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An Economic Evaluation of Tailor Welded Blanks in Automotive Applications

by

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Submitted to the Department of Materials Science and Engineering
in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE
in Materials Science and Engineering
at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 1997

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ABSTRACT

This study compares the costs of tailor welded blanks with the costs of conventional automobile body-in-white structures. Technical cost model was developed to estimate costs of alternative designs and manufacturing processes. CO_2 laser welding and mash seam welding systems are incorporated into the model to estimate the cost differences of welding systems typical in tailored blanking. To examine the cost impact of material change, the analyses were conducted for both steel and aluminum applications. The effect of blank complexity was determined by varying the specifications of tailored blank designs.

The case studies suggest that part integration can yield weight savings in tailored blanks. Also, the cost estimates demonstrated that tailored blanking can be economically feasible for vehicle body structures. Parts elimination reduced production steps in blanking, forming, and assembly, the highest potential for cost savings being in capital intensive forming process. Compared with conventional designs, tailored blanks resulted in 5 to 20% lower costs, but the economic benefits decreased at higher production volumes. Aluminum parts improved weight savings by an additional 40% for all the designs considered. However, there was a cost penalty of $3.00 to $6.40 per kilogram of weight saved. The results indicated also that to achieve maximum weight reductions and cost savings, the designs of tailored parts have to be carefully considered.

The analyses of different welding processes indicated that the cost effective welding system choice varies with blank complexity. Based on the sensitivity analyses, the loading of blanks seemed to be the main factor causing the variations in the welding costs. Also, the comparisons suggest that the most promising welding system for processing blanks with multiple, non-parallel welds is the two-axis CO_2 laser. The mash seam welder seemed to be the most favorable system for parts with short, parallel welds.

Thesis Supervisor: Dr. Joel P. Clark
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Acknowledgments

I would like to express my sincere gratitude to Professor Joel Clark for giving me the opportunity to work in the Material Systems Laboratory. I have been very fortunate to have him as my advisor and to support my entire stay at MIT.

I am also grateful to Dr. Frank Field for editing this thesis under stringent time constraints, and to Dr. Richard Roth for numerous helpful discussions and advice throughout this project.

My colleagues at the Materials Systems Laboratory have made my stay at MIT a truly enjoyable and rewarding experience. I would like to thank Luis German, Anil Jain, Randy Kirchain, J. Neely, Sam Newell, Elicia Maine, Deirdre Pettigrew, Paul Kang, and Brian Zuckermann for providing advice and support on all occasions.

I would also like to thank Simon Kragtwijk of Hoogovens and Ben Stokman of Automotive Tailored Blanks for arranging plant visits and providing information and advice.

Lastly, I wish to thank my parents for supporting me always, and my friends for encouragement in difficult times.

Table of Contents

Abstract 2
Acknowledgements 3
Table of Contents 4
List of Figures 6
List of Tables 7
1 Introduction 8
1.1 Automotive Industry and Technological Progress 8
1.2 Lightweighting Solutions for the Body-In-White 12
1.2.1 Material Selection 12
1.2.2 Design Innovations 14
1.2.3 Advanced Manufacturing Technologies 16
2 Problem Statement 19
3 Tailor Welded Blank Technology 21
3.1 Laser Beam Welding 22
3.1.1 Laser Beam Weldability–Steel vs. Aluminum 25
3.2 Mash Seam Resistance Welding 26
3.3 Welding Systems in Tailored Blanking 28
3.4 Properties of Tailor Welded Blanks 31
3.5 Developments in Tailor Welded Blank Technology 32
4 Review of Technical Cost Modeling 34
5 Description of Technical Cost Modeling 36
5.1 General Outline 36
5.2 Blanking 37
5.3 Laser Welding 38
5.4 Mash Seam Welding 43
5.5 Forming and Trimming 46
6 Manufacturing Case Studies 47
6.1 General Data 47
6.2 Front Door Inner 48
6.3 Rear Rail Inner 52

6.4 Body Side Outer 56
6.5 Production Parameter Sensitivity 60
7 Summary and Conclusions 65
8 Future Work 68
References 69
Appendix 1 75

List of Figures

Figure 1: Progression of CAFE Standards.......... 10
Figure 2: Attributes on which Automobile Body Materials Impact.......... 12
Figure 3: Potential Advantages of Tailor Welded Blank Technology.......... 17
Figure 4: Keyhole Laser Beam Welding Process.......... 22
Figure 5: Mash Seam Resistance Welding Process.......... 27
Figure 6: Schematic Diagram of Tailored Blanking Model.......... 37
Figure 7: Operations Generally Integrated in CO_2 Laser Welding Systems.......... 38
Figure 8: Operations Generally Included in Mash Seam Welding Systems.......... 43
Figure 9: Front Door Inner – Steel Conventional Design.......... 48
Figure 10: Front Door Inner – Steel Tailored Blank Design.......... 49
Figure 11: Rear Rail Inner – Alternative Steel Designs.......... 53
Figure 12: Body Side Outer – Steel Conventional Design.......... 57
Figure 13: Body Side Outer – Steel Alternative Design.......... 57
Figure 14: Steel Body Side Cost as a Function of Annual Production Volume.......... 61
Figure 15: Steel Body Side Cost as a Function of Welding Equipment Cost.......... 62
Figure 16: Steel Body Side Cost as a Function of Welding Speed.......... 63
Figure 17: Steel Body Side Cost as a Function of Setup Time.......... 64

List of Tables

Table 1: Features of Laser Welding Systems........ 39
Table 2: Features of Mash Seam Welding System........ 44
Table 3: Front Door Inner – Costs of Alternative Steel Designs........ 50
Table 4: Front Door Inner – Costs of Alternative Aluminum Designs........ 50
Table 5: Rear Rail Inner – Costs of Alternative Steel Designs........ 54
Table 6: Rear Rail Inner – Costs of Alternative Aluminum Designs........ 54
Table 7: Body Side Outer – Costs of Alternative Steel Designs........ 59
Table 8: Body Side Outer – Costs of Alternative Aluminum Designs........ 60

CHAPTER 1 INTRODUCTION

1.1 Automotive Industry and Technological Progress

The automobile has during its hundred-year-long existence undergone a variety of technological stages. In the past decades, the technical changes have mainly focused on gradual improvements, a typical example being the substitution of plastics for metals in interior and exterior parts. More profound technological improvements in the automobile include the recent introduction of electronic fuel injection, catalytic converters, and four-wheel drive and steering. However, technological progress is an ongoing concern for automotive manufacturers and the trend is likely to continue for different reasons. [Seiffert, 1991]

First, the intense international competition between automotive manufacturers has been a driving force for technological changes. The automobile industry experienced rapid growth in the developed countries in the past. At present, the demand for new vehicles is expected to increase only approximately 1% annually, which has intensified competition over the market shares. In North America, for instance, the Big Three automakers, General Motors, Ford, and Chrysler, dominated the automobile market until the 1980's, but have since then gradually lost market share, predominantly to Japanese and European manufacturers. The automotive industry is, however, forecast to grow constantly in developing countries with large market expectations emerging in nations such as China, Indonesia, Taiwan, and Thailand. [Riley, 1994] The fierce competition forces automotive manufacturers to consider every potential strategy that would enable them to capture global market shares. Technological innovations are one solution by which automakers can gain competitive advantage over rivaling companies.

Second, the automobile market has become a largely customer-oriented one, in which consumer preferences have a strong impact on technical developments. Although desired vehicle features are increasingly diversified, most consumers would prefer improvements in fuel efficiency, performance, safety, and comfort at the lowest possible vehicle price. Automakers are challenged to meet these often contradictory customer demands. [Seiffert, 1991]

Third, environmental standards and safety mandates direct a large part of technological changes in the automobile. In the U.S., the principal environmental regulations concerning the automotive industry are the federal Corporate Average Fuel Economy (CAFE) standards and Clean Air Act requirements. [Brown, 1995] For instance, the CAFE policy requires all major manufacturers selling automobiles in the United States to achieve fuel efficiency standards (miles per gallon, mpg) for their passenger vehicle fleets. Minimum acceptable CAFE standards were increased incrementally to 27.5 mpg (12 km/l) for passenger cars, but under intense lobbying pressures by the automotive manufacturers, the requirements have maintained the same since 1990. Even though the fuel economy of automobiles has increased measurably since the enforcement of CAFE regulations, the effectiveness of the CAFE policy has recently been questioned. [Kirby, 1995] [Conner, 1997]

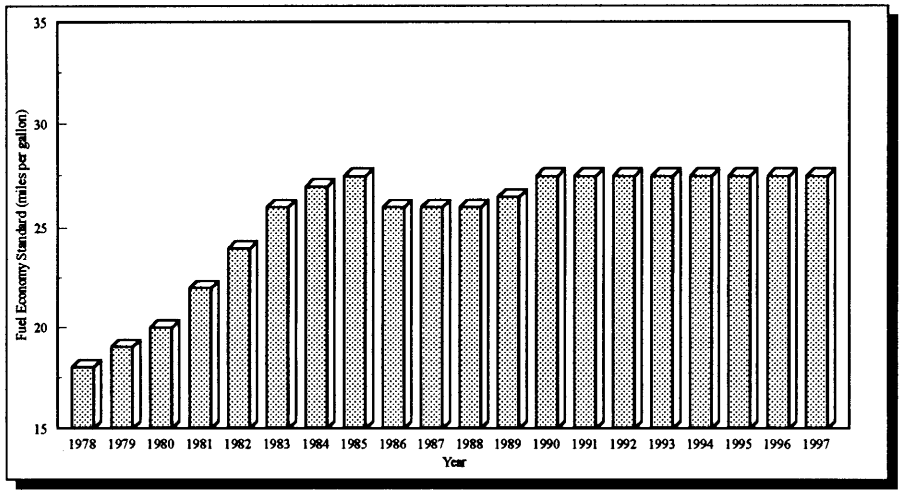

Figure 1. Progression of CAFE Standards.

The first attempts to improve fuel efficiency concentrated on simplifying and downsizing automobiles. At present, a variety of new features related to, for example, safety are demanded either in legislation or by consumers. These improved characteristics often add weight, leading to difficulties in meeting the required CAFE levels. [Brown, 1995] Thus, automotive manufacturers have recognized that in order to meet potentially stricter fuel consumption and environmental regulations in the future, more radical improvements have to be implemented.

The need for a more comprehensive approach for integrating environmental issues and vehicle development led the federal government to form together with the U.S. automakers a research and development program, the Partnership for a New Generation of Vehicles (PNGV), which focuses on improving fuel economy among other issues. The goal of the project is to develop an affordable, medium-sized vehicle that could achieve up to three times the fuel efficiency compared to 1994 family sedans. This would result in fuel economy as high as 80 mpg or 35 km/l in prototype vehicles that should be developed by 2004. To accomplish this, most of the research to date has focused on improving drivetrain efficiency, developing energy storage systems, and reducing vehicle weight. [Anon., 1996b] Lightweighting has an especially important role since a vehicle's energy usage is directly related to its mass. It is generally estimated that a 10% weight reduction results in 6 to 10% savings in fuel consumption. [Hayashi, 1995]

A number of weight reduction studies focus on the automobile body-in-white (BIW). The BIW consists of the load-bearing structures and exterior panels, generally representing a substantial part of a vehicle's mass, approximately 25 to 30%. [Bleck, 1996] Primary weight savings in the BIW also enable the downsizing of other components in the automobile. This so-called secondary weight saving can be significant without affecting vehicle performance. In many respects, lightweighting the BIW structures is of the utmost importance for fuel economy improvements. [Field, 1997] Mass savings in the BIW are feasible through various technological changes, including the use of alternative materials, design improvements, and advanced manufacturing techniques.

1.2 Lightweighting Solutions for the Body-In-White

1.2.1 Material Selection

The materials selected for body structures affect directly a variety of vehicle factors including the cost, design, manufacture, structural performance, and environmental impact of the BIW (Figure 2). Most vehicles are still built using a steel unibody structure which is assembled largely or entirely from stamped sheet components. Steel has been the primary material of choice for car bodies because it has several advantages regarding most of the categories in Figure 2. [Bleck, 1996]

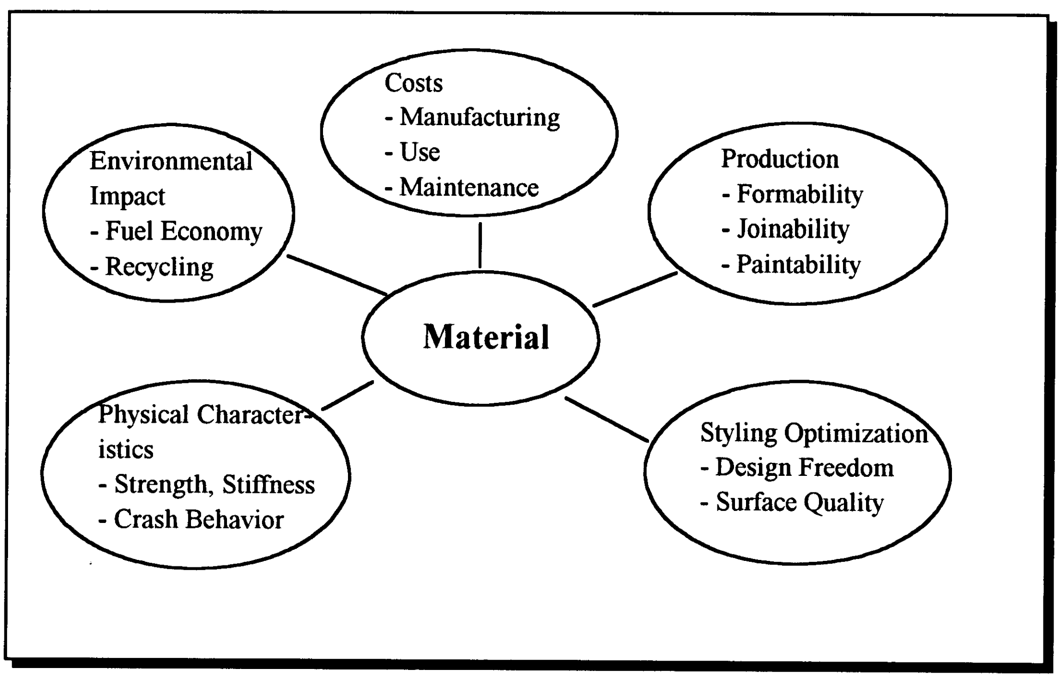

Figure 2. Attributes on which Automobile Body Materials Impact (based on: Bleck, 1996).

