An Investigation of the Challenges and Costs Associated with a High Volume All Aluminum Automotive Body Shop

by

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Submitted to the Sloan School of Management
and the Department of Electrical Engineering
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Abstract

This work compares the cost of joining all aluminum vehicles in a high volume automotive body-in-white manufacturing facility. A history of some of the pressures facing the automotive industry are explored, and the various regulatory agencies that are responsible are identified. Cost for two joining methods, self-piercing riveting, and resistance spot welding are discussed. Various technical problems that arise when manufacturing aluminum are investigated, and some possible solutions are proposed.

Strategic reasons for manufacturing all aluminum vehicles are investigated. Product advantages for producing aluminum are reviewed. Various goals for skunk-works projects are discussed. Finally conclusions and recommendations are made relative to the implementation of a high volume all aluminum automotive body-in-white manufacturing facility.

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1.0 Background

1.1 Introduction

In 1886 an era of new personal convenience was born when Gottlieb Daimler and Carl Benz combined two heretofore separate technologies, the internal combustion engine and the wooden coach. The coaches were modeled after horse and buggy carriages and were much different than the automobile of today.

> The horseless vehicle is the coming wonder...It is only a question of time when the carriages and trucks in every large city will be run with motors.
>
> Thomas A. Edison, 1895

Subsequently, automobiles have developed into technological wonders, while the automotive industry has developed into one of the most powerful industries in history. The $300 billion US automotive industry produces roughly 12 million vehicles annually:[1]

> The auto industry stands alone in its ability to affect the economic fate of nations, just as it is unparalleled in its effect on the lives of individual consumers. It is a powerful force. [2]

Paralleling the development of automobiles were various vehicle structural materials and joining technologies. Early vehicles were built on wood frames and joined together with wood screws, nails, bolts and dowels. Henry Ford, long a proponent of efficiency, made suppliers deliver to him components on precisely designed wooden pallets that had very tight tolerances and precision holes drilled in them. These pallets would eventually be included in the construction of the automobile.

Today the automobile is constructed of very different materials employing vastly different joining technologies. The primary material for automobile body construction today is steel: as Figure 1.1 shows, steel accounts for 70% by weight of the material content of an automobile. Nevertheless, steel structures represent 99.9% of all automobiles manufactured today. [3]

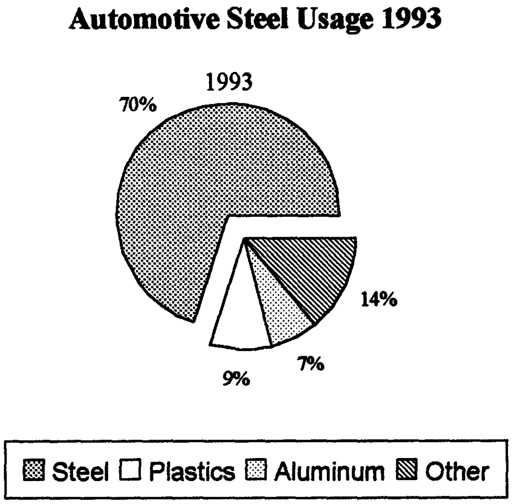


Figure 1.1 Steel Content of US Manufactured Automobiles 1993

Discrete fasteners are no longer the primary joining method of automotive structures. Currently, resistance spot welding (RSW) of steel automotive components is the primary automotive structure joining method. Because of the pervasiveness of RSW of steel, there is a large amount of capital invested in the automotive assembly plants. Therefore, this large capital investment the automotive manufacturers have in RSW represents a potential barrier to implementing any new joining technology.

The purpose of this thesis is twofold: 1) to summarize some of the problems associated with production of an all aluminum high volume automobile structure and 2) to provide a methodology for determining the cost of, and the analysis of, an all aluminum high volume body manufacturing facility. Lastly, a comparison to the cost of RSW will be contrasted to self-piecing riveting will be compared. This thesis is designed to give automotive body-in-white (BIW) design engineers a multi-disciplinary look at the material properties and technological challenges so that they can consider these issues as they design future vehicles. A broad overview of the automotive manufacturing process is included as Figure 1.2 below. While there are many areas in the automotive manufacturing process that an all aluminum vehicle will impact, this thesis will focus on the structure manufacturing.

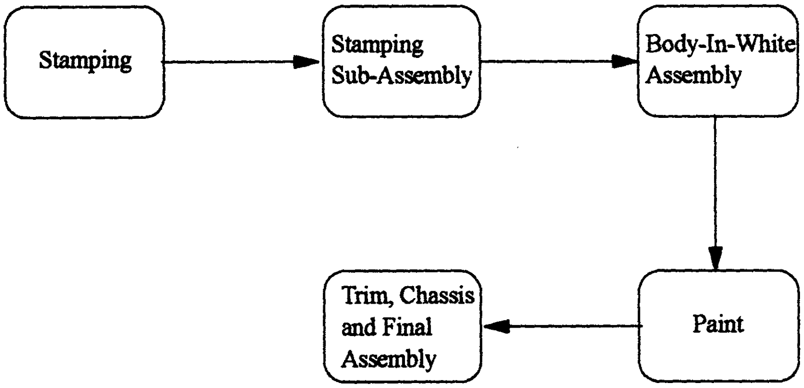


Figure 1.2 Automotive Production Process Overview

Two methods of joining were extensively investigated: RSW and self-piercing riveting. These methods will be the focus of the joining chapter and are compared and contrasted. Finally, a cost model will be presented for self-piercing riveting. The final chapter includes the conclusions that were drawn from this study, and offers some recommendations for automotive manufacturers who are embarking on aluminum vehicle manufacturing projects.

1.1.1 Subjects Requiring Further Investigation

Many topics pertinent to aluminum vehicle manufacturing were not fully investigated by the author. Before an all-aluminum high-volume automotive structure can be manufactured, these issues should be addressed. The purpose of including them here is merely to raise the awareness of the reader, not to propose a solution. Subjects requiring further investigation include:

- Analysis of the chemical effects of introducing all aluminum vehicles into a phosphate coating system
- Analysis of product life-cycle energy expenditures
- Investigation of training requirements for introducing aluminum into body shop
- Assessment of field reparability issues

While extensive research was not performed on the above, some thoughts on these issues follow.

Paint-Shop Implications

Introducing an all aluminum vehicle into a standard automotive paint shop upsets the delicate chemical balance that exists in the phosphate treatment system. The phosphate system is used to provide supplementary corrosion resistance for the automotive structure or body-in-white (BIW). If the assembly plant produces steel and aluminum cars simultaneously, the phosphate system can be used if certain conditions are met. If the aluminum to steel ratio is strictly less than 40%, the standard phosphate system can be used with the addition of regular fluoride treatments. [4] However, this does not resolve the problem of aluminum precipitation (which is classified as a hazardous waste by the EPA) but merely keeps the phosphate bath from being poisoned.

Life-Cycle Energy Analysis

Producing aluminum from bauxite requires much more energy than it takes to produce steel from its primary constituents. It takes roughly 40 kWh/kg to produce aluminum, while it takes approximately only 10 kWh/kg to produce steel. However, because of aluminum's low melting temperature, it takes only 1.0 -1.5 kWh/kg to remelt scrap aluminum. Therefore, as recycled aluminum becomes a larger proportion of the aluminum used, the energy content declines. Using 40 kWh/kg for producing aluminum from bauxite, and a standard of 4 kWh/kg for re-processing the aluminum (rolling etc.), and the 1.5 kWh/kg for remelting, the life-cycle energy content of 1 kg of aluminum can be determined numerically. [5]

The maximum energy content of a kg of aluminum that has been recycled *n* times is given by the relationship:

$$E_n \approx (40 + 4*(n-1) + 1.5*(n-1))/n$$

This is shown graphically in Figure 1.3 below.

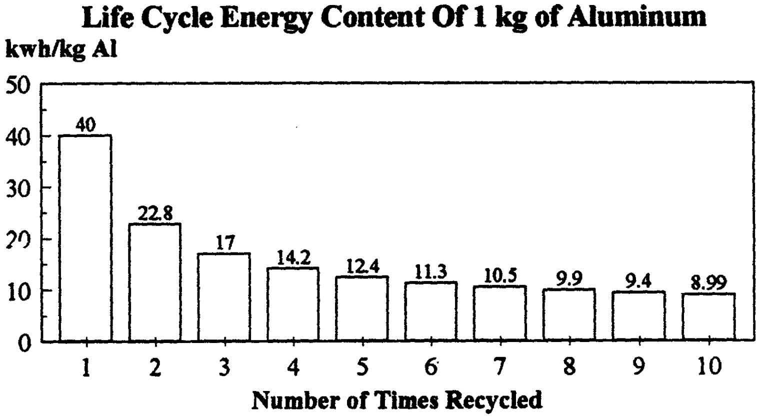


Figure 1.3 The Energy Content of Recycled Aluminum

Another factor hidden by focusing solely on the 40 kWh/kg number is that a vehicle uses less aluminum (based on weight) than would its steel counterpart. Therefore, if one includes this factor in the analysis, using aluminum rather than steel would lead to even greater energy savings overall.

Training Implications

When introducing a new technology, a company must accompany technological introductions with corresponding technical training. In the past, automotive manufacturers have often neglected this piece of technological introduction. Instead, automobile manufacturers have relied heavily on 'on the job training' to provide workers with the necessary skills. The introduction of aluminum will have a tremendous impact on an automobile assembly plant. Introducing aluminum without adequate training will ensure that the impact is disastrous.

One reason training is required is because aluminum is more sensitive to environmental factors. For example, an aluminum stamping area needs to be immaculate. Although stamping facilities are much cleaner today than several years ago, they will need to become much cleaner for processing aluminum. In addition aluminum scratches and dents easier than steel, and it can also be anisotropic, so forming can be difficult. Plant engineers have little awareness of these issues, and therefore awareness training must be performed to ensure high quality levels.

Welding of aluminum is yet another training requirement. Because aluminum does not provide visible cues such as the change of colors that occurs when welding steel, it is much more difficult to weld aluminum by hand. Additionally, the aluminum oxide layer tends to foster the development of micro-cracks due to inclusions upon welding. These differences are foreign to most repair and quality personnel in the plants, thus extensive training will be required to educate these important people.

Field Reparability of Damaged Vehicles

Repair of an aluminum structure by plant personnel was covered in the previous section. However, these in-plant repair people are not the only repair personnel who must learn how to repair aluminum vehicles. Indeed, service technicians in the automobile dealerships need to learn to repair aluminum structures as well. Failure to do so can lead to customer dissatisfaction. After a doctor in Scottsdale, Arizona wrecked his Honda Acura NSX (an all aluminum vehicle) Acura specialists had to be flown in from Japan to assist dealership personnel with the repair. Eventual bill for the moderate damage: $36,000 [6] This kind of expense can not be absorbed by the insurance policies for less expensive cars.

1.2 Pressures Affecting Automotive Industry

1.2.1 Introduction

The next few sections will provide some context in which to view the decisions facing automobile manufacturers. First the threat posed by the Japanese automotive industry will be discussed, followed by some of the relevant federal safety and emission regulations.

