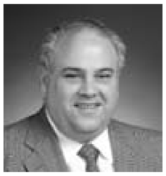

Design & Fabrication of Aluminum Automobiles

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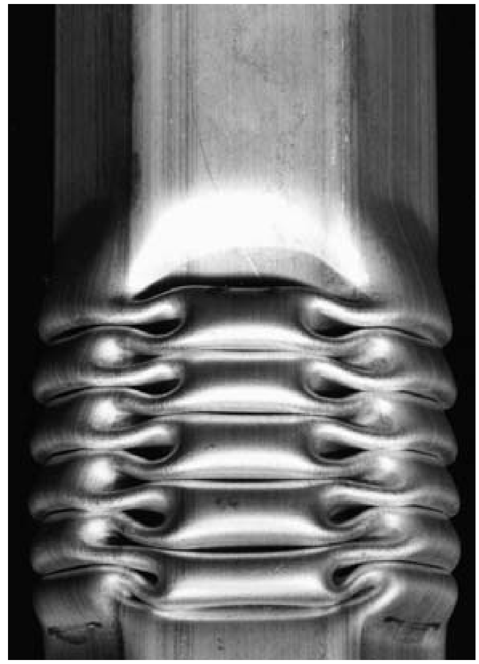

Figure 1. Aluminum front frame rail crushed in crash test showing uniform crushing and energy absorption.

History

Aluminum was first isolated in 1888 as an element. It rapidly gained in application as people learned how to alloy it to improve its mechanical properties. By the mid-1920s, Pierce Arrow had begun to make at least one model of its cars entirely from aluminum. While all-aluminum cars have appeared periodically over the years, the use of aluminum has never become widespread in the automotive industry. However, in the last ten to fifteen years, the use of aluminum in automobiles has increased dramatically. In fact, the average aluminum content of automobiles increased 113% between 1991 and 2000. Today, the average car contains over 250 lbs. (113 kg) of aluminum alloys.

Over the years, some very well-known cars have been built entirely from aluminum. These include:
- The Mercedes-Benz 300SL Gullwing in the 1950s
- The Shelby AC Cobra in the 1960s
- The Jaguar D type
- The Ford GT40

In the more recent past, the fabrication of high-end automobiles from aluminum has continued with:
- The Acura NSX
- The Aston Martin Vanquish
- The Audi A8
- The BMW Z8
- The Ferrari 360 Modena
- The Mercedes CL coupe
- The Plymouth Prowler
- The Shelby Series 1
- The new Ford GT40

All of these cars are made using either a monocoque body structure (in which the covering absorbs a large part of the stresses to which the body is subjected) or a space frame made entirely from aluminum. Therefore, it should be fairly obvious that it is possible to obtain very good structural performance from aluminum. However, all of the models listed above are made at relatively low volumes (20,000 per year maximum). Is it possible to manufacture aluminum vehicles at higher volumes? In fact, Audi has taken a large step by making the Audi A2 completely from aluminum alloys at a volume of 80,000 per year in Europe.

Aside from the all-aluminum car, there is increasing use of aluminum in outer body panels (i.e., fenders, hoods, decklids) in virtually every manufacturer's model lines. Most bumper beams today are made from aluminum alloys. Perhaps even more noteworthy from a structural standpoint, there are increasing volumes of aluminum engine cradles (the Chevrolet Impala and Malibu and the 2002 Nissan Altima) and rear suspension cradles (the Chrysler Concorde, the Dodge Intrepid, and the BMW 5 Series). The fact that these are being made at volumes as high as 700,000 per year goes a long way toward proving the viability of high volume, all-aluminum automobiles. As we will see below, welding is a major contributor to making this possible.

Why Aluminum?

Aluminum has a number of properties that make it attractive for application in automobiles. However, it has one characteristic that overrides all others: its light weight. Aluminum automotive alloys are one third as dense as steels, while many of them have tensile and yield strengths almost equal to those of construction grade steels. Does this mean that we can make aluminum parts that weigh one third of steel parts? In general, no. Most parts of a car are not strength-limited, but are stiffness-limited. (There are exceptions to this – the areas around the shock towers are usually strength-limited). Because stiffness is a function of Young's modulus, which is 10 x 10^6psi (68,950 MPa) for aluminum alloys and 30 x 10^6psi (206,850 MPa) for steels, weight reductions of 2/3 are not usually possible. Weight reductions of 40%–45% are more typical.