A major disadvantage of a conventional steel unibody is its high weight, which is on the order of 300 to 360 kg (650 to 800 lbs.) for sedans. [Read, 1995] Current efforts to decrease the weight of steel-based vehicles include the UltraLight Steel Auto Body (ULSAB) program by an international consortium of steelmakers. The goal of Phase I of the program was to design a steel body structure for a medium-sized passenger car with a minimum weight reduction of 20%, compared with the benchmark vehicles. The mass saving targets were realized through the increased use of high-strength steels and advanced manufacturing methods combined with design innovations. [Crooks, 1996]

Relative to mild steels, high-strength steels allow the use of thinner gauges while meeting structural performance requirements. However, the reduced plastic formability of high-strength steels limits their lightweighting capabilities, and further weight savings are achievable only if alternative materials are considered. [Tuler, 1996] Aluminum alloys and plastic composites are the lightweight materials that are currently evaluated or used to substitute for steel in vehicle bodies. Although some automotive manufacturers have experimented with plastics in body panels, aluminum alloys have so far shown more potential in structural BIW applications. [Field, 1997]

Compared to steel, aluminum can have similar strength values, but since its density is significantly lower (approximately 2.7 g/cm^3 vs. steel's 7.8 g/cm^3), aluminum possesses higher strength-to-weight ratios. A disadvantage is aluminum's lower modulus of elasticity which necessitates to use thicker aluminum gauges in order to achieve equivalent stiffness properties. Still, depending on the application, weight savings up to 50% are achievable with aluminum. [Tuler, 1996] The utilization of the lightweight materials has generally been limited to attached parts, such as hoods, doors, and deck lids, but recently there have been numerous efforts to expand especially the use of aluminum in BIW applications. [Brown, 1995]

1.2.2 Design Innovations

Since the 1980's, a number of automakers have, in close cooperation with material suppliers, produced aluminum intensive vehicles using two design approaches. First, the conventional steel unibody designs have been converted into all-aluminum body-in-whites through part-to-part substitutions. The stamped aluminum parts, although thicker than their steel counterparts, can yield substantial weight savings. An example of this concept is the Honda Acura NSX sportscar in which the weight of the aluminum BIW is 210 kg or 40% lighter than its theoretical steel-sheet equivalent. [Koewius, 1994]

More recently, Ford has developed a prototype of a medium-sized vehicle with a stamped aluminum unibody, the P2000. Due to the extensive use of aluminum and other lightweight materials in the P2000, its total weight is approximately 900 kg or about 40% less compared to the 1997 Ford Taurus and its weight of 1500 kg. [Anon., 1997] This innovative aluminum design is eventually targeted for high volume production, although the current prototype is estimated to be thousands of dollars more expensive to manufacture than the Ford Taurus. [Simison, 1997]

Another design approach for aluminum is the spaceframe technology, which exploits the excellent formability of aluminum, enabling better utilization of the potentials of aluminum in lightweighting of the BIW. Contrary to the unibody with all-stamped parts, the predominant load-bearing structure in aluminum spaceframe designs consists of extrusions joined together by cast nodes. Stampings are used to complete the design, forming the floor and exterior panels. The spaceframe concept yields BIW weights that are in the order of 130 to 175 kg (285 to 385 lbs.). [Politis, 1995] The Audi A8, GM EV1 electric vehicle, and Renault Spider sports car are examples of current production vehicles with spaceframes. [Brown, 1995] [Anon., 1995c] [Buchholz, 1996]

The different production vehicles and prototypes mentioned above have demonstrated the capabilities of the intensive use of aluminum in the BIW lightweighting. However, this usually results in a cost penalty because of the higher material and processing costs compared to all-steel bodies. [Tuler, 1995] [Anon., 1996a] First, the automotive aluminum sheet is significantly more expensive: the cost today is approximately $1.50 per pound versus $0.30 per pound for steel sheet. Also, automotive manufacturers have extensive technical experience on the stamping of steel, an important factor in the manufacturing cost differences between aluminum and steel unibodies. In the spaceframe technology, extrusion increases production costs due to slow processing rates and additional process steps required for extruded parts. Despite the generally higher manufacturing costs of aluminum designs, the difference in the raw material cost is still the main reason why the use of aluminum in holistic BIW designs has so far been limited only to niche market, low-volume vehicles. [Field, 1997]

1.2.3 Advanced Manufacturing Technologies

Conventional automobile bodies consist of a large number of parts, approximately 200, produced by stamping from different materials, thicknesses, coatings, and geometries. [Mombo-Caristan, 1992] Reducing the number of BIW parts can result in substantial weight savings and, thus, it is currently pursued by combining advanced manufacturing techniques with BIW design innovations. For instance, the use of a relatively unexploited processing method, extrusion, allows the integration and elimination of parts in aluminum spaceframe designs which, thus, require typically less than 100 extrusions, stampings, and cast nodes. [Politis, 1995] [Anon., 1992a]

In addition to lightweighting, the consolidation of BIW parts can lead to various cost savings. Tailor welded blank (TWB) technology and hydroforming are examples of manufacturing techniques that were developed to integrate parts and, potentially, reduce production costs especially in steel body structures. Tailor welded blanks are produced by welding individual flat metal sheets into one composite part before pressing. This technique enables optimizing the structural and corrosion properties in different areas of the finished part. [Mombo-Caristan, 1992]

During hydroforming process, metal tubes are formed into complex-shaped hollow components under high internal pressure in a shaping die. This technology offers the structural advantages of tubular parts with the shape flexibility of stamped assemblies. [Zotkovich, 1997] While hydroforming applications are still relatively rare in the automotive industry, tailored blanking is becoming an established technology due to various cost saving opportunities and technological improvements that may be related to the applications (Figure 3). [Prange, 1995]

Cost Savings	Technological Improvements
Material	Weight reduction
Capital investment	Improved structural performance
- tooling	Improved corrosion resistance
- blanking and stamping presses	Sealing unnecessary
- assembly	Improved dimensional accuracy
Labor	
Variable costs	
Logistics	
Indirect costs	

Figure 3. Potential Advantages of Tailor Welded Blank Technology.

In addition to weight savings, tailor welded blank technology generally improves material utilization. Part integration eliminates production steps in press shop and assembly and, thus, arguably reduces capital investments as well as personnel and variable costs. Also, tailored blanking may involve additional cost savings in material handling and in other, less directly related operations of production. Possible technological improvements include increased dimensional accuracy of components, and improved structural and corrosion properties due to continuous welds in tailored blanks compared to ordinary stampings assembled by spot welding. [Prange, 1995]

First tailored blanks were produced in the 1980's in Germany and Japan. [Irving, 1995] Various TWB car body applications today in production include door inner panels, pillars, motor compartment rails, body side panels, bumpers, floor pans, deck lids, wheel houses, and shock towers. [Prange, 1995] Up to eleven tailor welded parts per car are being used at present but the number is expected to increase especially in unibody designs, which are based on stamped sheet components. For example, the recent lightweight steel BIW design, the ULSAB, included a total of 18 tailored blanks. [Yang, 1995] [Corrodi, 1996]

The 1997 projection for the market size of tailored blanks was estimated to be 13 million blanks per year in the U.S., and approximately 40 million blanks for European market. However, the capabilities of this technology have not been fully utilized since, for instance, the forecast for the U.S. market represents only 10% of the potential applications. In Europe the market is expected to grow even faster as most car manufacturers are planning to use tailored blanks in future vehicles. [Van der Hoeven, 1994] [Van der Hoeven, 1995]

CHAPTER 2   PROBLEM STATEMENT

Since the development of tailored blanking in the 1980's, automotive manufacturers have gained experience on this technology through different BIW applications. The majority of current and pending applications are simple two-piece steel blanks, joined together using either laser welding or mash seam resistance welding. [Anon., 1996c] In most cases, tailored blanks have proved to be advantageous over conventional designs, which has encouraged automotive manufacturers to further investigate the capabilities of this technology for reducing the weight and cost of the body-in-white.

At present, some automakers are experimenting with more complex designs such as multi-weld body sides and shock towers with circular welds. The concept of aluminum tailor welded blanks has been introduced along with increasing use of aluminum in the automotive industry. There have also been research efforts focusing on alternative welding technologies, such as induction welding and electron beam welding, and on their applicability in tailored blanking. [Irving, 1995] [Van der Hoeven, 1996]

When considering tailor welded blank technology for body-in-white parts, the economic feasibility of potential applications has to be determined and compared to conventional designs. Because of the increasing flexibility in sophistication of this technology, an economic analysis of a new design can be arduous without a methodology that could provide a consistent means for analyzing the cost effects of alternative designs and production processes. Technical cost modeling is an established method that has been used extensively to assess, for instance, the cost impacts of material and process changes on automotive body-in-white structures. [Arnold, 1989] [Han, 1994]

The objective of this thesis is to investigate the economics of tailored blanking by developing a technical cost model for this technology. The goal is to create a model that automobile manufacturers could use for conducting realistic manufacturing cost analyses of different tailored blank designs. To provide flexibility, the model will include material and welding process alternatives that are currently used or considered for the production applications. In order to demonstrate the applicability of the model, the manufacturing costs of various steel and aluminum body-in-white components will be examined. The overall purpose of the analysis is to contrast the cost differences of welding systems used in tailored blanking and to identify potential economic benefits of tailored blanks over conventional stamped parts through the utilization of the model.

CHAPTER 3 TAILOR WELDED BLANK TECHNOLOGY

The successful implementation of tailor welded blank technology requires careful consideration and control of the entire production process. Especially critical is the welding operation since it influences the formability, structural performance, surface appearance, corrosion resistance, and cost of tailored blanks. The selected joining process must produce consistently high quality welds that can withstand the rigorous press forming operations that follow it. Currently, the prevalent welding technologies in tailored blanking are laser welding and mash seam resistance welding, although other joining methods are also considered.

Laser welding has been the process of choice for tailored blanking in the U.S. and in Japan, while in Europe the first tailor welded blanks were produced by mash seam welding. Mash seam technology dominated early applications because it appeared to be less expensive in terms of initial and operating costs. It still is a somewhat more favored joining process, but lately European automakers and blank suppliers have shown increasing interest in employing laser welding for TWBs. For the near future, both welding processes are expected to be used, complementing each other depending on the application. [Irving, 1994] [Baron, 1994]

3.1 Laser Beam Welding

Laser beam welding is a non-contact, fusion welding procedure. The physical properties of a laser beam, coherent light of a fixed wavelength, allow the focusing of the beam to a small area with energy densities over 10^6 W/in^2. The energy density of the impinging beam is so intense that it causes the metal surface to melt and vaporize, resulting in the formation of a deep cavity or so-called keyhole, surrounded by a thin cylinder of molten metal (Figure 4). As the keyhole moves, the molten metal flows in the opposite direction and forms a weld zone on rapid solidification. [Anon., 1991]

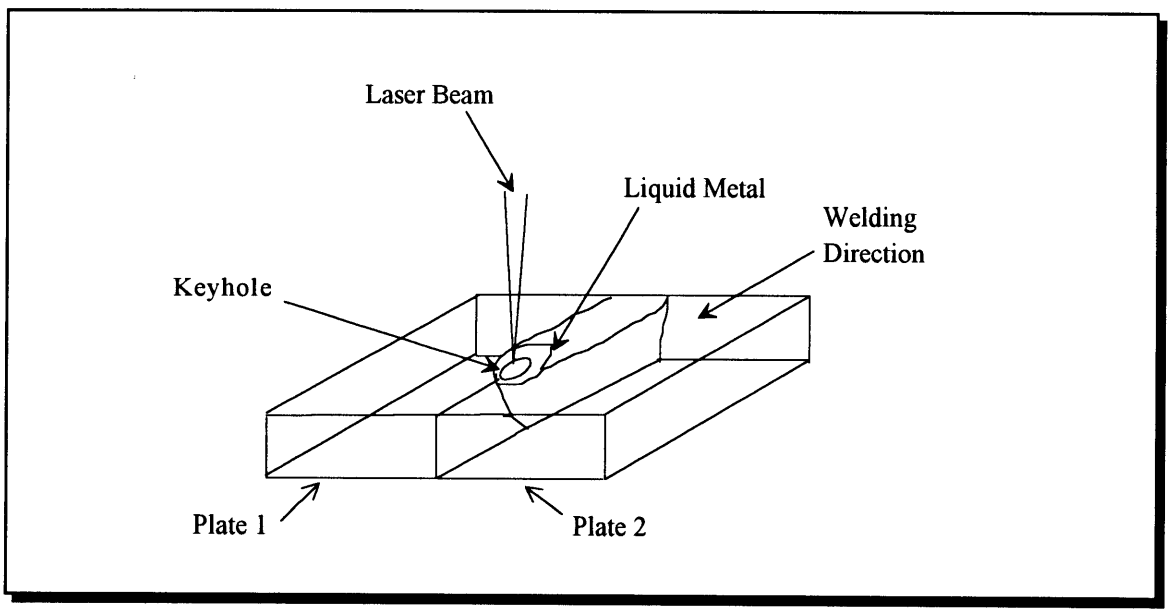

Figure 4. Keyhole Laser Beam Welding Process.