1.2.2 The Japanese Automotive Manufacturers Come On Shore

From the introduction of the Ford Model A to the seventies, the trend in cars was bigger, plusher, faster. However, with the first oil crisis in 1973, consumers became aware of an automotive performance metric called fuel economy. Prior to this point, the US. automotive industry dedicated little research effort relative to designing fuel efficient cars.

The Japanese automobile industry had been designing fuel efficient cars for quite some time. This was due, in part, to the Japanese reliance on imported oil and the subsequent high cost of gasoline there; for instance, in 1990 the average cost of gasoline was $1.15 in the US and $3.15 in Japan. In the late sixties and early seventies the Japanese started exporting some of those fuel efficient cars to the United States. The Big Three (GM, Ford and Chrysler) response to these new vehicles was ineffective at stopping the growing popularity of these imports :remember the Ford Pinto, Chevrolet Vega and AMC Pacer?. In a pattern that has been repeated many times in US industry (televisions and video cassette recorders for instance) the Big Three gradually lost this low end of the market to the Japanese. In a few years the Japanese would command a large portion of the small car market.

Soon the Japanese were manufacturing cars in the US in response to US legislation regulating the number of cars the Japanese could export to the US. Establishing transplant operations gave the Japanese automotive manufacturers a significant foothold in the US car market. When they established production facilities in the United States, however, they were not manufacturing the little econoboxes that they had been exporting from Japan. They were introducing newer, larger, and **higher margin** cars. The assault was on.

1.2.3 Motor Vehicle Safety Standards

To ensure occupant protection in vehicular accidents, the National Highway Safety Transportation Administration has adopted a series of standards known as Motor Vehicle Safety Standards (MVSS). While they do not affect the aesthetic design of the car, they have tremendous impact on the structural design. A list of some of these MVSS standards are included in Table 1.1 on the next page.

Standard Designation	Brief Description
MVSS-201	Occupant Protection in interior impact
MVSS-202	Head Restraints
MVSS-203	Impact Protection for the driver from the steering control system
MVSS-204	Steering Control Reward Displacement
MVSS-207	Seating Systems
MVSS-208	Occupant Crash Protection
MVSS-210	Seat Belt Assembly Anchorages
MVSS-214	Side Door Strength
MVSS-216	Roof Crush Resistance

Table 1.1 MVSS Standards Applicable to Structure Design

In addition to the safety standards mentioned above there are several other regulations that US automobile manufacturers must meet or exceed. Conforming with safety regulations becomes even more complicated when selling automobiles in the European Community or other foreign countries, as they have significantly different standards.

1.2.4 Emission Standards

In addition to passenger safety standards, the federal government imposes emission regulations upon automobile manufacturers. The first emission standards were set in 1968 and further tightened by the 1970 Clean Air Act. These standards regulate the amount of tailpipe emissions that a car may emit. There are many ways to meet these tougher emission requirements, but all either require, or are enhanced by, weight reduction of the vehicle. This unfortunately puts emission reduction diametrically opposed to the consumer requirement of better handling. This dynamic is shown in Figure 1.4 below.

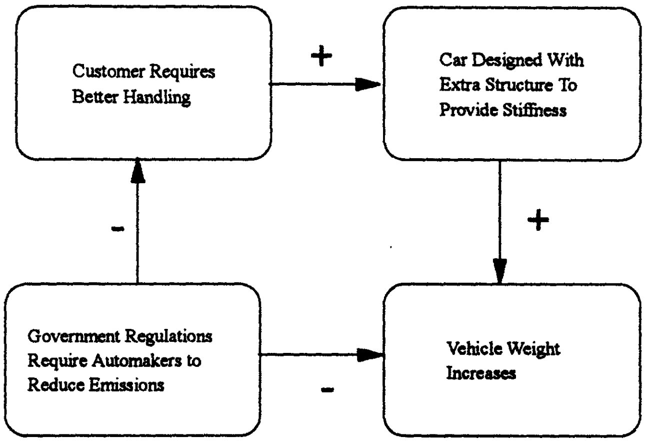


Figure 1.4 Causal loop diagram showing the conflicting requirements of reduced emissions and increased structural stiffness

This plethora of legislative and regulatory pressures, combined with the competitive pressures of offshore automotive manufacturers, makes the current environment for the automotive manufacturers challenging. This pressure, coupled with rapidly changing consumer demands, results in a very dynamic environment. The next chapter will cover some of the interventions tried by the automotive manufacturers in an attempt to cope with these pressures.

2.0 Automotive Industry Interventions

2.1 Introduction

To address these issues of safety, fuel emissions and fuel economy, many interventions have been attempted by the automotive industry. While these interventions have been implemented in one form or another, one thing is unequivocal: they are insufficient to meet all of the regulations and consumer requirements of the future. The next few sections discuss some of the interventions tried by the US automotive manufacturers and present the level of success they have achieved with these interventions.

2.2 Computer Aided Design

Computer aided design (CAD) and more specifically finite element model analysis, are tools that the automotive industry have utilized to develop more weight efficient structures. They have become more elaborate tools as they have matured:. the computer aided software has evolved from dealing strictly with simple models, to the current state of three dimensional solid models capable of performing assembly variation analysis. CAD products such as CATIA™ allow the BIW engineer to design structures three-dimensionally without resorting to prototyping. This has not only increased the speed to market of these designs, but has allowed the designer to implement a much more efficient design.

Additionally, finite element model analysis has allowed the engineer to rapidly iterate on design changes to assess their impact on structural performance. In many instances the design iteration has been performed to reduce the weight of the structure without significantly impacting the structural performance. This has allowed the BIW designer to eliminate the 'fudge-factor' (the inherent over-design of the structure).

But there is a limit to the effectiveness of CAD and finite element analysis. The limitation of the effectiveness of these tools lies in the density of the material with which they are working. Given that there is a basic envelope a car design will occupy, when a design is restricted to a material with a certain density, there is a limit to the amount of improvement one will achieve. These tools are additive in nature, however, and they will provide improvement with **any** other intervention adopted.

2.3 High Strength and Bake Hardenable Steel

Another intervention tried by the auto industry has been the use of high strength and bake-hardening steel. These types of steel utilize the current processes that are used in body-in-white assembly, while reducing structure weight and meeting structural performance requirements. However, high strength steel has manufacturability problems, mainly because of stamping problems due to reduced formability.

The lack of success of high strength steel, coupled with the fact that even higher levels of weight/stiffness performance will be needed to meet future CAFE requirements, suggest that high strength steel will be inadequate to address all of the problems. Therefore, the use of high strength steel will have limited impact in this area because of its inherent weight/stiffness ratio.

Bake hardenable steel combines the best of softer steels and high strength steels. It does this by hardening after forming in the paint ovens. Although bake hardenable steel does provide much better forming properties than high-strength steel, the impact it will have on lightweight structures will still be limited because of the inherent weight/stiffness of steel.

2.4 Aluminum

Aluminum is the latest intervention considered by the auto makers in an attempt to solve the dual problems of weight reduction and structural performance. Although aluminum is relatively new to the auto industry as a structural material, it has been used for decades by major manufacturers in the aerospace and appliance industries. As can be seen by Figure 2.1 below, aluminum use has increased since 1973, but still amounts to only 7% of the material content of an automobile. It is important to note that the majority of the 7% is in chassis components like wheels, HVAC components such as condensers and power train components including engines and transmissions.

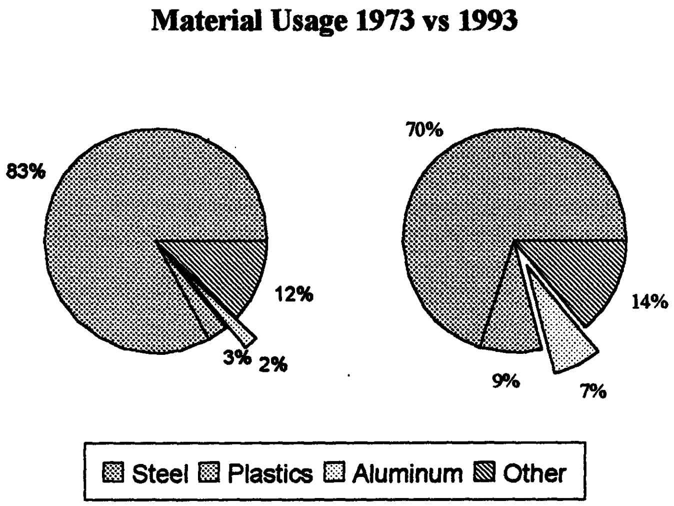


Figure 2.1 Aluminum Usage 1973 vs. 1993

Aluminum provides a potential solution to the structural performance requirements and the weight/environmental issue. In the past, barriers to using aluminum included the lack of applicable alloys, welding problems with aluminum, and the cost of aluminum. Recent developments in alloys have eliminated one problem, and new joining technologies, to be discussed in the next section, have challenged the traditional automotive manufacturing paradigm about joining. Couple these breakthroughs with aluminum being at an all time low in terms of real cost, and the time has never been better to consider aluminum for automotive structures.

3.0 The Joining of Aluminum Structures

3.1 Introduction

Aluminum, next to silicon, is the second most abundant elemental metal found on earth. Finding good applications for this material, once considered a precious metal, has not been so easy, although its abundance and low density make it an attractive option for structural engineers, particularly when weight is a concern. Therefore, decades were spent in trying to find ways in which to produce it from bauxite.

Joining of aluminum structures is not a new process: the aerospace industry has been doing it for years. However, the difference in focus in the automobile industry is on volume and cost; while the aircraft industry can be satisfied with a cycle time of days, a high volume automotive body-shop has cycle times of seconds. Therefore, whatever process is chosen to join aluminum structures, full consideration must be give to quantities such as cycle time and throughput.

Most of the initial research on automotive joining of aluminum has focused on RSW. This is due to the highly entrenched practice of RSW in automotive body-shops today. Every day millions of resistance spot welds are made in automotive body-shops worldwide. But just as using aluminum will require a paradigm shift for automotive designers and manufacturers, so will the eventual joining methodology.

The next several sections discuss developments that have occurred recently for aluminum to be considered as a cost effective alternative material to steel for automotive body structures. The first section will focus on aluminum alloy development and recent cost reductions. The next three sections will discuss three joining processes that are viable for joining aluminum automotive structures in high volume.

3.2 Aluminum as an Automotive Structure Material

The first advance that needed to take place for the high volume production of all aluminum automotive structures was alloy development. Early alloys were deficient purely from a mechanics of materials point of view. The 2XXX series exhibit excellent forming properties, however, because of other mechanical properties, are unfit for automotive structural applications. Indeed, the properties of 2XXX are so low that almost all the weight advantage is lost due to upgaging to meet structural requirements. The 5XXX and the 6XXX series alloys are much more appropriate for automotive structures. These alloys exhibit yield strengths and tensile strengths comparable to some steels. However, the 5XXX and 6XXX series alloys are not as formable as steel and therefore some product improvement is necessary.

