G. Plasma Arc Welding of Lightweight Materials

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Objective

- Develop and verify the welding technology required for the joining of lightweight materials (aluminum and magnesium) using plasma arc spot welding technology.
- Develop the necessary weld parameters and techniques required for a robust joining process.
- Develop guidelines for testing mechanical properties of the new technology that are appropriate for the various anticipated applications.

Approach

This project is divided into three phases: testing, analysis, and summary.

- Produce approximately 5000 material coupons to be used for tensile, shear, and metallurgical analysis and testing (Phase 1).
- Modify the material alloys based on Phase 1 results (Phase 2).
- Produce guidelines for welding parameters and quality control (Phase 3).

Future Direction

- Verify the capabilities of the process in joining lightweight material sheet stock to tubular structures.
- Investigate alternative designs and materials used for the process consumables with a view to increasing service intervals beyond presently known levels.
- Devise and implement a software-based process operation strategy that optimizes the weld through adaptive control.

Introduction

The overall deliverable for this project is a robust process to join lightweight materials economically. Current technology relies heavily on conventional resistance spot welding. High maintenance, tip wear, and accessibility continue to be major concerns. Rivets and/or mechanical clinching are costly alternatives that require high capital investment. The viability of plasma arc spot welds has been validated through the efforts of Arc Kinetics, Ltd., which developed a single-sided plasma arc spot welding process for Jaguar. It was used for joining the sheet metal floor pan assembly, which was not accessible with conventional resistance spot welding equipment. Arc Kinetics also developed a process called aluminum plasma arc welding (APAW). By combining the two processes (single-sided spot welding and APAW), Arc Kinetics developed a process that demonstrates excellent potential for joining lightweight materials.

Material Selection

The team decided by consensus that the most suitable alloy and thickness combinations for potential use in the automotive industry were those in the following table.

Alloy	Thickness	to	Alloy	Thickness
6022	1 mm		6022	1 mm
6022	1 mm		5754	3 mm
5754	2 mm		5754	2 mm
6022	1 mm		5754	1 mm
5754	2 mm		6022	2 mm

Tooling

Shield cup development. As developed for Jaguar Cars, the shield cup of the plasma spot welding gun was manufactured from a work-hardening grade of cupro-nickel, which was then plated with electroless nickel. The interior surface of the shield cup was plasma sprayed with a titania/alumina coating to a thickness of 0.15–0.2 mm to prevent adherence of any weld spatter and minimize radiated heat absorption into the cup. The production life of the part averaged 850,000 welds, and the cups cost around $200 each.

It was found that the bursts of reverse polarity arc current used for welding aluminum were destructive to both the ceramic coating and the copper alloy used in the manufacture of the shield cup. On the basis of durability and cost, we decided to investigate the potential of using a cup machined from 6××× grade aluminum bar stock that could be hard-anodized to completely prevent electrical conduction. Early trials focused on a free-floating cup design (Figure 1), which was only partially successful:

- During rapid cycling of the weld gun, excessive heat buildup was apparent.
- Coating adherence to the cup in the region of the contact annulus was poor when it was subjected to the impact of the welding gun on the workpiece.
- Once the coating was compromised, breakdown was rapid. The plasma arc then impinged on the inside of the cup, entirely destroying the anodic coating and even causing the cup to stick to the workpiece.

Enlarging the bore of the shield cup to increase the weld pool and arc-to-cup distance increased durability significantly; however, once the annular clamp face became damaged by impact, micro-arcing followed by breakdown of the anodizing still occurred on a less dramatic scale. Further revision of the cup profile to give a radiused inner and outer edge to the annulus, together with a thickening of the anodic coating from 50 to 80 µm, produced a robust part (Figure 1). Alternative anodic coatings such as “keronite” were tested but were found to be less durable than sulfuric acid hard anodizing.