The high travel speed and low heat input associated with keyhole laser welding produce narrow, deep-penetration welds with minimal distortions. For the steel sheet thicknesses encountered in automotive body structures, for instance, the laser weld widths are within the 0.5 to 1.5 mm range. [Baysore, 1995] The shielding gases typically used in laser welding are helium and argon mixtures of various compositions. In contrast with many arc welding processes, filler metal use is generally unnecessary, but if large amounts of alloying elements are vaporized during welding, it may be needed to ensure adequate mechanical properties in the weld. [Mazumder, 1993a]

The two most common types of lasers in welding applications are the CO_2 gas laser and Nd:YAG (Neodymium-Yttrium Aluminum Garnet) solid state laser. A major difference between these lasers is the beam wavelength, which is 10.6 μm for CO_2 and 1.06 μm for Nd:YAG laser. The development of high-power continuous-wave CO_2 (output powers up to 14 kW) and Nd:YAG (output powers over 3 kW) laser sources has greatly eased the implementation of laser welding. [Roessler, 1996] Most of the high speed and deep penetration welding has been carried out with CO_2 lasers, which have been more reliable and powerful compared to Nd:YAG systems. Nd:YAG lasers, however, are more flexible since these systems allow the laser beam to be delivered through fiber optic cables due to shorter wavelength. This is especially advantageous in three-dimensional welding such as in welding of body contours or in the assembly of the body-in-white. [Ishihara, 1994]

A typical laser welding system in tailored blanking employs a 6 kW CO_2 laser which can process the lightest gauges of bare steel blanks at approximately 10 m per minute. However, the welding speeds can be significantly lower with thicker blanks: for instance, travel speed has to be reduced to about 5 m per minute when joining 1.5 mm and 2 mm thick steel blanks. [Irving, 1994] In Nd:YAG laser welding the processing rates are generally somewhat lower because of the limited power levels (2 to 4 kW) currently available. A 2 kW Nd:YAG laser can produce average travel speeds of 4 m per minute, depending on the material type and thickness. [Sajatovic, 1996]

The main limitation in laser welding is the requirement for precise part fit-up and alignment due to the small focus of laser beam. Less than precise edges can be laser welded with the addition of beam weaving or filler metal, but the subsequent welding speed and process tolerance penalties may be severe and, thus, laser welding is generally performed without filler wire or beam weaving. [Prange, 1995]

The introduction of laser welding technology has also been restricted by the expensive equipment cost, which can be almost ten times that of comparable arc welding systems. However, laser welding generally increases productivity beyond the capabilities of conventional welding processes such as gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW). The throughput is higher mainly because of the faster welding speed but also due to the possibility to share laser beam between separate welding stations. Because of the numerous advantages of laser welding–low product cycle times, narrow welds, and good mechanical properties–it has become a competitive joining method for automotive applications. [Mazumder, 1993a]

3.1.1 Laser Beam Weldability–Steel vs. Aluminum

Laser beam welding can be used for joining most metals to themselves as well as dissimilar metals that are metallurgically compatible. Low carbon steels normally used in vehicle body-in-white parts are readily weldable, but carbon content exceeding 0.25% can cause weld cracking. [Anon., 1991] Considerable advances have also been made in improving laser welding process performance for both heat-treatable (2000 and 6000 series) and non-heat-treatable (5000 series) aluminum alloys that are being proposed for automotive applications. Laser welding has proved to be feasible for aluminum, although the specific thermophysical and optical characteristics cause aluminum to be more complex to laser weld than steel. [Jones, 1992] [Jones, 1995] [Venkat, 1997]

A major problem associated with laser welding of aluminum is its high reflectivity which complicates the initiation of the weld pool particularly in CO_2 laser welding. The shorter wavelength of Nd:YAG lasers is in this respect advantageous since it has 15 to 20% better beam coupling efficiency than the CO_2 laser light. [Stafford, 1996] Compared to low carbon steel, the thermal conductivity of aluminum is approximately four times higher and, thus, aluminum alloys require larger heat inputs during welding. [Anon., 1996a] However, high heat inputs increase weld crack sensitivity, which is already of concern due to aluminum's relatively high thermal expansion and large volume change upon solidification. Furthermore, the oxide surface layer inherent to all aluminum alloys and aluminum's high solubility for hydrogen in the molten state can cause weld porosity. Finally, some alloying elements, such as magnesium, evaporate readily from the keyhole deteriorating strength properties especially in non-heat-treatable aluminum alloys. [Yoshikawa, 1995] [Jones, 1996]

Although laser beam welding of aluminum alloys is complicated by the above mentioned factors, it can be performed with suitable precautions. The primary method for eliminating cracking in aluminum welds is to control the composition of weld metal through proper filler metal addition. Weld crack sensitivity can be reduced further by limiting heat input and, thus, high welding speeds are preferable in laser welding of aluminum alloys. High processing speeds are also beneficial in minimizing the loss of alloying elements, which, alternatively, can be compensated by using a filler metal overalloyed with the critical element. To avoid porosity in aluminum welds, the oxide layer has to be mechanically or chemically removed prior to welding and shielding gas rates should be adequate during welding process. [Thorstensen, 1989] Overall, the parameter range for achieving repeatedly good quality welds is more restricted for aluminum and, thus, the laser welding process must be controlled more closely than with steel. [Ostermann, 1993] [Glagola, 1996]

3.2 Mash Seam Resistance Welding

Mash seam resistance welding is a joining process in which heat generated by resistance to the flow of electric current in the base metal is combined with high-temperature plastic forming to produce a welded seam (Figure 5). Rotating electrode wheels are used to apply a high current and high force on the sheets to be joined, which are overlapped by a minimum amount, approximately one to two times the sheet thickness. The weld area is forged during welding, which results in a weld that is 5 to 25% thicker than a single sheet thickness and has a wider weld and heat-affected zone (HAZ) than a laser weld. [Karagoulis, 1993] [Baron, 1994]

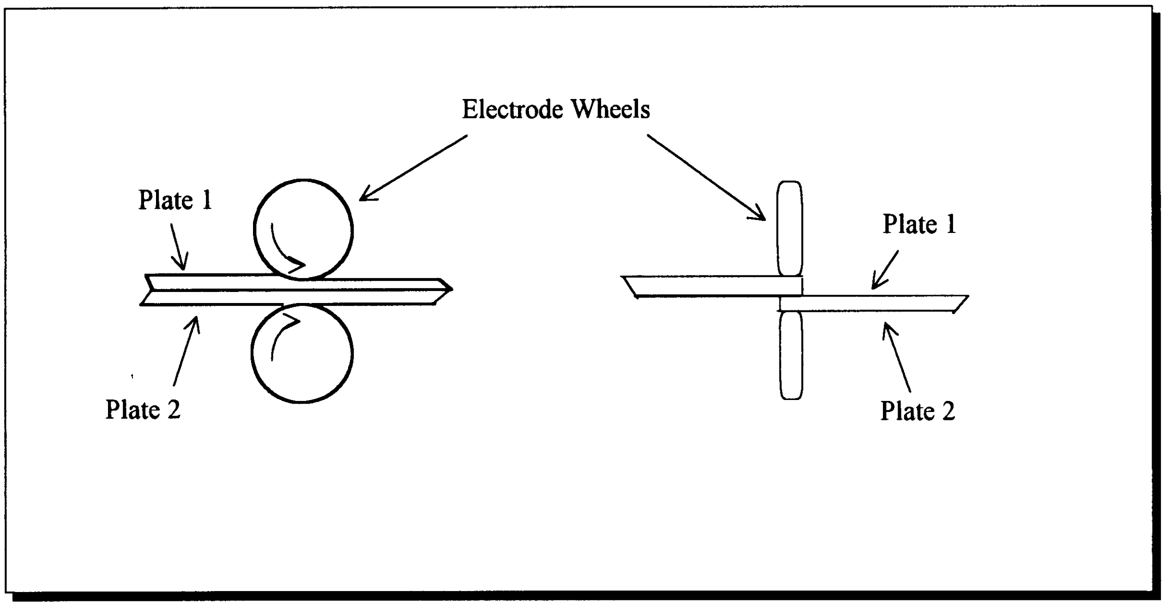

Figure 5. Mash Seam Resistance Welding Process.

Mash seam welding is suitable for different blank thickness combinations if the thickness ratio does not exceed 2.5:1 for uncoated materials and 2.0:1 for coated sheets. [Geiermann, 1995] Typical coating processes used for steel sheets are electrogalvanizing, galvannealing, and hot-dip galvanizing which produce zinc coatings with different thicknesses. These metallic coatings do not disrupt mash seam welding process but they can change the welding parameters. The main difficulty in mash seam welding of zinc coated steels is the alloying of copper electrodes with zinc. This affects detrimentally the electrode/sheet contact resistance and, thus, the electrode wheels require frequent maintenance to remove the zinc layer. Thick zinc coatings, especially hot-dipped galvanize, also slow the welding speed and reduce the process tolerances. [Prange, 1995] [Geiermann, 1995]

The primary advantage of mash seam welding is that the quality of normal sheared or blanked edges is adequate because of the sheet overlap and, thus, an additional edge preparation is not needed as in laser welding. However, the workpieces must be rigidly clamped or tack welded to prevent weld distortion. Coated steels are generally more weldable using seam welding than laser welding because coating volatility is minimized due to the high forces applied onto the weld zone. Furthermore, mash seam process can be performed at welding speeds similar to laser welding, but mash seam welding is not suitable for joining of aluminum blanks due to the narrow plastic range of aluminum alloys. [Karagoulis, 1993]

3.3 Welding Systems in Tailored Blanking

In order to be a cost-effective manufacturing method in the automotive industry, a welding system must produce reliably good quality welds at different production rates, despite whether laser welding or mash seam welding is used. This requires certain features from the welding line, including a modular design which adapts readily to various capacity demands, flexibility to process different blank shapes, and on-line process control for minimum rejects. [Corrodi, 1996] The welding systems used in the production of tailored blanks have somewhat diverse capabilities in these respects and, thus, the most suitable system may vary from application to application.

The majority of current laser welding systems are based on one-axis, 6 kW CO_2 lasers with fixed or moving optics. These systems are optimal for manufacturing blanks with only one weld, typical examples being rails and columns. Lasers with moving optics are also effective for in-line welds since they can rapidly traverse in one axis. Furthermore, some systems are capable of processing multiple blanks in one setup provided they fit within the range of the clamping table. A more complex design, such as a blank with multiple parallel or non-parallel welds, can be produced either by adding welding stations (parallel or serial) or by increasing the number of operations. [Anon., 1996c]

In addition to the different one-axis CO_2 systems, Toyota in Japan has developed welding installations around a two-axis laser gantry system. Two-axis laser systems enables parts with multiple welds in any orientation to be processed in a single setup. With this type of system, a tailored blank design is only limited by the maximum dimensions of the gantry and jig system since the position of each weld can easily be modified to improve the properties of a blank. [Van der Hoeven, 1996]

The higher cost, lower welding speed, and unreliability of Nd:YAG laser welding, as compared to CO_2 lasers, has so far prohibited its implementation in tailored blanking. The recent efforts to lower the cost and to increase output powers of Nd:YAG lasers are expected to enhance their use in welding applications and also in tailored blanking, where Nd:YAG laser welding systems could be especially beneficial in joining of aluminum applications and complex tailored blanks. [Stasik, 1996] [Sajatovic, 1996]

Mash seam welding systems are available in two basic configurations: fixed clamp with moving welder or moving clamp with fixed welder. The system with moving welder has lower capital costs, but its suitability is limited to lower volume components. Advantages of the fixed welder design are higher throughput and the capability to process large tailored blanks. As with one-axis laser systems, mash seam welders are most effective for single continuous welds or for in-line welds. Also, the most common systems allow for multiple blanks with short welds to be processed in one setup. A tailored blank with more than one welds can be joined by using two mash seam welders or by increasing the number of operations at one welding station. [Geiermann, 1995]

The capability to share laser beam between multiple work stations enables users of laser welding systems to expand gradually with increasing production needs. The mash seam process is less flexible in this respect since the welding equipment is dedicated to one mash seam welding system. So, if the demand exceeds the maximum capacity of one mash seam production line, a second welder has to be installed.

Besides the welding operation itself, the production lines of tailored blank may include a number of associated processes. In laser welding, for instance, the blanks require precision shearing before welding, while in mash seam welding this is unnecessary since the overlapping sheets allow larger edge tolerances. An additional process related only to mash seam technology is mechanical planishing, which can be performed after welding to improve surface appearance of welds. Laser and mash seam welding systems may also include weld seam cleaning and oiling, dimpling, and part numbering. The material handling (i.e., the transfer of blanks between different modules in the welding system) is often fully automated with pallet conveyors, destackers, restackers, robot loaders/unloaders, and magnetic conveyor systems, but it can also be carried out manually if production volumes are low. [Geiermann, 1995] [Carter, 1996]

3.4 Properties of Tailor Welded Blanks

As described in sections 3.1 and 3.2, laser welding and mash seam welding are two distinctly different joining technologies. Thus, it can be expected that these welding processes lead to significant variances in performance characteristics such as formability, mechanical properties, corrosion resistance, and surface appearance of tailored blanks. The main reason for the different blank properties is the weld geometry; laser welding with butt joints seems to be more favorable in some applications compared to overlapped joints in mash seam welding. For example, laser welding is generally preferred in exterior panels due to better appearance quality, although laser welds may also require rework in order to meet the surface finish requirements. [Baron, 1994] [Waddell, 1995]

Many of the problems related to the introduction of tailor welded blank technology concern the formability which is affected, among other factors, by the material chosen for blanks. Compared to carbon steels, the use of high-strength steels and aluminum alloys can cause more problems during press forming since the overall formability of these materials is inferior to mild steels. [Hayashi, 1994] Moreover, the dissimilar sheet thicknesses and different strength properties between the weld zone and the surrounding base metal limit the formability in tailored blanks. Comparing mash seam welding and laser welding, it seems that the latter joining technology is superior for multi-gauge blanks.