A second development required for aluminum to be considered as a replacement for steel in automotive structures was for aluminum to be cost effective in comparison with steel. Steel has become less and less costly as steel manufacturers increase their efficiencies, and as super-efficient mini-mills start production. Today aluminum is at an all time low in real dollars, but is still relatively expensive when compared to steel.

The next three sections introduce and detail the methods of joining aluminum that were investigated: resistance spot welding, self piercing riveting, and adhesive bonding.

3.3 Resistance Spot-Welding

Resistance spot welding (RSW) is the incumbent process for automotive joining. It deserves consideration, however, not because of its incumbency status, but because of its excellent economics and performance. The next section will discuss the process, and then a brief discussion of the advantages and disadvantages of RSW will follow.

3.3.1 The Resistance Spot Welding Process

In *resistance spot welding*, the tips of two electrodes deliver electrical energy and, through resistance heating, produce a spot weld. In order to achieve good adhesion between the parent material and the weld nugget, pressure is applied until the current is turned off. The resistance spot welding process is illustrated in Figures 3.1 -3.3 on the next two pages.

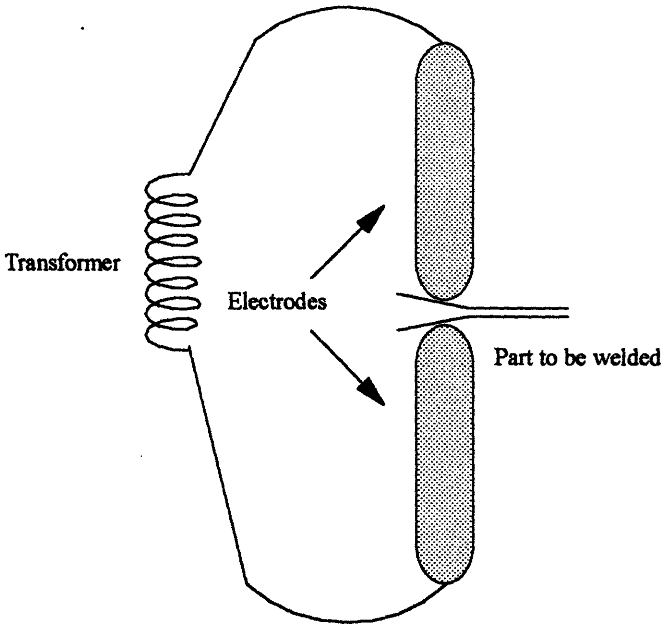


Figure 3.1 Part Presented to welding electrodes with slightly sprung flanges

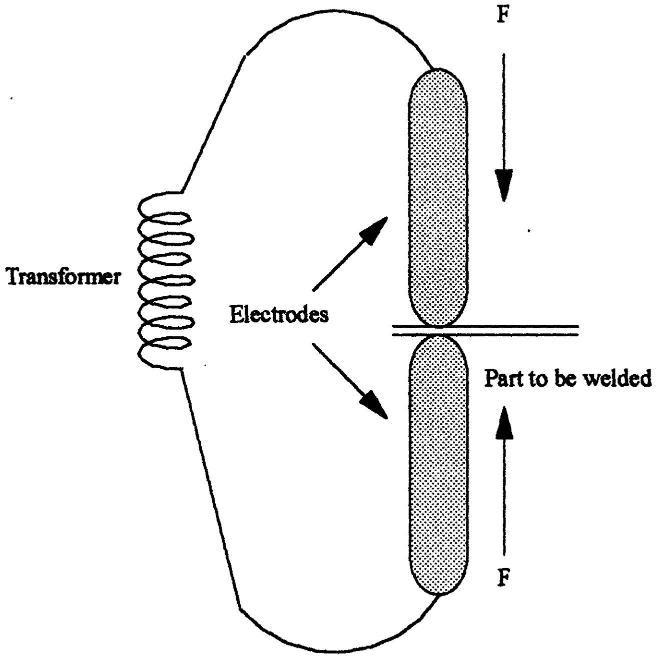


Figure 3.2 Force Being Applied to Part Prior to Welding to Bring Surfaces of Part into Contact

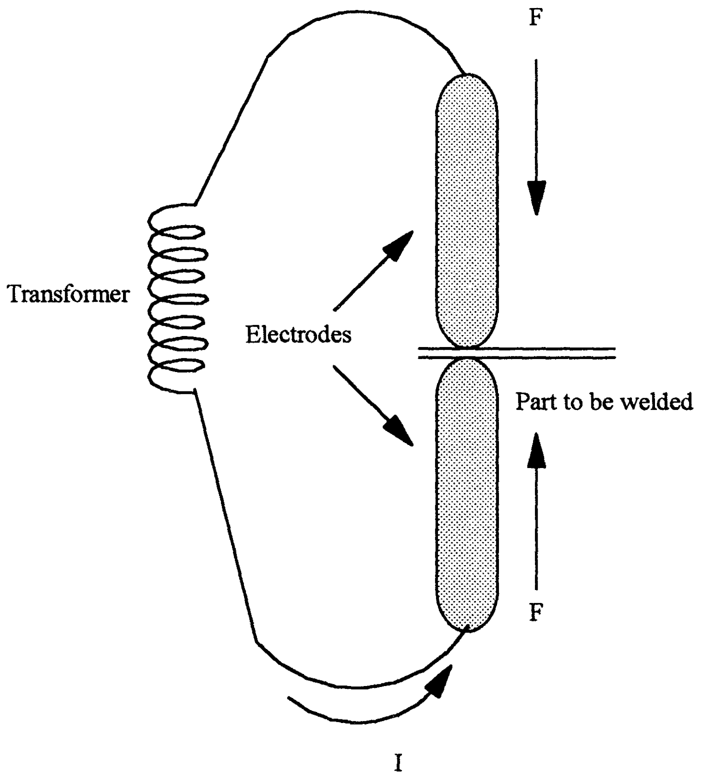


Figure 3.3 Part is Clamped and Current Flows to Perform Weld

The heat necessary to perform resistance spot welding, is governed by the equation [9]

$$H = I^2Rt$$

where

H = heat generated (joules)

I = current (amperes)

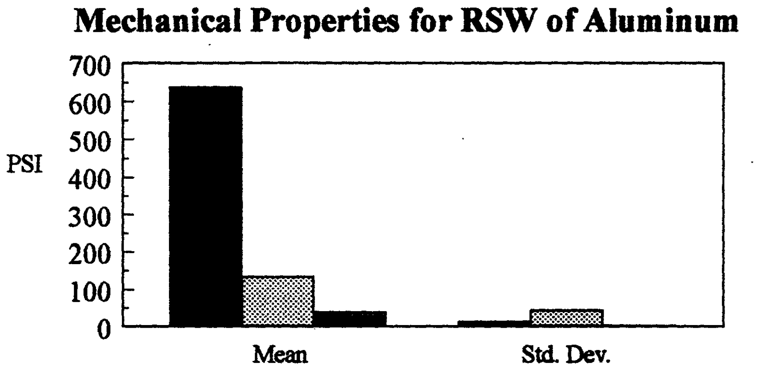
R= resistance (ohms)

t= duration of current flow (seconds)

The peak current required for welding aluminum of a given thickness is up to five times greater than that of comparable structures of steel. This is due to the lower resistance (R) of aluminum, the greater thermal conductivity of aluminum, and because with aluminum it is necessary to supply the heat of fusion. Welding steel only necessitates bringing it into the plastic range. Compound this with the thicker aluminum sheet metal that is used to meet the structural stiffness requirements of the part, and the peak current necessary to weld aluminum is even higher when compared to steel.

3.3.3 The Numbers for RSW of Aluminum

Figure 3.4 details some of the properties of interest for resistance spot welding of aluminum. These are included here because later they will be used to compare RSW with the other methods of joining.



	Mean	Std. Dev.
Shear Strength ■	637 PSI	12 PSI
Torsional Impact ▨	133 PSI	44 PSI
T-Peel ■	39 PSI	3 PSI

Figure 3.4 Summary of mechanical properties for RSW of aluminum

3.3.2 The Advantages and Disadvantages of Resistance Spot Welding

Advantages

Uses current technology

Requires minimal additional retraining

Introduces little surface distortion

Facilitates use of smaller flanges

Adds no additional weight to product

Disadvantages

Provides joint strength 30% that of steel RSW

Lacks robust compensation for sprung flanges

Generates Micro-cracks which are hard to visually identify and can propagate later

Generates fumes

Uses more peak current than other methods

Reduces weld tip life (<100 welds per tip)

Increases line down time due to reduced tip life

Requires some new equipment because of increased current requirement

3.4 Self-Piercing Riveting

Self piercing riveting is a common process in other industries, such as aerospace and appliances, but has found limited application in the automotive industry. The automotive industry is looking at self-piercing riveting now because it provides a possible solution to the problem of joining aluminum structures.

3.4.1 The Self- Piercing Riveting Process

Self-piercing riveting uses a tubular rivet as the fastener as shown in Figure 3.5. The process consists of the rivet being forced into two or more metal sheets which are supported on the bottom by a shaped die. The rivet, if properly designed, will not pierce through the bottom sheet: it will merely roll (or set) into the bottom sheet. Because of this feature no 'slug' of waste material is produced. The process is illustrated in Figures 3.5 - 3.7 below and on the following page:

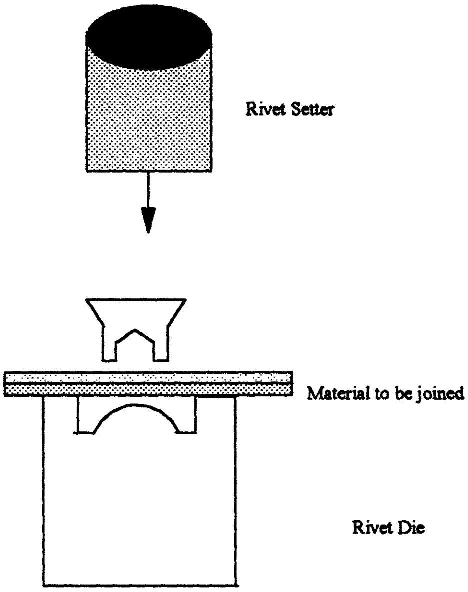


Figure 3.5 Rivet System Before Rivet Setting Force is Applied

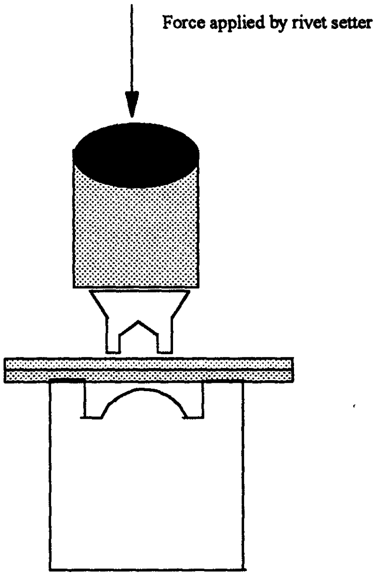


Figure 3.6 Rivet System With Force Applied Prior to Rivet Piercing

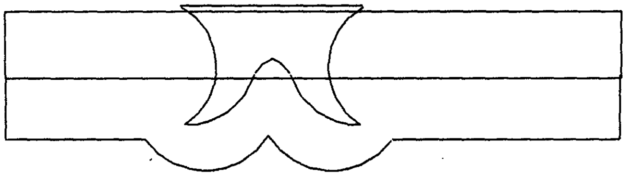


Figure 3.7 Self-Piercing Rivet in Joined Material

Rivets can be manufactured from steel, aluminum, stainless steel, brass, and copper, although, aluminum rivets are preferred for 'soft' aluminum alloys (2XXX series and 5XXX series), because they are inexpensive and do not promote galvanic corrosion. Harder alloys (6XXX and 7XXX series) generally require a stainless steel or steel rivet, that can be supplied with a PTFE coating to prevent galvanic corrosion.

