Automobile Bodies: Can Aluminum Be an Economical Alternative to Steel?

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Although the use of aluminum in cars has been increasing for the past two decades, progress has been limited in developing aluminum auto bodies. In fact, most aluminum substitution has come in the form of castings and forgings in the transmission, wheels, etc. Car manufacturers have developed all-aluminum cars with two competing designs: conventional unibody and the spaceframe. However, aluminum is far from being a material of choice for auto bodies. The substitution of aluminum for steel is partly influenced by regulatory pressures to meet fuel efficiency standards by reducing vehicle weight, and to meet recycling standards. The key obstacles are the high cost of primary aluminum as compared to steel and added fabrication costs of aluminum panels. Both the aluminum and the automotive industries have attempted to make aluminum a cost-effective alternative to steel. This paper analyzes the cost of fabrication and assembly of four different aluminum car body designs,making comparisons with conventional steel designs at current aluminum prices and using current aluminum fabrication technology. It then attempts to determine if aluminum can be an alternative to steel at lower primary aluminum prices, and improved fabrication processes.

INTRODUCTION

The automobile and aluminum became commercially viable at about the same time in the late years of the 19th century; there are references to the use of the latter in the former from their very beginnings. Although steel is preferred by most automakers, in recent years changing fuel economy and recycling regulations have intensified weight-reduction attempts by automakers. Aluminum offers the ideal engineering solution: Its density is one-third that of steel and satisfies the torsion and stiffness requirements of an automotive material. However, aluminum by weight is about five times more expensive than steel.

Despite the high cost, in the past two decades the amount of aluminum in automobiles has increased steadily. Aluminum's penetration has increased from 39 kg (3%) in 1976 to about 89 kg (7%) in the mid-90s.[1] However this use of aluminum at the expense of steel has been on a part-by-part basis, not the result of any radical design change. Most of the aluminum penetration has been in transmissions, engine blocks, and wheels, largely as castings with some forgings and extrusions. The wrought aluminum sheet penetration, however, is limited to A/C units and a few closure panels for the car body. Simply stated, it is proven that aluminum can be used to replace steel, iron, and copper for various parts in a car. In all cases, this substitution reduces weight without reducing performance, but in most cases cost increases significantly. That increase can be countered on grounds of reduced fuel consumption and increased ability to carry safety and electronic equipment and increased life of a car—if the user, the manufacturer, and perhaps most importantly, the legislator, deem those factors of sufficient merit.

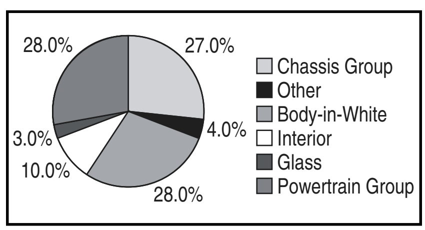

Figure 1. Passenger car mass distribution.

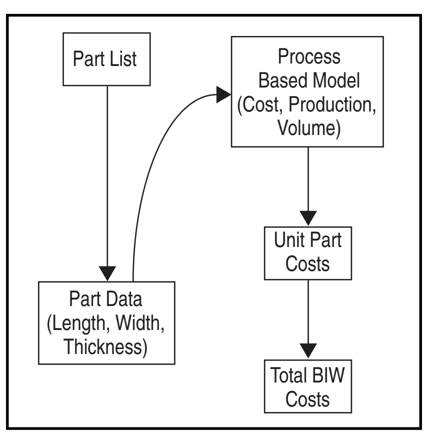

Figure 2. Flowchart for the methodology of estimating manufacturing costs of BIW.

The use of large amounts of aluminum in mass-produced cars, as distinct from expensive, low-volume models, has been frequently predicted but as yet has not come about. The only way aluminum can displace steel with any significance is when aluminum sheet replaces steel as the primary material in the chassis or the body of the car. During the past decade, vehicle manufacturers have repeatedly attempted to assess the status of aluminum vehicles. New types of alloys and advanced production techniques have been tested. Interest has been focused mainly on testing suitable joining methods. The Honda NS-X was the first (and only) aluminum vehicle made in a limited production run. The Audi A8 is another latest example of a luxury, low-volume all-aluminum spaceframe design car.