Although laser welds have higher hardness, the wider weld zone and the larger thickness increase related to mash seam welding generally inhibit the formability. This may not be as critical in simple body applications as it is for more complex parts involving highly formed areas, such as wheel houses, floor panels or body side panels. [Prange, 1992]

Corrosion resistance is another important feature of tailored blanks since many potential applications are lower body panels which are more exposed to corrosive substances. The corrosion performance is, in part, a function of the width of the weld fusion zone: the narrow laser welds (less than 2 mm) typically achieved in automotive steel sheets exhibit superior corrosion resistance to wider mash seam welds (5 to 6 mm). [Roudabush, 1993] In zinc coated steels, for instance, the adjacent zinc should provide adequate galvanic protection to the weld metal as long as the affected area is limited to about 2 mm. Since mash seam welds typically exceed this width, the sacrificial corrosion protection of zinc coating may be insufficient for some mash seam welded vehicle body components. [Waddell, 1995] [Prange, 1995] [Lee, 1996]

3.5 Developments in Tailor Welded Blank Technology

At present, tailor welded blanks with linear laser welds are a well established technology in the automotive industry. However, linear welding limits mass reduction opportunities in tailored blanking and in some cases there may even be a risk of adding weight depending on the design. To further optimize the properties of tailored blanks, automobile manufacturers have expressed interest in applying non-linear welding in laser welded blanks. Non-linear laser welds have shown potential for door inner panels and body side panels, for example, but compared to linear laser process, the implementation may be unfeasible because of the following reasons. First, clamping and positioning of blanks is more critical during the production of non-linear weld seams. Second, the formability must be thoroughly investigated and modeled prior to production since the forming behavior is unique for each non-linear design. Finally, manufacturing costs may be higher due to the increased part complexity and equipment costs. [Van der Hoeven, 1995] [Van der Hoeven, 1996] [Jansen, 1996]

With increasing experience on tailor welded blank technology, manufacturers are also starting to consider additional joining processes to laser welding and mash seam welding. High frequency induction welding, non-vacuum electron beam welding, and GTA welding are among the technologies that have been experimented, but only induction welding is currently used in the production of tailored blanks by one automotive manufacturer. Each of the new joining processes is claimed to have further advantages over laser welding and mash seam welding while resulting in comparable weld quality. [Prange, 1995] [LaFlamme, 1996] [Glagola, 1996]

CHAPTER 4 REVIEW OF TECHNICAL COST MODELING

The manufacturing costs of a product can be derived with several cost analysis techniques. A common approach is to use different rules of thumb to give rough estimates. In one of the most typical methods the material cost is multiplied by a fixed, industry specific factor. Other, somewhat more elaborate methods utilize accounting data in order to allocate the manufacturing costs for all the parts produced. For instance, a so-called machine rent cost can be calculated by summing the capital, energy, and labor costs that occur when production equipment is operated, and dividing it by the time used to manufacture parts. Both rules of thumb and accounting methods have a number of weaknesses, including the fact that they are based on past experience and data. This limits their usefulness when the cost implications of alternative designs and processing technologies are of interest.

In contrast, technical cost modeling is a systematic methodology specifically developed to enable detailed manufacturing cost estimates and analyses on the interactions between process variable changes and the part cost. The approach used in technical cost modeling is to treat each process step as an individual operation. Also, the processing costs are calculated separately for different variable and fixed cost elements, the concept of which is widely used in accounting. The variable costs represent expenses that vary as a function of production volume, including:

- Material Cost,
- Direct Labor Cost,
- Energy Cost.

The fixed costs are defined as cost elements that are independent of the production volume, i.e., these costs incur unaffected by changes in output. Technical cost modeling utilizes the following fixed cost elements:

- Main Machine Cost,
- Tooling Cost,
- Auxiliary Equipment Cost,
- Maintenance Cost,
- Overhead Cost,
- Building Cost.

Each cost element in variable and fixed cost categories is analyzed using empirical data, theoretical relationships, regression analysis, the physics of manufacturing processes as well as general economic factors. Intermediate calculations include typically estimates of equipment capacity, cycle time, and other processing variables.

The detailed nature of technical cost models enables analyses on the cost effects of design and production parameter changes. Also, the modular structure of cost models is beneficial for comparing alternative manufacturing schemes. The cost modeling approach is particularly useful for analyzing materials fabrication processes. Processing techniques modeled include stamping, sheet mold compounding, die casting, extrusion, powder forging, and injection molding, for instance. [Busch, 1987] [Han, 1988] [Nallicheri, 1990] [Neely, 1992] [Han, 1994] [Politis, 1995] More in depth discussions on technical cost modeling methodology have been covered in previous texts. [Poggiali, 1985] [Hendrichs, 1989] [Clark, 1997]

CHAPTER 5 DESCRIPTION OF TAILORED BLANKING MODEL

5.1 General Outline

The model developed for tailor welded blank technology is an extended version of the MSL stamping cost model which has existed in various formats for several years. The stamping cost model was originally developed to estimate the production costs of body-in-white parts made from individual metal blanks. The model consisted of two modules, one for blanking and one for forming and trimming operations. To capture the specific features for the production of tailor welded blanks, the stamping model was modified and completed with alternative joining process modules for laser welding and mash seam welding.

A schematic structure of the tailored blanking model is shown in Figure 6 (a complete version is in Appendix 1). The model requires general information on blank design, economic factors, and production parameters, which are applied to all manufacturing steps. The general economic and production variables include inputs for annual volume, direct wages, working hours per day, investment discount rate etc. Next, the user is requested to select the production steps for a manufacturing scheme and to give data on the process specific parameters. In the case of laser welding or mash seam welding, for instance, inputs for total weld length and number of parts per one setup are needed. Finally, the results are presented separately for each manufacturing process, categorizing the costs into variable and fixed cost elements. The following sections explain in detail the characteristics of the tailored blanking model.

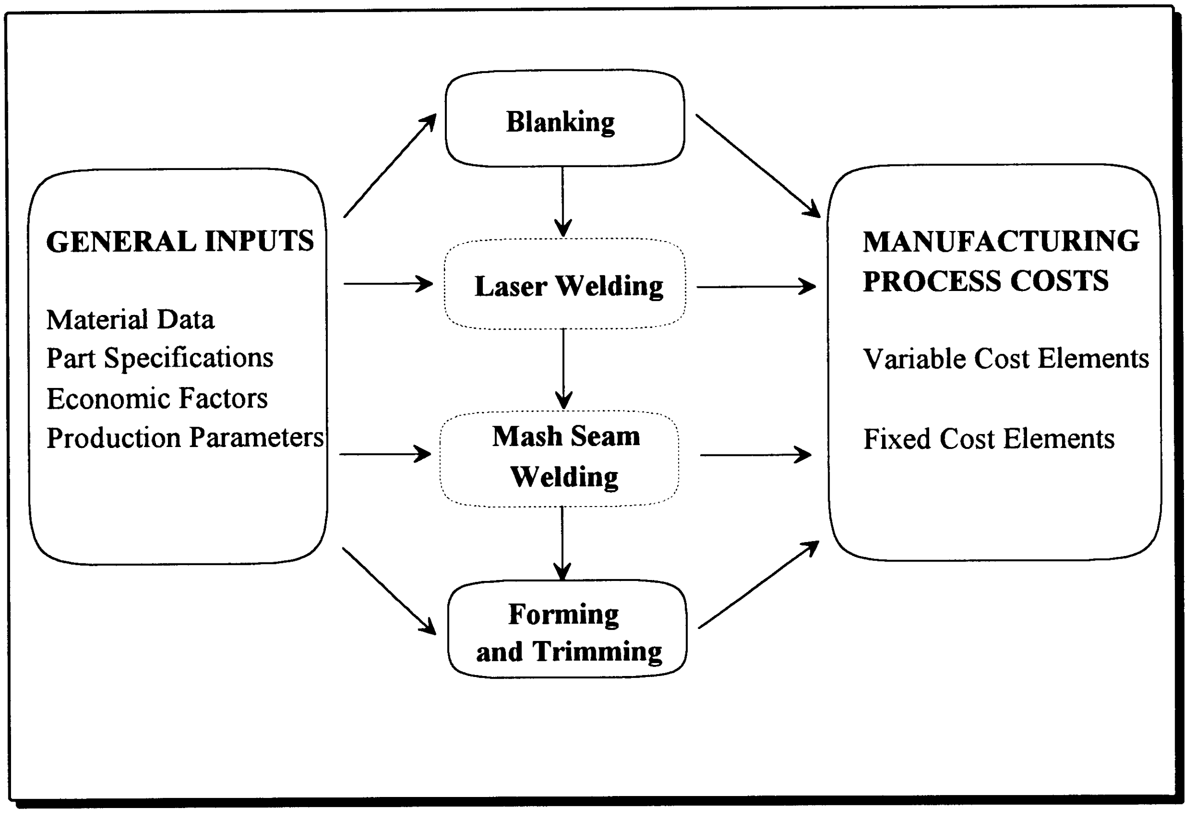

Figure 6. Schematic Diagram of Tailored Blanking Model.
Note: Laser welding and mash seam welding are alternative joining processes in the model.

5.2 Blanking

The first step in tailored blanking is to produce blanks, which are pieces of sheet metal that have been cut out of larger coils. The model has the options of performing blanking in-house or using an outside supplier. Automotive manufacturers rely often on out-sourcing if the capacity demand or blank specifications exceed the capabilities of in-house blanking facilities. The tailored blanking model was modified to adapt designs composed of up to eight blanks with different geometries, thicknesses, and strength properties. The majority of current tailored blank applications consist of only two pieces, but automotive manufacturers are increasingly interested in more complex designs and, thus, the capability to accommodate a larger number of blanks is a useful feature. Other calculations of the blanking operation, i.e. estimates for production rate, blanking press cost, power consumption, and building space requirement follow the formulas outlined by Hendrichs. [1989]

5.3 Laser Welding

Most North American and European automotive companies have indicated a preference for using outside suppliers in tailored blanking and particularly for blanking and welding operations. In contrast, Japanese manufacturers have installed several in-house manufacturing systems for producing tailored blanks. Besides the joining process itself, several related operations are typically integrated in welding lines as depicted in Figure 7 for laser welding systems.

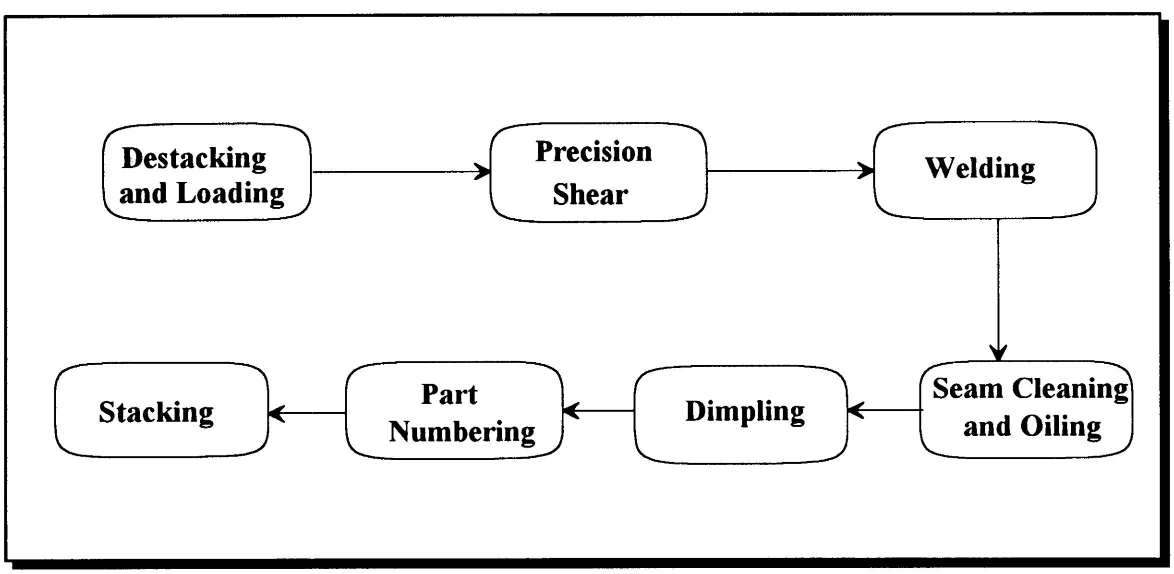

Figure 7. Operations Generally Integrated in CO_2 Laser Welding Systems.

Since laser welding of tailored blanks is currently performed using either one-axis or two-axis 6 kW CO_2 laser, both options were included in the tailored blank model. The individual production lines can, however, differ significantly depending both on the application and the manufacturer of the welding system. The system features considered in the model (Table 1) were chosen to reflect the most typical equipment attributes.

Feature	**One-Axis CO_2 Laser**	**Two-Axis CO_2 Laser**
System Details	Manual Loading, Seam Cleaning/Oiling, Dimpling	Manual Loading, Seam Cleaning/Oiling, Dimpling
Maximum Output Power	6 kW	6 kW
Investment Cost	\$3,500,000	\$3,400,000
Welding Speed	up to 10 m/min	up to 10 m/min
Maximum Weld Length	1600 mm [1)]	2300 mm
Maximum Blank Width	3200 mm [1)]	1800 mm
Workers/System	3-4	3-4
Reject Rate	2%	2%
Average Down Time	10%	10%
Maintenance Cost (% of Welding System Cost)	5%	5%

Table 1. Features of Laser Welding Systems.
[1)] Maximum weld length and maximum blank width vary somewhat depending on the system manufacturer.