In the next section many of the advantages and disadvantages of the self-piercing riveting process will be discussed.

3.4.2 Advantages and Disadvantages of Self-Piercing Riveting

Advantages

Produces a stronger joint than RSW

Because self-piercing riveting actually produces a mechanical head, it performs much better in mechanical tests such as T-Peel.

Leaves any corrosion protection intact

Requires fewer fastening points due to higher strength of joint

Accommodates sprung flanges when using pre-clamp riveters

Requires less power

Joins dissimilar metals

Generates very little noise

Produces no fumes

Disadvantages

Utilizes largely unfamiliar process

Adds weight to vehicle

Requires wider flanges

Introduces surface distortion.

3.5 Adhesive Bonding

Like resistance spot welding, adhesive bonding is utilized on steel automotive structures and throughout the automobile industry. Adhesive bonding is typically used when high structural stiffness requirements and exposed surfaces are involved. The cosmetic reasons usually stem from having a fastener or weld read through the exposed surface of a panel. For this reason common applications of adhesive bonding are, between the inner and outer panel of a closure panel such as a door, decklid, liftgate or hood.

Different problems arise when trying to bond aluminum panels with adhesive than when trying to adhesive bond steel panels. The non-uniform aluminum oxide layer inhibits good adhesion by the adhesive.

3.5.1 Advantages and Disadvantages of Adhesive Bonding

Advantages

Provides excellent stiffness

Utilizes processes currently used in automobile industry

Disadvantages

Inhibits repair of damaged or defective parts

Provides no deterrent to crack propagation

Generates mess

Requires extremely tight control of paint process

Adds weight to final product

Produces noxious and sometimes toxic fumes

4.0 Factors Affecting Cost in High Volume Aluminum Manufacturing

4.1 Introduction

We investigated many types of aluminum joining, and while many other joining processes were considered, we focused on the following joining processes:

- Resistance Spot Welding
- Self-Piercing Riveting
- Adhesive Bonding

In sections 3.2 - 3.5, many of the advantages and disadvantages were covered for resistance spot welding, self-piercing riveting and adhesive bonding. The next section will discuss some of the stamping cost factors associated with aluminum. Although these factors were not part of the cost model, it is important to consider these issues when determining overall part cost.

4.2 Stamping Factors

Stamping is a process that has changed very little since its adoption by the automotive industry. Some advances in technology have occurred, such as transfer presses, progressive dies, and quick or automatic die change, but the process remains relatively unchanged and unchallenged in terms of its economics.

What follows is an investigation of the stamping process relative to stamping aluminum.

4.2.1 Formability

Aluminum exhibits lower formability compared to steel. Because of this lower formability, and because of the fact that it is more rate sensitive than steel, aluminum is formed at much lower stamping rates than steel. The substantial capital investment is thus amortized over fewer pieces, and increases cost.

Furthermore as aluminum is formed the surface layer of aluminum oxide is stressed and often loosened from the substrate. This phenomenon occurs with galvanized steel as well, but the zinc is not as abrasive as aluminum oxide. Indeed, aluminum oxide is so abrasive that it is used in many grades of sandpaper. In many aluminum stamping production runs that we witnessed, the dies required wiping to prevent abrasive build up which would either marl or cause splits to occur in the panel.

Another problem with aluminum is its lower stretchability and formability. Due to this feature deep formations in aluminum panels cannot be achieved. This problem occurs in areas such as the wheel wells, apertures and in the spare tire mounting area.

Aluminum also requires larger bend radii in the formed stamping than steel. Due to the lower intrinsic formability of aluminum, the radii on the dies need to be larger to allow more metal to flow into the draw to allow for panel formation: empirical data generated showed that a ratio of 1.5 times the thickness (1.5*T) of the formed sheet to be a good approximation of the radii necessary. Initially, the 1.5*T radii requirement does not appear to be overly restrictive. However, when combined with the aluminum sheet thickness (which will be around 1.5 times that of steel) the radii is even larger.

Another problem with stamping aluminum is that it has higher (and often anisotropic) spring back. Engineers are accustomed to compensating for the spring back in steel. Since aluminum behaves radically different, and with the difficulty companies are having modeling this phenomena, it will be a while before companies feel comfortable designing in aluminum.

Additionally, age hardening constitutes another difficulty with stamping aluminum. Age hardening causes problems because blanks become unusable after awhile. Therefore, because of age hardening, meticulous inventory management is required: the inventory management must govern not only quantity, but also ensure that the system is truly first in first out (FIFO).Age hardening can also negatively affect the work-in-process (WIP), particularly for sub-assemblies such as doors, hoods, and deck lids. If one is not careful about how this is managed inventory spoilage can result. Again, JIT helps here but this must be managed carefully.

4.2.2 In Process Scrap Reclamation

Another factor affecting stamping aluminum in a central stamping facility is the reclamation of in-process scrap. Today central stamping plants process only steel, and all the in-process scrap is shed through the bottom of the press onto a press-line scrap conveyor. This is shown in Figure 4.1 below. From this press line conveyor, the material is delivered to the plants main conveyor where all plant scrap is combined. This is shown in Figure 4.2 on the next page. This is both efficient and practical for steel because there is little or no salvage value differential for the different alloys of steel. This is not true with alloys of aluminum. As shown in Table A.1, the price of scrap aluminum varies greatly. In addition, aluminum scrap can not be combined with steel or other types of scrap because of the difficulty in sorting later.

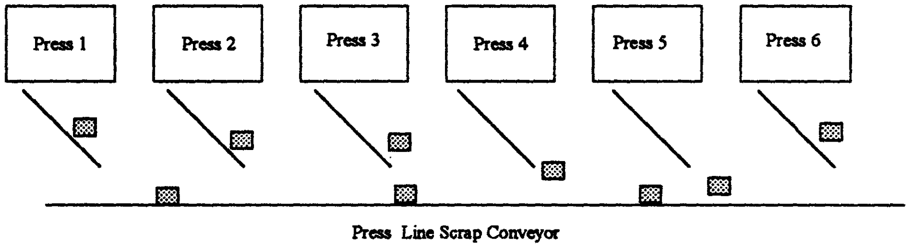


Figure 4.1 Showing scrap coming out of stamping presses onto conveyor

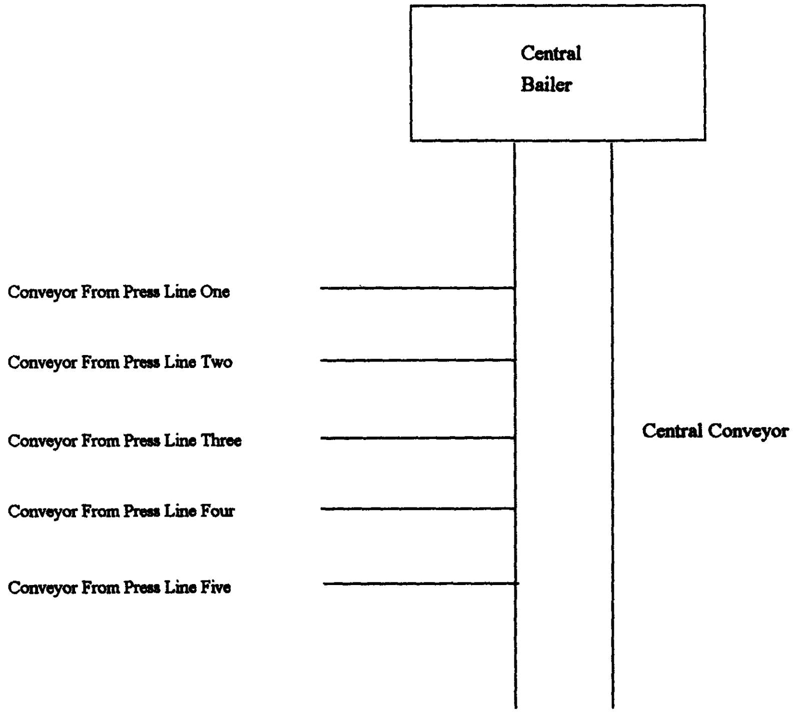


Figure 4.2 Press Line Conveyors Feeding Central Conveyor Which Delivers Scrap to Central Bailer

A simple (but wasteful) solution to this problem is self-evident: as shown in Figure 4.3, by introducing a magnetic sorter before the bailer, the aluminum can be sorted from the steel quite easily. However, this only partially solves the problem because it does not address sorting the different alloys of aluminum. Today this mixture of alloys is recycled and used as casting material. With casting tonnage requirements outpacing recycling of high alloy aluminum (the current situation), using recycled aluminum in this manner presents no problems. In the future, however, if tonnage of high alloy structural material outpaces the usage of casting material the problem will get worse.

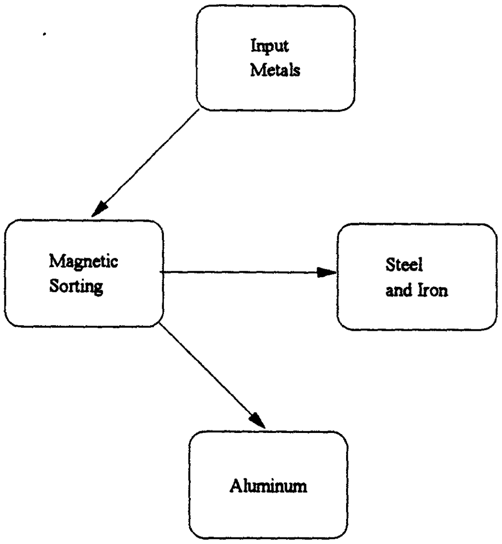


Figure 4.3 Sorting process for mixed metal scrap

Ideally, the in-process scrap should be diverted so that different alloys go to different staging areas, where they are bailed separately, instead of the current situation in which all scrap is being bailed simultaneously This will add complexity to the process, but ensure that the scrap reclamation process will meet the needs of the future.

4.3 Recyclability

While not currently regulated by the federal government, recycling will continue to receive increasing legislative attention. In Europe, which has traditionally lead the US in recycling and other environmental efforts, there are movements requiring automotive manufacturers to be responsible for the recyclability of their cars. In fact, there is pending legislation in Germany that would require automobile manufacturers to recycle their own cars after the consumer is done with them.