The U.S. Federal Government publishes Corporate Average Fuel Economy (CAFE) standards. These standards dictate the fuel economy levels that every auto maker must meet. Failure to meet them can result in penalties. Car manufacturers are under a great deal of pressure to increase fuel economy across the board. One of the easiest ways to do this is to reduce the weight of the automobile. Reducing the total weight of the car by 10% normally results in an 8%–10% improvement in fuel economy. Even something as simple a substitution of an aluminum hood for a steel one has a significant effect on average fuel economy.

Aluminum has another advantage over steel. It can be easily extruded, while steel can't. This allows the designer to create complex shapes of varying wall thickness using extruded sections. Internal stiffening ribs can be integrally extruded, so that cross sections consisting of multi-hollows are routinely used. The only closed section tubing available in steels is simple shapes such as rounds, squares, ovals, etc. This has allowed designers of aluminum auto structures to venture into automotive space frames and hybrid structures, instead of using only the monocoque sheet construction used in steel automobiles.

But what happens in a crash? Won't an aluminum car just crumple into a ball of aluminum foil? The answer is an emphatic "No!" For a detailed discussion of the behavior of aluminum automotive structures in crash tests, the interested reader is referred to "Automotive Aluminum Crash Energy Management Manual," publication AT5, published by the Aluminum Association in Washington D.C. For our purposes,

Aluminum can be easily extruded, while steel can't

it is sufficient to say that it is not difficult at all to make aluminum automobiles that meet or exceed the NHTSA crash test requirements set out in FMVSS 208, which is the same criterion steel cars must meet. Innovations in alloys and processing have resulted in materials that crush uniformly and absorb energy better than steels. Figure 1 shows an actual front crash rail from a production car. It has begun to crush and has buckled in a controlled, uniform manner, absorbing crash energy and ending up about half as long as it started. Good designs and improved materials are the keys to superior crash performance.

Space Frames versus Sheet Cars

Until approximately thirty years ago, cars were made as an assembly of a sheet metal body and a heavier, separate chassis. The body provided little, if any, structural strength and was assembled by resistance spot welding (RSW) and bolting. The frame, made from thicker members, was assembled primarily by arc welding, rivetting, and bolting.

Then, in the late 1960s and early 1970s, automotive design changed. The so-called "unibody" was born. In this construction method, the entire body, except for the hang-on panels, is part of the car's structure and contributes to the car's stiffness and strength. There is no separate frame, although small front or rear subframes may be used to hold the engine, suspension, etc. These cars are made almost exclusively of steel sheet of various thicknesses which is stamped and joined together by RSW. In 2002, the car makers have seventy plus years of experience in RSW and are very good at it. All of the infrastructure to support RSW is in place.

Why not just make aluminum cars by up-gauging the material thickness from steel to aluminum and assemble them by RSW? Indeed, that's possible and one of the major aluminum companies supports this strategy, using a combination of RSW and adhesive bonding. However, this approach often results in extra costs.