In the basic one-axis and two-axis CO_2 laser systems, the blanks are loaded manually and welded in one welding station with a 6 kW CO_2 laser, followed by seam cleaning/oiling and dimpling at separate stations. The laser welding lines used in tailored blanking include generally at least these elemental items and, thus, the investment costs shown in Table 1 are typical minimum costs. The model provides also a variety of optional features for the laser welding systems. First, instead of manual loading, the user can choose a fully automated line by specifying the number of robots needed for handling of blanks. In the former case, the number of workers needed to operate a laser welding line is generally 3 or 4, while an automated system may require 1 to 2 workers. The cost of one robot was assumed to be $110,000 in the welding system calculations.

An output power of 6 kW was selected for the baseline systems because it is generally regarded as minimum power level capable of high volume production. [Stokman, 1997] The user can also choose a higher laser power, but this will increase the overall investment cost of the welding system. Precision shear equipment is not included in the basic one-axis CO_2 laser installation, but if it is selected, a cost of $500,000 is added to the minimum system cost. Even when precision shearing is not chosen, the model will assume that this operation is necessary if the length of continuous welds exceeds 1.0 m. [Guastaferri, 1997] In the two-axis system the precision shear operation is eliminated by keeping welds short (blank dies are claimed to produce weldable edges up to 1.3 m in length) and, if necessary, using beam weaving. [Anon., 1996c]

The welding cost estimates of tailored blanks are complicated by the interdependency of different welding process and product variables. Some of the key welding system variables are the time needed for loading, welding speed, and the ability to process multiple parts in a single cycle. Number of welds, weld length, and weld type, i.e., whether the seam is continuous, in-line, parallel, or non-parallel, are examples of blank variables that affect critically the welding system cost.

The time it takes to position and clamp one set of blanks for welding operation is in the order of 8 to 10 seconds for the one-axis laser system. Although the clamping time may vary somewhat for different applications, experience has shown that it can be quite similar undependent whether loading is manual or automated. For two-axis processing, however, the loading time was estimated to be a function of the degree of automation. The standard two-axis laser installations include two dedicated fixtures on a turn table for positioning and clamping of blanks. In this case the cycle time is determined either by the welding time or the loading time, whichever is larger.

The model has the capability of estimating laser welding speeds with various regression relationships. Data for the regression analyses was collected from experts in industry and through literature survey. The estimated welding speeds are a function of laser output power, blank material and average thickness, and filler metal use. Laser welding of steels is assumed to be autogenous in all cases, but for laser welding of aluminum the model provides an option for joining with filler wire. The maximum travel speeds that can be achieved with a 6 kW CO_2 laser are on the order of 10 m/min, depending on the sheet thicknesses used in a blank. [Anon., 1995b]

The maximum dimensions that laser welding installations are capable of processing vary from system to system. The values used in the model for each of the welding equipment represent standard table sizes currently available. [Stokman, 1997] [Van der Hoeven, 1994] The one-axis laser is assumed to be suitable for welding continuos and in-line welds, but if a design includes parallel welds, the blank has to be either circulated or processed at another welding station. The two-axis laser system is generally selected for tailored blank applications that necessitate welding in different directions, i.e., when blanks include non-parallel welds.

The main consumable in CO_2 laser welding is shielding gas, which in tailored is blanking typically 100% helium with flow rates on the order of 38 l/min. A disadvantage of laser welding process is its low power efficiency; in the case of CO_2 lasers only 10% (or less) of the maximum power actually reaches the workpiece. Due to extensive development work, the reliability of CO_2 laser systems is normally very high, leading to down times in the range of 5 to 10%. However, this requires frequent maintenance work, estimated in the model as 5% of the total welding installation cost. Laser welding systems are equipped with different on-line monitoring and control systems to minimize the number of defective parts and, therefore, only 2 to 3% of the parts are normally below the quality requirements. [Stokman, 1997] [Guastaferri, 1997]

5.4 Mash Seam Welding

The welding systems installed for mash seam welding of tailored blanks include similar production steps to laser welding equipment, as Figure 8 shows. In contrast to laser welding process, precision shearing of blanks is unnecessary prior to mash seam welding, but an additional post-welding operation, planishing of weld seams, may be required.

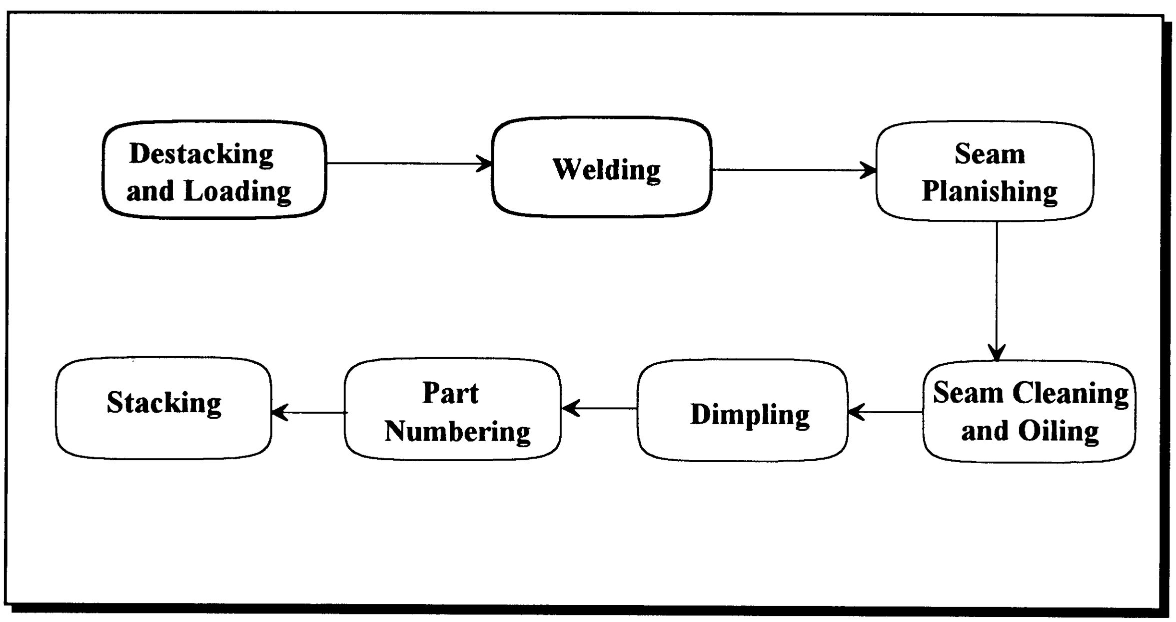

Figure 8. Operations Generally Included in Mash Seam Welding Systems.

The majority of mash seam welding lines in usage today have been supplied by one company, Soudronic of Switzerland. The latest version of their mash seam welders (RPQ 2500) was selected as a baseline system for mash seam welding calculations in the tailored blanking model. The general properties of this system are presented in Table 2. The basic installation considered includes manual loading of blanks, a single fixed welder with a moving clamp, and planishing, cleaning and oiling of seam, and dimpling as integrated post-welding operations.

Feature	**One-Axis Mash Seam Welding**
System Details	Manual Loading, Planishing, Seam Cleaning/Oiling, Dimpling
Investment Cost	$3,700,000
Welding Speed	up to 12 m/min
Maximum Weld Length	2500 mm
Maximum Blank Width	3200 mm
Thickness Range	0.7 to 3.0 mm
Maximum Total Thickness	5 mm
Workers/System	3-4
Reject Rate	2%
Average Down Time	10%
Maintenance Cost (% of Welding System Cost)	5%

Table 2. Features of Mash Seam Welding System.

In the mash seam welding system considered, the process starts when the blanks are placed onto the feeder tables, where they are positioned and clamped with a preset overlap. After welding of previous parts has been completed, the feeder tables insert the new set of blanks into the welding machine. The clamping device of the welding machine takes over at this point and the feeder tables release the blanks and retract. The idle time between successive welding operations is approximately 8 to 10 seconds. The basic system in the model includes manual loading and unloading of blanks, in which case 3 to 4 workers are typically needed. If the loading and stacking of blanks is fully automated, the system requires 1 to 2 workers for inspection and control of the production. [Stokman, 1997]

Up to four parts can be loaded for one weld cycle as long as they fit within the 2.5 m long feeder tables. A tailored blank with multiple welds can be mash seam welded either by using two welding systems or by increasing the number of operations at one welding station. [Anon., 1992b] [Rawyler, 1997] The travel speed for mash seam welding is estimated using the average thickness of the blanks and a regression relationship generated from empirical data. Compared with laser welding, the maximum welding speed can be somewhat higher in mash seam welding, up to 12 m/min.

Copper electrode wheels are the only consumable used in mash seam resistance welding. The cost of electrodes is currently about $1200 per pair, and they have to be replaced after a weld length of 40 to 60 km, or after only 25 km when joining steels with thick zinc coatings. The mash seam welding system requires approximately 8 hours of maintenance work per week if tailored blanks are produced continuously in three shifts.

The frequent maintenance work increases the system reliability, resulting in down times less than 10%. Furthermore, reject rates as low as 1 to 2% can be achieved since the quality of welds is controlled continuously through on-line monitoring and control systems. [Rawyler, 1997]

5.5 Forming and Trimming

The forming of tailored blanks is in most cases performed in the facilities of automotive manufacturers. The formability of welded blanks is generally somewhat inferior to that of one-piece stampings. However, if the characteristics of a tailored blank are incorporated into stamping die designs, acceptable forming performance is achievable both for steel and aluminum tailored blanks. [Stasik, 1996]

The stamping of automotive body parts includes typically a combination of stretching and drawing operations. However, the assumption used in the tailored blank cost model is that forming is either stretch- or draw-limited. The number of forming and trimming stations needed is then estimated based on the most restrictive forming operation and design specifications. More in depth discussions on the stamping cost calculations can be found in previous studies. [Park, 1988] [Hendrichs, 1989] [Han, 1994]

CHAPTER 6 MANUFACTURING CASE STUDIES

6.1 General Data

The tailored blanking cost model was applied to three body-in-white parts in order to study the potential weight saving opportunities and economic benefits of using tailored blanking. The case studies were selected to represent tailored blank designs with different degrees of complexity. Both steel and aluminum tailored blanks were compared in each case with conventional part designs. Welding of steel tailored parts was simulated with all the welding system options included in the model, i.e., with one-axis laser, two-axis laser, and mash seam welding. Only laser welding was considered for aluminum blanks since mash seam welding is not applicable for this material. The case studies developed were based on conceptual designs rather than on parts already in production and, thus, the design details, such as weld positions and blank thicknesses, are tentative.

The values of material inputs, general economic factors, and production parameters used throughout the case studies are listed in Appendix 1. It should be noted that the production of tailored blanks was assumed to take place in-house and the estimated costs do not include the costs of shipping, inventory, or other less directly related costs. The baseline calculations were conducted at a production volume of 100,000 vehicles per year. The part specifications and the results of cost simulations are discussed in the following.

6.2 Front Door Inner

A front door inner panel was selected to represent a category of tailored blank applications with one, continuous long weld. Two alternative designs were considered: A single blank reinforced with two smaller parts (Figure 9) and a two-piece tailored blank with one reinforcement (Figure 10). The hinge reinforcement was eliminated in the steel tailored part by increasing the thickness of the smaller blank from 0.7 to 1.2 mm. The steel gauges were converted into aluminum ones based on an equivalent structural stiffness criterion. [Chang, 1976] The same criterion was applied also to other case studies, resulting in a thickness increase of approximately 70% for aluminum blanks.

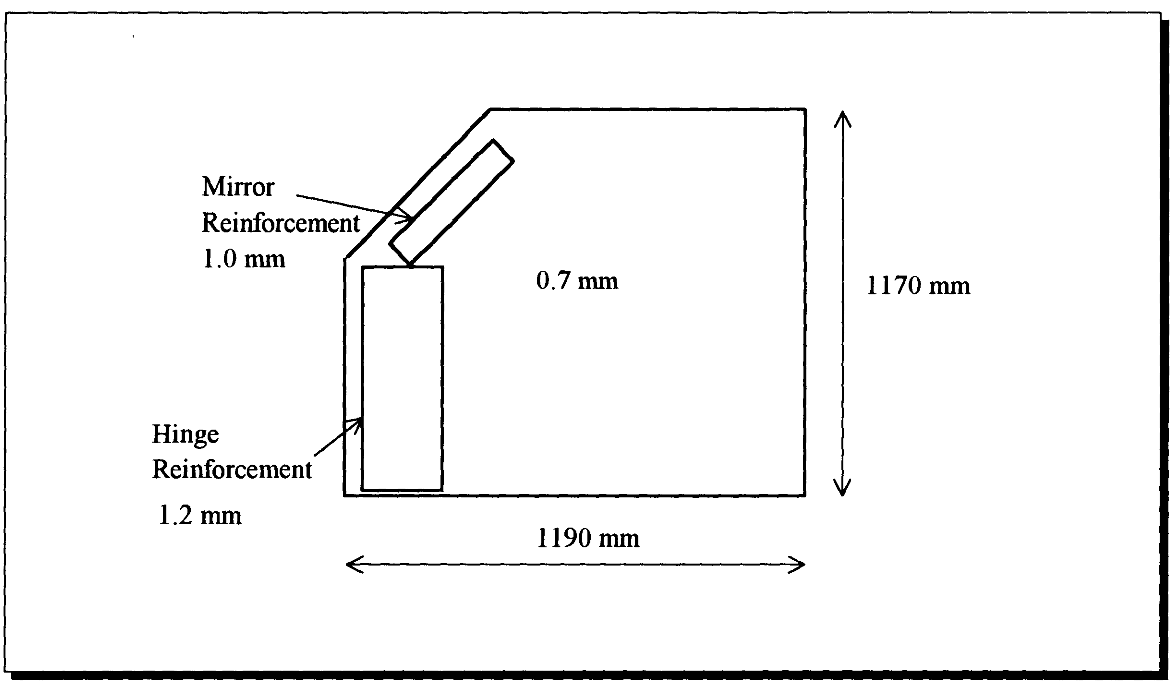

Figure 9. Front Door Inner – Steel Conventional Design.

