

The literature survey of part consolidation techniques helps identify areas where the parts can be integrated using tailor welded blanks and industrial origami. The usage of industrial origami and tailor welded blanks also helps to consolidate smaller panels into complex shaped larger panels with intricate shapes and geometries. Industrial origami has the ability to manufacture parts with multiple folds, 90^0 shaped folds, and intricate closed shapes with the existing hard/soft tooling and low cost. This makes it an ideal process to fabricate panels used in applications such as wheel housing, door interiors, front dash panel and instrument cluster.

5.2.1 Part consolidation by usage of Industrial Origami

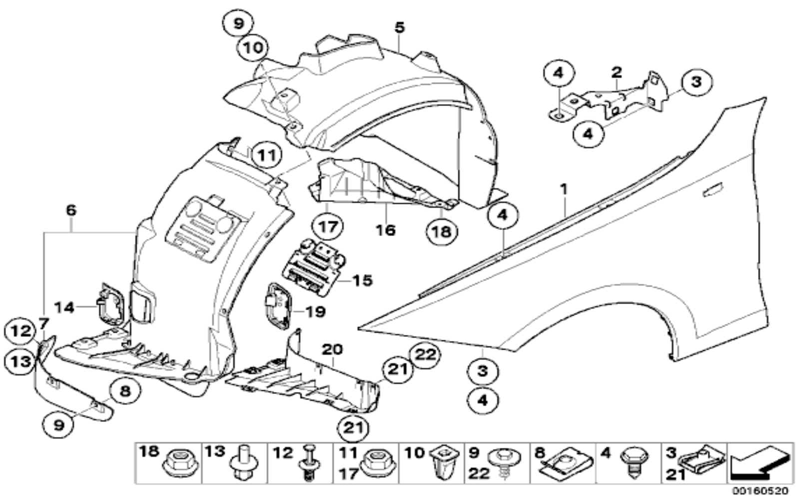


Figure 5-3 Body side panel- Front

The side panel front part assembly consists of 12 major part sub-assemblies which include 8 non load bearing panels and 4 major load bearing panels. Currently the panels are manufactured using stamping and machining. Cover wheel housing (Part ID 5 and 6) are non-load bearing panels which is semicircular in shape as it traces the curvature of the tires. Protect front body from dirt, withstanding tire heat and accommodating wire harness are some of the key functional aspects. This cannot be currently manufactured as a single component due to circularity tooling constraints in stamping. Hence two parts, cover wheel housing front (Part ID 5) and cover wheel housing bottom (Part ID 6) are currently stamped. Application of industrial origami can used controlled bending to manufacture one big cover wheel housing which will perform he necessary functions. Smile features have to be designed into a hexagonal shaped sheet metal coil which can be bent using bending presses. This part consolidation is achieved by placing no additional cost and no major tooling changes from the shop floor perspective. Part consolidation in this case helps reduce the sub-assemblies part count to 10 from 12.

Table 5.2 Part consolidation using origami

Part Sub Assembly	Part ID	Quantity	Current process	Type of loading	Consolidated part list	Alternate process
cover wheel housing ,front left	5	1	Stamping	NLB	cover wheel housing ,left	Origami
cover wheel housing ,front right	5	1	Stamping	NLB		
cover wheel housing,bottom left	6	1	Stamping	NLB	cover wheel housing ,right	Origami
cover wheel housing, bottom right	6	1	Stamping	NLB		
side panel front left	1	1	Stamping	LB	side panel left	Stamping
side panel front right	1	1	Stamping	LB	side panel right	Stamping
bracket side panel,top left	2	1	Machining	LB	bracket side panel,top left	Origami
bracket side panel,top right	2	1	Machining	LB	bracket side panel,top right	Origami
pressure lip seal front left	7	1	Stamping	NLB	pressure lip seal front left	Origami
pressure lip seal front right	7	1	Stamping	NLB	pressure lip seal front right	Origami
lid wheel house cover, front left	14	1	Machining	NLB	lid wheel house cover, front left	Machining
lid wheel house cover, front right	14	1	Machining	NLB	lid wheel house cover, front right	Machining

