Joining Aluminum Sheet in the Automotive Industry – A 30 Year History

Resistance welding, mechanical fasteners, and ultrasonic welding are examined in this overview of joining technology

BY J. E. GOULD

ABSTRACT

Aluminum has been used in the automotive industry for more than half a century. During the last 30 years, however, interest in the use of aluminum has been coupled with needs for improved vehicle performance. This has largely focused on improved fuel economy, and by extension, weight reduction. Aluminum generally cannot be implemented in vehicle construction without an associated manufacturing infrastructure. A key element of that infrastructure is welding. Conventionally, resistance spot welding is the dominant joining technology for unitized vehicle construction. This paper reviews the impact of aluminum implementation on the joining technologies used in body-in-white construction. This review includes a discussion of the specific aluminum alloys used (nominally 5XXX and 6XXX sheet products, and 3XX cast products) as well as a discussion of candidate joining technologies. It is noted that assembly of aluminum sheet products is still dominated by resistance spot welding. Basic requirements for aluminum spot welding are discussed, as well as key manufacturing challenges. The state-of-the-art technology is described, including the impacts of new generation approaches that are entering the industry. A description is also provided of alternative resistance welding approaches that are applicable to aluminum automotive fabrication. The use of mechanical fasteners for aluminum construction is discussed. On emerging technologies, this paper also provides an overview of ultrasonic spot welding. This method is being investigated as a candidate replacement technology for resistance spot welding.

Vehicle Lightweighting and the Need for Aluminum in Body-in-White Construction

For more than 30 years, body-in-white development has been dominated by the need to achieve weight reduction while improving crash worthiness (Refs. 1, 2). Weight reduction is considered a primary key to improvements in fuel economy. One area of considerable development has been through materials substitution. Thirty years ago, automotive structural elements were made almost exclusively from relatively low-strength steels. Today, however, a variety of materials can be found within the vehicle structure. This includes a range of steels (interstitial free grades up to martensitic grades), magnesium alloys, plastic composites, and of course, aluminum (Refs. 3, 4). Aluminum has been of particular interest for these applications for a number of reasons. First and foremost, the aluminum alloys under consideration today offer strength-to-weight ratio improvements over mild steel on the order of 3:1. This suggests that for an equivalent design, body-in-white weight reductions on the order of 70% could be achieved simply by this direct substitution. Even given strength and stiffnesses between aluminum and steel, weight reductions of 40 to 60% can still be realized. Additionally, aluminum sheets typically offer considerable corrosion benefits over even galvanized steels. This is of considerable advantage when addressing increased reliability requirements on newer generations of vehicles. A recent survey assessing trends in the automotive industry clearly showed an increase in aluminum usage (Ref. 5). This has also been reflected in the numbers of aluminum-intensive vehicles that have been either developed or are under evaluation. These include the Mercedes-Benz CL Coupe (Ref. 6), the Audi A-2 (Ref. 7), Audi A-8 (Ref. 8), and the General Motors EV-1 (Ref. 9), just to name a few.

It is well understood that vehicle manufacturing is dominated by three design/assembly strategies. These include the unitized vehicle, body on frame, spaceframe, and check (Refs. 1–4). The unitized vehicle approach is most commonly used for higher volume production vehicles. Unitized vehicle manufacture typically incorporates stamped components as structural elements. Stamped components are then assembled into the unibody assembly, generally incorporating subframes for suspension attachments. Structural load paths are then through the vehicle (unitized) body itself. For steel designs, unitized bodies are assembled almost exclusively by resistance spot welding. Resistance spot welding offers a number of advantages, including low cost, minimal fixturing, application flexibility, and high process robustness. Body-on-frame as well as spaceframe approaches incorporate a structure (frame) that acts as a loadpath in design. Body-on-frame approaches are commonly used for truck and SUV applications. Spareframe applications are less common, and more generally associated with low production run vehicles. In both cases, body panels are designed to be attached to this frame, and are not considered significant to the structural performance of the vehicle. Manufacture

KEYWORDS

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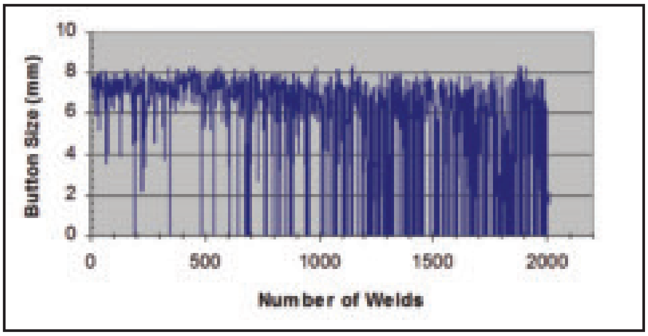

Fig. 1 — Electrode life test results of a 2-mm-thick 5754 aluminum alloy. Note that electrode wear is characterized by increasing numbers of no-weld conditions through the test. All data are taken from Ref. 23.

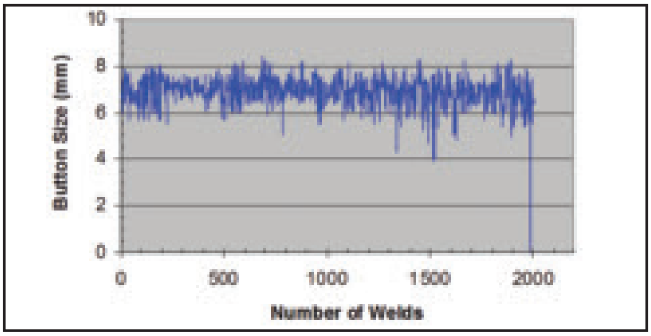

Fig. 2 — Electrode life test results of a 2-mm-thick 6111 aluminum alloy. Note that partial weld failures have replaced no-welds throughout the majority of the test. All data are taken from Ref. 24.

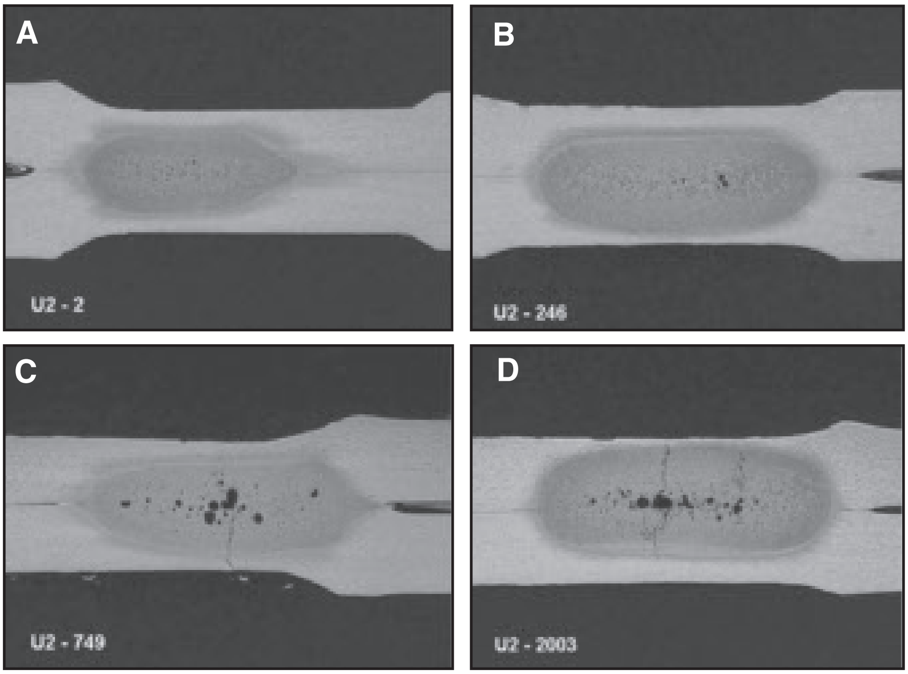

Fig. 3 — Weld microstructure variations during electrode life testing for 6111. All data are taken from Ref. 24. A — Weld Number 2; B — weld Number 246; C — weld Number 749; D — weld Number 2003.

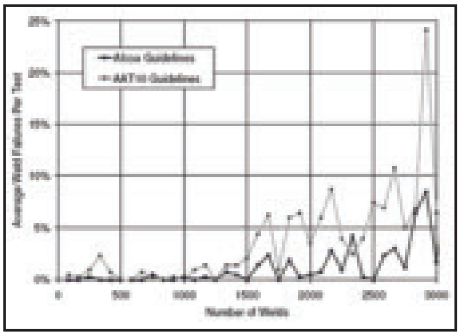

Fig. 4 — Results showing the average numbers of interfacial failures during electrode life testing 0.9-mm 6111 Al sheet. Aluminum Association guidelines refer to radiused electrodes with larger face diameters. Alcoa guidelines refer to truncated cone electrodes with smaller face diameters. Figure taken from Ref. 25.

of such vehicles is dominated by assembly of the frame itself. Such frames have been assembled in a number of ways, including direct welding of tube or channel ends, and even the use of nodes for inter-tube attachment. Such manufacturing is dominated by direct metal deposition practices (predominantly gas metal arc welding [GMAW]). Gas metal arc welding offers considerable manufacturing flexibility for complex frame designs. However, cycle times for GMAW are relatively slow (with corresponding increases in component costs) largely restricting design approaches to lower-volume production vehicles.