BODY-IN-WHITE

While aluminum has been able largely to conquer the drive train and heat exchanger areas, the chassis, body and equipment must be regarded as development areas for lightweight construction using aluminum. The key issue has been optimizing the design to exploit the advantages of aluminum and, at the same time, be cost effective. As shown in Figure 1, the body-in-white (BIW) accounts for about 27% of the weight of the entire average car. Thus, it is in the BIW that large-scale penetration of aluminum must come about.

Part-by-part substitution of aluminum for steel, although providing the light weight and better corrosion resistance of aluminum, is not the optimal solution. Because cars are still essentially made of steel, a complete redesign of the automobile is nec-

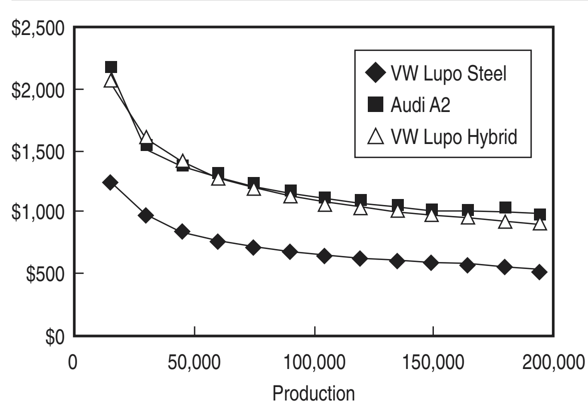

Figure 3. Parts-fabrication costs of the three small cars.

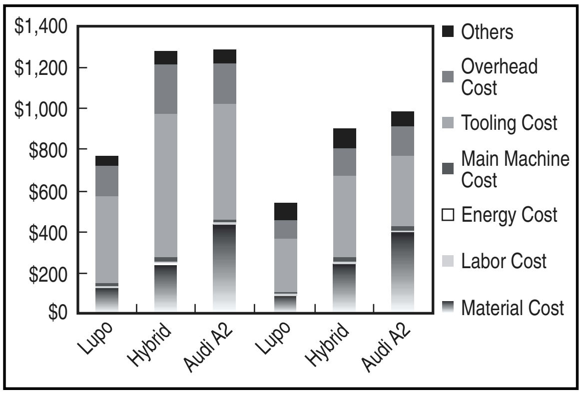

Figure 4. Part-cost breakdown for small cars (60,000 and 195,000 cars annually).

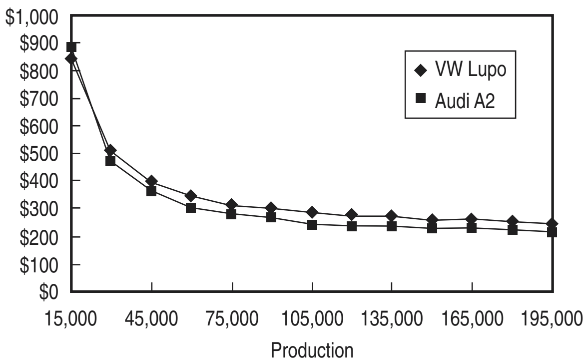

Figure 5. Assembly costs of small cars.

essary to make optimal use of aluminum.

Some aluminum and auto companies have promoted the aluminum spaceframe design, using stampings, castings, and extrusions of aluminum. Others have been developing the conventional unibody design, which is predominantly a stamped body, in aluminum. Although both designs have demonstrated their functionality and effectiveness, it is unclear which design would be economically better suited for mass production. The ultimate success of one or both of the designs depends on the progress and developments in the general area of aluminum fabrication technology, particularly in aluminum stampings. This paper compares and analyzes the fabrication and assembly costs of aluminum and steel auto bodies in two classes: small, fuel-efficient vehicles and mid-size vehicles.

METHODOLOGY

The manufacture of the BIW is comprised of two costs: fabricating the parts and assembling the parts. These costs are estimated using a technique developed at MIT's Materials Systems Laboratory titled technical cost modeling (TCM). Technical cost modeling is a spreadsheet-based analytical tool that breaks down the costs of a manufacturing process into elemental process steps.[2,3] The costs associated with each step are derived from a combination of engineering principles and empirical data for manufacturing practices. Factor inputs include design specifications, material parameters (e.g., engineering properties, material prices), processing parameters (e.g., equipment-control parameters, space requirements, power consumption) and production parameters (e.g., production volumes, scrap rates, down times, maintenance time). Models also take into account the economic opportunity (i.e., cost of capital associated with equipment ownership). Inputs are transformed into estimates of fixed and variable costs for each manufacturing step. Variable costs include energy, materials, and direct labor; fixed costs cover capital equipment required for the manufacturing process, including machinery, design-specific tooling, building expenses, maintenance, and overhead from indirect labor. In the absence of accurate and site-specific data, the machine and tooling costs can be predicted based on the design specifications of the product using regressions derived from empirical data.