Tip design. The original Jaguar gun used a Thermal Dynamics PWM6A machine torch. Consumable changes involved replacing two O-rings during servicing of the water-cooled tip. Experience indicated a skills issue for this operation. To preclude recurrence of this

Figure 1. (Left to right): Small-diameter free-floating shield cup showing breakdown of anodic coating. Large-diameter fixed shield cup with impact damage on annulus and subsequent breakdown of coating. Final design showing radiused contact annulus that provides increased durability under impact.

issue, a dry change tip design was adopted; the plasma gun in this case was manufactured by PWP Industrial in the United Kingdom. The tips used with this gun had a flat front face of approximately 10-mm diameter into which the arc orifice was drilled. During the reverse polarity current cycles of the alternating current (ac) power source, a phenomenon known as "double-arcing" regularly occurred. A thin ceramic coating was applied to the front face of the tip to eliminate this condition; however, the coating rapidly cracked as a result of thermal expansion, and small pieces detached themselves from the tip. Experiments showed that radiusing the front face was the best method of preventing double arcing. The current-carrying capacity was somewhat reduced, but the reduction was insufficient to be problematic within the current range available from the power source (300-A rms).

Because it is not feasible to change the tip orifice diameter from weld to weld in a production environment, work focused on coping with all the sheet thickness combinations previously outlined with one size of tip. After considerable experimentation, good welds could be made throughout the range with a 4-mm-diam tip orifice.

Downsizing of weld gun assembly. The original spot weld gun, designed to effect good fit-up between steel panels, had a clamp force capacity of 200 kg (450 lb). The coaxially configured pneumatic ram assembly produced a relatively bulky package that was about 5 in. in diameter and 18 long. With a wire feeder incorporated, the assembly weighed approximately 22 kg (47 lb). Selection of the PWP torch with an offset pneumatic actuator reduced the bulk of the gun assembly considerably—the gun width was reduced to under 3 in. Trials conducted during this work indicated that much lower clamp forces were required for welding lightweight materials than for welding steel. The maximum clamping force found necessary was 30 kg (65 lb); therefore, the pneumatic cylinder required could be of 1-in. diameter or smaller. Thus, much potential exists for further downsizing the gun assembly, which presently weighs about 12 kg (25 lb).

Development of weld backups. During the early development of the AC-Thermospot process with Alcan, Arc Kinetics made important discoveries relating to the design of weld backups. At Jaguar, attention had focused on the single-sided access capabilities of the plasma arc spot welding process, provided the rigidity of the parts being welded could support the gun clamping forces. In the case of the XJ40 transmission tunnel, special supports had to be built into the tooling where such rigidity did not exist. It was noted at that time that additional scope for the process existed in the building of monocoque vehicles if a C-frame gun configuration were used. To produce weld coupons as in this program, some form of backup was obviously required. Much work was undertaken to find a single configuration that can encompass all the thickness combinations investigated during the program. Concave designs in a variety of radii and diameters were tested, as described in the original patent; however, no one configuration suited all the thickness combinations. A perfectly flat-faced backup was tried, with encouraging results. Additional tests showed that configuring the backup with a gap between the lower sheet and the flat face of the backup of about 30–40 thousandths of an inch (0.75–1.0 mm) gives satisfactory results.

Torque tester for destructive evaluation of weld specimens. Weld porosity is one of the most significant issues common to welding lightweight materials using arc and laser welding techniques. Minimizing porosity is important in optimizing weld strength and dynamic performance. Although gross porosity can often be seen with the naked eye and is usually clearly evident in a weld subjected to tensile testing, reduced levels of macro- and micro-porosity are not easily identified through mechanical testing. Work with Alcan showed that subjecting the weld to pure torsional failure reveals porosity defects in a spot weld simply and cost-effectively. Subjecting a coupon to torsion testing immediately after welding provides useful data that speed the process of weld parameter optimization.

A simple torsional testing rig was designed and manufactured by which all the thickness combinations considered could be tested in a reasonably consistent manner; the use of an indicating torque wrench to apply torsional loading to failure allowed a strength value to be assigned to any given coupon, another useful indicator to assist with parameter optimization. This simple piece of equipment has been effective in revealing macro-porosity, outgassing, nugget size and shape, base material thinning, and the efficacy of various surface oxide removal/stabilization treatments.