In addition to the problem posed by different alloys of aluminum are the difficulties caused by steel plastics and other contaminants in the scrap. Plastics and the sort of scrap usually obtained from recycled automobiles do not present a problem when recycling steel since steel melts at around 2700°F: at this temperature the contaminants mixed in with the steel are burned off. In contrast, as shown in Table A.1, aluminum melts at around 1000° F. At this lower temperature, many plastics and other contaminants are not burned off. This means that much more care has to be taken in recycling aluminum from autos than has typically been taken when recycling steel. Indeed, design for recycling becomes a big issue here. The presence of mixed material scrap (as opposed to mixed metal scrap) introduces another step in the separation process. This extra step is illustrated in Figure 4.4 .

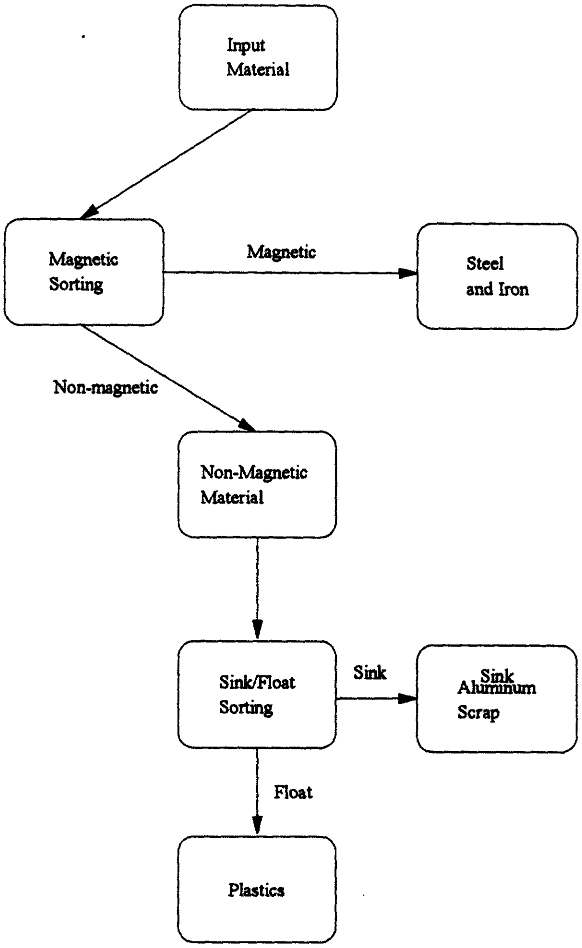


Figure 4.4 Sorting Process for Mixed Material Scrap

Even the presence of small amounts of steel and iron presents a problem for recycling. This complication is due to the difference in melting temperature. As discussed earlier one can use magnetic sorting to sort out most of the iron/steel. However, small fasteners such as screws and rivets present an additional problem: currently, removing them by mechanical means such as drilling out remains the only reliable source of removal.

Consideration of recyclability issues at the design stage certainly simplifies post-use recycling. For instance, if economical, designing the inner and outer panel of a given component (such as doors, hoods and deck lids) out of the same alloy would greatly increase the recyclability of that component. If components must be manufactured from different alloys, making them detachable by removal of mechanical fasteners (screws, bolts etc.) would also improve recyclability significantly. Eventually, there needs to be an industry-wide set of recycling symbols for various alloys of aluminum (such as there is now for plastics) to facilitate recycling. These recycling symbols would facilitate easy identification of different alloys of aluminum, which currently are extremely difficult to differentiate.

Unfortunately there is a good reason for running different alloys. The 5XXX series alloys offer good formability, good corrosion resistance, and moderate strength and relatively low cost. This combination of factors makes the 5XXX series alloys excellent choices for unexposed panels such as underbody panels, inner door and hood panels and wheel house inner panels. The 6XXX series alloys offer moderate formability, moderate corrosion resistance, and excellent strength, but with a slightly higher cost. This set of attributes makes the 6XXX series alloys excellent choices for exposed panels such as door and hood outer panels, deck lid outer panels and fenders.

4.4 Destacking of Aluminum Sheet

Because aluminum scratches so easy, is susceptible to contaminants, and is non-magnetic, destacking of aluminum is complex to accomplish. This difficulty arises partially because standard automatic destacker for steel utilize the magnetic properties of steel in two very important areas: fanning of sheets and transport.

4.4.1 Fanning Magnets

Fanning magnets are used to separate the sheets of steel in a typical steel destacking unit. The fanning magnets are required to perform this function because the mill oil left on the blanks and the large amount of surface area of the sheet make it impossible in some cases for the vacuum cups on the destacker unit to pick up the blank. More vacuum cups and increased vacuum can typically circumvent the suction problem from the mill oil; however, this is a precarious situation because the cup marks start to show through the sheet if one is not careful. A stack of steel with fanning magnets spreading the sheets is shown in Figure 4.5 below.

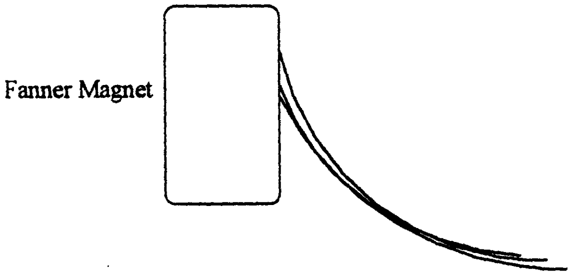


Figure 4.5 Fanner Magnet Spreading Sheets Breaking Suction Between the Sheets

4.4.2 Transport of Blanks

The transporting of blanks constitutes another problem. The following depicts the typical transport process:

1. Blank is lifted to transport belt by pick-up cage
2. Blank is held to transport belts by permanent magnets
3. Belt rotates, moving blank into press area

A plan view of a typical pick-up cage is shown below in Figure 4.6. Because it uses vacuum cups to pick up the part, only minor modifications are required for this component. The only change necessary might be a denser arrangement of vacuum cups to compensate for the lack of fanning magnet assistance in sheet separation.

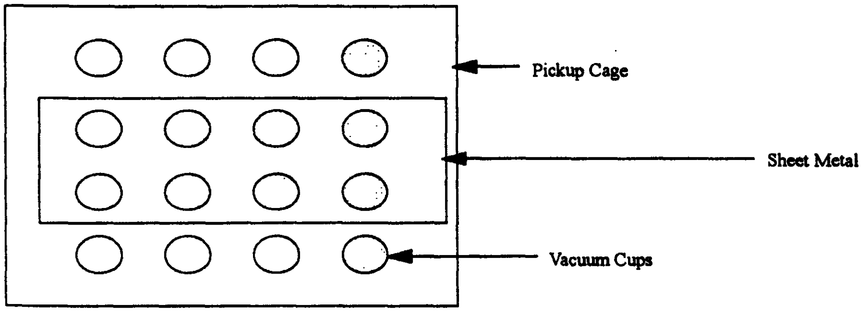


Figure 4.6 Plan View of Pickup Cage Component of Destacker

Once the pick-up cage has picked up one piece of the sheet metal and delivered it to the transport belt the transport unit uses permanent magnets to keep the part on the transport belt. After the vacuum has been released from the vacuum cups, the transport belt indexes the part into the press area. A standard transport mechanism is displayed in Figure 4.7 on the next page.

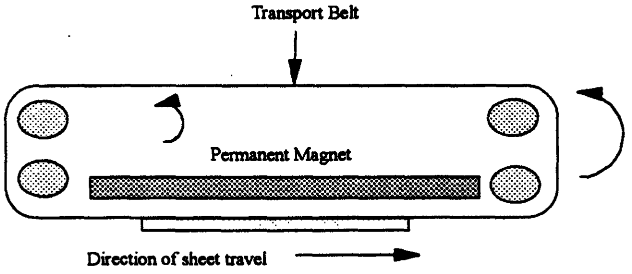


Figure 4.7 Side View of Transport Belt Component of Destacker

Transporting aluminum blanks will have to be accomplished in a much different way. Destackers that use a derivative of the vacuum pickup cage to transport the blanks are possible but complex. While this method of transport will work, it cannot approach the speed of the current destacking methods, which can accommodate press speeds of up to 20 press strokes per minute (SPM). The reduced SPM rating of the destacker may not be an issue initially, since current press speeds are limited to approximately 8 SPM.

4.5 Material Costs

As mentioned earlier the cost per pound of aluminum is five times higher than steel. This is mitigated by the fact that aluminum is roughly 1/3 the density of steel. However, because of structural rigidity requirements, roughly 1.5 - 2.0 times the thickness of aluminum is used, therefore mitigating a large amount of the advantage aluminum has over steel.

Also, as previously discussed, aluminum is at an all time low cost per pound. This price may be artificially low however, because of Russian dumping aluminum that was previously produced for the Russian defense industry. As costs continue to rise in Russia, capitalism takes hold, and wages begin to increase, the price will once again start to rise.

5.0 Cost Model For All Aluminum Automotive Body Shop

5.1 Introduction

This chapter analyzes the impact on product cost that aluminum and its associated processes will have in an automotive body manufacturing facility. This analysis assumes that the joining process to be used will be self-piercing riveting, since it showed the broadest promise in terms of production viability. The first section of this chapter will analyze the capital cost to replace the RSW equipment of a typical automotive assembly plant. The cost model will assume that no additional expenses are incurred for things such as additional robots, automation, etc., since most production riveting equipment is designed to replace resistance spot welding equipment, and thus easily adapts to current automation.

5.2 Capital Costs of Self-Piercing Riveting

The methodology used to determine the capital costs associated with self-piercing riveting is as follows:

1. Determine Volume Requirements For Plant per year(V)
2. Determine Number of Rivets to be in BIW (R)
3. Determine Cycle Time of Riveter (CT)
4. Determine Inter-Rivet Time (IRT)
5. Determine Part Transfer Time (PTT)
6. Determine Number of Shifts (S)
7. Determine Hours Per Shift (HPS)
8. Determine Days of Production Per Year (DPY)
9. Calculate Rivet System Efficiency (EFF)

Given the preceding information a straightforward calculation determines the number of rivet systems required to facilitate the body-shop specified.

Minimum number of rivet systems required ≈

$$\frac{V*R*(CT/EFF)}{S*HPS*60(\text{mins/hr})*60(\text{secs/min})*DPY}$$

The term CT/(CT+IRT) can be thought of as the maximum efficiency of the riveting system, for it represents the maximum fraction of the time that the riveting system can actually perform riveting. The cycle times for the processes involved are depicted below in Figure 5.1.

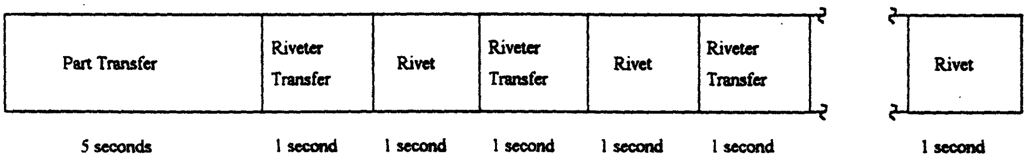


Figure 5.1 The Components of Rivet System Cycle Time

The efficiency of the above system can be precisely calculated by the following equation:

Efficiency = Riveting Time/ (Total Cycle Time)

Efficiency = n*CT/(n*CT + n*IRT + PTT)

Cycle time and inter-rivet time are multiplied by n (the number of rivets set per part) because they occur n times per part, while part transfer time occurs only once per cycle. By substituting the actual values for CT, IRT and PTT one arrives at the equation on the following page:

$$\text{Efficiency} = n/(5 + 2n)$$

(2)

The corresponding curve equation (2) is displayed in Figure 5.2 below.