Designs intent on increasing relative contents of aluminum (composed to other structural materials) have largely paralleled those for steel vehicles. As a result, aluminum welding approaches parallel those already demonstrated for steels. This paper addresses our understanding of those processes as applied to aluminum in an automotive context. As the discussion below describes, the welding aluminum alloys offer unique challenges different than those seen on steels. As a result, research and development associated with welding these materials goes on to this day. In addition, the challenges seen with welding automotive grades of aluminum alloys has helped foster a range of new joining technologies. These, as have been investigated in an automotive context, are also described in this paper. Of note, this paper focuses on sheet metal construction, rather than joints made in heaver sections. As a result, the discussion provided below addresses technology appropriate for thin sheet materials (body-in-white), rather than those used for heaver section frame and suspension applications.

Table 1— Representative Physical Properties for Iron and Aluminum

	Melting Point (K)	Specific Heat (J/kg-K)	Density (g/cm^3)	Thermal Conductivity (cal/cm^3-s-°C)	Electrical Resistivity (μΩ-cm)	Latent Heat of Fusion (csl/g)
Iron	1809	460	7.87	0.18	9.17	65.5
Aluminum	933	900	2.7	0.53	2.65	95.5

Ratios are provided showing the relative variation of each property between the two materials.

Aluminum Alloy Sheet and Its Use in Vehicle Construction

Aluminum alloys for automotive construction are largely dominated by three classes of materials. These include both sheet and casting grades. Sheet materials include both 5XXX and 6XXX alloy classes (Ref. 10). 5XXX materials are nominally solid solution strengthened /work hardenable grades. These materials are typically alloyed with magnesium (2–5%), and are also applied where corrosion resistance is required. These materi-

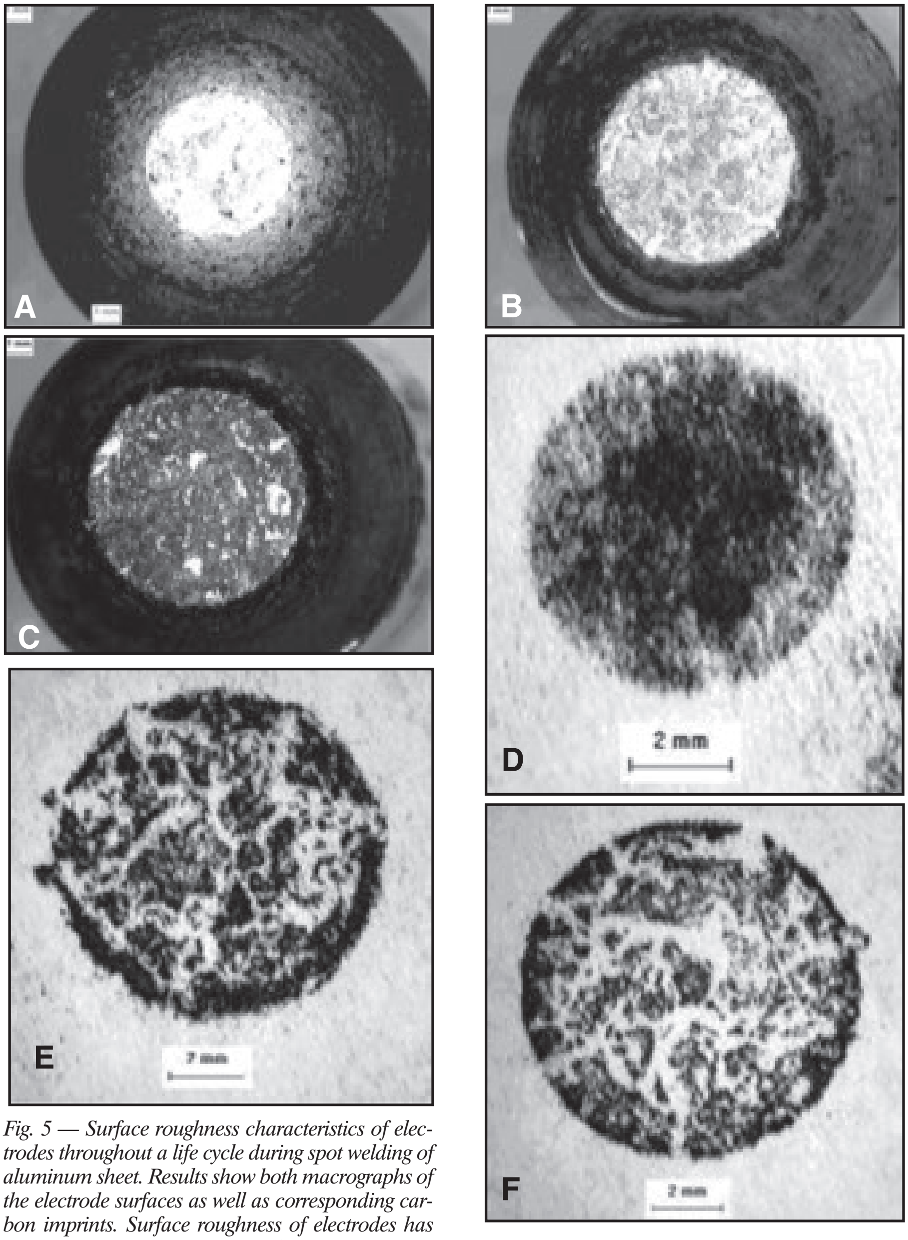

Fig. 5 — Surface roughness characteristics of electrodes throughout a life cycle during spot welding of aluminum sheet. Results show both macrographs of the electrode surfaces as well as corresponding carbon imprints. Surface roughness of electrodes has been shown to insure RSW quality. Figures taken from Ref. 27. A — Weld Number 0, electrode; B — weld Number 1000, electrode; C — weld Number 3000, electrode; D — weld Number 0, carbon imprint; E — weld Number 1000, carbon imprint; F — weld Number 3000, carbon imprint.

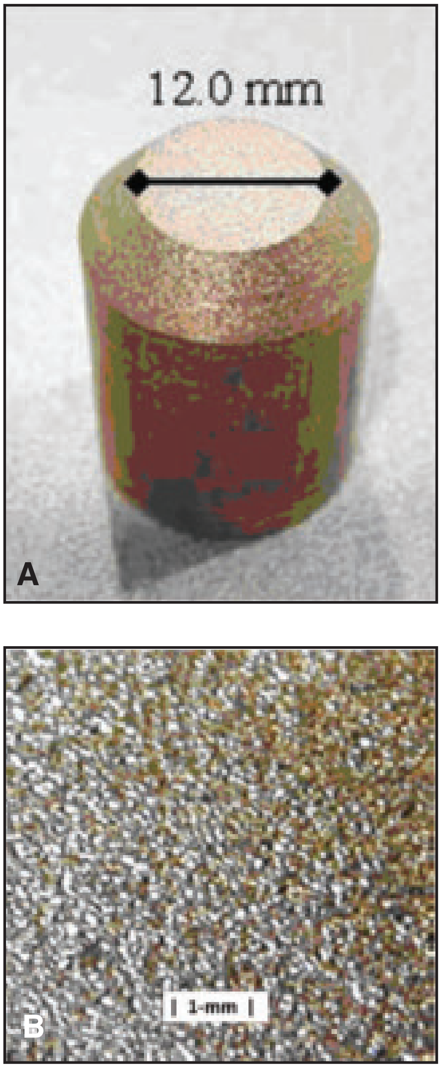

Fig. 6 — The use of grit blasting to achieve electrode surface roughness for RSW of aluminum sheet. Figures are taken from Ref. 28. A — Standard electrode after grit blasting; B — surface showing ~5-μm texture.

als are primarily used in under-body applications. Most common alloys here are 5754, 5182, and more recently 5083 (Refs. 11, 12). 5083 is considered a quick plastic forming alloy, and is under consideration by General Motors. 5XXX alloys are largely used for underbody applications. 6XXX materials are precipitation hardening type alloys, containing additions of both Mg (0.5 to 1%) and Si (0.5 to 1.5%). Specific variants under consideration include 6111 and 6022 alloys. Materials are generally supplied in the T4 (natural aged) condition, and then subjected to forming and subsequent welding. Peak strengths are then obtained as part of the paint bake aging cycle. This class of alloys is attractive for dent resistance applications (skin panels) due to the high-tensile strengths obtainable (<300 MPa) after aging.

Aluminum castings have become attractive for spaceframe applications (Refs. 1, 3). Castings offer potential for lower-cost nodal connections, and are a critical component of the Audi A8 design. Aluminum casting alloys used in automotive construction are typically of the A3XX grade. These are aluminum-magnesium-silicon alloys using the high silicon content to promote castability.