Process

Software development. The software package and weld parameters enumerated in the standard Arc Kinetics aluminum weld process controller had been highly refined before this project began, partly as a result of collaboration with European auto manufacturers and suppliers. A puddle welding procedure for aluminum had been developed and implemented for a DaimlerChrysler product at Denso manufacturing in Battle Creek, Michigan. One important parameter added to the software package was preheat time—a short period immediately after the welding arc was established at its start-current level that aided initial removal of the surface oxide film, stabilizing the surface area of the weld before the rapid increase in arc current and heat input. Consistency of weld pool formation, particularly as filler wire was introduced into the weld puddle, was improved considerably. Preheat times in the region of 200 ms were found to be effective, adding little to the cycle time required per weld.

Filler metal selection. The logical first choice for filler wire composition when joining 6×××, 5×××, and combinations thereof was 4043 grade (5% silicon alloy). In cases where the formation of magnesium silicide would be a concern (possibly when welding 5754 to itself), an alternative composition of 5554 grade (5% magnesium alloy) may offer an advantage. For ease for feedability, a 1.2-mm diameter was selected for the two wires. X-ray and photomicrographical analyses indicated that certain combinations evaluated might suffer from slight but persistent solidification cracking toward the center of each spot weld. Consultation with program partner AlcoTec suggested a filler wire with a broader freezing temperature range might help eliminate the problem. AlcoTec supplied 4047 (12 % silicon alloy), which did help control solidification cracking.

Cleaning. We anticipated that joining lightweight materials to form a vehicle structure would always involve a variety of joining processes [e.g., riveting and bonding, metal inert gas (MIG) welding, laser-MIG hybrid welding, toggle-locking, bolting]. An enabler for some of these processes is surface conditioning via chemical cleaning to ensure stability of the surface film. Initial studies with Alcan had shown that welding of material coated with ALO70 wax-based press lube (generally applied to 5754 material for pressing purposes) or Hannifin MP404 oil-based press lube (applied to 6111/6022 material during pressing) could be hazardous because those compounds produce toxic vapors. In this project, all weld coupons were degreased/cleaned with acetone before welding. Additional mechanical and chemical conditioning processes undertaken are discussed in the test results.

Results

Background

Collaboration between Arc Kinetics and Alcan prior to this project had yielded encouraging results for the potential of plasma arc spot welding of lightweight materials. Tensile testing done at an Alcan laboratory in England for a variety of material combinations indicated average tensile strengths to be 20 to 50% higher than the strengths specified in military standard specifications. Microsectional analysis indicated that porosity levels within the spot welds were in the range of 1–5%. Gross porosity was not evident in any sample sections. International standards for allowable porosity levels vary; they generally are stated in terms of pores per linear inch of weld rather than for individual spot weldments. Alcan's technical advisors thought, however, that if porosity consists of randomly distributed spherical voids, levels of up to 20% porosity would have little effect on overall structural behavior.

Fatigue testing was limited because of limited test equipment availability; however, performance results were encouraging compared with those for resistance spot welds in identical material and thickness combinations. The good performance was attributed to the relatively large diameter of weld nuggets attainable compared with resistance spot welding.

Test Results

Using the example of the Jaguar XJ8 aluminum monocoque as a structure that could potentially use plasma arc spot welding, weld trials initially focused heavily on joining 5754 material. The greatest number of welds would be made in this material, because it forms the entire underbody and main structure of the vehicle. This section briefly outlines some of the issues encountered during the production of test coupons in this material.

Solidification cracking

Early test results from the United Kingdom on welding 5754 base material with a 5554 filler wire did not identify solidification cracking as an issue, but work conducted in the United States demonstrated sometimes severe solidification cracking. Exploration of a wide range of weld parameter settings, inert gas combinations, and amount of filler wire addition failed to completely eliminate the problem. The composition of filler wires was explored as an issue in solidification cracking. The broader freezing range offered by silicon-based filler wire alloys such as 4043 (5% silicon) was expected to be helpful, but X-ray analysis and macrosectioning of sample welds revealed only partial success with the use of this wire. A higher-silicon-content filler wire, 4047 (12% silicon), was tried, and the cracking problem was reduced, though not completely eliminated. Adding larger amounts of this filler to the weld pool eventually eliminated (Figure 2) the appearance of microcracking.

Spot welds produced in 6022, 6111, and combinations of the two with 5754 sheet were all performed with 4047 filler wire.