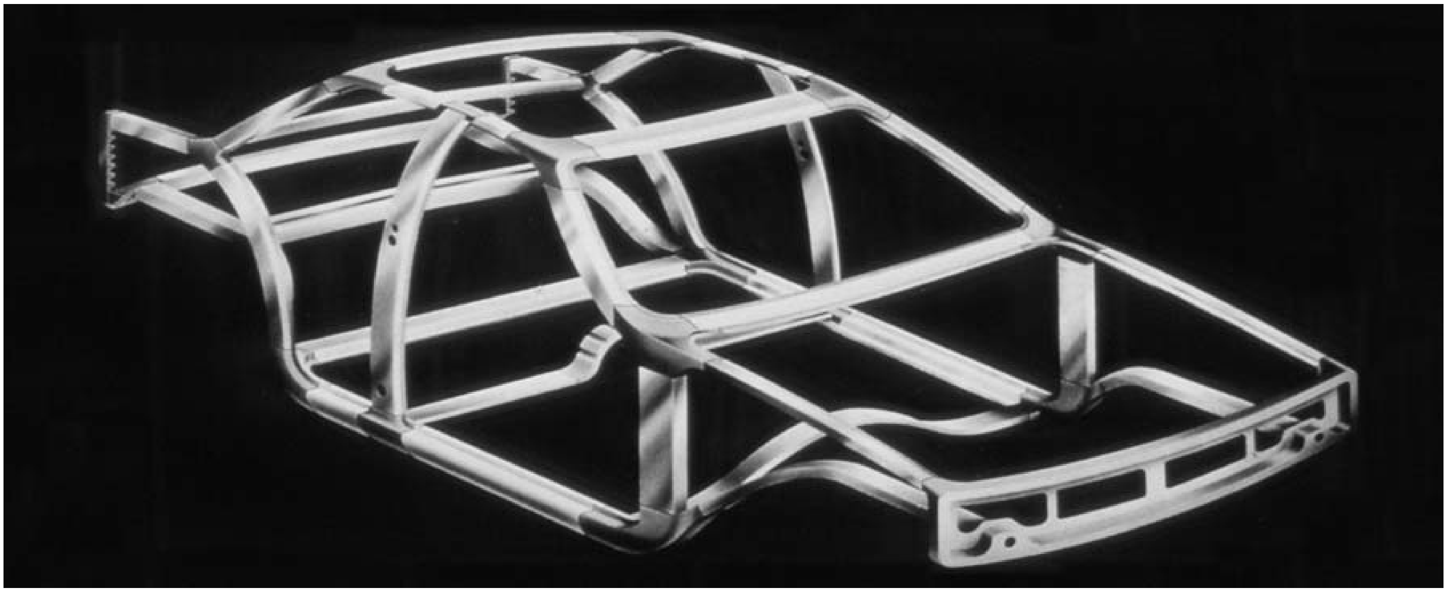

Figure 2. The Audi A8 spaceframe.

For production volumes under 100,000 per year, it has been shown that either a pure space frame or a hybrid space frame/sheet approach is more cost effective. This results mostly from the fact that extrusion dies are relatively inexpensive, while stamping dies are much more costly.

Figure 2 shows a photograph of an Audi A8 space frame. This method of construction employs “nodes” which are made from castings, formed sheet or extrusions. Each node serves as a joining point for several structural members. The nodes are designed so that there is at least one slip plane for each joint. This serves to minimize gaps between the node and the structural member coming into it. While it is possible to use other joining methods, such as adhesive bonding, most of the existing aluminum space frame cars, including the Audi A8 and A2, the Ferrari 360, the Ford GT40, the BMW Z8, and the Shelby Series 1, are arc welded. The Audi A8 space frame contains 70 m (approximately 230 ft.) of gas metal arc welding. Only the Aston Martin Vanquish is adhesively bonded and riveted.

Why Gas Metal Arc Welding?

If automakers go to aluminum vehicles, why not just spot weld them together as they do now on steel vehicles? There are a number of reasons.

RSW of aluminum presents some unique challenges. The aluminum readily alloys with the copper spot welding tips, so electrode life can be very short. The electrical conductivity of aluminum is much higher than that of steel, so not as much resistance heating takes place at the interface of the two pieces to be joined.

There are 17 pulsing variables that can be programmed

Consequently, currents required for RSW are often three times what they are for steel, so the equipment used for steel seldom can be used for aluminum.

Because of these issues, many automakers have moved away from RSW for aluminum. For joining aluminum sheet parts, many have gone to self-piercing riveting, often in combinations with adhesives. However, for joining extrusions and/or castings, these processes have some limitations:

- Only lap joints are possible. Tee or butt joints cannot be made.
- Physical access to both sides of the joint is required.
- When joining castings or extrusions, it is usually necessary to add a flange in order to make the joint. This adds back some of the weight that has been saved.

GMAW is not without limitations either. When joining thin sheet, welding distortion is sometimes excessive. The heat of the welding arc softens the HAZ of the joint, reducing mechanical properties. However, GMAW has a number of advantages that have made it the preferred method for joining of castings, extrusions, and thicker sheet (thicker than 0.070 in. or 1.8 mm), as follows

- It is usable for all types of joints – lap, tee, and butt.
- It is easily automated using robotics
- Access to only one side of the joint is required.
- It is fairly tolerant of part misalignment and joint gaps.
- Capital equipment costs are low.
- It is a well-established, widely used process.