Another material aspect almost universal for automotive-grade aluminum alloys is surface pretreatment. Aluminum is a reactive metal and well known to form an instantaneous oxide on contact with air (Ref. 13). This surface is also known to hydroxylate on exposure to humid conditions (Refs. 14, 15). Generally, instabilities in surface conditions are known to lead to quality variations in a range of joining technologies. As a result, considerable work has been done to develop specific surface treatments for automotive aluminum alloys. The majority of the treatments used in the automotive industry include a bonding agent and a lubricant (Ref. 10). The bonding agent is used to provide surface stability, adhesive bond durability, and, in some cases, painted surface performance. Successful pretreatments have historically been related to chromate formulations (Ref. 10), though considerable work has been done to define silicate-based alternatives (Refs. 16, 17). Such alternatives are considered more environmentally friendly. Other alternatives are based on titanium or zirconium formulations.

Resistance Spot Welding

Without question, the dominant joining technology in automotive construction

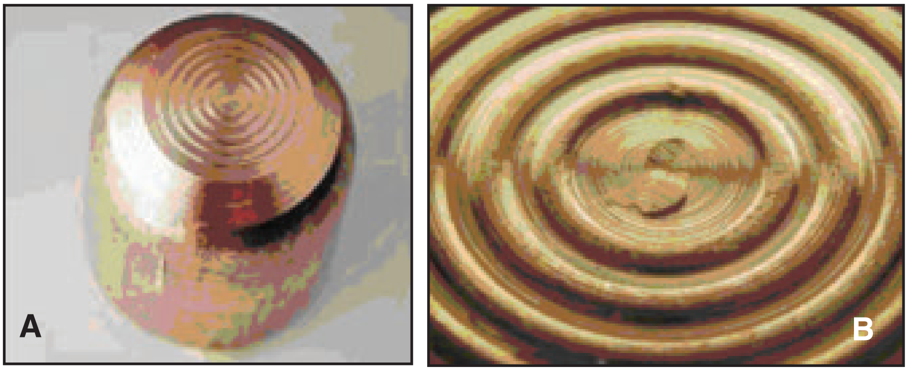

Fig. 7 — The use of a dressing tool to add ridges to the surface of faced electrodes. The ridges provide the same function as other surface roughening techniques. Figures taken from Ref. 28. A — Cap dressed with a ridged tool; B — ridges resulting from dressing.

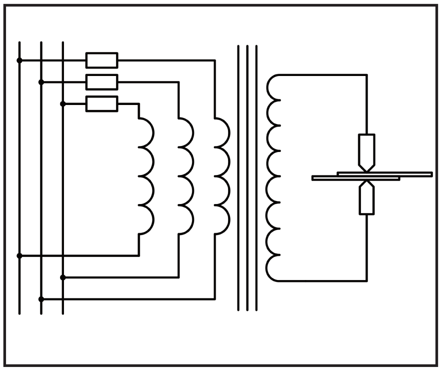

Fig. 8 — Schematic power configuration for a frequency converter direct current (FCDC) resistance welding system. Figure taken from Ref. 10.

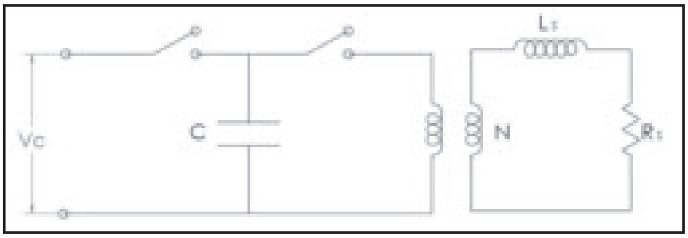

Fig. 9 — Schematic power configuration for a capacitive discharge resistance welding system. Figure taken from Ref. 24.

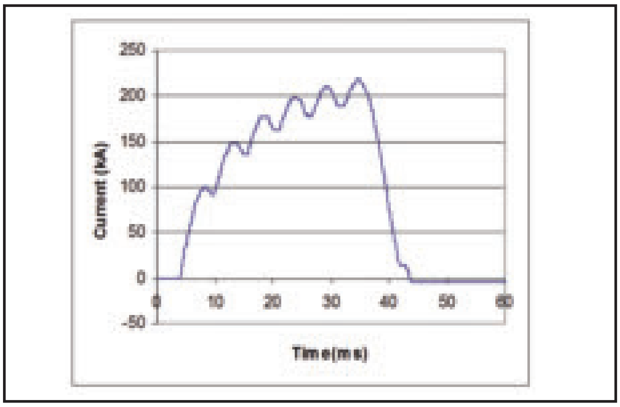

Fig. 10 — Current waveform for the FCDC process.

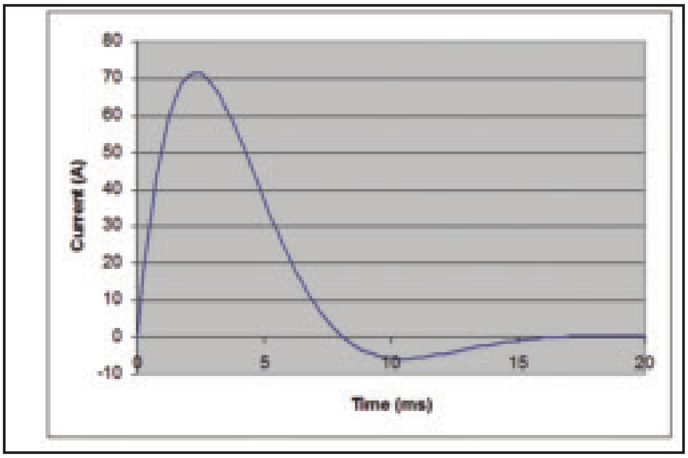

Fig. 11 — Current waveform for the CD process.

today is resistance spot welding. A typical body-in-white constructed today contains as many as 6000 resistance spot welds. A recent automotive roadmap (Ref. 5) suggests that trend is not likely to change any time soon. Not surprisingly, the majority of the materials joining research with regard to aluminum in automotive assembly concerns resistance spot welding. Resistance spot welding of steel body assemblies has been commonplace in the industry dating back to the 1950s (Ref. 18). Resistance spot welding of steels has been characterized by high reliability, low costs, and considerable manufacturing robustness. There has also been considerable experience resistance spot welding aluminum sheet. Many design aspects from resistance spot welding steels are transferable to aluminum sheet. These include flange dimensions and weld sizes. Spot welding of aluminum sheet for automotive applications has traditionally focused on closure panels (hoods, deck-lids) and is transitioning into body-in-white.

Development of basic practices for resistance spot welding of aluminum date back to roughly the 1940s (Ref. 19). This practice was based on welding of aerospace components, and has largely been embodied today in resistance spot welding guidelines made available by the Aluminum Association (Ref. 20). Resistance spot welding requirements of aluminum differ greatly from those of steel. This is largely based on differences in material physical properties. These differences are highlighted in Table 1. Aluminum shows roughly one- third the electrical resistivity and three times the thermal conductivity of steel. As a result, aluminum generally requires considerably higher welding currents and shorter times compared to steels (Ref. 19). The basic welding practices as defined in the Aluminum Association recommended guidelines (Ref. 20) also include relatively large face diameter and shallowly radiused electrodes (compared to steels). These electrodes are used primarily to avoid excessive indentations during welding.

Early on, it was identified that practices such as defined in the Aluminum Association guidelines would be problematic for automotive applications (Ref. 21). Within an automotive context, application of practices initially defined for aerospace components resulted in a number of manufacturing issues. These included process instability, poor robustness, excessive electrode wear, and poor weld microstructures. Much of the early activity focused on variations in aluminum surface condition (Refs. 13, 22). In particular, it was shown that following surface cleaning, contact resistances could change markedly over short durations in time. A key aspect of adding pretreatments to the aluminum was to stabilize the aluminum surface, reducing this process instability (Ref. 10).

Electrode life, however, has been the major issue affecting resistance spot welding aluminum in automotive applications. Original practices for spot welding aluminum (Ref. 20) allowed frequent redressing of the electrodes, mitigating

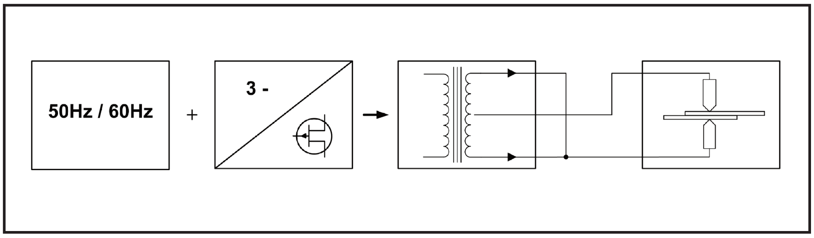

Fig. 12 — Schematic representation of a medium-frequency direct current (MFDC) resistance welding power supply. In this approach, AC power is rectified to DC, electronically switched to create MFAC, and then finally rectified following transformer voltage step-down. Figure taken from Ref. 10.

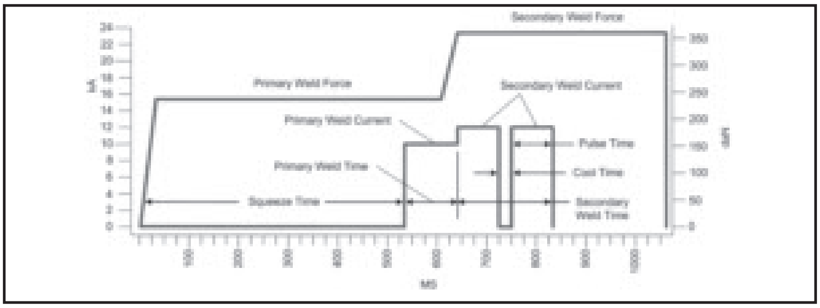

Fig. 14 — Schematic diagram showing the programming relationships between current and force with the ARO electric servo-gun.