5.2.2 Part consolidation by usage of Tailor Welded Blanks

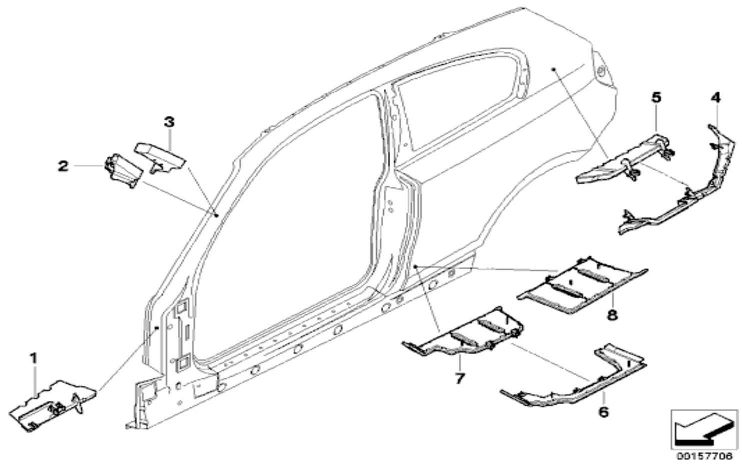


Figure 5-4 Cavity Shielding/Side Frame

The side frame serves the purpose of proving structural integrity to the body frame along with housing the doors and reinforcements. The side frame consists of 13 smaller part sub-assemblies a majority of which provide reinforcements to the A, B and C pillars. Tailor welded blanks use friction stir welding to weld panels of different thickness which can later be stamped to achieve required panel profile. Thicker sections for high strength applications and thinner sections of similar or dissimilar materials for aesthetic advantages can be welded together without loss of strength. This provides good part consolidation opportunity in the case of side frames where combinations of thick and thin panels are common. Molded part column A consists of two panels which had thick exterior panels (Part ID 3) for strength and thinner interior panels (Part ID 2) for light weight. These panels can be combined using friction stir welding to form blanks which can be press formed to achieve the required profile. Dimensional variation, flexibility and physical appearance are some of the key factors which have to be considered while performing a feasibility analysis for the usage of tailor welded blanks. By consolidating the parts using TWB the number of components reduced to 9 from 13.

Table 5.3 Part consolidation of Side frame

Part Assembly	Part Sub Assembly	Part ID	Quantity	Current process	Type of loading	Consolidated part list	Alternate process
cavity shielding/side frame	Molded part f wheel housing support left	1	1	TWB	LB	Molded part f wheel housing support left	TWB
	Molded part f wheel housing support right	1	1	TWB	LB	Molded part f wheel housing support right	TWB
	Molded part coloumn A,interior	2	1	TWB	LB	Molded part coloumn A,interior& exterior	TWB
	Molded part coloumn A,exterior	3	1	TWB	LB		
	Molded part f coloumn C,exterior left	4	1	TWB	NLB	Molded part f coloumn C,exterior & interior left	TWB
	Molded part f coloumn C,exterior right	4	1	TWB	NLB		
	Molded part f coloumn C,interior left	5	1	TWB	NLB	Molded part f coloumn C,exterior & interior right	TWB
	Molded part f coloumn C,interior right	5	1	TWB	NLB		
	Molded part f coloumn B, interior left	6	1	TWB	NLB	Molded part f coloumn B, interior & exterior left	TWB
	Molded part f Coloumn B, interior right	6	1	TWB	NLB		
	Molded part f Coloumn B, exterior left	7	1	TWB	NLB	Molded part f coloumn B, interior & exterior right	TWB
	Molded part f Coloumn B, exterior right	7	1	TWB	NLB		
	Molded section B pillar , rear left	8	1	TWB	NLB	Molded section B pillar , rear left	TWB
	Molded section B pillar , rear right	8	1	TWB	NLB	Molded section B pillar , rear right	TWB

The complete bill of materials for the sedan is given below. Non load bearing panels which are currently made using stamping are substituted with origami in order to save tooling cost and enable the fabrication of components with intricate shapes. The usage of origami and TWBs were optimized based on the advantages of deploying them in the place of stamping as discussed in chapter one.