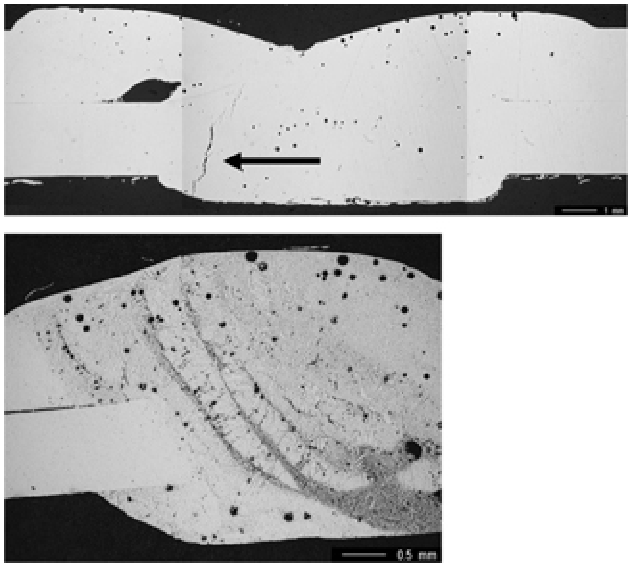

Figure 2. Macrosection showing solidification cracking within the weld on 5754 base material (top). Use of 4047 filler addition slightly increased microporosity but substantially reduced solidification cracking.

Samples of 1-mm 6022 to 3-mm 5754 were produced using 5554 filler wire as a comparison, and despite the expectation that cracking would be present in the latter, strength and fatigue results (discussed later in this section) indicated that microcracking had no effect on overall structural performance.

Porosity

Porosity within welds in aluminum alloys can result from various conditions: the presence of press lubricants and drawing oils, moisture within the parent material oxide film, moisture and drawing oils within the filler wire, and possibly inadequate flow or contamination of the plasma and shielding gases. Welds made with silicon-based filler wires by any arc process usually exhibit more microporosity than those made with magnesium-based filler wires because the former tend to absorb more moisture. Generally speaking, although some microporosity was always evident in the welds made during this project, the levels were sufficiently low not to be considered detrimental to structural performance. Certainly excessively large pores could be produced, particularly in the underside of the spot welds, but optimization of the backup design to a flat, rather than concave, surface appears to have effectively discouraged such formations (Figure 3). Investigation into the most significant of the potential sources for microporosity focused on the condition of the parent material. The use of filler wires generally regarded as being of the highest quality available (supplied by AlcoTec), and shielding gases of certified composition, relegated the impact of these potential sources of microporosity to a minimal level.

The parent sheet was cleaned by various means, because differences were apparent in the effectiveness of the processes used during the manufacture of sheet material in Europe and those used in the United States; more microporosity was evident in welds made in

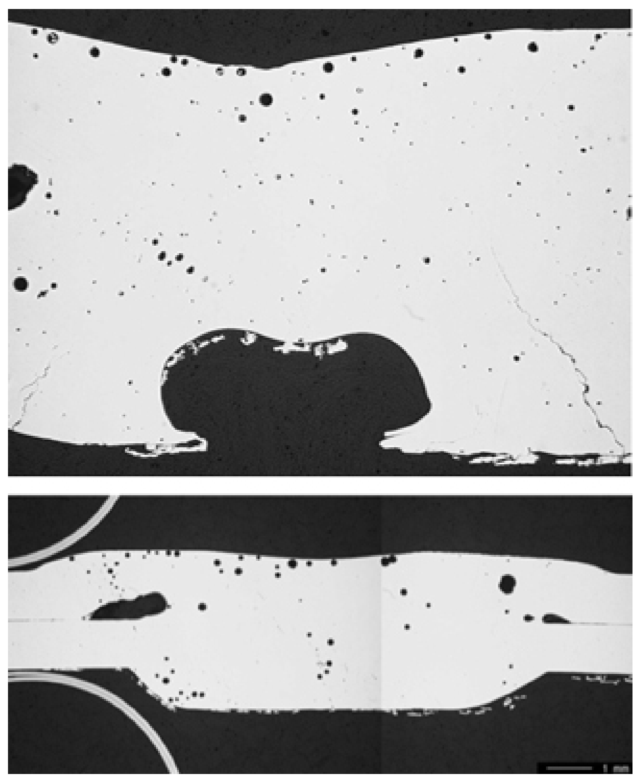

Figure 3. Macrosection illustrating the formation of a cavity on the weld underside due to entrapment of gases in the concave designs of the backup (top). The use of a flat backup eliminated the voids (bottom).

the United States on domestically sourced material.