Fig. 13 — ARO electric servo-gun with MFDC power supply.

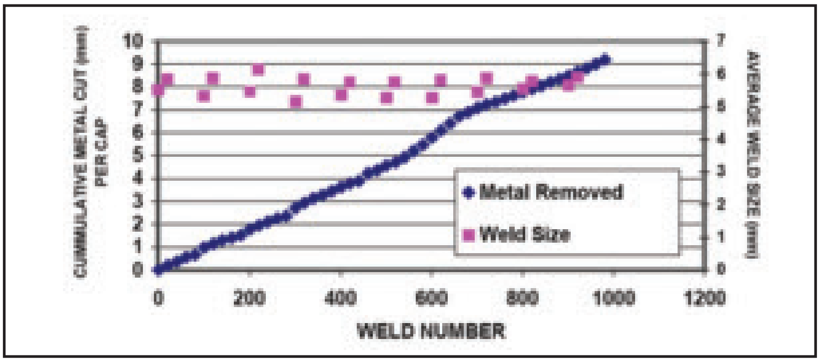

Fig. 15 — Relationship between dressing schedule and weld size throughout an electrode life cycle. Work was done on a nominally 2.5-mm-thick 5083 aluminum alloy. Figure was taken from Ref. 32.

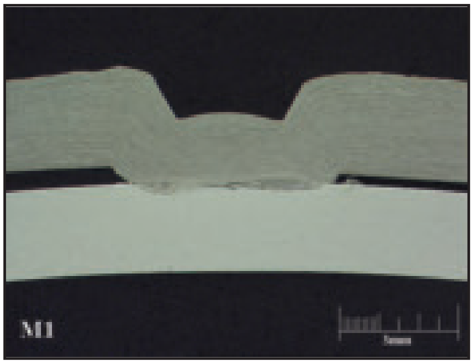

Fig. 16 — Macrosection of a projection weld between 6111 (top) and 6061 (bottom) aluminum alloys.

electrode life influences. In an automotive context, however, this is not practical, so electrode life became a concern. Examples of typical electrode life tests on aluminum sheets are provided in Figs. 1 and 2. These results are for 5754 and 6111 sheets, respectively (Refs. 23, 24), and provide data showing the variation in weld size following 100% peel testing. Results are defined by two characteristics. Most notably, the tests are characterized by periodic "drop-outs," that is, where the apparent peel button size falls dramatically, often to zero. The second is that the non-drop-out button size appears to continuously increase throughout the test. Metallurgical characterizations done through these electrode life tests provide some insights into this behavior. Sample sections through one of these tests are presented in Fig. 3. These results demonstrate that drop-outs during electrode life testing are largely related to metallurgical phenomenon with the weld nuggets themselves. These include the formation of shallow welds early in the electrode wear cycle, increasing weld size (leading to reduced drop-outs), and then finally expulsion and coarse defects toward the end of the wear cycle.

Through this and similar sets observations, it was identified that stability, rather than cleanliness of the electrode face, was the key to consistent welding behavior. This, in turn, offered potential for improved electrode life. Work by Spinella and Patrick (Ref. 25) showed that by modifying resistance spot welding practices themselves (primarily by reducing electrode face diameters), improvements in both electrode life and weld consistency could be achieved. This improvement is shown in Fig. 4. Later work from the same group (Ref. 26) showed that by stepping the welding force and current could add additional improvements in electrode life. This was related to taking advantage of roughened surfaces, and maintaining specific pressures and current densities as the electrodes wore. Related works by other authors provided confirmation to this approach. Work by Chan and Scotchmer (Ref. 27) showed that pretexturing the electrode faces with TiC added the necessary roughness to create stability and extend electrode life. The impressions taken throughout a sample electrode life test (Fig. 5) demonstrate consistency of surface roughness throughout the trial. Finally, work done by Sigler et al. (Ref. 28) examined several variations of electrode face surface roughening on spot weld process robustness. Work included examining grit blast electrodes (shown in Fig. 6) and radially ridged electrodes (shown in Fig. 7). The studies done did not include electrode life testing. However, both variants of artificially roughened electrodes showed improved weld consistency and tolerance to variations in fitup conditions.

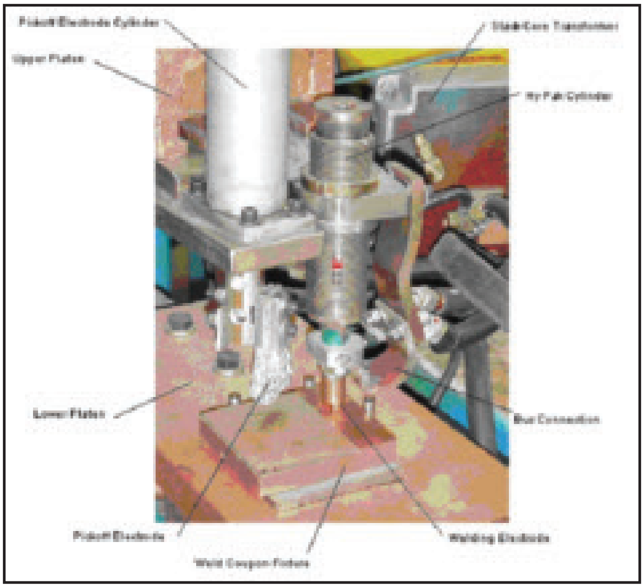

Fig. 17 — Physical layout of the HYPAK® system used for projection welding aluminum alloys. Figure taken from Ref. 36.

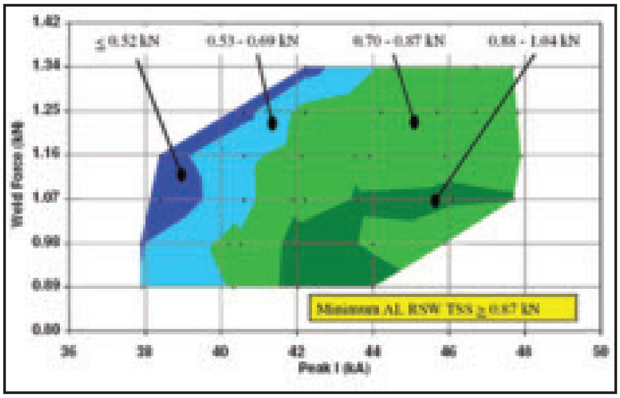

Fig. 18 — Weldability lobe for RPW of 0.8-mm 6111-T4 aluminum sheet. The lobe shown provides weld strengths as a function of peak current and applied force. Figure taken from Ref. 36.

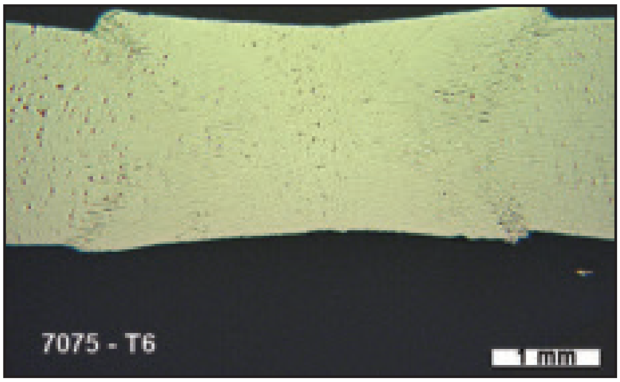

Fig. 20 — Cross section of a CHRW on a 2-mm-thick 7075-T6 aluminum alloy.

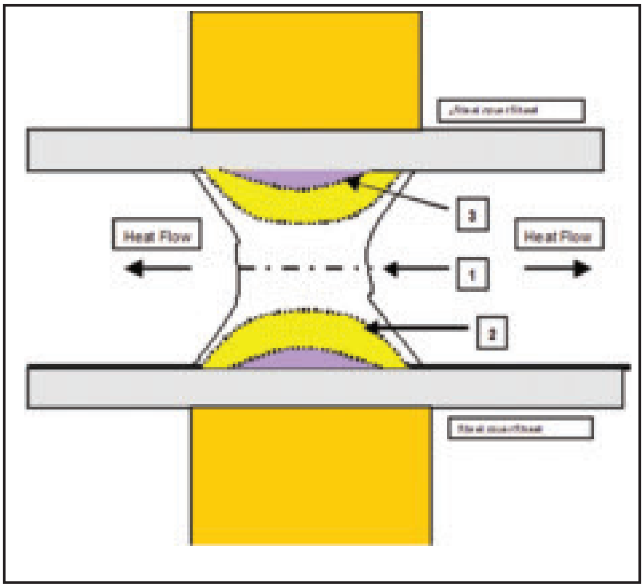

Fig. 19 — Schematic representation of the conductive heat resistance welding (CHRW) process. Note steel coversheets providing heat generation and constraint of the Al weld metal.