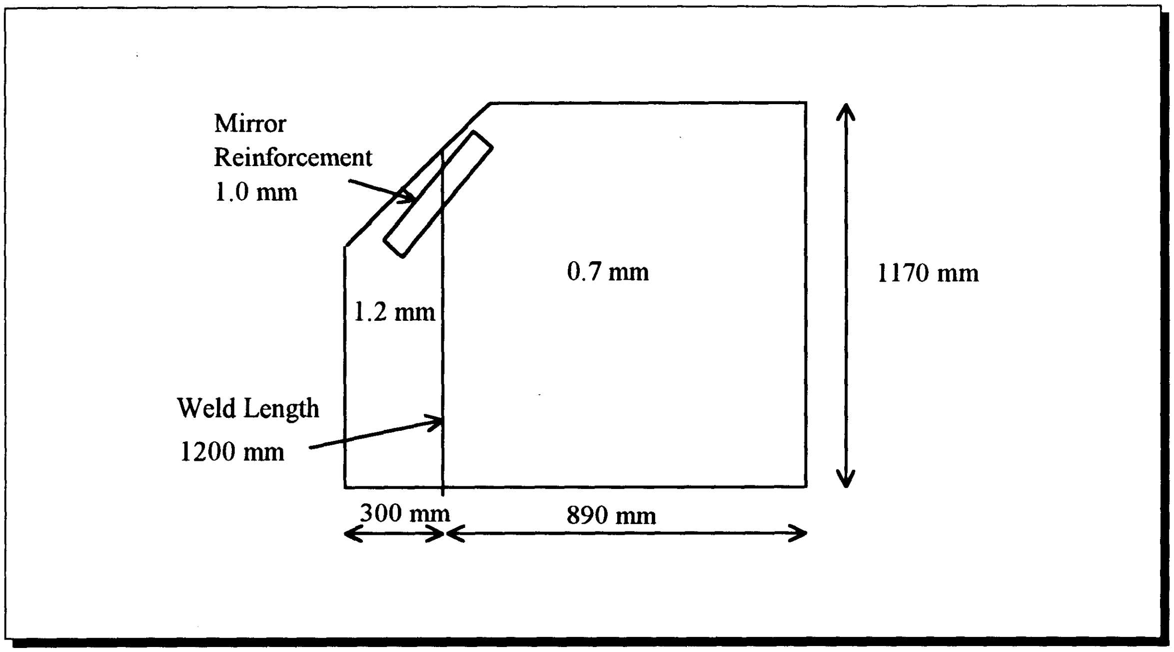

Figure 10: Front Door Inner – Steel Tailored Blank Design.

The cost estimates of alternative steel and aluminum designs are presented in Tables 3 and 4, respectively. The weight of the conventional design was estimated as 4.8 kg. Tailored blanking yielded in this case a weight saving of 0.9 kg, or approximately 19%, since the hinge reinforcement was eliminated. Compared with the percentage of material trimmed from the one-piece design, the overall material utilization was also slightly improved in the tailored blank design, decreasing further the material cost. The blanking cost estimates were similar since both the conventional and tailored door inner panels included three blanks.

Cost Category	Steel Conventional Design	Steel TWB 1-Axis LW[1)]	Steel TWB 2-Axis LW[1)]	Steel TWB MSW [2)]
Material	$9.00	$7.50	$7.50	$7.50
Blanking	$0.70	$0.70	$0.70	$0.70
Welding	$0.00	$2.70	$1.60	$2.30
Forming	$9.60	$8.70	$8.70	$8.70
Assembly	$2.10	$1.10	$1.10	$1.10
Total Part Cost	**$21.40**	**$20.70**	**$19.60**	**$20.30**

Table 3. Front Door Inner – Costs of Alternative Steel Designs.
[1)] Laser welding; [2)] Mash seam welding

Cost Category	Aluminum Conventional Design	Aluminum TWB 1-Axis LW	Aluminum TWB 2-Axis LW
Material	$22.40	$18.80	$18.80
Blanking	$0.70	$0.70	$0.70
Welding	$0.00	$3.00	$1.70
Forming	$7.80	$7.20	$7.20
Assembly	$2.30	$1.20	$1.20
Total Part Cost	**$33.20**	**$30.90**	**$29.60**

Table 4. Front Door Inner – Costs of Alternative Aluminum Designs.

The elimination of one reinforcement in the tailored part reduced also the forming and assembly costs somewhat. For instance, the press tooling investment cost was about $90,000 lower for the tailored blank. The assembly costs were approximated using a cost of spot welding per meter. The costs per meter of robotic spot welding were estimated in a recent study for steel and aluminum as $1.24 and $1.37, respectively. [Jain, 1997] Although the costs per meter of joining were generated using certain simplifications for the assembly operation, it was assumed that these values can be used to obtain rough estimates of the cost of joining the relatively small reinforcements.

The welding cost variances between the one-axis laser, two-axis laser, and mash seam welding systems resulted from the differences in the loading and welding speed capabilities. Two-axis processing seemed to be the most efficient system for producing door inner blanks. This is because the two-axis laser system typically includes two fixtures, allowing simultaneous loading and welding operations. The production rate of the two-axis laser is generally determined by the loading time since CO_2 lasers are capable of producing high welding speeds, in this case estimated as 8.0 m/min for steel and 6.6 m/min for aluminum blanks. Although the door inner design included a relatively long weld, the loading time restricted the throughput also in this case.

In the case of one-axis laser and mash seam welder, the clamping of blanks can only take place after the welding of previous part is completed. Thus, there is a short idle time between the consequent welding operations, which is allocated to the number of parts joined in one setup. The dimensions of the door inner panel prevented processing of multiple blanks per one set-up and, thus, the throughput was decreased with one-axis laser and MSW systems, compared to two-axis laser system. The cost of one-axis CO_2 laser welding was increased further due to the expense of precision shearing equipment, which was assumed to be necessary since the weld length exceeded 1.0 m.

Comparing steel and aluminum designs, the aluminum parts were lighter than all steel alternatives studied. The part weights were reduced by about 40%, yielding the weight of 2.8 kg for the conventional design and 2.3 kg in the case of tailored blank. The total costs, however, increased 50-55% from the equivalent steel parts due to the higher aluminum price. The cost penalty varied from $5.90 to $6.40 per kilogram of weight saved, depending on the design. The marginal difference between welding costs of steel and aluminum designs resulted from the slower welding speed necessary to join the aluminum blanks. A similar production rate was used for both the stamping of steel and aluminum blanks although this may be in some cases a somewhat idealized assumption. The excellent formability of aluminum is reflected in the lower forming costs that were estimated for the aluminum designs.

6.3 Rear Rail Inner

A large number of current and pending tailored blank applications include one or two short parallel welds. A rear rail inner is a typical representative of this category, other examples being cross members, pillars, and interior reinforcements. A three-piece tailored blank design was compared with a more traditional design consisting of one large blank and two reinforcements (Figure 11). The details of the tailored blank design were taken from the ULSAB study. [Anon., 1995a] The design was modified for the conventional part, including two reinforcements in order to achieve similar structural properties.

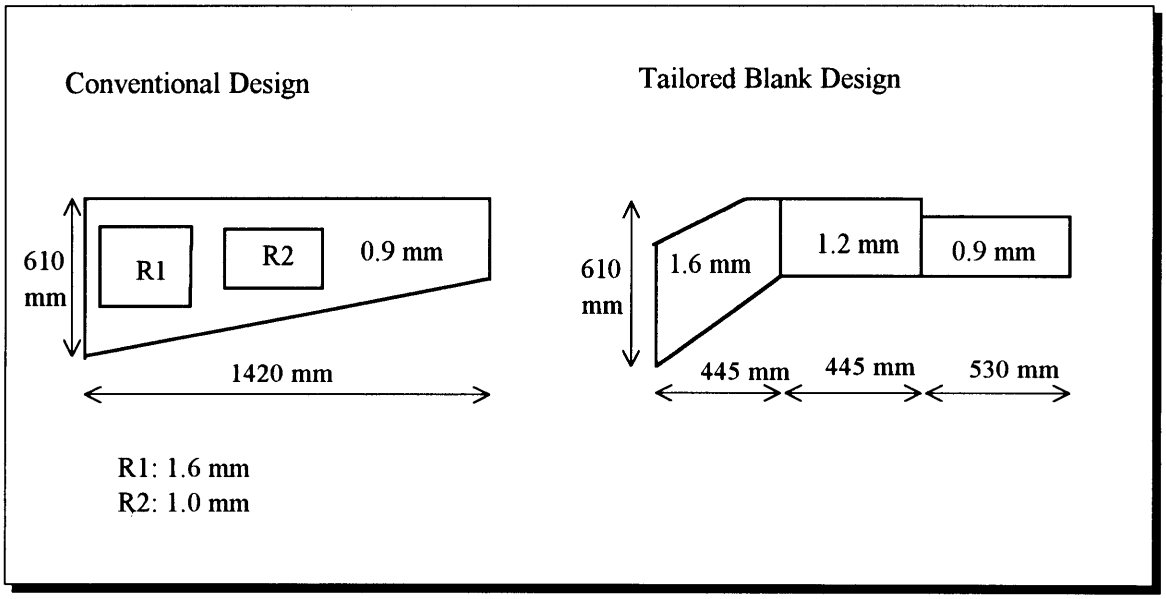

Figure 11. Rear Rail Inner – Alternative Steel Designs.

The manufacturing cost estimates are presented in Tables 5 and 6 for the alternative steel and aluminum designs. The weights of the steel conventional design and tailored part were 3.2 kg and 2.9 kg, respectively. The weight savings achieved through tailored blanking were thus less than 10%. However, tailored blanking resulted now in larger cost reductions: Both steel and aluminum tailored designs decreased the overall part cost by 17 to 22% compared with a cost reduction of 5 to 10% related to the alternative door inner designs.

Cost Category	Steel Conventional Design	Steel TWB 1-Axis LW	Steel TWB 2-Axis LW	Steel TWB MSW
Material	$4.20	$3.20	$3.20	$3.20
Blanking	$0.40	$0.40	$0.40	$0.40
Welding	$0.00	$2.00	$2.40	$1.60
Forming	$10.30	$7.10	$7.10	$7.10
Assembly	$0.80	$0.00	$0.00	$0.00
Total Part Cost	**$15.70**	**$12.70**	**$13.10**	**$12.30**

Table 5. Rear Rail Inner – Costs of Alternative Steel Designs.

Cost Category	Aluminum Conventional Design	Aluminum TWB 1-Axis LW	Aluminum TWB 2-Axis LW
Material	$9.00	$7.00	$7.00
Blanking	$0.30	$0.30	$0.30
Welding	$0.00	$2.10	$2.40
Forming	$10.20	$7.00	$7.00
Assembly	$0.90	$0.00	$0.00
Total Part Cost	**$20.40**	**$16.40**	**$16.70**

Table 6. Rear Rail Inner – Costs of Alternative Aluminum Designs.

One of the factors contributing to the lower total cost was the improved material utilization in tailor welded blanks. Moreover, parts consolidation eliminated the forming and assembly of two reinforcements necessary in the conventional rear rail inner. This resulted in a press tooling cost saving of $425,000, or about $3.00 lower total forming cost per a tailored part. Again, the aluminum blanks reduced the weight of rear rail inner by approximately 40% from the steel parts, but as a result the total part cost increased 30% because of the higher material cost. The cost of further weigh reduction was now on the order of $3.00 per kilogram.

The additional expense of welding was on the order of $1.60 to $2.40 per a tailor welded blank. As in the case of door inner, the cost differences between the welding system options were relatively small. The mash seam welding system appeared to be the least expensive alternative for the rear rail inner design with two parallel welds. Although the MSW system is not capable of two-axis welding, it can process multiple parts in one welding cycle. Based on the design details and limitations of the clamping table, it was assumed that three rails could be loaded for one set-up, which increased the overall throughput.

In contrast, it was estimated that only two blanks could be joined in one setup for both one-axis laser and two-axis laser systems due to the smaller clamping table sizes. It should be noted, however, that some one-axis laser installations may be capable of processing only one blank per set-up because of the differences in clamping systems. For the two-axis laser system, the time needed for removing the welded blank and loading six blanks was again the factor determining the production rate. Although a total of four welds are produced during one welding cycle, the time used for welding operation was smaller because of the high welding speed; estimated as 7.4 m/min for steel and 6.3 m/min for aluminum. In the case of mash seam welding and one-axis laser welding, blanks with more than one weld are either circulated or processed in another welding station, requiring repeated loading operations. However, the welding costs with mash seam and one-axis laser systems were still lower than what was estimated for two-axis laser welding, since the total pre-welding time associated to these joining processes could be allocated to three or two blanks, depending on the system.

6.4 Body Side Outer

The majority of tailored blank applications today include only one or two parallel welds, but automotive manufacturers have also recognized the potential benefits of more complex tailored blank designs. To simulate the cost implications of increasing blank complexity, a body side outer panel was selected as the third case study. Body side panels are often made from individually stamped pillars, headers, and sills, which are spot welded together after forming. Some manufacturers have also produced body panels from either one or two large stampings, completed with several inner parts and reinforcements.

Figures 12 and 13 illustrate the body side design alternatives considered in the present study. The conventional design consisted of one large blank and five reinforcements. The blank thicknesses were similar to gauges used in the body sides of production vehicles. [Shami, 1995] The alternative body side design included a door frame opening and a quarter panel, requiring assembly after forming operations. The door frame opening consisted of four blanks joined together with four welds, all of which were less than 500 mm.

