Static and Fatigue Behavior of Spot-Welded 5182-0 Aluminum Alloy Sheet

The limited effect of discontinuities in resistance spot welds on joint properties is demonstrated for automotive applications

BY A. GEAN, S. A. WESTGATE, J. C. KUCZA AND J. C. EHRSTROM

ABSTRACT. There is a strong interest in the use of aluminum alloy sheet for vehicle applications, particularly the body, where resistance spot welding is the principal joining method. It is important that the particular discontinuities that are often found in aluminum alloy spot welds do not adversely affect the weld properties. The objectives of this work were to provide information about the effect of excessive porosity and surface indentation and the effect of weld size on the fatigue performance of spot welds in aluminum alloy sheet.

Trials were conducted on 1.2-mm-thick 5182-0 aluminum alloy in the mill-finished condition. Static shear and fatigue tests were conducted on welds over a range of welding conditions to simulate severe weld discontinuities. The work indicated that nugget porosity, up to about 40% of the weld diameter, deep surface indentation and variation in weld size had no major impact on the fatigue properties of the welds.

Introduction

The need to reduce vehicle weight, improve fuel economy and reduce exhaust emissions has led to increased use of lightweight materials such as aluminum alloys. While the space frame concept (Ref. 1) has been claimed as being a cost-effective way of achieving a high-performance vehicle structure, it remains suited to low-volume manufacture. Aluminum alloys have found applications in the more classical design of high-volume vehicles, competing with zinc-coated steels for hoods, trunks and doors.

A. GEAN, J. C. KUCZA and J. C. EHRSTROM are with Pechiney CRV, Voreppe, France. S. A. WESTGATE is with TWI, Abington, Cambridge, U.K.

Resistance welding remains the principal joining process in the vehicle industry. It is a rapid, reliable, cost effective and now highly automated joining process for the low-carbon, high-strength and coated steels currently used. Aluminum alloys can also be spot welded to commercial-quality levels without the need for special cleaning or surface treatment of the material (Refs. 2–5). Typically, the welding current is double that required for zinc-coated steels, but only one-third the weld time is required.

Extensive work has been done to improve the suitability of spot welding of aluminum alloys for mass production industries, particularly on welding conditions, electrodes and power supply types. The main emphasis is to improve electrode life (Refs. 5–9). Fewer studies have been made on the quality of the spot welds themselves (Refs. 5, 9, 10). Discontinuities such as porosity, cracks and indentation are often found in commercial-quality spot welds in aluminum alloys. It is important that such discontinuities do not adversely affect the fracture mode of welds during testing or the properties of welds, particularly fatigue (Refs. 11, 12).

KEY WORDS

Spot Weld
Electrode Force
Aluminum Sheet
Automotive
Shear Strength
Resistance Welding
Fatigue Strength

The objectives of this work were to provide information about the effect of excessive porosity, surface indentation and weld size on the fatigue performance of spot welds in aluminum alloy sheet. Guidance from French vehicle manufacturers has been taken as a baseline for welding conditions.

Experimental Study

Materials

The material studied was the nonheat-treatable aluminum alloy 5182-0 in a thickness of 1.2 mm. This was supplied by Pechiney Rhenalu in the mill-finished, as-received condition and was not cleaned prior to welding. The specified chemical composition and mechanical properties are shown in Table 1. Due to its high mechanical properties, good stamping performance and ease of weldability, it finds application in inner strengthening panels.

Limited comparison was made with 0.8-mm zinc-coated low-carbon steel (XSG) typical of current automotive use. The details are also shown in Table 1.

Equipment and Test Samples

The welds were made on a 315-kVA pedestal machine having a 100-kA current capacity and a 15+15-kN force capacity with an in-line tandem cylinder.

Static tests were conducted on a 200-kN Avery Denison tensometer. The shear and cross-tension test samples were made according to the French standards A 87-001 and NF A 89-206 — Fig.1. The fatigue tests were conducted on a 20-kN Amsler Vibrophore at a test frequency of approximately 100 Hz and a load ratio of R = 0.1 (min./max load during the cycle). A two-spot shear test sample was used in this case, as shown in Fig. 2.

Experimental Procedure

Test welds were made at conditions taken from the French Standard NF 87 001. These conditions were used for the baseline condition, referred to as "the standard series." The electrodes were Cu/Cr/Zr with an 11-mm tip diameter with a 100-mm face radius. A 4-kN electrode force and a three-cycle weld time were used. Current was nominally 26.5 kA. This was adjusted to maintain a constant weld size of nominally 6.3 mm ($5.8\sqrt{t}$, where t = sheet thickness in mm) on the cross-tension test samples.