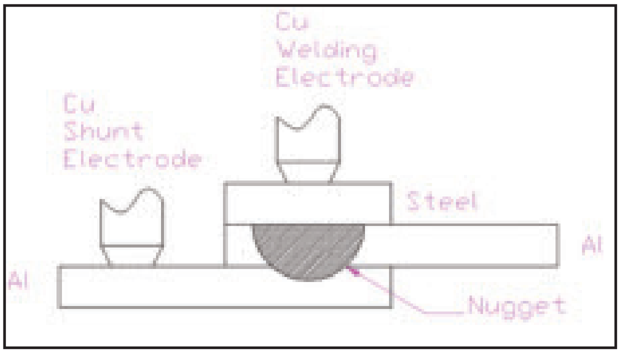

Fig. 21 — Schematic representation of a single side conductive heat resistance spot welding (CHRSW) application.

Process consistency and electrode life have also been affected by advances in power supplies and equipment. As has been suggested from other reviews (Refs. 10, 19) and recommended practice documents (Ref. 20), aluminum sheets have traditionally been welded using DC systems, often with postweld forge capability. Historically (largely in an aerospace context), two types of power supplies have dominated resistance welding of aluminum. These included frequency converter (FCDC) and capacitive discharge (CD) systems. The basic power supply arrangements for FCDC and CD systems are provided in Figs. 8 (Ref. 10) and 9 (Ref. 29), respectively. Resulting process waveforms are shown in Figs. 10 (Ref. 19) and 11 (Ref. 29), respectively. Both power supply configurations result in DC current flowing into a low-impedance secondary. Typical secondary impedances for such systems are typically measured in 10s of μohms. This allows the necessary high currents for resistance welding of aluminum sheet to flow at relatively low secondary voltages. It has also been suggested that a key factor for aluminum spot welding is the implicit rise time of the current waveform (Ref. 19). Faster rise times reduce conduction effects and allow spot welds to be made at shorter times with less thermally related effects. This implies lower currents and reduced levels of electrode wear.

Two-stage forcing systems have also been employed for welding aluminum sheet (again, largely in the aerospace industry), generally paralleling the development of FCDC and CD power supplies. Two-stage forcing systems are typically pneumatically driven, employing a "bucking cylinder" that works against the main welding cylinder force. Weld force then becomes the difference between the main and bucking cylinder forces, while the forge force is applied by rapidly venting the bucking cylinder. Venting the bucking cylinder allows full application of the weld cylinder force, providing a consolidating spike at the end of the cycle.

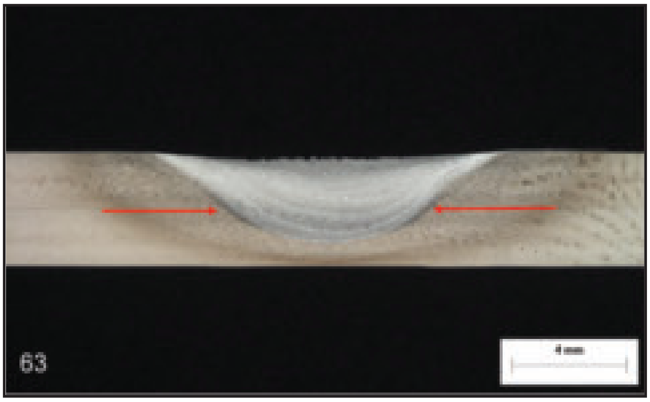

Fig. 22 — Cross section of a single-side CHRSW lap joint on 2-mm-thick 7075-T6 Al.

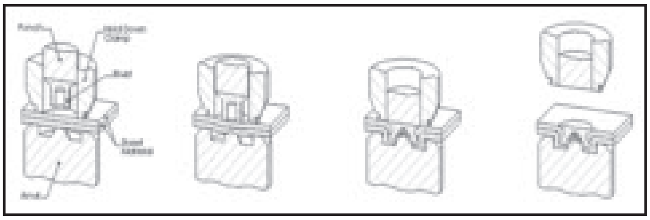

Fig. 23 — Schematic representation of the self-piercing riveting process.

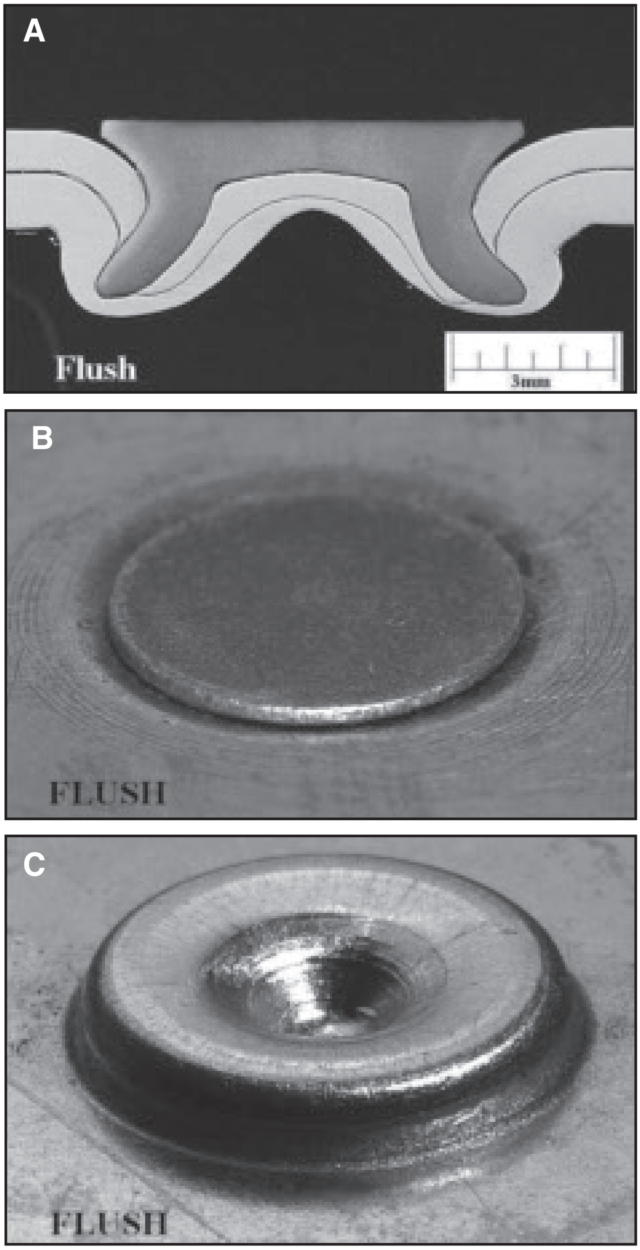

Fig. 24 — Morphological details of a self-piercing rivet between sheet materials. A — Rivet cross section; B — rivet head; C — rivet root.

As suggested, such systems have been effectively used since the 1940s (Refs. 10, 19, 25) in the aerospace industry. However, they are both cost prohibitive and physically inflexible for automotive applications. As a result, much of the original work on resistance spot welding of aluminum for automotive applications focused on AC power supplies (though some 1- and 3-phase DC systems are used) and single force systems. Two recent equipment innovations, however, have changed this outlook. These include the development of medium-frequency DC (MFDC) power systems, and electric-servo controlled forcing systems. The medium-frequency power system is diagramed in Fig. 12 (Ref. 10). MFDC power essentially takes 3-phase current, rectifies it to DC, electronically switches this power to create single-phase AC power at frequencies ranging from 300 Hz to 20 kHz, achieving welding voltages currents through a transformer, and finally rectifies that output to provide DC on the secondary. This system allows significant reduction in transformer sizes while delivering the necessary high currents for welding aluminum alloys, and is seen as a vehicle for economic joining in an automotive context (Refs. 10, 19, 25). More recently, these systems have been coupled with electric-servo units for providing welding force. A typical welding system is shown in Fig. 13, and a diagram detailing the relationships between current and force is provided in Fig. 14. These combined current/force cycles have been recently demonstrated to provide benefits for welding complex stack-ups of steel (Ref. 30), and offer advantages mirroring combined current/forge cycles typical of previous FCDC and CD systems of the past.

A primary drawback of using DC power for resistance spot welding of aluminum, however, is electrode life. Various researchers have compared electrode lives using AC and DC power, and consistently find electrode lives reduced by ½ to ¾ (Refs. 19, 21, 31). This reduction in electrode life has been related to polarity effects during resistance welding (Refs. 10, 19). Polarity effects are known to cause excessive heating and preferential wear on the anode side of the stackup. For this reason, electrode life is considered enhanced by frequency converter DC machines due to the polarity switching that occurs between pulses (Ref. 10). Generally, however, the economic and manufacturing flexibility advantages of MFDC (in combination with electric-servo guns) outweigh concerns with electrode life. Current strategies are to employ dressing to maintain weld integrity while using these systems (Ref. 32). Dressing frequencies are known to vary from 10s to 100s of welds depending on the application. An example of the relationship between frequent dressing (every 20 welds) and electrode life is presented in Fig. 15. These results demonstrate that the use of MFDC power combined with such frequent dressing can achieve effective electrode lives in access of 1000 welds.