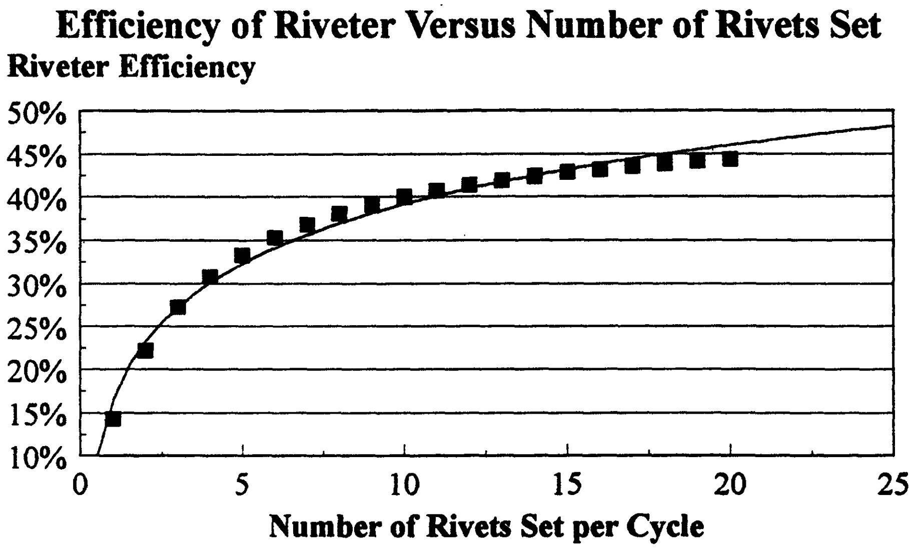


Figure 5.2 Efficiency of Riveting System as a Function of Number of Rivets Set

Table 5.1 provides the number of rivet systems required for various volumes and number of rivets per BIW. The table shown assumes a riveter efficiency of 45 %.

Number of Rivets in BIW	250000	275000	300000	325000	350000
1000	42	46	50	54	58
1250	52	57	62	67	73
1500	62	68	75	81	87
1750	73	80	87	94	101
2000	783	91	99	107	116
2500	9103	114	124	134	145
3000	124	136	149	161	173

Table 5.1 Number of Riveting Systems Required For Various Production Volumes and Number of Rivets per Body-in-White.

Once the number of rivet systems has been calculated the total capital investment is given by:

Total Capital Investment ≈

Number of Rivet Systems Required * Cost Per Rivet System

Table 5.2 on the following page displays the capital cost of riveting systems corresponding to the required number as determined previously and shown in Table 5.1 above. The cost per rivet system is $16,500. [7]

	Vehicle Produced per Year				
Number of Rivets in BIW	250000	275000	300000	325000	350000
1000	$1,008,000	$1,104,000	$1,200,000	$1,296,000	$1,392,000
1250	$1,248,000	1,368,000	$1,488,000	$1,608,000	$1,752,000
1500	$1,488,000	$1,632,000	$1,800,000	$1,944,000	$2,088,000
1750	$1,752,000	$1,920,000	$2,088,000	$2,256,000	$2,424,000
2000	$1,992,000	$2,184,000	$2,376,000	$2,568,000	$2,784,000
2500	$2,472,000	$2,736,000	$2,976,000	$3,216,000	$3,480,000
3000	$2,976,000	$3,264,000	$3,576,000	$3,864,000	$4,752,000

Table 5.2 Capital Cost to Facilitize Manufacturing Facility to Produce Various Combinations of Number of Rivets and Production Volumes

5.3 Cost Impact on a per Vehicle Basis

The next step in this cost analysis is to amortize these cost over the vehicles to be produced. To do this one must determine the lifetime of the equipment; in the body of this paper the lifetime of the equipment is assumed to be 10 years. To put this assumption in perspective, this equipment would go through two vehicle renewals in the same assembly plant, and cycle at least 2.5 million times. Eventually process equipment repair costs (and the associated downtime) will exceed replacement costs. Ten years is also the approximate lifetime of current RSW equipment in the assembly plants.

	Vehicle Production Per Year				
Number of Rivets in BIW	250000	275000	300000	325000	350000
1000	$0.40	$0.40	$0.40	$0.40	$0.40
1250	$0.50	$0.50	$0.50	$0.50	$0.50
1500	$0.60	$0.60	$0.60	$0.60	$0.60
1750	$0.70	$0.70	$0.70	$0.70	$0.70
2000	$0.80	$0.80	$0.80	$0.80	$0.80
2500	$0.99	$0.99	$0.99	$0.99	$0.99
3000	$1.19	$1.19	$1.19	$1.19	$1.19

Table 5.3 Capital Costs from Table 5.2 Distributed Over the Number of Vehicles Produced

This traditional approach, however, does not recognize the cost of capital. Therefore, factoring in the cost of capital (for debt financing) one obtains the equivalent per car costs in Table 5.3 on the next page. The table values were calculated using the following formula:

Per year amount = Capital expenditure $*(1/r - 1/[r(1+r)^t])$ [8]

	Vehicle Production Per Year				
Number of Rivets in BIW	250000	275000	300000	325000	350000
1000	$0.71	$0.71	$0.71	$0.71	$0.71
1250	$0.88	$0.88	$0.88	$0.88	$0.88
1500	$1.05	$1.05	$1.05	$1.05	$1.05
1750	$1.24	$1.24	$1.24	$1.24	$1.24
2000	$1.41	$1.41	$1.41	$1.41	$1.41
2500	$1.75	$1.75	$1.75	$1.75	$1.75
3000	$2.11	$2.11	$2.11	$2.11	$2.11

Table 5.4 The Cost of Equipment from Table 5.2 Distributed Over the Number Of Vehicles Produced Plus the Cost of Capital

Finally to determine the total cost of joining the vehicle, one must include the cost of the rivets. Assuming a cost of $.05 per rivet, the cost per vehicle joined is derived and is provided in Table 5.5.

Number of Rivets in BIW	Vehicle Production Per Year 250000	275000	300000	325000	350000
1000	$51	$51	$51	$51	$51
1250	$63	$63	$63	$63	$63
1500	$76	$76	$76	$76	$76
1750	$89	$89	$89	$89	$89
2000	$101	$101	$101	$101	$101
2500	$127	$127	$127	$127	$127
3000	$152	$152	$152	$152	$152

Table 5.5 The Total Cost of Joining the Vehicle Including the Cost of the Rivets

One important observation needs to be made here: **the cost is completely driven by the cost of the rivet**. Even if different efficiencies are used, the cost is still determined by the price of the rivet.

6.0 Cost Comparison Between Resistance Spot Welding and Self-Piercing Riveting

In chapter 5 a technical cost model for self-piercing riveting was presented. Some sensitivity analysis was performed, and it was demonstrated that the cost for assembly was primarily driven by the cost of the rivet. In this chapter the cost of self-piercing riveting will be compared with the cost of resistance spot welding.

6.1 Assembly Costs Using Resistance Spot Welding

In Han [1994] a technical cost model was constructed for resistance spot welding of aluminum vehicles. In the referenced cost model, the author included expenses not included in the cost model detailed in chapter 5 of this thesis. Those expenditures will be incorporated here, so that the comparison presented here is accurate. The major assumptions of the cost model in Han [1994] include:

- BIW Uses Resistance Spot Welds Only (No Adhesive Bonding)
- Aluminum Design Requires 20% more welds
    - Aluminum BIW Requires 5,280 Welds
    - Steel BIW Requires 4,400 Welds
- Welding Tip Lasts 1,000 Cycles

Table 6.1 Summary of Assumptions in Cost Model [10]

It is interesting to note the generous tip life the author assumed. In experiments performed during the internship, the tip life observed was significantly smaller. Although tip life will not be adjusted for the comparison, a reduction in weld tip life, and the associated down time, would significantly increase the manufacturing cost.

A summary of the results of the technical cost model in Han [1994] are as follows:

- ➤ Total Assembly Cost of Aluminum BIW $598
- ➤ Total Assembly Cost of Steel BIW $469
- ➤ Additional Cost per Aluminum Spot Weld $0.04
- ➤ Additional Cost per Steel Spot Weld $0.03

Table 6.2 Results of Cost Model in Han [1994]

While the resistance spot welding cost model for aluminum used 5,280 welds, a comparable riveted vehicle will comprise significantly fewer rivets. This is due to two factors: 1) The number of welds in the RSW model for aluminum necessarily compensates for the inherent variability in the weld quality, therefore increasing the number of welds by 20%, and 2) The steel BIW includes 10 % -20 % extra welds to ensure a minimum number of good welds is obtained. However, because of the excellent process capability of self-piercing riveting, only 4000 rivets will be included for the BIW.

6.2 Comparison of Costs

Once the extra expenditures were included in the model presented in chapter 5, comparable numbers were obtained. The numerical results are presented in Table 6.3 pn the following page::

p. 52

7.0 Strategic Advantages of Aluminum Intensive Vehicles

Even with all the problems of manufacturing aluminum structures, there are many strategic reasons why automakers would want to produce them. Thus, even if a financial analysis of the situation suggests that an aluminum vehicle is more expensive, there are several benefits to automobile manufacturers for producing an aluminum vehicle. The next several sections will discuss some of the possible advantages of manufacturing a structure out of aluminum. Sections 7.1.1 and 7.1.2 discuss process advantages while sections 7.2.1- 7.2.7 will concentrate on product advantages. Finally, a summary section will discuss will discuss possible objective alternatives for aluminum prototype development projects.

7.1 Process Advantages of Manufacturing Aluminum Vehicles

7.1.1 End of the Process Laggard

One of the many possible strategic advantages of aluminum-intensive vehicles is the possibility of a company that has typically been a process development laggard to assume the process leadership for a new technology. Because of the long history of resistance spot welding by automotive manufacturers, some companies have developed superior RSW technology. If aluminum intensive vehicles are the cars of the future, then joining methods such as self-piercing riveting are going to be required. This new joining technology can enable an automotive manufacturer that has typically been a process development follower to suddenly become a leader, and thus effectively eradicating decades of followership.

The preceding argument assumes that a company that is going to change its decades of followership, will be proactive and aggressively pursue this technology. If the company follows a conservative wait and see approach, it will once again find that itself behind the learning curve, and will be left in the wake of the change to yet another technology.

7.1.2 Process Knowledge Can Be Included in Steel Designs

Because aluminum is more difficult to process than steel, particularly forming and joining, process knowledge obtained manufacturing aluminum vehicles can be applied to manufacturing steel cars. For example, any forming analysis that is done for aluminum, can be easily modified to understand steel forming better. Also, new processes that are developed to accommodate aluminum may be improvements and cost effective for manufacturing steel vehicles.