All sample material was washed with acetone before welding to remove wax or oil lubricant from test coupon material, thus minimizing weld contamination and providing a hazard-free environment for the operatives. Welding material in this condition produced the highest levels of microporosity.

Three different cleaning techniques were tried: mechanical abrasion of the sheet surfaces immediately before welding, immersion in a warm caustic solution of sodium hydroxide and potassium hydroxide followed by water rinsing and air drying (using a commercially available solution), and a cleaning process used by Alcoa based on a phosphoric acid treatment. All three processes reduced microporosity levels; the chemical treatments generally appeared to be the most effective. Probably because of closely controlled processing, the process used by Alcoa seemed to offer the greatest consistency.

Haloes

Haloes are tunnel-like pores or indentations on the underside of the top sheet of parent material surrounding the part, and sometimes the whole periphery of the weld, that create annular voids. Their appearance was the least anticipated, most significant difficulty encountered in this project. These voids often reduced the effective thickness of the upper sheet to 25% of its specified thickness in the area surrounding the weld. The most likely root cause was determined to be the outgassing of hydrogen entrapped within the surface oxide films at the sheet interface. Mechanically abrading both faying surfaces immediately before welding dramatically reduced the size and extent of halo formation; however, from a production standpoint, abrasion was considered unrealistic outside the aircraft industry (Figure 4). Several chemical cleaning methods were investigated for their potential to replace mechanical abrading as a way to remove entrapped hydrogen. A cleaning process suggested by Alcoa, involving treatment with a phosphoric acid-based solution, was found to be the most successful. Hundreds of coupons in all the material grades and combinations were treated by this process and torsion tested, and halo formation was never evident. The success resulting from this cleaning process is a key factor for the acceptability of the plasma spot welding technique in lightweight materials.

Strength

It can be anticipated that the tensile strength of a spot weld will be in direct proportion to the diameter (and thus shear area)

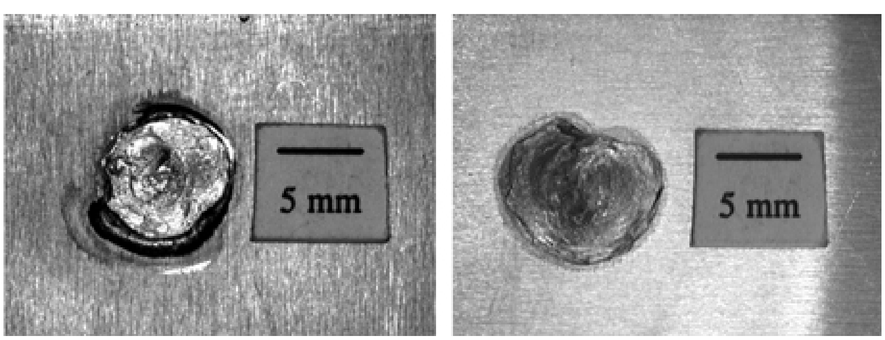

Figure 4. The underside of the a sheet showing the halo effect around 75% of the weldment periphery (left). The material in this case was cleaned using acetone washing only. At right, a phosphoric acid–based cleaning process has completely eliminated halo formation.

of the weld nugget. It is difficult to develop weld nuggets larger than 7 mm in diameter with resistance spot welding of lightweight materials because extremely large equipment is required to do so. In plasma arc spot welding, the lower rate of energy input and high thermal conductivity of the alloys used tends to engender the formation of a larger weld puddle and weld nugget. In this project, nugget diameters typically ranged between 6 and 11 mm, and 8-mm-diam welds were possible in all thickness combinations tried. As a consequence, the tensile strengths of plasma spot welds were significantly higher than those of resistance spot welds (Figure 5).

At Jaguar Cars, thickness combinations similar to those used in this program are all joined with a 5-mm rivet on the XJ8 monocoque. Thus, this was the only size of rivet used in this project.