Figure 2 explains the methodology employed in estimating the fabrication costs of the BIW. For the car designs, a list of parts was prepared from the detailed exploded drawings of the cars.

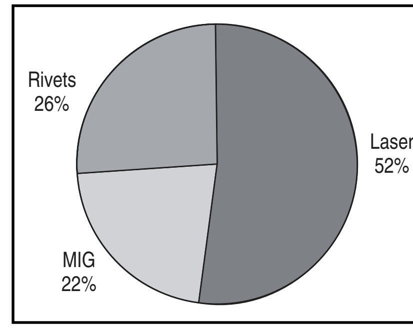

Figure 6. Audi A2 assembly-costs breakdown by joining methods.

The list included the dimensions and weight of the parts, which were then broadly categorized into two groups. Small parts, which were not feasible to run through the cost model, were assigned an average cost based on their weight. Larger parts were classified according to their manufacturing process—stamping, casting, or extrusion. Each of the part dimensions was then fed as an input to the relevant process-based cost model (stamping, casting, and extrusion) to estimate the fabrication cost of that part. The process was repeated for each part using a spreadsheet macro to estimate the cost and the cost breakdown (material, tooling, machine cost, labor) in the manufacture of every part. The sum of the costs provided the total BIW fabrication costs.

The assembly model also developed at MIT's Materials Systems Laboratory was used to develop cost estimates for

Table I. Parts Data for the Fuel Economy Cars

Car	Number of Parts	Manufacture	Total Part Weight
VW Lupo (2-door)	190	Stampings	210 kg
VW Lupo Hybrid	190	Stampings	166 kg
Audi A2 (4-door)	210	Stampings (120) Extrusions (40) Castings (50)	153 kg

Table II. Parts Data for Mid-Size Cars

Car	Number of Parts	Manufacture	BIW Weight
Ford Contour	200	Stampings	215 kg
Ford P2000	288	Stampings	152 kg
Size-adjusted Audi A8	300	Stampings (160) Extrusions (75) Castings (65)	160 kg (actual weight 249 kg)

Table III. Assembly Technologies Used in the Mid-Size Cars

Car	Joining Method	Lengths
Ford Contour	Resistance spot welding	2,630 spot welds
Ford P2000	Resistance spot welding	2,000 spot welds
Size-adjusted Audi A8	Spot welds MIG welding Punch rivets Mechanical clinches	400 points 65 meters 1,000 rivets 150 clinches

the assembly of the BIW.[4] The assembly model is a TCM based on a relational database rather than a spreadsheet. A BIW is assembled by attaching together various subassemblies, which are then joined together at the final assembly line to form the completed product. The assembly model calculates cost using relational databases to capture the relevant information needed for each joining method. The model then calculates costs based on the amount of joining that can be conducted at each station during the time available. The station time then determines the number of stations that would be required for the specified production volume and, thus, the equipment and auxiliary machine costs. In order to calculate costs, the assembly model selects the necessary information stored within each data table for every joining method (laser welding, metal inert gas [MIG]) welding, spot welding, riveting, adhesive bonding, etc.) as inputs for the calculation.

In order to compare the fabrication and assembly costs of car designs, it is imperative that the designs be of a similar size. Six designs were analyzed, three of which are fuel-efficient, compact cars: the all-steel Volkswagen Lupo, the hybrid Lupo, and the Audi A2, all of which are similar in size and dimensions. The midsize cars compared are the Ford Contour, the Ford P2000, and the Audi A8. The A8 is targeted toward the luxury market and is much larger than the other two. To compare the fabrication costs of the designs, the relative difference in the sizes must be accounted for, so, for this study, the parts of the A8 were compared to the dimensions of the Ford Contour. This was done by scaling down the parts and panels of the Audi A8 in the ratio of the exterior dimensions of the two designs. The part weight was also reduced by assuming that the sheet thickness remained constant. This scaling enabled a 1:1 comparison of the designs, despite their size difference. The scaling normalizes the material costs, while scaling down the tooling and machine costs. Those costs are dependent on the part dimensions through empirically derived regressions.