Other Resistance Welding Processes

A range of other resistance welding processes has also come under consideration for aluminum auto body construction. A major effort has been to develop projection welding for aluminum. The use of resistance projection welding on steels is commonplace (Ref. 33). However, the high thermal conductivities and tenacious surface oxides make projection welding problematic. Here, the high conductivities require extremely rapid current rise times

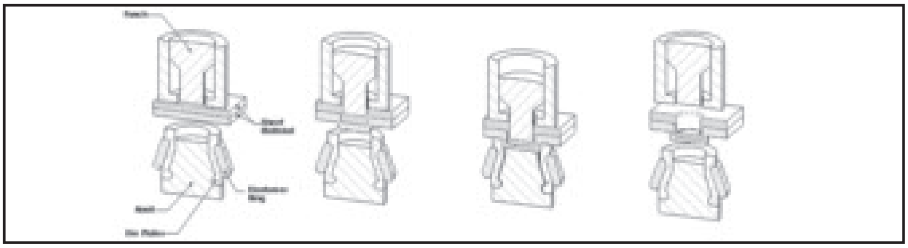

Fig. 25 — Schematic representation of the sheet metal clinching process.

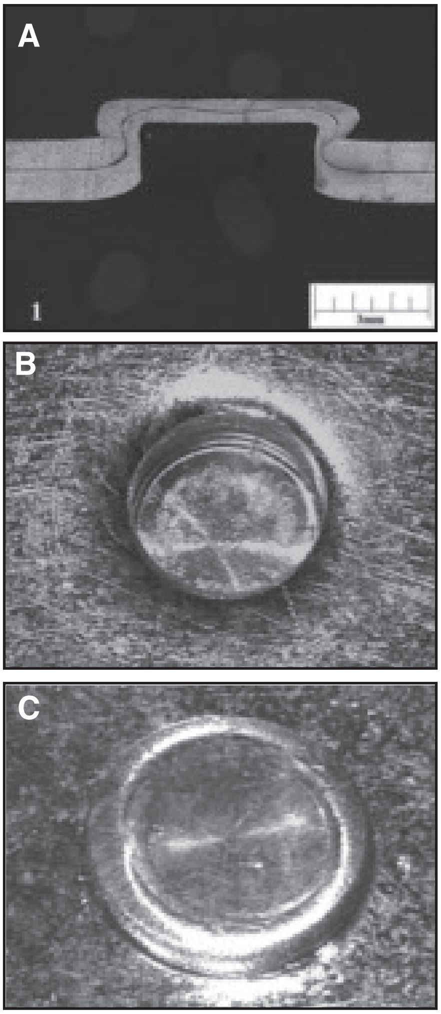

Fig. 26 — Morphological details of a clinch joint between sheet materials. A — Clinch joint cross section; B — top view of the clinch joint; C — root view of the clinch joint.

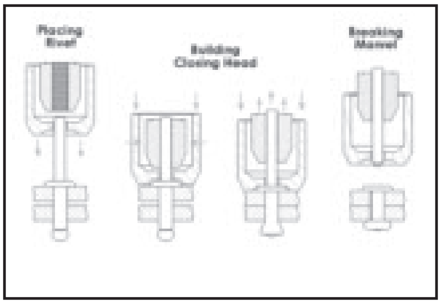

Fig. 27 — Schematic representation of the blind riveting process. Figure from Ref. 41.

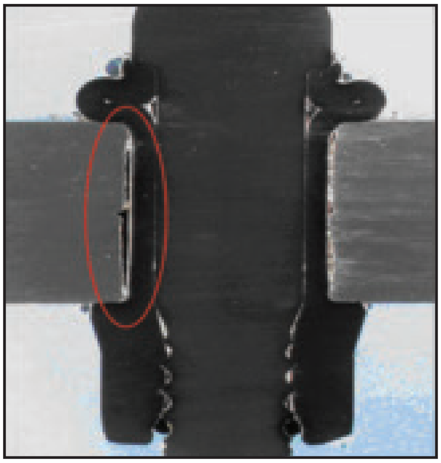

Fig. 28 — Cross section of a blind rivet made between sheet materials. Figure from Ref. 44.

to allow localization of forging (Ref. 29). In addition, work on mechanisms of bonding has demonstrated that thermal dissociation of Al_2O_3 particles present on the aluminum surfaces is nearly thermodynamically impossible (Ref. 34). As a result, bonding occurs chiefly from two mechanisms; deformation associated with forging and potentially surface destruction associated with localized melting. An example cross section of an aluminum projection weld is shown in Fig. 16. In this case, bonding occurred through the disruption of the contact surfaces as is clearly evident from the micrograph. Applications for projection have been described as early as the mid 1980s (Ref. 35). More recently, projection welding has been demonstrated with a system is marketed under the tradename HY-PAK®. This system combines a ½ cycle AC power supply with a fast mechanical follow-up mechanism. The system itself is shown in Fig. 17. That system has been used to develop aluminum hem flange attachments (Ref. 36). A plot of weld strength as a function of applied current is provided in Fig. 18. Here, it can seen that for a 0.8-mm 6111 aluminum alloy, joint shear strengths on the order of 1 kN were observed over a range of processing conditions.

Another novel resistance welding approach for aluminum alloys was developed by Edison Welding Institute. This process is termed conductive heat resistance welding (CHRW). The process essentially is resistance welding of an aluminum stack-up with one or more cover sheets employed (Refs. 37–39). A schematic representation of the process is provided in Fig. 19. In this process, the cover sheets are made from steel and consumables with two intended functions. First, the high resistivity of the steel provides the necessary heat generation for the process. Second, the steel cover sheets are of relatively high thermal stability and actually act to constrain the melting aluminum which occurs during the process. A representative cross section of a conductive heat resistance weld is provided in Fig. 20. It is of note that welds are typically hour-glass shaped (responding to heat generation in the cover sheets) and free of internal porosity. In this latter case, it has been shown that the cover sheets transmit sufficient stress to the weld pool to suppress hydrogen gas evolution during solidification (Ref. 37), minimizing any gas related porosity. The process has also been adapted to single side welding (Ref. 40). Here, welding is done with a push-pull arrangement, with the cover sheet located only where the location of the weld is desired. The welding configuration as well as the resulting cross section is shown in Figs. 21 and 22, respectively. The morphology of the weld clearly indicates the location of the cover sheet, and again shows no porosity in the joint.

Mechanical Fastening

Mechanical fastening is perhaps the oldest of joining technologies, accomplishing attachment by mechanical interference rather than metallurgical bonding. Mechanical fastening covers a broad range of approaches, including screwing, folding, clamping, riveting, and clinching (Ref. 41). Mechanical fastening offers the opportunity to assemble aluminum sheet structures at relatively high speeds and low cost (comparable to resistance processes), without the thermal effects associated with welding. The most attractive mechanical fastening approaches for aluminum body assembly have included clinching, self-piercing riveting, and blind riveting (Refs. 41–44).

The self-piercing riveting process uses a rivet to join two or more pieces of sheet metal in a lap configuration. The process is illustrated in Fig. 23. Essentially, a hollow rivet is forced through the sheets intended for joining. On the back side of the sheets, there is typically a mandrel or die. This die primarily facilitates spreading of the hollow rivet, accomplishing the joint. In addition, the geometry of the mandrel guarantees adequate penetration of the rivet, and facilitates formation of an adequate profile on the back side of the joint. A cross section of a self-piercing rivet on similar thickness sheet steels is shown in Fig. 24. The configuration of this equipment is relatively simple, consisting of a forcing system and a relatively heavy backup system for the mandrel. Most recent

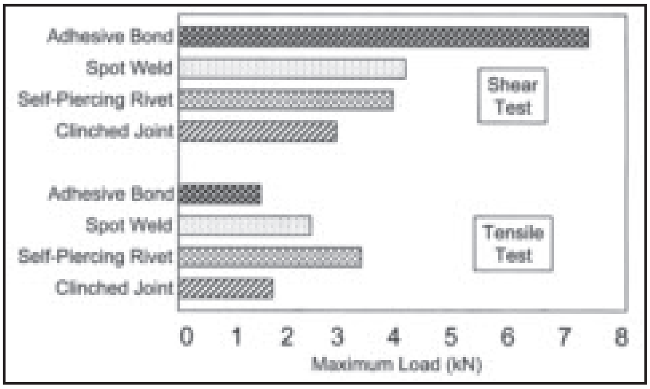

Fig. 29 — Representative mechanical properties for adhesive bonds, resistance spot welds, self-piercing rivets, and clinch joints on 1.6-mm/1.6-mm lap joints.

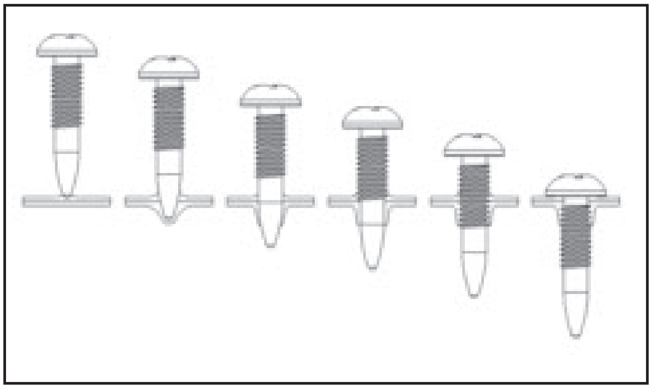

Fig. 30 — Schematic representation of the flow-drilling process for applying mechanical fasteners. Figure from Ref. 45.