Fatigue

Fatigue testing of all specimens was conducted on a single Instron machine calibrated to international standards to avoid differences in test equipment. All specimens were tested at a frequency of 10 Hz. In all cases, the fatigue curves generated for the plasma arc spot welds were classic representations of the concave, exponential curve associated with this test method. The same cannot be said in all cases for the riveted specimens; however, the endurance of these coupons to 2 million fatigue cycles was at a higher percentage of their tensile strength than that of plasma arc or resistance spot welds.

It is significant (particularly in light of the testing performed in the joining of 1-mm 6022 to 3-mm 5754 where a 5554 filler wire was used) that plasma arc spot welding specimens known to contain microcracks did not appear to suffer in strength or durability compared with uncracked welds (Figure 6). The suppliers of lightweight materials acknowledge this and consider microcracking within the weld to be of relatively low significance; the automotive manufacturers remain much more circumspect on this matter. However, the automakers have amassed few or no data to support this stance.

Process/consumable robustness

A 486 microprocessor was used to manage current regulation, waveform shape, timing, plasma gas flow, filler wire feed velocity, and retraction during the plasma arc spot welding event; consistency of the arcing event thus was highly accurate and repeatable. Weld power input variance caused by inconsistency in the distance from torch tip to workpiece was prevented because

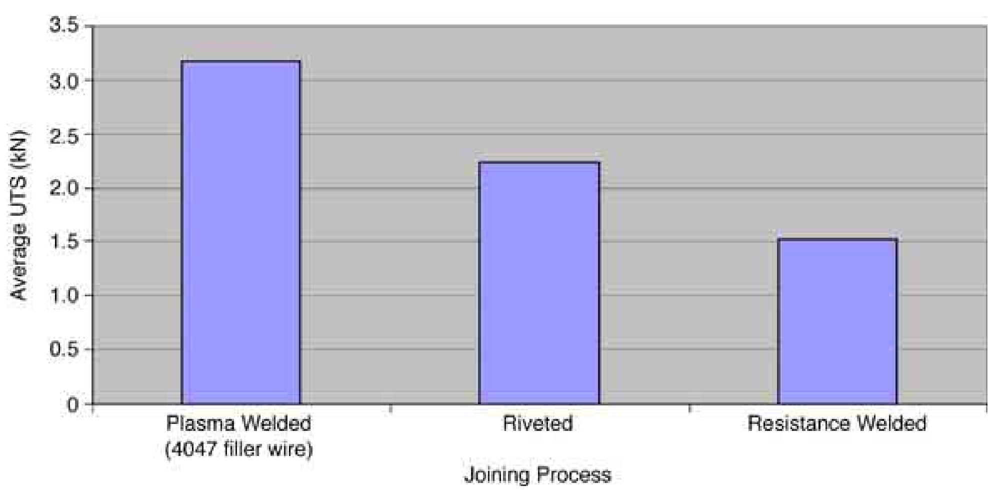

Figure 5. Comparison of tensile strengths attained by plasma arc welding, riveting, and resistance welding in joining 6022 steel.