7.2 Product Advantages

7.2.1 Consumer Perception of Aluminum Cars

While other automobile manufacturers are marketing their steel cars, a car company that has mastered high volume manufacturing of aluminum vehicles will possess a strategic advantage. Although a low-volume car, the Audi ASF is being marketed this way. The ASF boasts the attractive combination of higher performance and higher efficiency which are two key characteristics that a consumer is looking for today. As the perceptual; map below demonstrates, aluminum vehicles are able to deliver **both** higher performance and higher economy simultaneously.

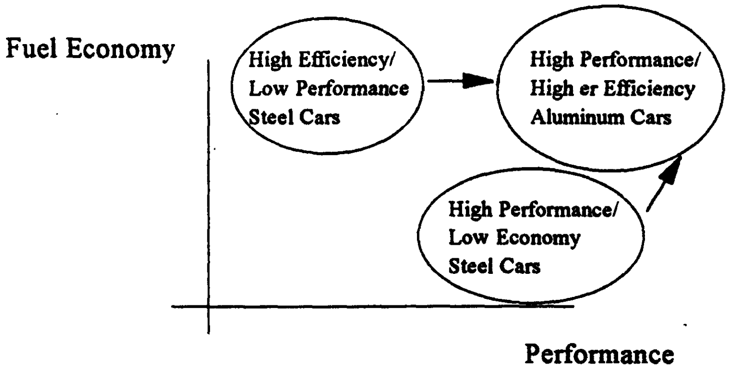


Figure 7.1 Perceptual Map Showing Position of Aluminum Versus Steel Cars on Metrics of Performance and Efficiency

7.2.2 Reduced System Cost

Although the aluminum BIW is more expensive at current economics, such a narrowly focused comparison is a mistake. While the BIW is a large part of the overall cost of a vehicle, it is but one component. Other major modules include: engine, transmission, suspension, brakes, cooling module, instrument panel, and fuel tank.

Since an all aluminum vehicle has a lower BIW weight, this poses two possible alternatives an automaker can pursue. First is the path most often proposed: keeping the engine the same as for a steel car and, therefore, by virtue of the lower weight of the vehicle, the performance (both acceleration and fuel economy) will have increased. This is certainly an option one would want to pursue for lightweight performance cars, or if investment for a new engine line needs to be avoided.

Another avenue is taking the system perspective and reducing overall component sizes to reflect the lower body weight. For example, a smaller displacement engine in an aluminum intensive car can achieve the same performance as a larger engine in a car with a steel structure. Since the overall system weight is lower the vehicle achieves better fuel economy and requires less fuel and a smaller fuel tank. This is best illustrated in chart form below:

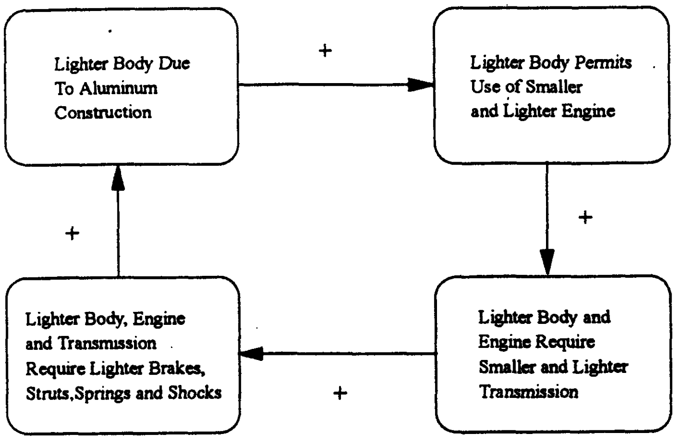


Figure 7.2 Illustration of Systemic Effects of the Reduction in BIW Weight

This **virtuous cycle** can deliver the vehicle features a customer wants while meeting the regulatory demands of the various regulatory bodies.

7.2.3 Increased Safety

With the reduced weight of the BIW and the reduced overall vehicle weight, the all aluminum vehicle has an advantage in safety. Because of the reduced weight of the vehicle, we have less energy to manage in a single vehicle impact. Since the vehicle will have to meet other requirements, it will perform as well, or better, than a steel vehicle in multi-car accidents.

7.2.4 Increased Performance of Aluminum Vehicles

By virtue of its lower BIW weight, an all aluminum vehicle will demonstrate better performance numbers. For example, for every 125 lb. reduction in vehicle weight, the fuel economy is increased 0.5 mile per gallon, while taking 0.2 seconds off the zero to sixty time. [11]

7.2.5 Reduced Noise Vibration And Harshness

Aluminum has a different damping coefficient as well. Because of this the all aluminum vehicle will exhibit a quieter ride. It will also demonstrate different harmonic frequencies which will enhance the feel of the car during handling --giving the owner a feeling that the car is better.

7.2.6 First Mover Advantage

Clearly Audi has the first mover advantage. But because of where the car is positioned, in the luxury sports car realm, there is still room for a mass produced vehicle to assume the first mover advantage. Clearly this has enhanced Audi's reputation as an excellent engineering company as well. A car company that would mass produce an aluminum intensive vehicle would be perceived as an excellent engineering firm. This perception could even impact perception of the other vehicles the manufacturers produce.

7.2.7 Electric Vehicle Applications

An untapped source of competitive advantage for aluminum cars is in production electric vehicles. Clearly the biggest challenge that faces electric cars today is battery technology; it has been for years and will continue to be so for many years to come. However, aluminum body construction may serve as a intermediate step for electric vehicles, since it is estimated that for every pound of weight removed from a vehicle, it is possible to reduce the battery weight by approximately a pound. For example, vehicles such as the GM Impact hold great promise for electric vehicles. At 295 lb. the Impact structure weighs in at 55 lb. less than the Acura NSX structure(another all aluminum vehicle). This lower body weight will increase the range of the vehicle.

The Impact also delivered high numbers for two key BIW measures: first bending moment and first torsional moment. First bending moment measured 28 Hz. The first torsional moment registered 33 Hz. Static torsional stiffness measured 16,000 Nm/degree. As a comparison, standard car today is in the 8,000 -10,000 Nm/degree range. This clearly shows that aluminum vehicles can deliver comparable, if not better, performance than comparable steel cars.

The numbers for the Impact are impressive, but the manufacturability of the Impact still puts it in the mid to low volume market. In addition, because it is a two passenger vehicle, it will probably have limited demand in the vehicle market. Again, another problem here is the lack of appropriate battery technology.

7.3 Preemptive Measure Against Future Government Regulations

Maybe one of the most compelling reasons to design and develop all aluminum cars is as a preemptive measure against future government regulations. Currently there are a number of US and state regulatory agencies affecting the US automotive industry. Among them are:

- United States Environmental Protection Agency (EPA)
- California Air Resources Board (CARB)
- State legislatures in Massachusetts, New York, Texas and other States

7.3.1 Corporate Average Fuel Economy (CAFE)

Recently the US government enacted a new higher CAFE standard for light trucks and vans of 20.1 mpg, a much lower standard than what was proposed by many environmental groups. Indeed, this small increase was seen by many as a victory for the Big Three. Currently, CAFE standards for passenger cars remains 27.5 mpg, however, with President Clinton's campaign promise of 40 -45 mpg in hand, environmental lobbyists are increasing the pressure on the Clinton administration. Presently, due to consumer preference for larger cars, the Big Three are barely able to meet this standard.

7.3.2 California Air Resources Board (CARB)

California has the largest number of registered vehicles of any state in the United States. It also has some of the worst air quality, particularly in the LA metropolitan region. Largely in response to public and governmental pressure the California Air Resources Board was formed. CARB issues emissions control legislation that dictates emission standards for vehicles sold in California. Typically these standards are stricter (i.e. require lower emissions) than federal standards set by the EPA.

Simply having control over the largest single state in terms of vehicle registrations gives CARB tremendous leverage. This leverage is compounded by the several other states (Maine, Massachusetts, and New York) who look to California for guidance in setting their emissions standards.

7.4 Organizational Reasons for Producing Aluminum Vehicles

While the goal of a skunk works project such as producing prototype aluminum vehicles can have many purposes, this paper will identify and briefly discuss only three of them. These three goals have been chosen because they represent two extremes and a middle ground of the continuum of goals.

Three possible goals for a project of this type:

- Prepare against the eventuality of having to use aluminum
- Develop new manufacturing processes
- Learn about aluminum designing and aluminum manufacturing processes

It is also interest to note that as mentioned in 7.1.2, that much of what is learned in processing aluminum vehicles can be applied to other vehicles.

7.4.3 Prepare Against the Eventuality of Having to Use Aluminum

Of the three goals presented preparing against having to use aluminum is the most defensive in nature and, consequently, the least proactive. The intent here is to learn only as much as is necessary in the event future manifestations, such as CAFE increases, mandate higher fuel economy or reduced emissions; thus, requiring a manufacturer to utilize some light weighting technology to meet the new standards. Indeed this is not much more than a simple feasibility project.

It is important to note that in this scenario very little organizational learning occurs. The objective of preparedness is affable if one is merely looking to learn about one aspect of a technology. However, in the case of aluminum, there is a plethora of technologies and processes to learn, thus, having simple preparedness as the objective is short sighted.

7.4.2 Investigate New Manufacturing Processes Required for Processing Aluminum

The desired results of this approach are more proactive than merely a feasibility analysis. In this scenario the engineering community is proactively looking toward the future of automotive design. This forward looking group is looking to incorporate the latest available technologies into their designs of next generation vehicles; furthermore, they are perusing the associated processes that accompany the new technologies.

While a great deal of organizational learning occurs here it is limited to only one function of the manufacturing company- engineering. This approach, while superior to simple preparedness, lacks the cross-functional organizational learning that needs to take place in order to fully exploit aluminum.

7.4.3 Learn About Aluminum Vehicle Design and Manufacturing Processes

The mission of learning about aluminum vehicle design and manufacturing processes can lead to a tremendous amount of organizational learning. This approach involves all functions, from engineering to purchasing and manufacturing, whereas, previously discussed tactics predominantly involved engineering. Verily, it is the multi-disciplinary approach to this method that provides the cross-functional organizational learning.

Many reasons can be espoused for not following this approach: we are understaffed, we are too busy fighting fires, aluminum will never make it as an automotive material.. the list is endless. People often fail to realize that it is less expensive, and easier, to experiment now, than to tinker around when full volume production is approaching.

7.4 Summary

Several product and process reasons have been presented in the preceding sections detailing why an automaker would want to produce an aluminum vehicle. If an automotive manufacturer is willing to dedicate resources to a 'skunk-works' project that focuses both on developing design capabilities in conjunction with the appropriate manufacturing process, tremendous organizational learning can result.

The next chapter provides some recommendations for automotive companies, and the particular functions within the automakers, to follow when embarking on the design and manufacture of a high volume all aluminum vehicle.