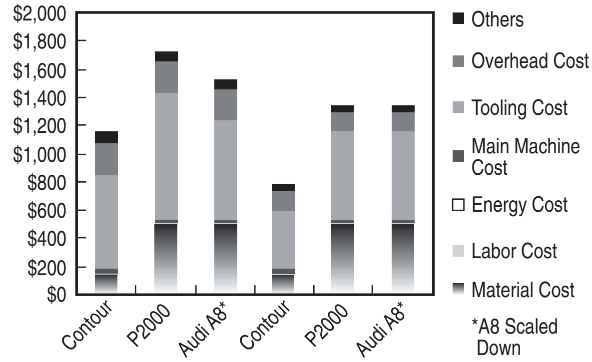

Figure 9. Parts-cost breakdown of midsize cars (60,000 and 195,000 per annum).

ANALYSIS OF SMALL CAR DESIGNS

The Lupo is a small car with a conventional steel unibody design. The hybrid Lupo bears an exact exterior resemblance to the steel version, but the doors, bonnet, and fenders are made from aluminum (one of the panels is made out of magnesium). Parts of the brake system, chassis, and wheels are also made from lighter metals than the steel version. Inside the car, weight has been saved with special seats, steering wheel, and pedals. In the Audi A2, the structural members consist of extrusions and cast nodes that are laser-welded together. The overhang panels are made of aluminum sheet that are then attached to the spaceframe. Table I gives the part manufacture and the weight details of the three designs.

Figure 3, which shows the fabrication costs of the three designs, clearly shows the scale economies involved in the manufacture of the designs. Although the Lupo steel and hybrid curves show a similar shape. The A2 has about 40% extruded and cast parts, and it flattens out earlier since it cannot take advantage of the economies of scale in stamping. The Lupo hybrid is expensive compared to the steel version at all production volumes because all the closures are made of aluminum, which incurs a material penalty and the added tooling costs of stamping all the parts. The A2, on the other hand, was designed as an aluminum car and the spaceframe has been optimized by parts consolidation, using large, cost-effective castings instead of aluminum stampings. Figure 4 shows the absolute cost breakdowns of the fabrication costs by category for two production volumes.

Figures 3 and 4 show that the materials and tooling costs are the categories are of greatest interest in this comparison. The breakdown shows that at medium production volumes (60,000 per annum), the total costs of the Lupo hybrid and the Audi A2 are comparable, although the material cost of the A2 is higher. This is offset by the high tooling costs of the hybrid. The added costs are accounted by two factors: Reduced line rates, because aluminum sheet tends to tear, requiring slow stamping and extra hits for the stampings; ανδ increased die costs due to special coatings for the dies. At the higher production volume, the costs for the Hybrid decline substantially because the capital costs of the stamping processes are spread over larger sproduction volumes.

In this analysis, only the joining costs of the car without the closure panels were considered. Thus, the joining costs for the Lupo steel and hybrid are the same in this analysis. In reality, joining the aluminum panels and the magnesium back door to the steel unibody results in additional costs to avoid stress and galvanic corrosion at the joints. The two designs employ different joining technologies and methods—for the Lupo the only joining technology employed is resistance spot welding. The A2 consists of about 35 meters of laser seams, 20 meters of mash seam welding, and 1,800 punch rivets.

As shown in Figure 5, the A2 is cheaper to assemble except at low production volumes (i.e., less than 20,000 vehicles per year) because of the economies of scale involved in the laser-welding pro-

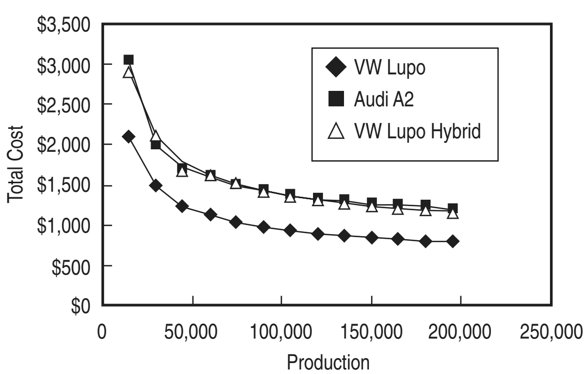

Figure 7. Total production costs of the small cars.