GMAW Technology Development

On the surface, gas metal arc welding (GMAW) might appear to be an older, low tech process. It is anything but. Even ten years ago, it would have been very difficult, if not impossible, to GMAW aluminum members as thin as 0.040 in. (1 mm) thick. Today, welding thin aluminum is fairly easy and the development of GMAW has become an enabling technology for the use of aluminum in automotive fabrication.

GMAW of thin aluminum was complicated by the fact that short circuiting arc transfer (short arc) is not recommended for GMAW of aluminum alloys. When gas metal arc welding steels to weld thin material, the welder uses a finer welding wire and keeps going lower in current and deeper into short arc transfer. However, if this approach is used on aluminum, incomplete fusion defects occur. Short circuiting arc transfer is never recommended for aluminum because of this.

Spray transfer is always recommended for welding aluminum. In years past, it was impossible to weld thin aluminum, say, of 1/16 in. thickness (1.6 mm), because even with the smallest diameter aluminum wire available for GMAW, 0.030 in. (0.8mm), the welding current had to be above 85 amperes to get spray transfer. This was just too much current to weld thin materials, so GMAW of thin aluminum simply was not performed in production.

However, electronics technology developed and made it possible to control the welding process much more precisely and to change the welding current very quickly. Pulsed GMAW was developed. In fact, it was developed over twenty years ago. However, it is very different today than it was then.

Pulsed GMAW has proved to be especially applicable to welding of thin aluminum. Fundamentally, the welding current is pulsed between a high peak current where spray transfer is obtained and a low background current where no metal is transferred across the arc. This means that we have spray transfer, but the average welding current is much lower. So now we can weld aluminum as thin as 0.020 in. (0.5 mm) and we can have spray transfer at average currents as low as 30 amperes or so, even with larger diameter 0.047 in. (1.2 mm) wires.

Early pulsed GMAW power supplies were transformer controlled and limited to 60 or 120 Hertz pulsing frequencies. Today's power supplies are inverter based, software controlled, and programmable. Control frequencies are often 20 KHz. This flexibility has allowed a tremendous amount of GMAW process development.

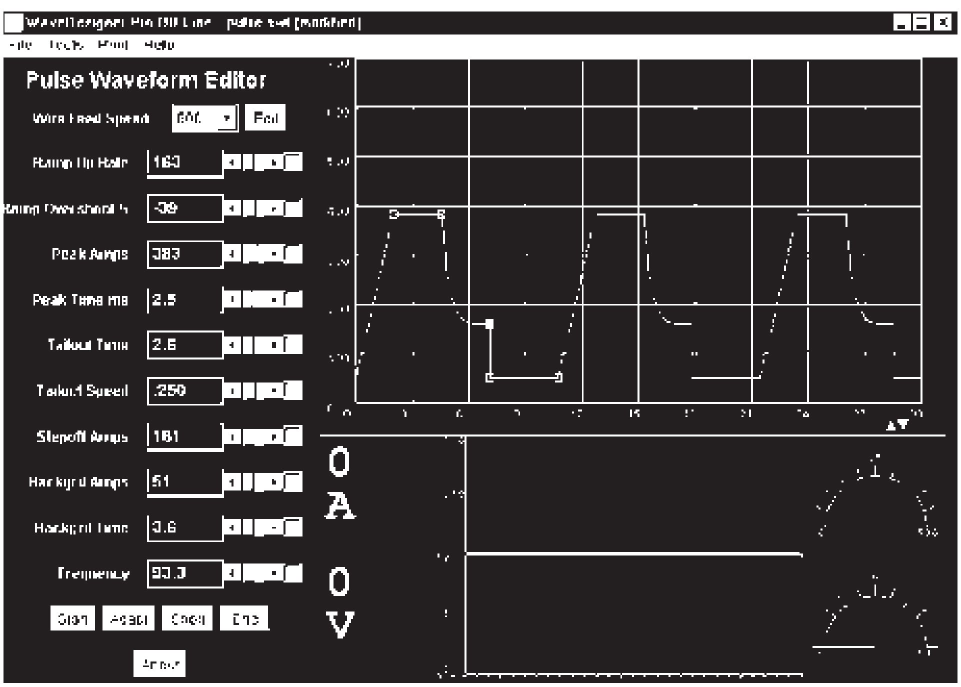

Figure 3. Software screen used for programming Lincoln pulsing power supplies.

Figure 4. Multi–process programmable welding system.