Table 5.4 Consolidation of front body assembly

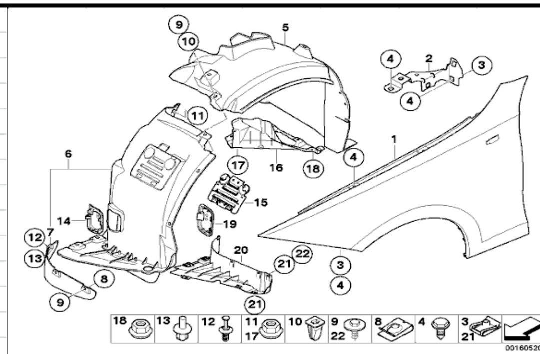
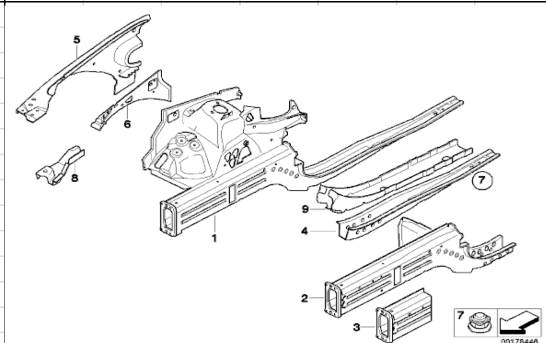
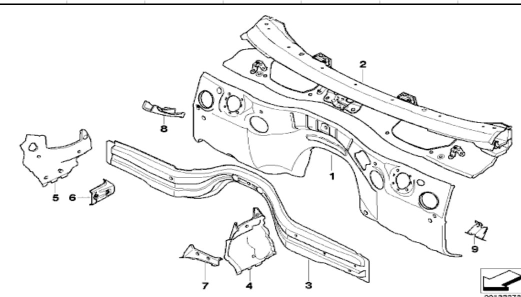
side panel front	cover wheel housing ,front left	5	1	Stamping	NLB		cover wheel housing ,left	Origami
	cover wheel housing ,front right	5	1	Stamping	NLB			
	cover wheel housing,bottom left	6	1	Stamping	NLB		cover wheel housing ,right	Origami
	cover wheel housing, bottom right	6	1	Stamping	NLB			
	side panel front left	1	1	Stamping	LB		side panel left	Stamping
	side panel front right	1	1	Stamping	LB		side panel right	Stamping
	bracket side panel,top left	2	1	Machining	LB		bracket side panel,top left	Origami
	bracket side panel,top right	2	1	Machining	LB		bracket side panel,top right	Origami
	pressure lip seal front left	7	1	Stamping	NLB		pressure lip seal front left	Origami
	pressure lip seal front right	7	1	Stamping	NLB		pressure lip seal front right	Origami
	lid wheel house cover, front left	14	1	Machining	NLB		lid wheel house cover, front left	Machining
	lid wheel house cover, front right	14	1	Machining	NLB		lid wheel house cover, front right	Machining
wheel house/engine support	Front left wheel house	1	1	Casting	LB		Front left wheel house	Casting
	Front right wheel house	1	1	Casting	LB		Front right wheel house	Casting
	Front left engine support	2	1	Casting	LB		Front left engine support	Casting
	Front righ engine support	2	1	Casting	LB		Front righ engine support	Casting
	rear left engine support	4	1	Stamping	LB		Rear left engine support	TWB
	rear right engine support	4	1	Stamping	LB		Rear right engine support	TWB
	Support strut,wheel house exterior left	5	1	TWB	LB		Support strut,wheel house exterior & interior left	TWB
	support strut,wheel house exterior righ	5	1	TWB	LB			
	support strut, wheel house,interior left	6	1	TWB	LB		Support strut, wheel house,exterior & interior right	TWB
	support strut ,wheel house interior righ	6	1	TWB	LB			
	crash reinforcement left	9	1	TWB	LB		Crash reinforcement left	TWB
	crash reinforcement right	9	1	TWB	LB		Crash reinforcement right	TWB
splash wall parts	Splash wall	1	1	Stamping	LB		Splash wall	Stamping
	Lower apron	2	1	Stamping	LB		Lower apron	Stamping
	Support strut/front wall	3	1	Stamping	NLB		Support strut/front wall	TWB
	Left engine compartment partition	4	1	TWB	NLB		Left engine compartment partition	TWB
	Right engine compartment partition	5	1	TWB	NLB		Right engine compartment partition	TWB
	Right partition reinforcement	6	1	Machining	LB		Right partition reinforcement	Machining
	Cover panel engine compartment left	7	1	Machining	LB		Cover panel engine compartment left	Origami
	Cover panel engine compartment right	7	1	Machining	LB		Cover panel engine compartment right	Origami
	Brake/Accelerator module	9	1	Machining	LB		Brake/Accelerator module	Origami
	Covering right	8	1	Machining	NLB		Covering right	Origami