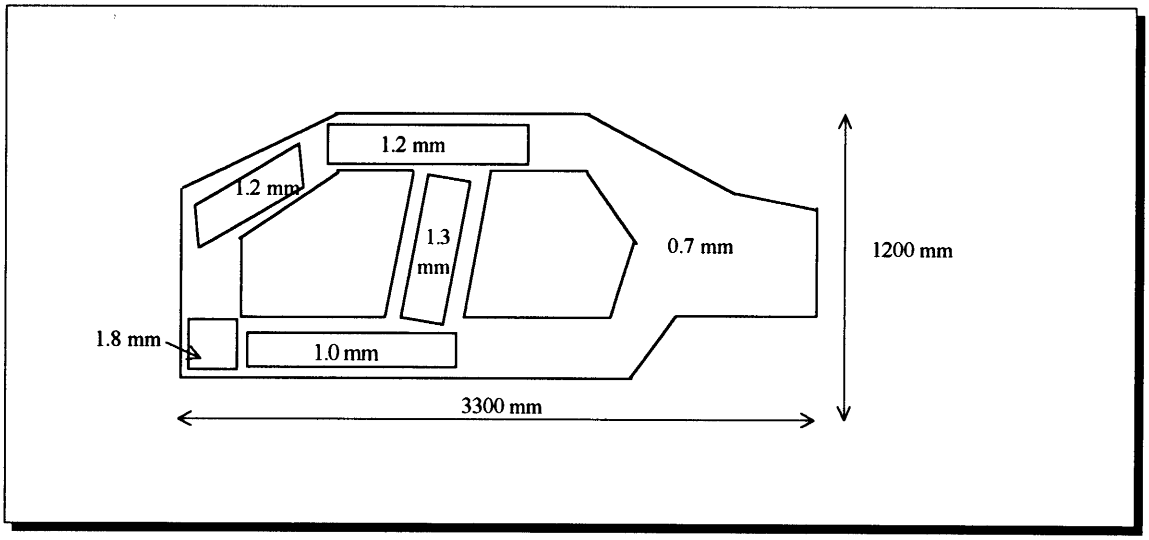

Figure 12. Body Side Outer – Steel Conventional Design.

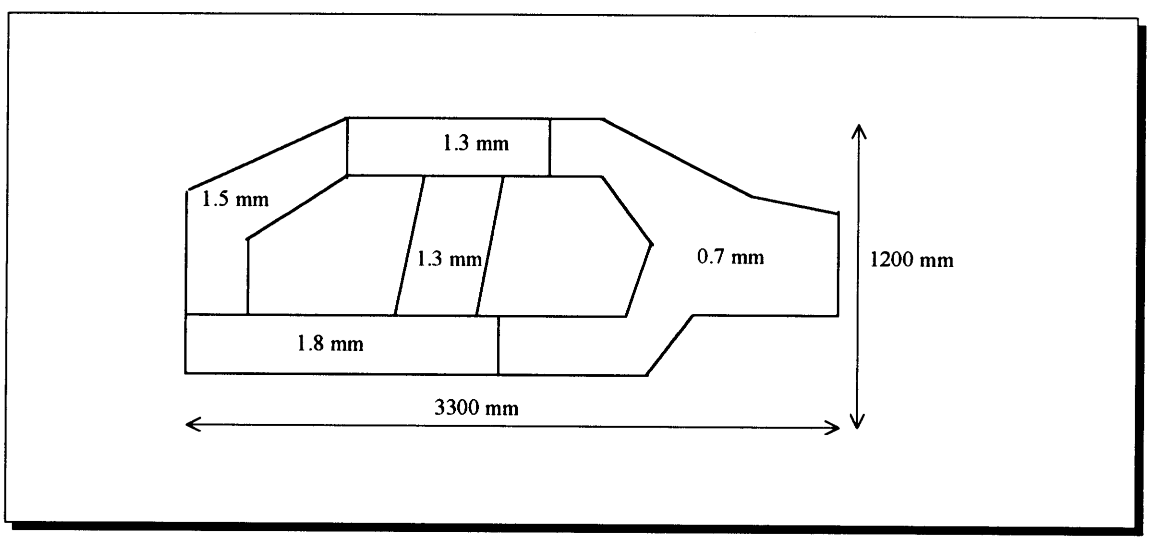

Figure 13. Body Side Outer – Steel Alternative Design.

Tables 7 and 8 list the costs generated with the tailored blanking model for steel and aluminum designs. In contrast to previous case studies, tailored blanking gave no weight savings. Instead, the steel body side weight increased from 18.0 kg estimated for the conventional part to 18.9 kg for the tailored blank. This explained also the higher material cost. Still, tailored blanking resulted in overall cost savings of approximately 10 to 15% because the forming and assembly operations of four parts were eliminated. The total press tooling cost saving was estimated as $2,070,000 for the steel tailored design, and as $2,780,000 for the aluminum body side. The forming of aluminum designs was more costly since the stamping model introduces a piercing operation before the trimming of aluminum outer parts. The extra piercing station is assumed necessary to prevent slivering during the trimming process. Compared with equivalent steel parts, the usage of aluminum reduced again the weight by approximately 40%, the respective weights being 10.5 kg for the conventional design and 10.9 kg for the tailored blank. The cost penalty was estimated as $4.50 to $5.30 per kilogram of weight reduced.

Of all the case studies considered, the body side outer had the largest range of welding costs, from $2.70 to $6.30. The body side design illustrated the strength of the two-axis system in processing of tailored blanks with increased complexity. These estimates assume that all four blanks can be loaded and welded in one set-up with the two-axis laser, while both the one-axis laser and MSW systems require at least three passes for the design in consideration. Since the one-axis systems are not designed to handle this type of part, their capacities were lower and the resulting welding cost per part increased significantly from the welding expense of two-axis laser system. The MSW system yielded in this case the highest cost since the welding speed estimated from the blank thicknesses was somewhat slower compared with the travel speed in one-axis laser welding. The slightly higher cost of laser welding of aluminum is explained by the welding speed variation: The model estimated a welding speed of 6.1 m/min for aluminum gauges and 7.0 m/min for steel thicknesses.

In order to maximize the utilization of one-axis laser, one laser source is sometimes used at two or more welding stations. To fully exploit the beam switching option, however, welding time should exceed the time required for loading and unloading operations. Since all the four welds in the body side design are short, it is unlikely that beam switching would yield improvements in the throughput and, thus, this welding system alternative was not considered in the cost calculations.

Cost Category	**Steel** Conventional Design	**Steel** TWB 1-Axis LW	**Steel** TWB 2-Axis LW	**Steel** TWB MSW
Material	$25.60	$26.30	$26.30	$26.30
Blanking	$1.20	$1.00	$1.00	$1.00
Welding	$0.00	$5.60	$2.70	$6.30
Forming	$50.90	$38.80	$38.80	$38.80
Assembly	$4.60	$1.90	$1.90	$1.90
Total Part Cost	**$82.30**	**$73.60**	**$70.70**	**$74.30**

Table 7. Body Side Outer – Costs of Alternative Steel Designs.

Cost Category	Aluminum Conventional Design	Aluminum TWB 1-Axis LW	Aluminum TWB 2-Axis LW
Material	$56.00	$57.10	$57.10
Blanking	$0.90	$0.90	$0.90
Welding	$0.00	$5.90	$2.90
Forming	$60.30	$44.20	$44.20
Assembly	$5.10	$2.10	$2.10
Total Part Cost	**$122.30**	**$110.20**	**$107.20**

Table 8. Body Side Outer – Costs of Alternative Aluminum Designs.

The welding cost generated for the one-axis laser welding, $5.60, was significantly lower than the estimate of $10.00 quoted in a recent report for a similar body side ring. [Anon., 1996] However, some part of the cost variation results presumably from the different manufacturing scenarios since the former cost was for in-house welding while the latter estimate was for a fully out-sourced welding operation. Also, the changes in welding production parameters are likely to contribute to the cost difference. The effects of some of the most relevant production parameters are studied in the following section.

6.5 Production Parameter Sensitivity

The effect of production volume, welding system cost, welding speed, and welding set-up time on the manufacturing cost of the steel body side was investigated by varying one parameter at a time while other variables were hold fixed. Figure 14 shows the sensitivity of the total body side cost to production volume variation. The tailored blank joined with mash seam welding is not displayed since this cost was very similar to the expense of one-axis laser welding. The figure shows that the cost difference between the two tailored blank designs remained the same also with increasing volume. The cost of the conventional body side declined more rapidly, approaching the tailored blank costs at the maximum production volume considered. This is because the higher tooling investment cost required for the stamping of conventional design was allocated to a larger number of parts as the annual volume increased.

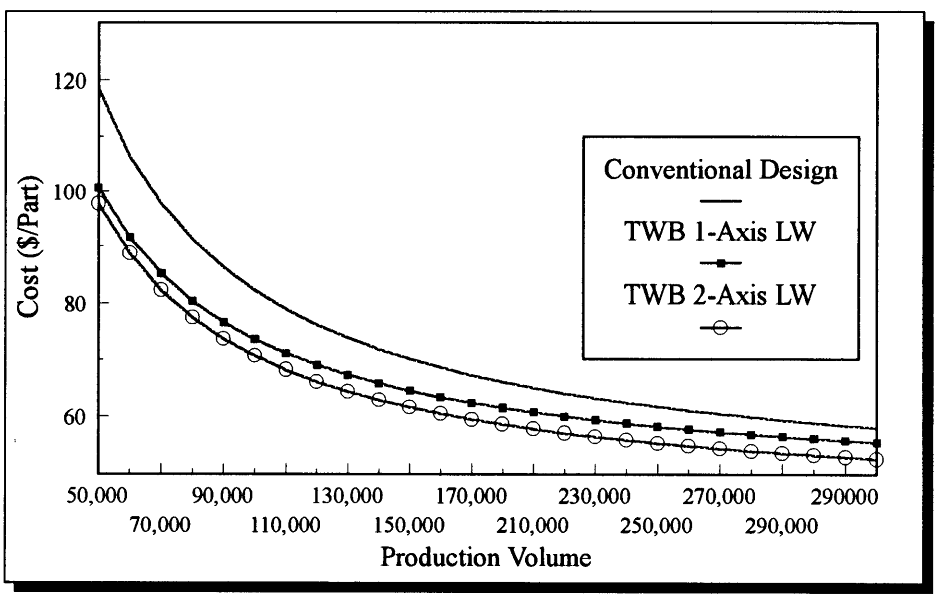

Figure 14. Steel Body Side Cost as a Function of Annual Production Volume.

The costs given in sections 5.3 and 5.4 for laser welding and mash seam welding systems represent typical values at present. Still, the welding equipment costs may vary somewhat depending on the specific system features The effect of welding line cost on the steel body side cost is shown in Figure 15. The tailored blank alternatives were less costly than the conventional body side design even with welding equipment costs that were unusually high. The increasing welding line cost seemed to impact more on the blanks joined with one-axis laser and mash seam welding, compared with two-axis laser welding. The difference resulted from the higher throughput of two-axis laser system, allowing the more expensive welding system to be allocated to a larger number of body sides. Note that the cost of one-axis laser welding increased from the baseline cost of $5.60 to approximately $9.00 with the highest welding system cost considered.

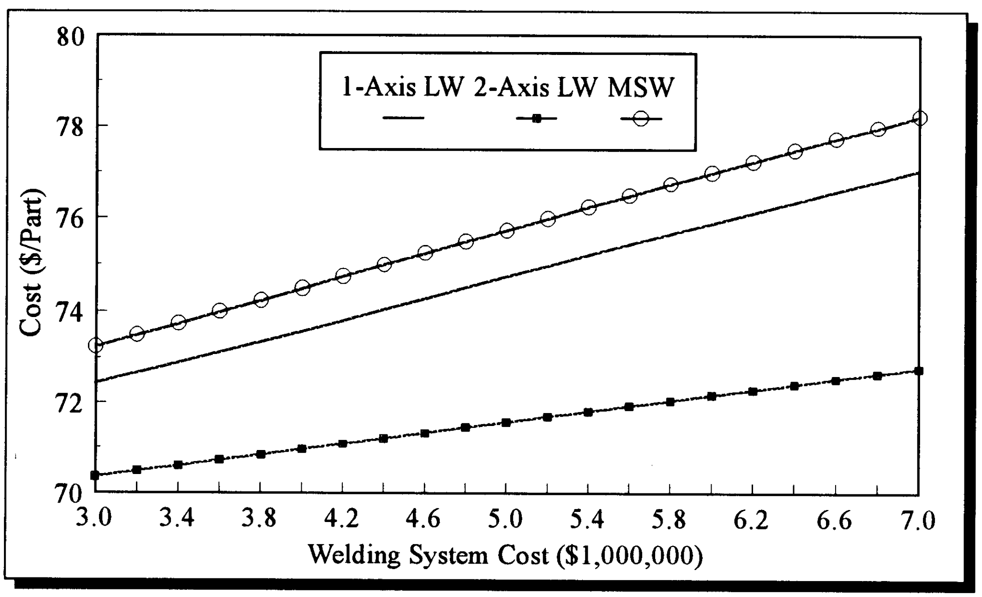

Figure 15. Steel Body Side Cost as a Function of Welding Equipment Cost.

Figure 16 displays the variation of the body side cost as a function of welding speed. The tailored blanks were less expensive than the baseline cost of the conventional design even at the slowest welding speed. It can also been seen that as the laser welding speed approached the value of 8.0 m/min, the time needed for loading blanks became more critical in the case of two-axis laser system.