8.0 Recommendations

8.1 Introduction

With all the undecided aspects of producing a high volume all aluminum automobile, clearly there will not be one rolling off the assembly line in the immediate future. That doesn't mean that in 5 - 10 years the economics will not be favorable. Currently, with the low price of gasoline (approximately $1/gallon), consumers are unwilling to bear **any** additional costs associated with the all aluminum body structure. This unwillingness is a pure economic decision: until the money saved due to the extra economy provided by an all aluminum vehicle exceeds the additional cost associated with the aluminum vehicle.

In addition, the uncertainty of the price of aluminum in the future is another problem. As mentioned earlier, aluminum is at an all time low due to worldwide over capacity with the exporting (dumping) of post cold war Russian aluminum. This trend will not last very long. Already ALCOA has moved to reduce capacity by 100,000 metric tons in response to this issue while the Russians have pledged to reduce capacity by 500,000 metric tons by the middle of this year (1994).

The most recent Delphi study performed by the University of Michigan's Office for the Study of Automotive Transportation interviewed 200 auto industry executives. A summary of the auto executives' projections for the year 2003 which are relevant to this thesis follow:

- Aluminum usage in automobiles will increase significantly
- Corporate Average Fuel Economy will be 32 mpg for cars
- Corporate Average Fuel Economy will be 25 for trucks
- Fuel prices will be $1.75 per gallon
- Regulations (fuel economy, emissions, and safety) will become more restrictive

While this is not a scientific study, it does provide some insight into where executives of the automotive industry think the business is headed. It is clear that aluminum will play a larger role in enabling the companies to meet the above listed challenges.

The next several sections will provide some recommendations an automotive manufacturer may want to pursue in order to develop some of the competencies required to become an efficient producer of a high volume all-aluminum automobile.

8.2 Start Now!

With all there is to learn and master, process development must start as soon as possible. To maximize cross-functional learning, the groups set up to develop this technology should represent all the traditional functional areas: engineering, finance, human resources, manufacturing, purchasing and quality. The areas outside of manufacturing have to be involved: just as it will require a paradigm shift for manufacturing, so will it require many changes within other functions. A list of some of the issues by function follow:

8.3 Engineering Issues for High Volume Aluminum Intensive Automobile Manufacturing

Designers were notorious for some of the requirements they demanded for car designs. However, over the years engineering has developed a much better rapport with manufacturing. Aluminum, with its lower formability, will require many design compromises from the design community. It will no longer be satisfactory to specify the depth of draw that occurs in many areas (as mentioned in section 4.2.1 in areas such as wheel houses and apertures): for example current one panel designs with deep drawn panels may require two panel designs. A design of deep drawn panels for an exposed surface with two panel designs, requires a joint which will be noticeable.

Flanges and hems will also have to be seen in a different light. The traditional flat hems may not be possible: for instance we observed severe splitting on flat hemmed panels. Therefore, a less traditional rope hem or other alternate methods may need to be explored.

8.4 Human Resource Issues to be Considered for High Volume Aluminum Intensive Vehicles

As mentioned earlier, significant training will be required for plant personnel in regard to aluminum and its properties related to manufacturing. Because of the amount of training, it needs to be well planned and executed in a timely fashion. The training also should be action-oriented so that the training is effective. It should also be performed just-in-time so that the training is fresh in the minds of the plant personnel.

Another human resource issue concerns employment of the hourly personnel who perform welding equipment repair and related activities. The obvious answer is to say they will work on the riveting equipment; however, these people are not trained for repairing riveting equipment and indeed requiring them to work on the equipment probably will violate union past practices or contract stipulations. If training is the answer, it must start early. If redeploying the welder repair people is the answer, then issues revolving around that need to be investigated.

8.5 Purchasing Issues to be Considered for High Volume Production of Aluminum Intensive Vehicles

Today long term relationships are being built between automotive suppliers and the automotive manufacturers. Simultaneously, supplier rationalization is reducing the number of suppliers from which a company will purchase parts and equipment. However, when introducing a new technology, the supplier of choice is frequently not within the current supplier base. In the case of self-piercing riveting, for example, the suppliers are non-traditional automotive suppliers. For large companies such as automobile manufacturers to feel comfortable with these companies they need to start developing relationships now.

Also, the mercurial nature of aluminum prices must be addressed. Because it is traded as a commodity, the price of aluminum fluctuates greatly. Automotive manufacturers are used to dealing with very steady (even declining) prices of steel. Therefore, long term agreements between the automobile manufacturers and aluminum producers may be required.

8.6 Quality Issues to be Considered for High Volume Production of Aluminum Intensive Vehicles

Not all of the issues involved in ensuring quality in aluminum vehicles have been covered in the body of this thesis; there are still other issues worth exploring. One concern is shipping of blanks. Traditionally this matter has been left to an economic decision, i.e. the least expensive way to ship the blanks. However, the shipping requirements for blanks made of aluminum are different than the requirements for steel. As was mentioned earlier aluminum scratches very easily; thus, when shipping blanks of aluminum, if one is not careful to package the blanks such that no relative movement of the blanks occur, fretting will occur and the blanks will be damaged. Often this goes unnoticed until the parts have been stamped. Indeed, the whole value chain of stamping, shipping, and assembling must be reexamined due to aluminum's low scratch resistance.

8.6 Recommendations

The following section is going to be divided into three sections covering the recommendations for near term, medium term, and long term.

8.6.1 Near Term Recommendations

Determine equipment performance data

Because of the unfamiliarity of automotive manufacturers with aluminum joining and the related processes, some process reliability investigation must occur. It is unwise to try to equip a plant with a particular type or brand of processing equipment without knowing its reliability, accuracy, and maintainability. Therefore, performance tests on these important metrics must be performed. In fact with all the consortia activity going on at the Big Three, this would be a perfect opportunity to save collective money.

Generate long term fatigue data

Start generating long-term fatigue data now. Static and dynamic testing has been performed on aluminum intensive prototypes. Long term durability and fatigue data is now required. Because of the length of time it takes to generate this type of data, companies must start now.

Examine equipment purchases for compatibility with aluminum

Begin looking at the capital equipment purchases that are going to occur over the next several years. In every case, ask the question " What would it take to make this equipment compatible with aluminum?" This is not to propose that all equipment purchases be aluminum compatible, rather to increase awareness. If there is no extra (or minimal) expense required to have this feature, it is much less expensive to do it now than later.

Develop relationships with aluminum vehicle unique suppliers

Initiate relationships with the suppliers of the equipment that will be required to produce aluminum vehicles. While some may be the same, many will be different. Some of the equipment requirements may limit design features of the cars. Some may actually allow designs to be manufactured that were not feasible in steel.

Start stamping trials with aluminum now

Stamping of aluminum will be another barrier. Stamping trials need to be performed to get the die designers and stamping engineers comfortable with stamping aluminum. There are plenty of old dies and presses around that we can experiment with. Use this opportunity to learn about stamping aluminum.

Work with paint suppliers to develop coating processes

Start developing the next generation corrosion protection coating system for all aluminum vehicles. Don't let this be the only technical problem that is not overcome, just because it is someone else's problem. Partner with suppliers now.

8.6.2 Medium Term Recommendations

Produce a low volume all aluminum vehicle

Even after some of the near term recommendations are followed, it would be unwise to plunge ahead into a high volume aluminum intensive vehicle project. There are just too many unknowns. One can not think of every combination of problems or outcomes. The next logical step would be to produce an aluminum intensive vehicle, but in lower volume, such as a niche vehicle. This is where an automotive manufacturer can leverage the requirement of producing electric vehicles, while gaining knowledge for producing a high volume all aluminum car. Currently California is requiring that by 1998, 2% of all vehicles sold there be zero emission Electric automobiles are the only vehicles that currently meet this requirement, therefore, 2% of the vehicles sold in California in 1998 will likely be electric. Instead of resisting, the automobile manufactures can leverage this situation and develop technologies that can be transferred to future high volume vehicles.

8.6.3 Long Term Recommendations

Once the decision to manufacture an all aluminum high volume automobile has been made, the following recommendations should be followed to enhance the probability of success of the project. They assume the implementation of the preceding recommendations and the learning the fundamentals about manufacturing an aluminum car.

Increase vehicle development time

An all aluminum high volume vehicle will take more time to bring to market, by virtue of the number of technical challenges that must be overcome. Therefore, once the decision is made to produce a high volume car, more design and development time should be given. This will be tough for car manufacturers, because of the recent efforts to reduce time to market, but is necessary. The program employees will be under enough pressure, with all the technical challenges, a short development time would make it just that much worse.

Partner with an aluminum company to develop vehicle

Partner with one of the aluminum companies for stamping development. One of the aluminum companies should be chosen as key supplier for the vehicle and provide program support very early on. This begins at the design stage of the vehicle. They can help ensure that the vehicle is manufacturable, and that the car designers are aware of the current capabilities of the aluminum.

Fully exploit aluminum in design of vehicle

When designing the vehicle, make sure that the aluminum advantage is fully exploited. Don't design a steel vehicle and simply substitute aluminum. Aluminum lends itself to many processes that the automotive industry does not use for structures such as: extruding and super-plastic forming. Also exploit the weight advantage of aluminum. Many components can be downsized it response to the lower body weight.

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Appendix

	Mild Steel	Bake Hardening Steel	High Strength Steel	Aluminum Alloy	6XXX-T4 Aluminum Alloy	Cast Aluminum
Yield Strength	27 ksi	35 ksi after paint	50 ksi	13 ksi ≈ 16 ksi formed	24 ksi ≈ 30 ksi formed ≈ 35 ksi after paint	33 ksi
Ultimate Tensile Strength	48 ksi	55 ksi	67 ksi	26 ksi	45 ksi	45 ksi
Modulus of Elasticity	$30x10^8$	$30x10^8$	$30x10^8$	$10x10^8$	$10x10^8$	$10x10^8$
Elongation	≈38 %	≈30 %	≈20 %	≈ 23 %	≈19 %	≈13 %
Thermal Conductivity	27 - 30	27 - 30	27 - 30	80	100	
Electrical Conductivity	16 - 18	16 -18	11 - 12	30 - 50	40 -50	
Coef. of Thermal Expansion	8 - 10	8 - 10	12 -14	12 - 14	12- 14	12 - 14
Specific Heat	0.10 - 0.12	0.10 - 0.12	0.10 - 0.12	0.23	0.23	0.23
Melting Temperature	≈2700°F	≈2700°F	≈2700°F	≈1000°F	≈1000°F	≈1000°F
Poisson's Ratio	0.29	0.29	0.29	0.33	0.33	0.33
Density	0.285	0.285	0.285	0.1	0.1	0.1
Cost	≈$0.31/lb.	≈$0.35/lb.	≈$0.40/lb.	≈$1.55/lb.	≈$1.73/lb.	
Scrap Value	$0.01/lb.	$0.01/lb.	$0.01/lb.	$0.50/lb.	$0.50/lb. $0.30 if not segregated	

Table A.1 List of Aluminum and Steel Properties

Suffix Designation	Suffix Meaning
XXXX-F	As Fabricated
XXXX-O	Annealed
XXXX-Hxx	Strain Hardened
XXXX-W	Solution Heat Treated
XXXX-Tx	Thermally treated to produce stable tempers, other than F,O, or H

Appendix A.2 List of Suffix Designations and Their Meanings

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