Table 5.5 Process alternatives to fabricate front module and underbody

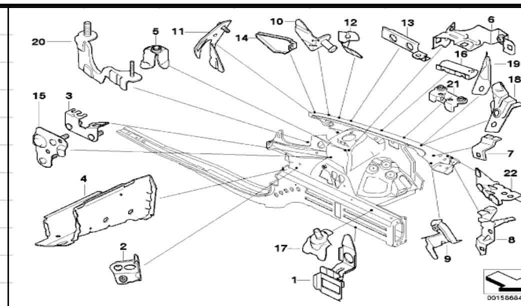
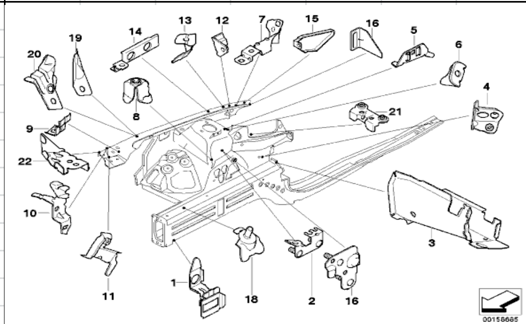
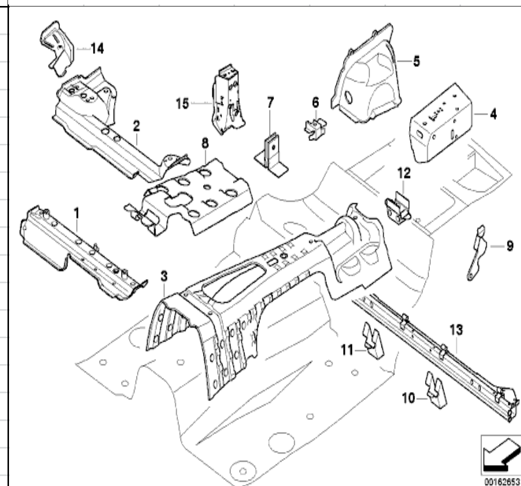
front body bracket left	Support for left radiator	1	1	Machining	LB		Support for left radiator	Machining
	Bracket intake silencer , bottom left	2	1	Machining	NLB		Bracket intake silencer , bottom left	Origami
	Connector engine support/side frame le	4	1	Stamping	LB		:onnector engine support/side frame lef	Stamping
	Bracket intake silencer , top left	5	1	Machining	LB		Bracket intake silencer , top left	Machining
	Bracket side panel, top left	6	1	Machining	LB		Bracket side panel, top left	Machining
	Bracket side panel, front	7	1	Machining	LB		Bracket side panel, front	Machining
	Bracket, active steering, top	10	1	Machining	LB		Bracket, active steering, top	Machining
	Bracket, active steering, bottom	11	1	Machining	LB		Bracket, active steering, bottom	Machining
	holder,brake hose left	15	1	Machining	NLB		holder,brake hose left	Origami
front body bracket right	Support for right radiator	1	1	Machining	LB		Support for right radiator	Machining
	Connector engine support/ side frame r	3	1	Stamping	NLB		onnector engine support/ side frame rig	Origami
	Bracket intake silencer,bottom right	4	1	Machining	LB		Bracket for intake silencer and filler pipe, bottom right	Origami
	Filler pipe brackett	5	1	Machining	LB			
	Fluid container brackett, SWA/SRA	6	1	Machining	LB		Fluid container brackett, SWA/SRA	Origami
	Bracket side panel ,top right	7	1	Machining	LB		Bracket side panel ,top right	Machining
	Bracket ,intake silencer,top right	8	1	Machining	LB		Bracket ,intake silencer,top right	Machining
	Bracket side panel ,front	9	1	Machining	LB		Bracket side panel ,front	Machining
	Bracket wash water container top	16	1	Machining	LB		Bracket wash water container top	Machining
	Holder ,brake hose ,right	17	1	Machining	LB		Holder ,brake hose ,right	Machining
partition trunk/floor parts	Left front seat console	1	1	Stamping	LB		Left front seat console	Stamping
	Right front seat console	1	1	Stamping	LB		Right front seat console	Stamping
	Left rear seat console	2	1	Stamping	LB		Left rear seat console	Stamping
	Right rear seat console	2	1	Stamping	LB		Right rear seat console	Stamping
	Reinforcement tunnel	3	1	Stamping	NLB		Reinforcement tunnel	Origami
	Support belt reel,left	4	1	Machining	LB		Support belt reel,left	Machining
	Support belt reel,right	4	1	Machining	LB		Support belt reel,right	Machining
	Support, wheelhouse left	5	1	Stamping	LB		Support, wheelhouse left	Origami
	Support, wheelhouse right	5	1	Stamping	LB		Support, wheelhouse right	Origami
	Bracket backrest outer left	6	1	Machining	LB		Bracket backrest outer left	Machining
	Bracket backrest outer right	6	1	Machining	LB		Bracket backrest outer right	Machining
	Centre backrest bearing bracket	7	1	Machining	LB		Centre backrest bearing bracket	Machining
	Bracket f shifting arm bearing	8	1	Stamping	LB		Bracket f shifting arm bearing	Origami
	Holder, backrest left	9	1	Machining	NLB		Holder, backrest left	Origami
	Holder, backrest Right	9	1	Machining	NLB		Holder, backrest Right	Origami
	Floor pan cross member, rear	13	1	Machining	LB		Floor pan cross member, rear	Machining