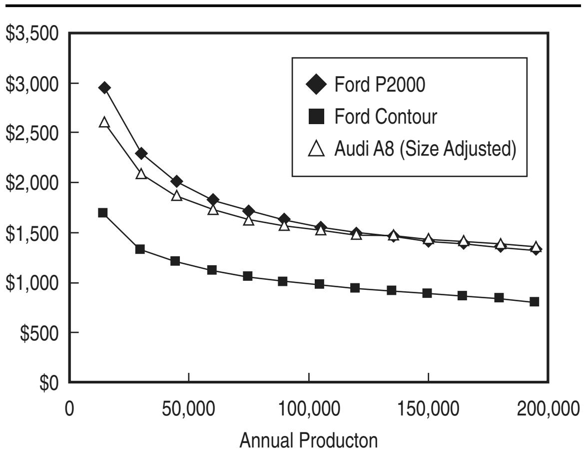

Figure 8. Fabrication costs of the midsize cars.

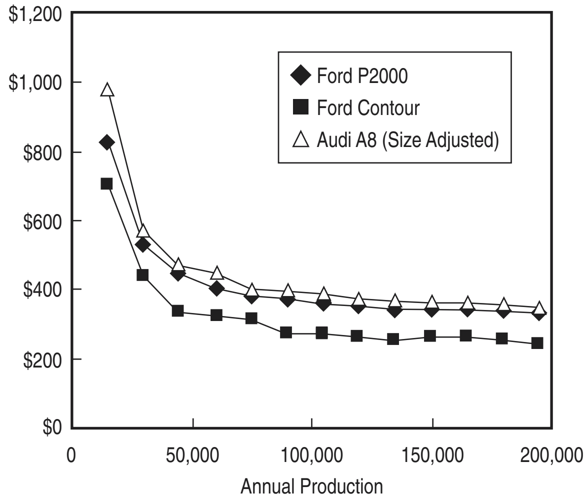

Figure 10. Assembly costs of the midsize cars.

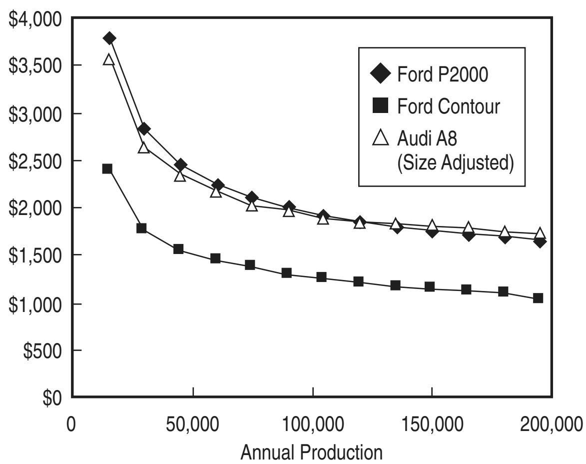

Figure 11. Total production costs of the midsize cars.

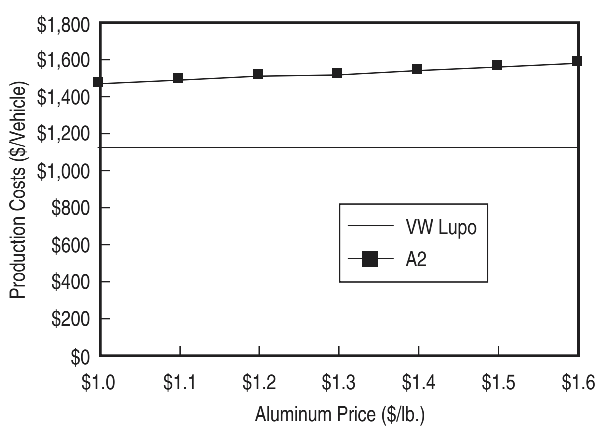

Figure 12. Sensitivity of A2 production costs to aluminum price.

cess. At low production volumes, the high capital expense of the laser-welding machines is responsible for the high costs. However as the production levels increase, the economies of scale cause the price to drop below the Lupo. The only consumable involved in laser welding is the nitrogen gas, which is a marginal expense. Most of the costs are the machine and laser-head costs. Figure 6 shows a breakdown of the joining costs by technologies for the A2 at a production volume of 60,000 cars per annum where the predominance of laser costs in the assembly process can be clearly seen (about 52%).

Figure 7, which shows total manufacturing costs at different production volumes, is similar to the parts-fabrication cost curves. The hybrid Lupo and the A2 are cost competitive. The hybrid unibody design is much more expensive than the steel equivalent because the design has been optimized for the steel vehicle and adding aluminum and magnesium outer panels adds not only to the material costs, but also to the tooling costs for stamped aluminum parts. Moreover, all the non-steel parts in the car are stamped, and thus, relatively more expensive than extruded profiles or cast parts. At a production volume of 60,000, there is a cost difference of $510 between the A2 and the steel Lupo.