Static shear and cross-tension tests were conducted and the failure mode, weld size and load to failure recorded. Some of the welds were radiographed to illustrate the extent of nugget discontinuities, and metallographic sections were taken. These were polished to 1-µm finish and etched in Keller's reagent.

Fatigue tests were conducted and a log/linear plot produced of test load against endurance, over the range 10^4 to 10^7 cycles. A regression analysis of the 36 standard series tests gave a Wohler curve of the form log S = a log N + b, including the 90% failure probability limits, accord-

Table 1 — Typical Chemical Composition and Mechanical Characteristics of the 5182-0 Aluminum Alloy and the XSG Steel

			Chemical Composition wt-%						Mechanical Properties		
Alloy	Condition	Thickness, mm	Si	Fe	Cu	Mn	Mg	Cr	R 0, 2 (MPa)	Rm (MPa)	A % Rupture
5182	0	1.2	0.10	0.31	0.025	0.34	4.32	0.025	140	275	28
			C	Mn	Si	P	S	Al			
XSG	—	0.8	0.08	0.42	0.01	0.013	0.025	0.02	179	312	42

Table 2 — Welding Conditions for the Aluminum Alloy Series and Comparison with Steel

	Standard Series (H)	Porous Series (I)	Drilled Out Series (HP)	High Force Series (P)
Electrode force, kN	4	1.5	4	6.5
Weld time, cycles(a)	3	3	3	3
Welding current, kA mean (standard deviation)	26.5 (0.3)	24.2 (0.4)	26.5 (0.3)	30.2 (0.6)
Electrodes(b)	Dome tip 11-mm diameter 100-mm radius dome			
	Heavy Indent Series (K)	**Small Welds Series (L)**	**Large Welds Series (M)**	**Steel Series (T)**
Electrode force, kN	6	4	4	2.3
Weld time, cycles(a)	5	3	3	10
Welding current, kA mean (standard deviation)	33.1 (0.6)	21.6 (0.4)	34.9 (0.3)	9.6 (0.09)
Electrodes(b)	Truncated cone 120 deg 6.5-mm diameter 100-mm radius dome	Dome tip 11-mm diameter 100-mm radius dome		Cnomo (G) 30 deg 6-mm-diameter tip 40-mm radius dome

(a) 1 cycle = 0.02 s at 50 Hz.
(b) Electrode material — Cu/Cr/Zr.
Hold time 30 cycles.

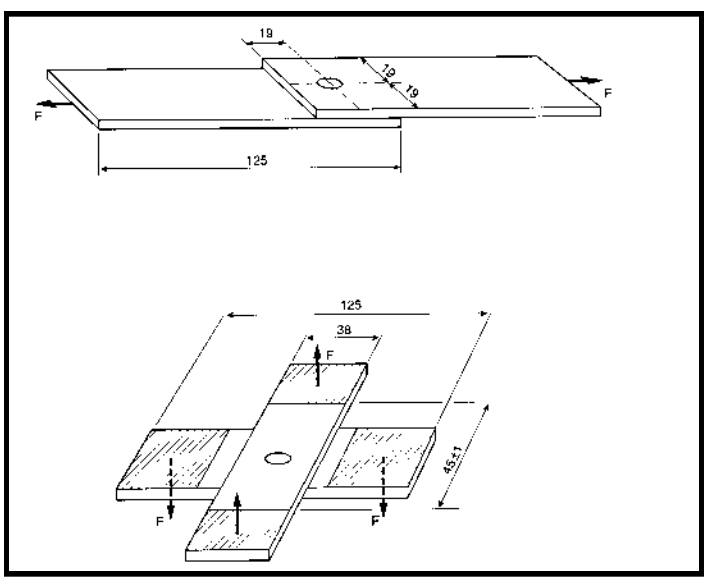

Fig.1— Static tensile-shear and cross-tension test specimens (dimensions in mm).

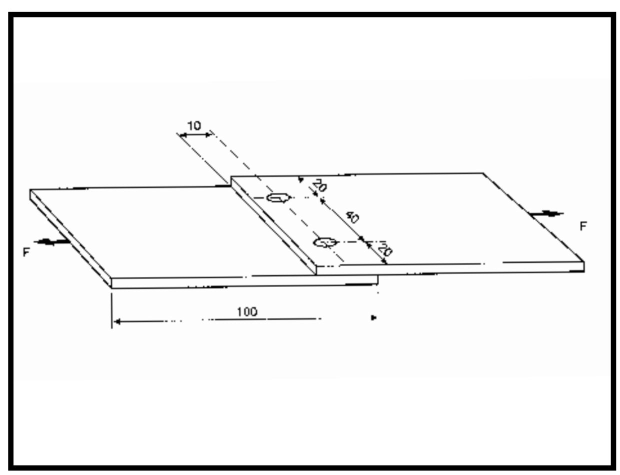

Fig. 2 — Fatigue specimen (dimensions in mm).