Table 5.6 Part consolidation body side panels

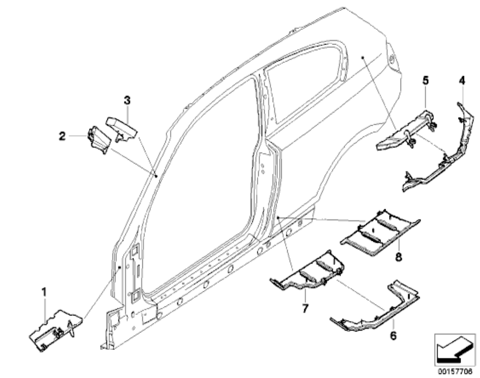
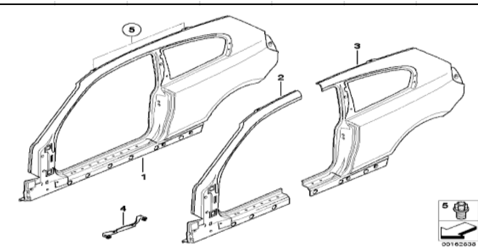
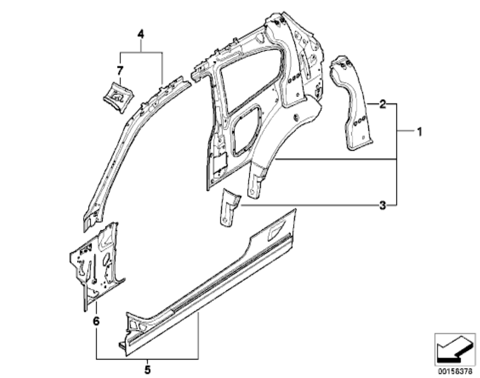
cavity shielding/side frame	Molded part f wheel housing support le	1	1	TWB	LB		Molded part f wheel housing support lef	TWB
	Molded part f wheel housing support ri	1	1	TWB	LB		Molded part f wheel housing support righ	TWB
	Molded part coloumn A,interior	2	1	TWB	LB		Molded part coloumn A,interior& exterior	TWB
	Molded part coloumn A,exterior	3	1	TWB	LB			
	Molded part f coloumn C,exterior left	4	1	TWB	NLB		Molded part f coloumn C,exterior & interior left	TWB
	Molded part f coloumn C,exterior right	4	1	TWB	NLB			
	Molded part f coloumn C,interior left	5	1	TWB	NLB		Molded part f coloumn C,exterior & interior right	TWB
	Molded part f coloumn C,interior right	5	1	TWB	NLB			
	Molded part f coloumn B, interior left	6	1	TWB	NLB		Molded part f coloumn B, interior & exterior left	TWB
	Molded part f Coloumn B, interior right	6	1	TWB	NLB			
	Molded part f Coloumn B, exterior left	7	1	TWB	NLB		Molded part f coloumn B, interior & exterior right	TWB
	Molded part f Coloumn B, exterior right	7	1	TWB	NLB			
	Molded section B pillar , rear left	8	1	TWB	NLB		Molded section B pillar , rear left	TWB
	Molded section B pillar , rear right	8	1	TWB	NLB		Molded section B pillar , rear right	TWB
body side frame	Side frame exterior left	1	1	Stamping	LB		Side frame exterior left	Stamping
	side frame exterior right	1	1	Stamping	LB		side frame exterior right	Stamping
	left exterior coloumn A	2	1	Stamping	LB		left exterior coloumn A	Stamping
	Coloumn A exterior Right	2	1	Stamping	LB		Coloumn A exterior Right	Stamping
	left rear side panel	3	1	Stamping	LB		left rear side panel	Stamping
	right rear side panel	3	1	Stamping	LB		right rear side panel	Stamping
	bracket side panel coloumn A,left	4	1	Casting	NLB		bracket side panel coloumn A,left	Origami
	Bracket side panel coloumn A,right	4	1	Casting	NLB		Bracket side panel coloumn A,right	Origami
single components for body side frame	left interior side frame	1	1	Stamping	LB		roof side panel	TWB
	right interior side frame	1	1	Stamping	LB			
	C pillar reinforcement left	2	1	Casting	LB		rail case	TWB
	C pillar reinforcement right	2	1	Casting	LB			
	Cover panel wheel house left	3	1	Casting	NLB		Cover panel wheel house	Origami
	Cover panel wheel house right	3	1	Casting	NLB			
	Connector,A-pillar/roof frame left	4	1	Casting	LB			
	Connector,A-pillar/roof frame right	4	1	Casting	LB		central pillar	TWB
	left side member	5	1	Stamping	LB			
	right side member	5	1	Stamping	LB		side member	TWB
	left interior coloumn A	6	1	Casting	NLB			
	Right interior coloumn A	6	1	Casting	NLB		side column	TWB
	Left upper apron reinforcement	7	1	Casting	LB			
	right upper apron reinforcement	7	1	Casting	LB		apron reinforcement	