Figure 3 shows a computer screen of proprietary software used for programming pulsed GMAW in a contemporary power supply. There are seventeen pulsing variables that can be programmed. The programmer chooses a wire feed speed (WFS) and develops the optimum pulsing variables for that WFS and saves them. This process is repeated over the range of wire feed speeds and the data is saved as a program.

This whole process is invisible to the user, who merely picks a WFS. The power supply then automatically sets all of the pulsing variables. The only other control is a "Trim" control that gives the welder control over arc length. All the welder has to do is pick a program number and a WFS to have access to a program that is optimized for pulsing for the specific filler alloy and wire diameter being used. Furthermore, if the specific application is so unique that the standard program is inadequate, it can easily be reprogrammed by the manufacturer or, in some cases, by the user.

Figure 4 shows a photo of one such power supply. This power supply can be combined with a push-pull welding torch. Using such a welding system,

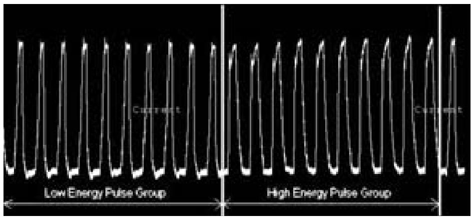

Figure 5. Schematic of Pulse On Pulse waveform.

aluminum wires as fine as 0.030 in. (0.8 mm) can be fed as far as 50 ft. (15 m).

However, GMAW technology development still has not stopped, or even slowed down. The tremendous capabilities available today to control and switch the welding process are stimulating continuing development. For instance, a recent development is a control pulsing logic for thin aluminum called “Pulse On Pulse.” This waveshape is shown schematically in Figure 5. In this process, a number of relatively high energy pulses are alternated with the same number of low energy pulses, causing a weld ripple to be formed each time the low energy pulses fire, and resulting in a very uniform weld bead. An example of Pulse On Pulse welding is shown in Figure 6. This type of pulsing has shown itself to be very applicable to automotive fabrication and is in use already in such applications.

The Future

As in all areas of life, the future is hard to predict. Is there an all-aluminum car in your future? This depends on a lot of factors. If the Federal government increases CAFE requirements, it will drive automakers to reduce vehicle weight further. If aluminum ingot prices stay low, additional aluminum use is more likely. However, ingot prices have been volatile in the past, and that scares auto manufacturers. Whatever the future, though, there is likely to be greater use of aluminum in cars. That means that some of us will continue to try to improve gas metal arc welding technology.

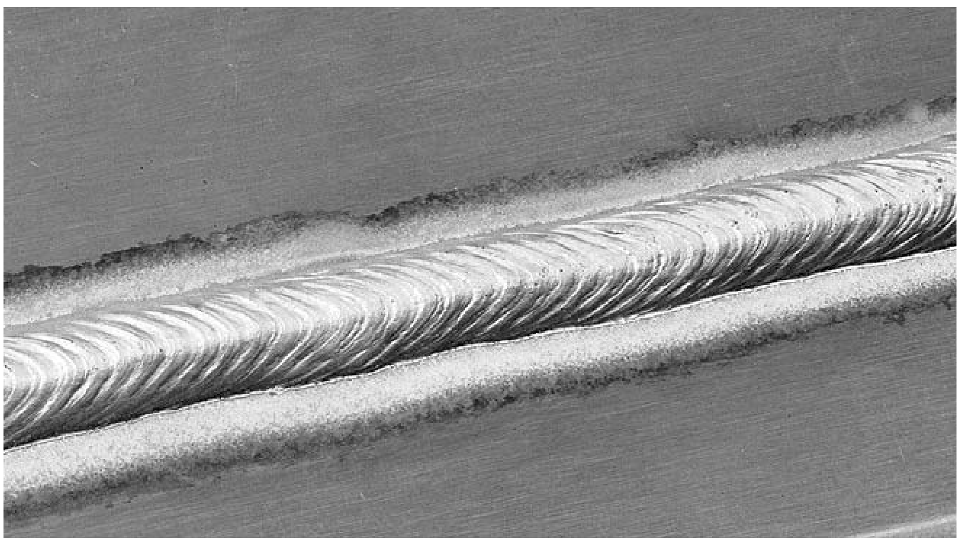

Figure 6. A weld in 3 mm aluminum made using Pulse On Pulse welding.