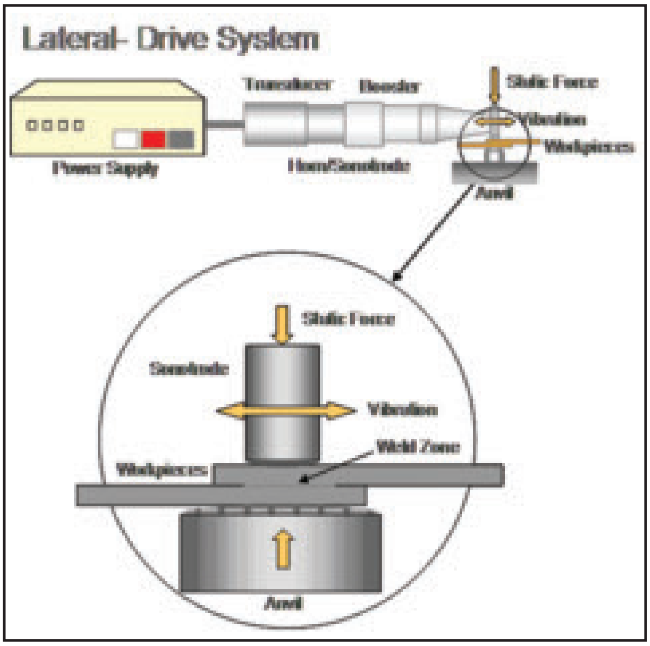

Fig. 31 — Schematic layout of a lateral drive ultrasonic spot welding (USW) system with details of reactions at the workpiece itself.

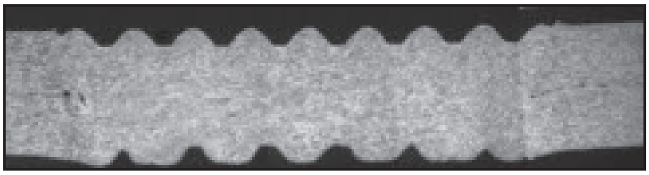

Fig. 32 — Cross section of an ultrasonic spot weld made on 0.8-mm-thick 1100 aluminum alloy.

equipment incorporates electric servos for accomplishing necessary riveting forces. The configuration is in many ways quite similar to electric-servo resistance spot welding guns. One major difference is the absence of a welding transformer. This results in substantial weight reduction of the gun, making the system considerably more adaptable to robotic applications. Generally, self-piercing riveting guns use a feeding tape to deliver the rivets to the head of the gun assembly. More recently, air-driven feed systems have been used to deliver rivets to the gun.

Clinching is a somewhat related technology in which the materials are pressed and drawn to form an interlocking, interference type of a joint. The clinching process is illustrated in Fig. 25. Essentially, a local die set is used. The top die (or punch) basically extrudes the top and bottom sheets into a lower die assembly. The resulting forming operation leaves material from the top sheet formed to a larger diameter than the apparent hole in the bottom sheet, affecting an interlock type of joint. A macrograph of a clinch joint is shown in Fig. 26. Apparent in this micrograph are the diameters of the punch and lower die as well as the change in diameter of metal extruded from the top sheet. Clinching is again done with small press-type machines. These are commonly configured as clinch-type guns, with similar appearance to the self-piercing rivet guns described above. Two-side access is again required for clinch joining applications.

Blind riveting allows attachment of sheets through preformed holes. The rivet itself has a head for seating on one side of the joint, and a built-in mechanical expander to form the rivet on the back side of the joint. This mechanical expander is connected through the body of the rivet with a tension ligament. The joining process is shown in Fig. 27. As a load is applied to the ligament, the expending element is drawn up into the rivet, causing expansion. Once the expanding region of the rivet bottoms out on the lower sheet, the tension ligament fails, and joining is complete. A typical cross section of a completed blind rivet is shown in Fig. 28. The most recent adaptations of this process include improved designs for expansion of the rivet itself into the formed hole (Ref. 44). These are referred to as form-fit or FF® style blind rivets. This variant on the process has been reported to improve slippage loads on aluminum joints by greater than a factor of 5, as well as enhance fatigue strengths. Mechanistically, blind riveting differs from self-piercing riveting and clinching in that the primary deformation required for joining is in the rivet, rather than the attached sheets. Blind riveting also offers considerable advantages in that only one-side access is required. However, the requirement of a preformed hole is a major drawback compared to other mechanical fastening technologies.

Mechanical behavior of mechanically fastened joints has also been studied extensively. An example of these results is presented in Fig. 29. In this figure, data have been collected for lap joints between 1.6-mm aluminum sheets using adhesive bonding, resistance spot welding, self-piercing riveting, and clinch joining. Data have also been collected for tensile shear and direct tension (cross tension) configurations. It is of note that self-piercing rivets show comparable performance to resistance spot welds in both shear and direct tension. The performance of the clinch joints is generally somewhat poorer than for the spot welds, averaging roughly 70% of resistance spot weld strengths in both the shear and direct tension configurations. It is further of interest that the self-piercing rivets minimal reduction in strength between shear and direct tension configurations. Generally, for resistance spot welds, performance is substantially poorer in the direct tension configuration.

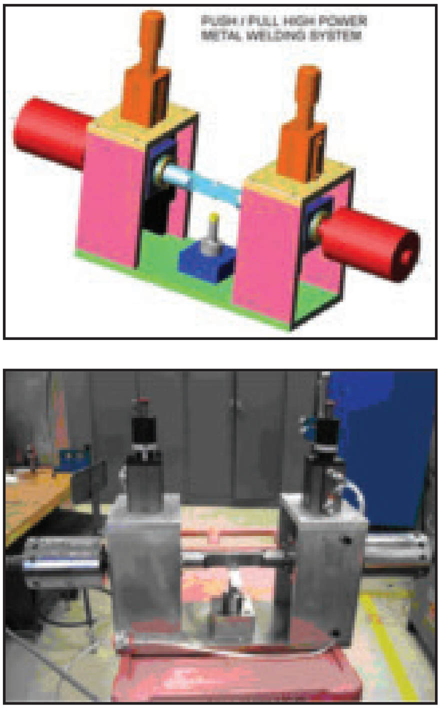

Fig. 33 — Configurations of push-pull systems for ultrasonic spot welding. Figures are from Ref. 50. A — Schematic representation of a direct acting push-pull system; B — an actual push-pull system configured for USW of sheet aluminum.

An additional mechanical fastening technology receiving attention in the automotive industry is the use of flow-drilling screws (Refs. 41, 45). Flow drilling implies the use of self-tapping screws with a hardened (unthreaded) end effector. The fastener is applied to undrilled workpieces at high rotational speeds. The hardened end effector generates heat within the workpieces, allowing plastic deformation and flow. This then results in a self-pierced hole, which on further feeding engages the threads on the screw portion of the fastener. The result is a single-side mechanical joint without the need for a preprepared whole. The process is diagrammed in Fig. 30. Fasteners for aluminum sheet are generally of stainless steel, applied with dedicated design C-guns (Ref. 45). The approach is being used on a number of automotive platforms in Europe, with cycle times ranging from 1.5 to 5s.

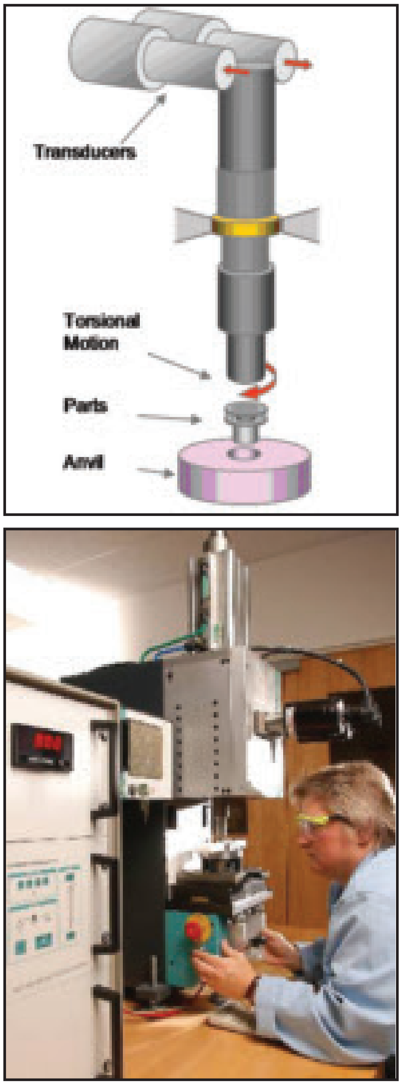

Fig. 34 — Configurations of torsional welding systems for ultrasonic spot welding. A — Schematic representation of the torsional ultrasonic welding configuration; B — actual 10-kW torsional welding system at Edison Welding Institute.