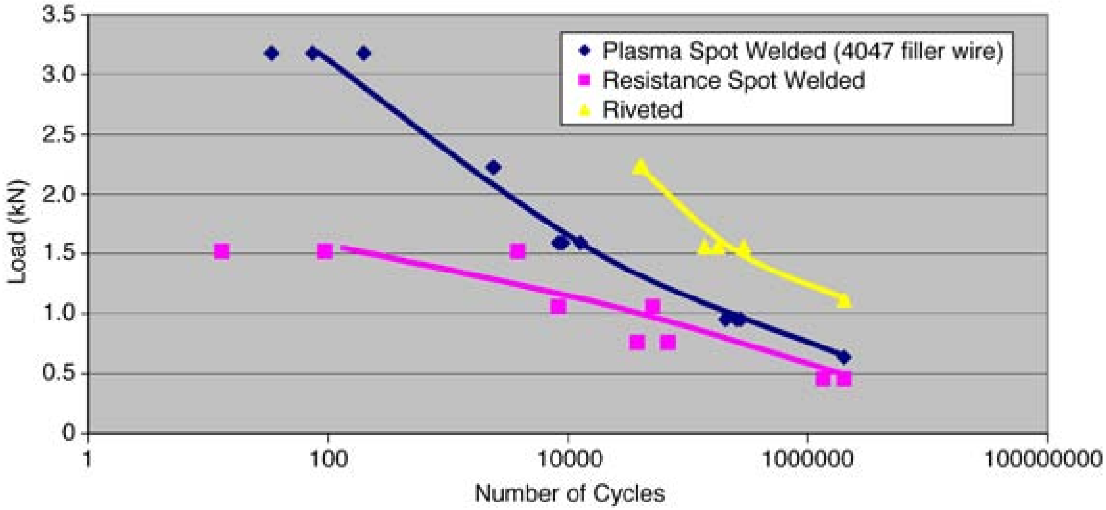

Figure 6. Comparison of fatigue tests for joining 6022 to 6022 by plasma arc spot welding, resistance spot welding, and riveting.

the shield cup contacting the workpiece controlled the distance in every case.

The main factors likely to cause variance in the weld thus became the parent material itself, the presence of contaminants, plasma torch electrode or nozzle erosion, or shield cup damage. The integrity of the shield cup was maintained though careful design and manufacture; likewise the nozzle geometry prevented double arcing. The only choice of electrode material for ac welding is tungsten, containing 2% thorium oxide, all other rare-earth elementally doped varieties of tungsten having failed in earlier trials by Arc Kinetics. The design and geometry of electrodes made from this material have been subject to intensive investigation prior to this project, so no work was considered necessary in this area.

In resistance spot welding of uncoated steels, the ability to perform 3000 spot welds has historically been the benchmark for electrode life. Resistance spot welding of lightweight materials has yet to achieve such long electrode life. It was perceived that if plasma arc spot welding could match the benchmark used for uncoated steels, acceptance of the process for production would be likely. Erosion of the electrode during 3000 or more welds has not been found to significantly affect the quality or size of spot welds produced in the trials to date.

The 4-mm-diam nozzle orifice selected as encompassing all the thickness combinations of parent material used in the program also performed well in achieving 3000 or more welds. Erosion of the copper backup in the design evolved in this program did not appear to significantly affect spot weld nugget size. Redressing this part, much as is done in resistance welding, rather than replacing it during weld torch servicing could offer an economic advantage.

Project Status

- Fatigue testing of two batches of resistance spot welded coupons remains to be completed. Completion is expected in late 2003.
- Additional testing to 2,000,000 cycles of some plasma spot welds is needed if the statistical data are to be fully satisfied. However, each test occupies 55 h of machine time at considerable expense.
- When the data available on the resistance weld fatigue tests are received, complete comparative analysis of the three processes will be possible.
- Plans were to produce some coupons incorporating Alcan 6111 material in

much the same way as alternative Alcoa 6022 material was used. There may now be little value in performing such a study because promotion of this material for use in the automotive industry is to discontinue in favor of 6022 and/or alloys of similar composition and performance.

Conclusions

- Absorbed hydrogen compounds (i.e., hydrated oxides) in the surface films of sheet aluminum at present require a phosphoric acid-based pretreatment prior to plasma arc spot welding to eliminate haloes.
- The addition of appropriate amounts of 4047 grade filler material appears to eliminate microcracking within spot welds.
- Destructive testing of spot welds by torsional shear is valuable for assessing the likely strength, degree of macroporosity, and material thinning through the outgassing effects of the welds.
- Plasma arc spot welds typically offer tensile shear strengths 40% higher than those of competitive technologies.
- Under ac welding conditions used in this project, use of a convex radiused tip geometry prevents damage to the plasma torch nozzle through double arcing.
- Service intervals in excess of 3000 welds can be achieved for the consumables associated with plasma arc spot welding. This greatly exceeds service intervals associated with resistance spot welding of lightweight materials.
- Hard anodizing of an aluminum shield cup of appropriate design can produce a cup that is lower in cost and more robust than the ceramically coated copper alloy shield cups previously associated with the process.
- A flat-surfaced backup positioned between 0.75 mm and 1.0 mm below the lower sheet surface gives better performance in terms of weld quality than do alternative geometries.