ANALYSIS OF MIDSIZE CAR DESIGNS

The Ford Contour is a midsize four-door, steel unibody car, used in the analysis as the base-case scenario. The Ford P2000 is the all-aluminum unibody design similar in exterior dimensions to the Ford Contour. The P2000 project is associated with Ford's participation in the Partnership for a New Generation of Vehicles (PNGV) program. The unibody design is weld-bonded aluminum sheet in the BIW structure and closure panels, cast aluminum front and rear shock towers, a fabricated aluminum front sub-frame, an aluminum cylinder block, and aluminum composite rotor/drums.

The Audi A8, a large luxury car, was Audi's first-generation spaceframe design. The A8 has an extruded spaceframe made up of two- and three-dimensional extruded profiles joined by vacuum-cast aluminum nodes. The assembly techniques used are punch rivets, MIG welding, and some resistance welding. Although this 1.8 tonne sedan is not classified as a midsize car for this analysis, the three cars were compared due to availability of data and the distinct design features of the three cars. As discussed earlier, to compare the A8 with the other two designs the parts of the A8 were scaled down to the dimensions of the Ford Contour. Table II gives the part manufacture and the weight (scaled down for the A8) details of the three designs, which were anlayzed with cost models.

Figure 8 shows the total part fabrication costs of the three cars. It also shows that the Ford P2000 and the Audi A8 are much more expensive than the steel car. The P2000 is more expensive to produce at lower volumes than the equivalent Audi A8 since it is made up of all stamped aluminum parts. Figure 9 shows the absolute cost breakdown of the fabrication costs at production volumes of 60,000 and 195,000 cars per annum.

A large portion of the cost of the P2000 can be accounted for by the tooling costs for the stamped parts. As can be seen in Figure 9, the tooling costs account for more than 40% of the costs at a low production volume.

The assembly model enables analysis of the joining costs of assembling these midsize cars without closures. Table III shows the various joining methods and their lengths in each of the cars.

Figure 10 shows the assembly costs of the three cars at various production volumes. The Audi A8 is the most expensive to assemble among the three cars due the complexities involved in using different joining techniques. The capital costs of the MIG welding equipment is high; however, economies of scale can be seen in the sharp drop in costs form 15,000 to 30,000 cars per annum.

As shown in Figure 11, a graphic illustration of the total manufacturing costs at different production volumes mimics the parts-fabrication cost curves. The costs of the Audi A8 tend to flatten out beyond the medium production volumes. At the current tooling estimates for stamping of aluminum, the aluminum unibody design is relatively more expensive than the equivalent spaceframe design, especially at low and medium production volumes.

ECONOMICS OF SUBSTITUTION

The fabrication cost analysis of the six car designs shows two key obstacles to aluminum becoming a substitute to steel: Higher material costs and higher tooling costs of aluminum panels.

Auto manufacturers aim to produce an aluminum car with the same overall manufacturing costs as steel. It is believed that to do this, the price of aluminum must decrease to about $1 per pound ($2.2 per kg). Analysis shows that it may be possible to produce aluminum (5xxx)

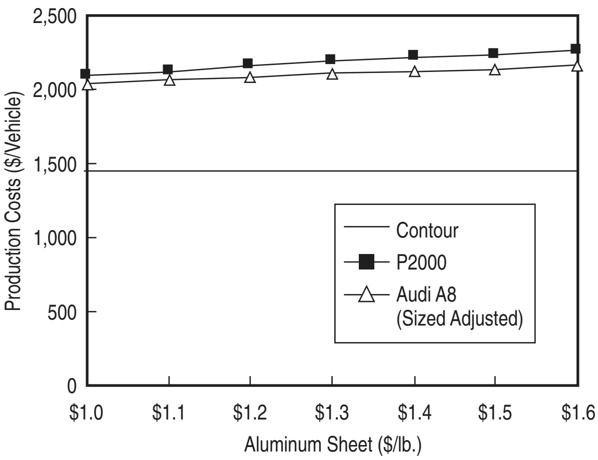

Figure 13. Sensitivity of production costs to aluminum sheet price.