Table 5.7 Part consolidation of trunk floor and rear body panels

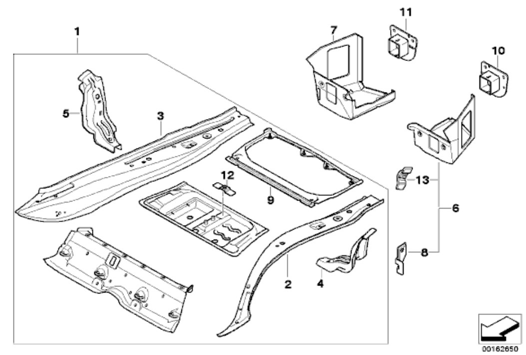
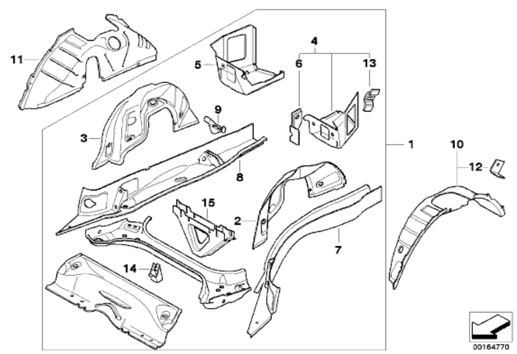
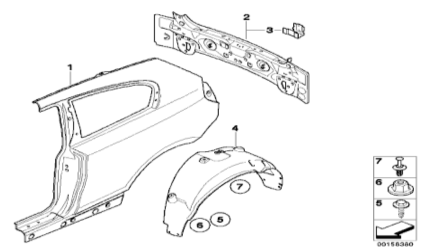
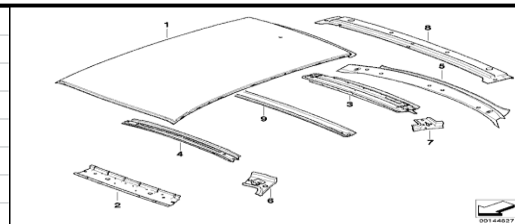
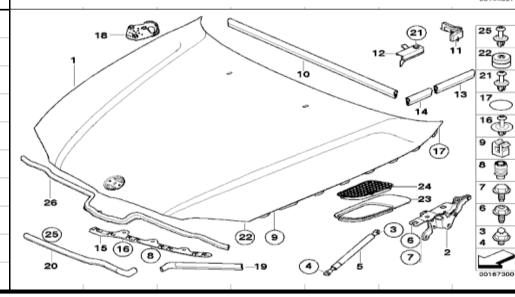
mounting parts for trunk floor panel	Trunk floor upper part	1	1	Stamping	LB		Trunk floor upper part	TWB
	Side member top left	2	1	Stamping	LB		Side member top left	TWB
	Side member top right	3	1	Stamping	LB		Side member top right	TWB
	Support for frame side member,left	4	1	Stamping	NLB		Support for frame side member,left	Origami
	Support for frame side member,right	5	1	Stamping	NLB		Support for frame side member,right	Origami
	Trunk floor frame	9	1	Stamping	NLB		Trunk floor frame	Origami
	Bracket for components	12	4	Casting	NLB		Bracket for components	Casting
	Trunk floor left	6	1	Stamping	NLB		Trunk floor left	Origami
	Trunk floor right	7	1	Stamping	NLB		Trunk floor right	Origami
	Audio universal bracket	8	4	Machining	NLB		Audio universal bracket	Origami
	Mount bumper left	10	1	Machining	LB		Mount bumper left	Machining
	Mount bumper right	11	1	Machining	LB		Mount bumper right	Machining
floor parts rear exterior	Rear axle carrier	1	1	Stamping	LB		Rear axle carrier	Stamping
	Support wheelhouse left	2	1	Stamping	NLB		Wheelhouse and trunk floor left	Origami
	Support wheelhouse right	3	1	Stamping	NLB			
	Trunk floor left	4	1	Stamping	NLB		Wheelhouse and trunk floor right	Origami
	Trunk floor right	5	1	Stamping	NLB			
	Audio universal bracket	6	1	Casting	NLB		Audio universal bracket	Machining
	left side member	7	1	Stamping	LB		left side member	Stamping
	Right side member	8	1	Stamping	LB		Right side member	Stamping
	Holder, brake hose	9	1	Machining	LB		Holder, brake hose	Machining
	Rear left wheelhouse,inner half	10	1	Stamping	NLB		Rear left wheelhouse,inner half	TWB
	Rear right wheelhouse,inner half	11	1	Stamping	NLB		Rear right wheelhouse,inner half	TWB
	Bracket CD changer	12	1	Machining	NLB		Bracket CD changer	Origami
side panel/tail rim	Left rear side panel	1		Stamping	LB		Left rear side panel	Stamping
	Right rear side panel	1		Stamping	LB		Right rear side panel	Stamping
	Tail trim	2		Stamping	NLB		Tail trim	Stamping
	Rear silencer bracket	3		Stamping	NLB		Rear silencer bracket	Machining
	cover wheel housing ,rear left	4		Stamping	NLB		cover wheel housing ,rear left	Origami
	cover wheel housing ,rear right	4		Stamping	NLB		cover wheel housing ,rear right	Origami

Table 5.8 Selection of alternate manufacturing process for hood and roof

roof	Roof cover	1	1	Stamping	LB		Roof cover	Stamping
	Upper apron	2	1	Stamping	LB		Upper apron	TWB
	Rear window frame upper part	3	1	Stamping	NLB		Rear window frame upper part	TWB
	Roof bow	4	1	Stamping	LB		Roof bow	TWB
	left upper apron reinforcement	6	1	Stamping	LB		left upper apron reinforcement	TWB
	Right upper apron reinforcement	6	1	Stamping	LB		Right upper apron reinforcement	TWB
engine hood/mounti ng parts	Hood	1	1	Stamping	LB		Hood	Stamping
	Left engine hood holder	2	1	Casting	LB		Left engine hood engine	Casting
	right engine hood holder	2	1	Casting	LB		right engine hood engine	Casting
	Rear engine hood sealing	10	1	Machining	NLB		Rear engine hood sealing	Machining
	Supporting ledge left	15	1	Stamping	NLB		Supporting ledge left	Origami
	Supporting ledge right	15	1	Stamping	NLB		Supporting ledge right	Origami
	Sealing engine compartment lateral rea	13	2	Machining	LB		Sealing engine compartment lateral rea	Machining
	Sealing engine compartment lateral fro	14	2	Machining	LB		ealing engine compartment lateral fron	Machining