Ultrasonic Welding

Ultrasonic metal welding is a technology that employs translational motion between opposing sheet workpieces to generate the necessary heat and deformation for bonding. The process functions at frequencies on the order of 20 kHz (Refs. 46–48) with displacements on the order of 100s of microns. The vibratory action is developed by electrical excitation of a piezoelectric element, which is then amplified through a booster arrangement. A schematic representation of this welding process is provided in Fig. 30. The exact mechanism of bonding during ultrasonic welding is still the subject of much debate. There are questions regarding the temperatures achieved, as well as the specific metallurgical behaviors that facilitate bonding. It has been suggested that both melting (Ref. 47) and solid-state deformation (Ref. 49) might both play a role. The microstucture of a typical ultrasonic spot weld in aluminum is provided in Fig. 31. This micrograph provides good insight to the transitions occurring in aluminum sheets during ultrasonic spot welding. Evident are the indentations on the sheet surfaces, as well as the characteristic wavy bond line indicative of proper welding. The major limitation of ultrasonic welding appears to be the power delivery capability of the ultrasonic power source itself (Ref. 50). State-of-the-art power supplies are limited to roughly 5500 W. At these power levels, the process is restricted to relatively thin gauge materials or welding times in excess of several seconds. To address these power limitations, so called "tandem systems" are now in use. These systems may be of either "push-pull" or "torsional" types. Push-pull systems use two ultrasonic elements configured on opposite ends of the driving element. An example is shown in Fig. 32. The piezoelectric elements are then excited 180 deg out of phase, resulting in a doubling of the deliverable power to the workpieces. Torsional systems function in a similar fashion, though with the ultrasonic power units located on opposite sides of a rotary-oscillating mechanism. The power systems are again excited 180 deg out of phase, resulting in a short arc displacement being transferred to the workpieces. The system is diagramed in Fig. 33, and a torsional ultrasonic spot weld is presented in Fig. 34. Such systems now allow ultrasonic power levels on the order of 10 kW to be achieved for spot welding purposes.

Considerably more efforts have been expended understanding process-related effects for ultrasonic spot welding. Ultrasonic spot welding is typically done at constant power with the total energy input defined by the weld time itself. Given the limitation of power available from current systems, ultrasonic spot welding typically employs weld times on the order of seconds. Generally, it is understood that weld strengths increase with higher levels of power, time (total energy), and force. Another major factor affecting weld quality is the area of the sonotrodes themselves. As demonstrated in Fig. 35, larger contact areas between aluminum sheets generally result in higher shear loads (Ref. 50). This is consistent with similar data on resistance spot welding. There has also been considerable work assessing manufacturing robustness associated with ultrasonic spot welding of aluminum sheets (Refs. 46, 51). Process factors studied have included the relationships between power, sonotrode amplitude, weld time, clamping force, etc. Generally, higher energies (expressed predominantly by larger amplitudes and longer times) are advantageous. However, there appears to be an upper limit where excessive softening and indentation reduce the strength of these joints. The process also tends to benefit from higher welding (or clamping) forces. Considerable work has also been done evaluating the influence of material conditions on the quality and reliability of joints made. Variations in surface finish have received the most attention. Generally, the process is unaffected by levels of surface oxides (Refs. 44, 51), the presence of lubricants (Ref. 51), or substrate texture (Ref. 51). The data do suggest, however, that increases in the degree of residual

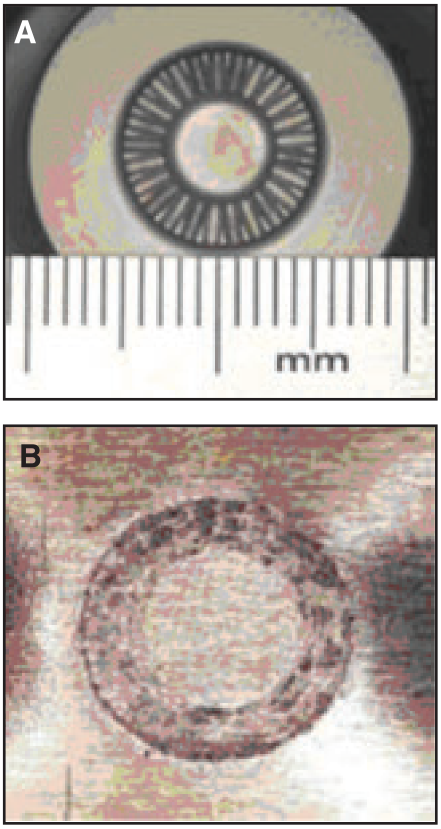

Fig. 35 — Details of a torsional USW made on a nominally 0.8-mm 6111 aluminum alloy. Figures are from Ref. 50. A — Top surface of the torsional USW indicating the gripping marks resulting from the process; B — interfacial failure of a sheared torsional USW showing the apparent bond area.

cold work in the aluminum substrate correspond to higher weld strengths (Ref. 44). Finally, there appears to be little correlation (outside of simple contact area) between the profile of the sonotrode itself and resulting joint strengths (Refs. 44, 47).

Summary

The last 30 years have seen a progressive increase in the use of advanced materials for automotive construction. Aluminum and its alloys have played heavily into this mix. Sheet and wrought products as well as castings have been considered for various subsystems of advanced material vehicles. A key to the implementation of aluminum alloys for automotive construction is the identification/development of cost-effective joining technologies. This paper is focused on a number of key developments that have enabled these technologies. The general focus is on body-in-white applications, or sheet metal construction. It is understood that such construction is dominated by resistance spot welding (RSW). To that end, developments in resistance spot welding technology (and associated weld bonding) are addressed first. These included the progression from AC to DC to MFDC current, development of proper electrode designs, and use of dresser systems to maintain electrode profiles. Also discussed are recent capabilities enabled by electric-servo guns for production spot welding.

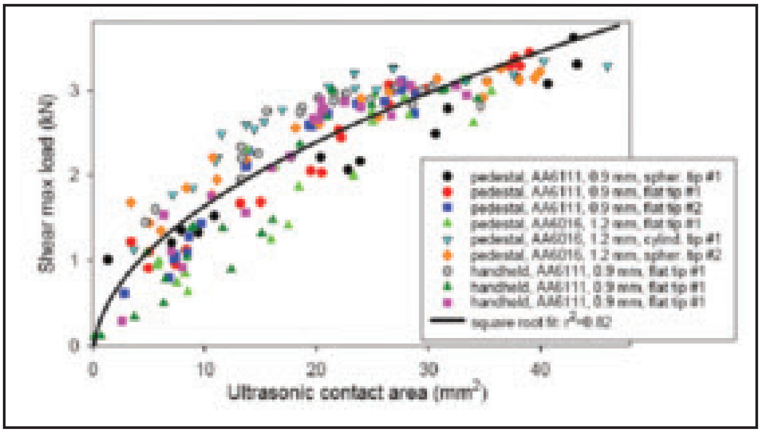

Fig. 36 — Relationship between sonotrode contact area and resulting joint strength. The data here cover several different substrates, equipment configurations, and sonotrode profiles. Figure is from Ref. 50.

A discussion is provided on alternative resistance welding technologies appropriate for aluminum sheet materials. These include resistance projection welding (RPW) and conductive heat resistance welding (CHRW). These are widely disparate technologies, but they are being investigated for specific applications within the body-in-white framework.

This overview then examines use of various forms of mechanical fastening. These technologies are currently being used as alternatives to resistance spot welding for both steel and aluminum body-in-white structures. The methods described include self-piercing riveting, clinching, blind riveting, and flow drilling. These technologies are all basic mechanical interference joining approaches, alternately with (riveting, screws) or without (clinching) a third body element. The basic approaches are described with some baseline mechanical properties data. Of particular interest are new generations of blind riveting. These approaches have been shown to increase the mechanical stability of the joint itself, and facilitate one-side application.

Finally, developmental efforts on ultrasonic spot welding are described. Basic configurations are outlined, including direct action, push-pull, and torsional approaches. Joints are generally solid-state in character, showing joint strengths that generally increase with energy inputs. A key limitation of this technology is deliverable power to the workpiece. A single power element is limited to roughly 5500 W, driving tandem based (push-pull and torsional) systems to weld heavier sections and incorporate shorter weld times. Numerous studies have shown the process to be robus, with little sensitivity to aluminum surface condition, the presence of lubricants, substrate texture, and even variations in sonotrode geometry.

The review represents a sampling of the technology innovations that have occurred for assembling aluminum body structures in an automotive context. Exploitation of these technologies will, of course, require continued development, enabling improved reliability and reduced costs of such welded aluminum structures. Such requirements will carry aluminum joining research throughout the next several decades.

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AWS, Weld-Ed Web Site Promotes Welding Careers

The American Welding Society (AWS) and National Center for Welding Education & Training (Weld-Ed) Web site at *www.CareersInWelding.com* offers the following details: people and companies in the welding industry; fun facts; salary information; industry news; videos; articles; and upcoming training opportunities, seminars, and events.

Additionally, the site features pages geared directly for students with scholarship information and a welding school locator; for welding professionals to build a résumé, find welding-related jobs, and learn about AWS certifications; and for educators to discover tips for teachers and guidance counselors, information about curricula, professional development, and other resources.

This Web site serves a valuable tool for students, parents, educators, counselors, and welding professionals. It also allows visitors to send questions, comments, or ideas for people profiles.