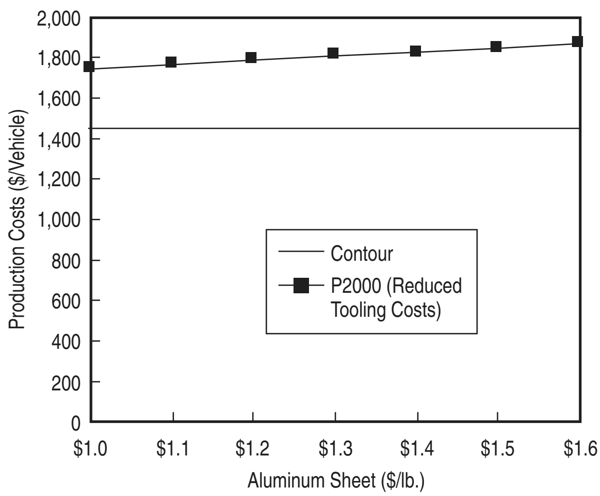

Figure 14. Sensitivity of P2000 production costs at reduced tooling costs.

at these prices using continuous casting and exploiting large economies of scale.[5,6] However, most aluminum used in outer-body panels is a 6xxx alloy, which is relatively expensive to produce. Figure 12 shows the production costs of the A2 if the price of automotive aluminum sheet were to fall to $1 a pound. A difference of about $320 between the Audi A2 and the steel Lupo could be expected at the current target production volume of 60,000 vehicles (at current prices the difference is about $510).

A similar analysis of the midsize cars at a volume of 60,000 vehicles per annum is shown in Figure 13. Even at $1 per pound, the P2000 is still about $600 more expensive than the Contour.

The additional tooling costs of stamping aluminum make aluminum a less favorable alternative to steel, even at reduced material prices, because of the material-forming characteristics of aluminum.[7] For instance, aluminum panels cannot have sharp flanges for joining the inner and outer panels, it tends to split if stamping angles are too sharp, and it also has more springback than steel, and is more sensitive to die contamination since it is relatively soft. As a consequence the costs of stamping aluminum are relatively larger than equivalent steel due to the following:

- Higher die development costs to compensate springback
- Development and application of special coatings and lubricants for dies
- Slower stamping rates to prevent tears and damage

Figure 14 shows a scenario where there is a 50% reduction in the incremental costs incurred in aluminum stamping. In this optimistic scenario, with automotive aluminum sheet available at $1 per pound and a 50% reduction in the incremental tooling costs of stamping aluminum, the P2000 would be about $300 more expensive than a comparable steel auto body. However, as the design and fabrication technology matures and the industry moves down the learning curve, the costs can be expected to decline significantly. In fact, design developments by Audi already have resulted in significant cost reductions between its first- and second-generation vehicles. These have come about through parts consolidation, process substitutions, and part simplification.[8]

CONCLUSION

The analysis of the six car designs clearly provides insight into the economics of substitution of aluminum in steel auto bodies. The analysis shows that:

- Hybrid designs like the Lupo-hybrid serve well as examples of vehicles that can achieve fuel economy or recycling standards. However, these are not an economically feasible solution for weight reduction because the car designs are usually variants of an existing design, where part-by-part substitution of certain closures is done using lighter materials. The method, thus, does not allow the manufacturer to fully exploit the advantages of one material and achieve the optimal production efficiencies.
- The analysis of the P2000 and the Audi A8 (equivalent size adjusted) designs shows that under existing fabrication conditions, the spaceframe design is slightly cost competitive vis-a–vis the unibody, primarily due to the higher stamping costs of aluminum.
- The analysis of the joining techniques of the first- and second-generation aluminum spaceframes shows there can be significant reductions in costs as the technology matures. The Audi A8 was the most expensive of the three car designs in its class to assemble. On the other hand, the second generation Audi A2 is cheaper to assemble than the steel equivalent at all except very small production volumes. This can be primarily attributed to the development in joining technologies—improved understanding of laser welding of aluminum and faster laser-welding machines.

Aluminum still has to overcome significant technological and economic hurdles before it can replace steel in the car body. However, these hurdles are by no means insurmountable, as the case for the laser welding of aluminum has shown. The shift of aluminum producers from being merely material suppliers to being partners with the automakers is a step in this direction. It can be expected that there will be significant developments in the aluminum stamping in the near future. This, coupled with the right legislative pressures in terms of fuel economy and recycling targets, might make aluminum a significant, if not primary material in the auto body.

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