5.3 Results of part consolidation and process substitution

Usage of consolidation techniques based on selection of manufacturing processes the overall numbers of components in the bill of materials were reduced by 10. The reduction of part count from 149 to 139 provides significant cost savings in the form of material handling cost, supplier purchasing cost, transportation cost, energy cost and factory overheads. The other significant achievement is the reduction of dependence on stamping and increasing usage of industrial origami and tailor welded blanks. As discusses earlier these processes require low cost tooling, provide good functional characteristics and help use reduce the overall manufacturing lead time and cost.

Table 2.11 Overall part reduction achieved based on part consolidation using origami and tailor welded blanks

Current Process	Count	Proposed Process	Count
Stamping	67	Stamping	23
Machining	40	Machining	29
Casting	20	Casting	7
TWB	22	TWB	33
Origami	0	Origami	37
Total	149		129

CHAPTER SIX – CONCLUSIONS AND FUTURE WORK

- In chapter 2 it is assumed that the OEMs currently use stamping to manufacture a majority of the BIW components. The decision making tool results have shown that in order to maximize profits and lower product lead time the OEMs have to consolidate parts based on the selection of manufacturing processes. The top two technical requirement results from the decision making tool were consolidation of parts and reduction in number of components.
- In Chapter 3, the current BIW consolidation strategies were evaluated. Hydroforming can be used as a stamping alternative but the cycle times to manufacture hydroformed components are higher. SPF also suffers from the same limitation in addition to being expensive and hence cannot be considered. TWB appears to be the best strategy to consolidate the parts with the costs being almost the same as that of stamping.
- In Chapter 4, industrial origami process is studies in detail and the potential advantages it holds compared to stamping are listed. The existing stamping bending presses can be employed to fabricate origami components which means no extra machinery required. This will also reduce the product lead time due to the absence of stamping die validation time.

  Origami is still a new process and research is still underway to find the optimal design feature, ‘smile’ which would help achieve better loading conditions compared to the current mode. The current model is unable to match stamped components in terms of tensile and shearing load. Future research can also be focused on the choice of aluminum to make origami components. Current models are simulated for steel applications only.

- Application of origami to consolidate body panels has been carried out based on the results from chapter 3 and chapter 4. Due to the loading limitations discussed in chapter 4, only stamped parts which are non-load bearing requirements have been substituted with origami. This substitution using origami and TWB reduced the number of stamped component in a small sedan from 67 to 23. This is a major savings in the die investment and validation time of 44 components which are being currently stamped.

References

[1] Bezdek, R. H., and Wendling, R. M., 2005, "Potential Long-Term Impacts of Changes in US Vehicle Fuel Efficiency Standards," Energy Policy, 33(3) pp. 407-419.

[2] Comeau, J., and Chapman, D., 2002, "Gasoline Taxes, CAFÉ and the Kyoto Protocol," Ecological Economics, 40(3) pp. 317-320.

[3] Liddle, B., 2009, "Long-Run Relationship among Transport Demand, Income, and Gasoline Price for the US," Transportation Research Part D: Transport and Environment, 14(2) pp. 73-82.

[4] Bassi, A. M., Powers, R., and Schoenberg, W., 2010, "An Integrated Approach to Energy Prospects for North America and the Rest of the World," Energy Economics, 32(1) pp. 30-42.

[5] Greene, D. L., 1998, "Why CAFE Worked," Energy Policy, 26(8) pp. 595-613.

[6] Kirby, E. G., 1995, "An Evaluation of the Effectiveness of US CAFE Policy," Energy Policy, 23(2) pp. 107-109.

[7] Cao, J., Kinsey, B. L., Yao, H., 2001, "Next Generation Stamping Dies — Controllability and Flexibility," Robotics and Computer-Integrated Manufacturing, 17(1-2) pp. 49-56.

[8] Michalos, G., Makris, S., Papakostas, N., 2010, "Automotive Assembly Technologies Review: Challenges and Outlook for a Flexible and Adaptive Approach," CIRP Journal of Manufacturing Science and Technology, 2(2) pp. 81-91.

[9] Yang, Y. S., and Lee, S. H., 1999, "A Study on the Joining Strength of Laser Spot Welding for Automotive Applications," Journal of Materials Processing Technology, 94(2-3) pp. 151-156.