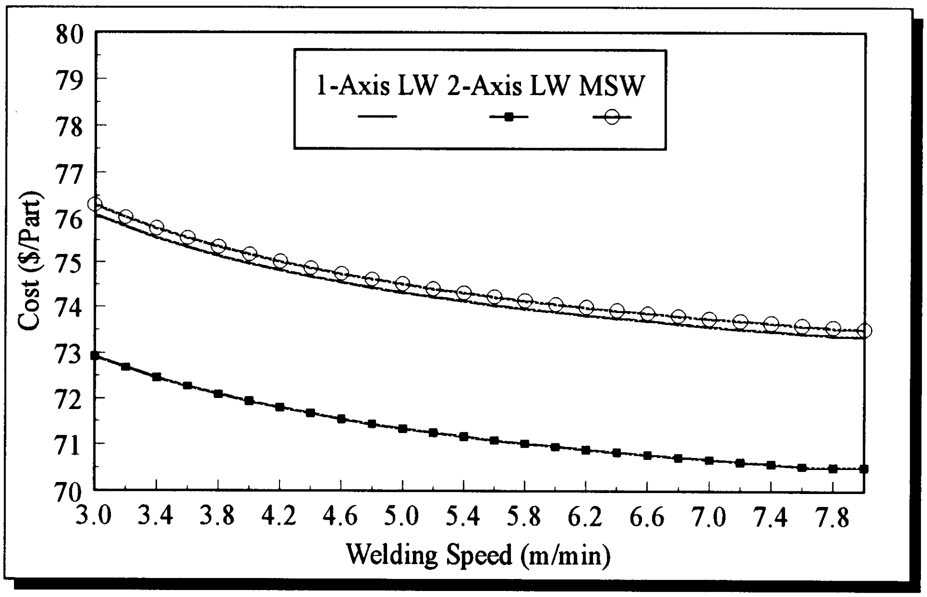

Figure 16. Steel Body Side Cost as a Function of Welding Speed.

The time between consequent welding operations is another critical factor in tailored blanking since it affects the throughput and, thus, the total part cost. The sensitivity of the body side cost to set-up time is presented in Figure 17. Note that the set-up means in this case either the loading time per blank (two-axis laser) or the clamping time per welding operation (one-axis laser and mash seam welding). The total body side costs were less expensive than the cost of conventional design at all loading times. The two-axis laser welding seemed to be the most promising alternative even when set-up time was estimated as 15 sec. Under highly optimistic loading conditions, welding speed became the factor restricting the cycle time in two-axis welding.

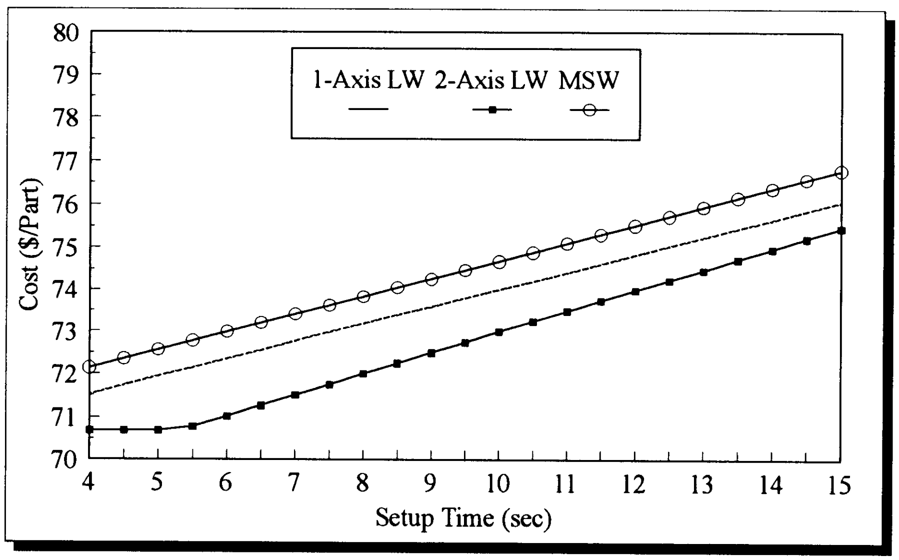

Figure 17: Steel Body Side Cost as a Function of Setup Time.

CHAPTER 7 SUMMARY AND CONCLUSIONS

An increasing number of research and development efforts in the automotive industry focus on reducing vehicle weight. The issue of weight reduction became acute upon the enforcement of environmental regulations requiring fuel efficiency improvements. In particularly, lightweighting the automobile body-in-white structures is necessary to achieve the fuel economy standards since the vehicle body represents a substantial part of a vehicle's mass. Weight savings are currently pursued through, for instance, various advanced manufacturing techniques that allow consolidation of body-in-white parts. An example of the technologies that has been developed to integrate body-in-white parts and, potentially, reduce production costs is tailor welded blanking.

The objective of this study was to contrast the economic feasibility of tailor welded blank technology to conventional part designs. This was achieved by analyzing the manufacturing costs of various body-in-white parts utilizing the developed tailored blanking cost model. The focus was on examining the cost effect of alternative materials (steel and aluminum), blank complexity (number and position of welds), and welding system options (one-axis CO_2 laser, two-axis CO_2 laser, and mash seam welding).

The case studies of alternative steel and aluminum designs suggested that parts integration can reduce the weight and improve material utilization over conventional body-in-white part designs. In order to achieve these benefits, however, each tailored blank design has to be highly scrutinized before implementation. If the design specifications are not carefully considered, tailor welded blanks may have the risk of increasing the part weight.

The comparisons of the total manufacturing costs demonstrated that tailored blanking can be economically feasible for the production of body-in-white parts although the technology involves an additional process step. At the annual production volume assumed (i.e., 100,000 units), tailored blanking gave part cost savings of 5 to 20% compared with conventional body-in-white parts. The results were found to be sensitive to production volume, since the cost of the conventional designs approached the expense of tailored blanking as the volume increased.

The total cost savings in tailored blanking resulted from the elimination of structural reinforcements, which reduced the number of production steps in blanking, forming, and assembly processes. Forming process is generally the most capital intensive of these three operations and, thus, it has the highest potential for cost savings when parts are consolidated. Also in this study the highest cost savings were found in the forming operation, mainly because the die investment costs were reduced.

The analyses of aluminum designs used a somewhat idealized assumption of forming and CO_2 laser welding operations being as applicable to both steel and aluminum. The results of equivalent steel and aluminum designs suggested that the aluminum parts improve weight savings by 40% both in the case of steel tailored blanks and steel conventional designs. However, the aluminum designs include generally a large cost penalty, which was estimated in this study as $3.00 to $6.40 per kilogram of weight saved.

The cost differences were mainly attributed to the higher material cost of aluminum designs.

The welding process alternatives considered–one-axis CO_2 laser, two-axis CO_2 laser, and mash seam welding–were assumed to be equally suitable to mass production of tailored blanks. Based on this assumption, the comparisons of the welding costs indicated relatively small differences between the welding systems when tailored blanks with only one or two parallel welds were considered. In contrast, selecting the optimal welding system became increasingly important with a more complex blank design. The sensitivity analyses of tailored blanking cost to various joining process parameters revealed the loading time as the principal reason causing the welding cost variations.

The comparisons of the welding costs indicated also that some welding systems were more applicable for certain type of tailored blanks, compared with other systems considered. The two-axis CO_2 laser was the most promising welding system for processing blanks with multiple, nonparallel welds, such as a body side outer panel. Moreover, the one-axis mash seam welding system seemed to be a slightly favorable system for joining tailored blanks which included parallel welds less than 600 mm in length. Rails and pillars are typical body-in-white parts having these qualities.

Overall, the results of the analyses conducted in this study suggested several advantages of using tailor welded blanks in the body-in-white structures. The cost model developed allows automotive manufacturers and tailored blank suppliers to compare the economic feasibility of alternative manufacturing scenarios in tailored blanking for the purposes of research and development.

CHAPTER 8 FUTURE WORK

Tailor welded blanks produced with mash seam welding and CO_2 laser welding have become by now well established in the automotive industry. The experience gained on the technology has led to new promising innovations, such as non-linear laser welds. The concept of non-linear laser welding can improve further material utilization, weight savings, and cost savings in tailored blanking, but several issues in welding and forming require still careful consideration before non-linear welds can be implemented into mass production applications. [Van der Hoeven, 1995] [Van der Hoeven, 1996] If non-linear welded blanks gain wide acceptance in the future, the tailored blanking cost model can be applied to this technology by modifying the relevant calculations, especially the estimates of welding equipment cost, welding speed, and forming cost.

The future developments in the tailor welded blank technology may also include the introduction of alternative welding processes, particularly Nd:YAG laser welding and high frequency induction welding. Compared with CO_2 laser welding, Nd:YAG laser welding process has been found to be more promising for joining aluminum blanks and complex parts requiring three-dimensional welding. While there are currently no production lines utilizing Nd:YAG laser welding, at least one automotive manufacturer produces tailor welded blanks with induction welding. [Prange, 1995] If cost estimates of additional joining processes are necessary in the future, the tailored blanking model can be easily adjusted due to its modular structure.

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APPENDIX 1

TAILORED BLANKING COST MODEL

Material Inputs

Material	Price/kg	Scrap price/kg	Density g/cm³
Steel	$0.77	$0.11	7.89
High-strength steel	$0.85	$0.11	7.89
Aluminum	$3.31	$0.66	2.7

Exogenous Cost Factors

Annual production volume	100,000	
Lot size	100,000	
Product lifetime	4	years
Die change time	0	min
Direct wages	$35.00	/hour
Working hours	16	/day
Working days	250	/year
Capital recovery rate	12.0%	
Capital recovery period	10	years
Fixed overhead (% of physical plant)	35.0%	
Building cost	$800	/m²
Building recovery life	20	years
Auxiliary equipment cost (% of main machine cost)	20.0%	
Maintenance cost	10.0%	
Tooling unit maintenance cost	5.0%	
Price of electricity	$0.08	/kWh
Lubricant	$1.6	/liter

TAILORED BLANKING COST MODEL

Blanking Inputs

Blank #	1	2	3	...	8
Blanking in-house (1=YES; 0=NO)	1	1			
Blank cost <OPTIONAL>					
Material (1=steel;2=hs steel;3=al)	1	1			
Coated material (1=YES; 0=NO)					
Thickness (mm)	1.2	0.7			
Input metal stock surface area (cm^2)	2,550	10,413			
Surface area (in the finished part)(cm^2)	1,913	3,280			
Dedicated equipment (1=YES; 0=NO)	0	0			
Number of parts per hit	2	2			
Blanking trimming scrap rate (%)	0.0%	0.0%			
Reject rate (%)	1.0%	1.0%			
Direct laborers per machine	2	2			
Average down time (%)	50.0%	50.0%			
Installation cost (%)	20.0%	20.0%			
Blanking coupled to line (1=YES; 0=NO)	0	0			

TAILORED BLANKING COST MODEL

Laser Welding Inputs

Laser welding operation (1=YES; 0=NO)	1	
Laser source (1=CO2; 2=Nd:YAG)	1	
Number of laser stations	1	
Output power	6	kW
Total number of welds	1	
2-axis welding system? (1=YES; 0=NO)	1	
Number of parts per welding cycle	1	
Total weld length	1,200	mm/part
Maximum weld length (SEE NOTE)	1,200	mm
Automation (1=YES; 0=NO)	0	
Number of loading/unloading robots	0	
Dedicated equipment (1=YES; 0=NO)	0	
Reject rate	2%	%
Filler metal for aluminum (1=YES; 0=NO)	0	
Direct laborers	3	/line
Average down time	10.0%	%
Maintenance cost	5.0%	%
Installation cost	20.0%	%

TAILORED BLANKING COST MODEL

Mash Seam Welding Inputs

Mash seam welding operation (1=YES; 0=NO)	0	
Total number of welds	1	
Number of parts per welding cycle	1	
Total weld length	1,200	mm/part
Number of loading and unloading robots	0	
Dedicated equipment (1=YES; 0=NO)	0	
Reject rate	2%	%
Direct laborers	3	/line
Average down time	10.0%	%
Maintenance cost	5.0%	%
Installation cost	20.0%	%

TAILORED BLANKING COST MODEL

Forming Inputs

Maximum length	870	mm
Maximum width	180	mm
Projected surface area (of finished part)	294	cm²
Class A finish (1=YES; 0=NO)	0	
Number of parts per hit	2	
Restrictive forming operation (1=STRETCHING; 2=DRAWING)	1	
Flanged part (1=YES; 0=NO)	1	
Number of re-entrant flanged sides	0	
Maximum draw depth (NA)	0	mm
Draw type (1=BOX; 2=CYLINDRICAL) (NA)	0	
Box length (NA)	0	mm
Box width (NA)	0	mm
Box corner radius (NA)	0	mm
Punch diameter in cylidrical draw (NA)	0	mm
Input metal stock diameter in cylidrical draw (NA)	0	mm
Dedicated equipment (1=YES; 0=NO)	0	
Baseline tool life	2,500,000	cycles
Reject rate	1.0%	%
Number of idle stations	0	
Number of inspection stations	1	
Direct laborers	3	/line
Direct laborers at inspection	1	/station
Average down time	50.0%	%
Installation cost	20.0%	%

TAILORED BLANKING COST MODEL

Cost Summary

VARIABLE COST ELEMENTS	per piece	per year	percent	
Material Cost	$6.11	$611,300	65.57%	
Labor Cost	$0.83	$83,442	8.95%	
Energy Cost	$0.04	$3,682	0.39%	
Total Variable Cost	**$6.98**	**$698,424**	**74.91%**	
FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$0.80	$80,403	8.62%	$454,295
Tooling Cost	$0.55	$54,585	5.85%	$165,795
Fixed Overhead Cost	$0.61	$60,635	6.50%	
Building Cost	$0.05	$5,097	0.55%	$38,069
Auxiliary Equipment Cost	$0.16	$16,081	1.72%	$90,859
Maintenance Cost	$0.17	$17,078	1.83%	
Total Fixed Cost	**$2.34**	**$233,879**	**25.09%**	
Total Fabrication Cost	**$9.32**	**$932,304**	**100.00%**	