[10] Scialpi, A., De Giorgi, M., De Filippis, L. A. C., 2008, "Mechanical Analysis of Ultra-Thin Friction Stir Welding Joined Sheets with Dissimilar and Similar Materials," Materials & Design, 29(5) pp. 928-936.

[11] Li, Z., and Gobbi, S. L., 1997, "Laser Welding for Lightweight Structures," Journal of Materials Processing Technology, 70(1-3) pp. 137-144.

[12] Sieben, M., and Brunnecker, F., 2010, "Laser-Hybrid Welding, an Innovative Technology to Join Automotive Body Parts," Physics Procedia, 5(Part 2) pp. 61-68.

[13] Chen, H., Pinkerton, A. J., Li, L., 2011, "Gap-Free Fibre Laser Welding of Zn-Coated Steel on Al Alloy for Light-Weight Automotive Applications," Materials & Design, 32(2) pp. 495-504.

[14] Barnes, T. A., and Pashby, I. R., 2000, "Joining Techniques for Aluminium Spaceframes used in Automobiles: Part I — Solid and Liquid Phase Welding," Journal of Materials Processing Technology, 99(1-3) pp. 62-71.

[15] Endregaard, E. A., 2002, "Paint robotics—improving Automotive Painting Performance," Metal Finishing, 100(5) pp. 8-10.

[16] Meschievitz, T., Rahangdale, Y., and Pearson, R., 1995, "U.S. Council for Automotive Research (USCAR) Low-Emission Paint Consortium : A Unique Approach to Powder Painting Technology Development," Metal Finishing, 93(10) pp. 26-28.

[17] Supply Pro, "Automotive Tooling Management," whitepaper, .

[18] Cartwright, D., Drake, P. R., and Godwin, M. J., 1999, "A Method for Comparing the Performance of Low-Cost Press Tools for Sheet Forming," Journal of Materials Processing Technology, 95(1-3) pp. 49-54.

[19] Lovell, M., Higgs, C. F., Deshmukh, P., 2006, "Increasing Formability in Sheet Metal Stamping Operations using Environmentally Friendly Lubricants," Journal of Materials Processing Technology, 177(1-3) pp. 87-90.

[20] Fournier, L., 2005, "A Method to Assess Cost Implication of Automotive Customization," pp. 59.

[21] von Schöning, K. -., Sünkel, R., Hillmann, M., 1995, "Mathematical Modelling as a Means to Bridge the Gap between Material and Tooling," Journal of Materials Processing Technology, 50(1-4) pp. 348-360.

[22] Kim, S., 2007, "Improvement of the Surface Quality of an Automotive Member by a Modification of the Stamping Tool," Journal of Materials Processing Technology, 187-188pp. 387-391.

[23] Karbasian, H., and Tekkaya, A. E., 2010, "A Review on Hot Stamping," Journal of Materials Processing Technology, 210(15) pp. 2103-2118.

[24] Gan, W., and Wagoner, R. H., 2004, "Die Design Method for Sheet Springback," International Journal of Mechanical Sciences, 46(7) pp. 1097-1113.

[25] Vari-Form Pressure Sequence Hydroforming, "http://www.vari-form.com/knowledge.asp?area_2=pages/knowledge/d0_knowledge.dat&area_3=pages/knowledge/d0_knowledge_col2.dat&area_4=pages/knowledge/d0_knowledge_col3.dat&area_5=pages/knowledge/title.dat&objectid=B34A4100&ml_index=2&NC=4679X," .

[26] Bruce Constantine, Richard Roth, Joel P. Clark, 2001, "Substituting Tube-Hydroformed Part for Automotive Stampings: An Economic Model," .

[27] Luckey, S. G., Subramanian, S., Young, C., 2006, "Technical and Cost Study of Superplastic Forming of a Light Weight Aluminum Door Structure," .

[28] Lokka, M. A., 1997, "An Economic Evaluation of Tailor Welded Blanks in Automotive Applications," .

[29] Auto-Steel, P., 1995, "Tailor Welded Blank Design and Manufacturing Manual," .

[30] Anonymous 1993, "Stamping And Formability: Automotive Design Guidelines for Steel Stampings: Design for Manufacturability," .

[31] Auto/Steel partnership program, 2000, "Event-Based Functional Build: An Integrated Approach to Body Development," .

[32] Gregory, J.,Dr, and Roth, R.,Dr, 2007, "Technical Cost Modelling of Tailor Welded Blanks," 1.1, .

[33] Gregory, J.,Dr, Roth, R.,Dr, and Mould, P., 2006, "Cost Modeling of Laser-welded Blanks in Automotive Applications," v1.1, .

[34] Industrial Origami, "Http://www.Industrialorigami.com/technology/overview.Cfm,".

[35] Realoem, "Http://www.Realoem.com/bmw/select.do?kind=P&series=E81&body=HC&model=116d&arch=0," .

[36] Davies, G., 2003, "Materials for Automobile Bodies,"Butterworth-Heinemann, Oxford, pp. 252-269