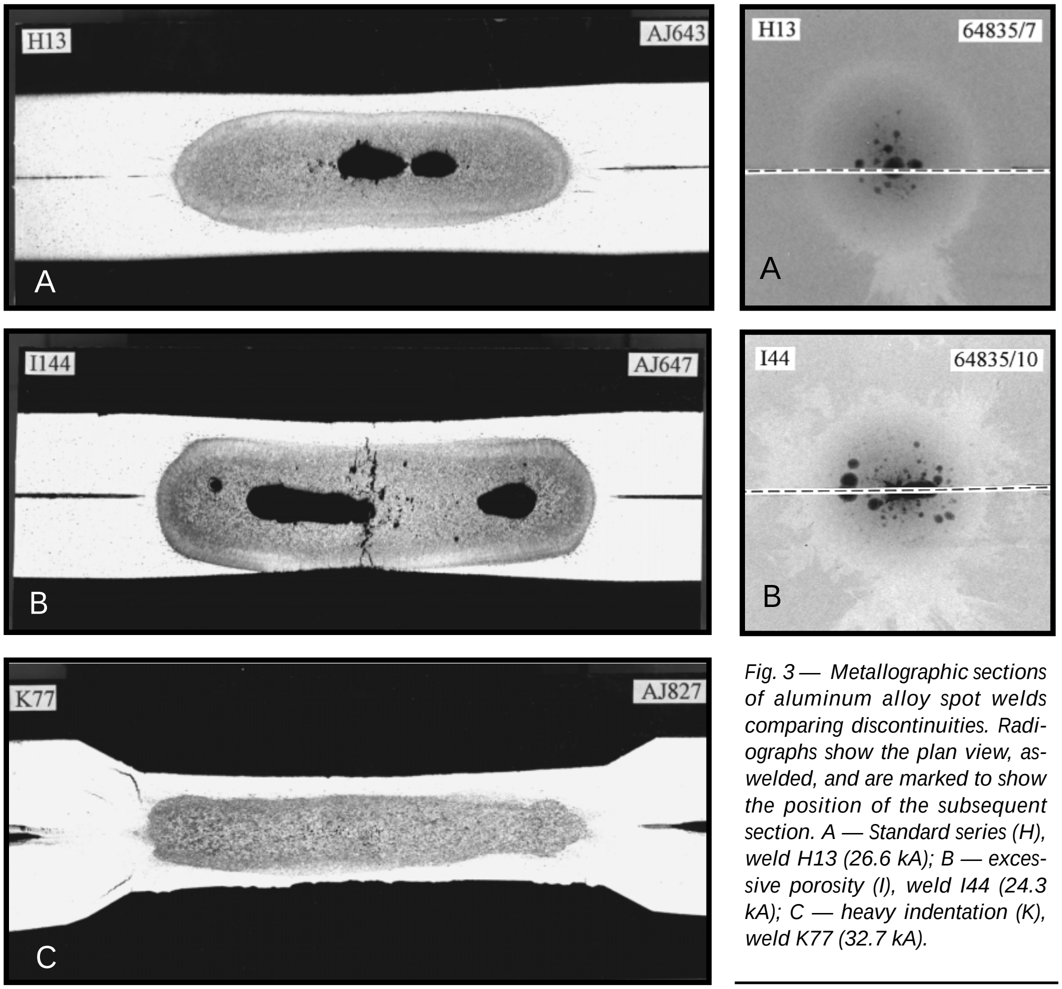

Fig. 3 — Metallographic sections of aluminum alloy spot welds comparing discontinuities. Radiographs show the plan view, as-welded, and are marked to show the position of the subsequent section. A — Standard series (H), weld H13 (26.6 kA); B — excessive porosity (I), weld I44 (24.3 kA); C — heavy indentation (K), weld K77 (32.7 kA).

ing to the French standard A 03-405 (S is the load applied, N is the number of cycles to failure and the constants a and b are derived from the regression analysis).

Welding conditions were modified in the study of discontinuities and weld size, and the details are given in Table 2. The weld series are shown below.

Standard series H — baseline condition,

Series I — excessive porosity (low electrode force),

Series HP — nugget center drilled out 2.5-mm diameter (as baseline condition),

Series K — excessive indentation (truncated cone electrodes),

Series L — small weld size (low current),

Series M — large weld size (high current).

Weld testing was conducted in a similar way to the standard series and the results compared. In addition, welds were made in the steel for comparison with the standard series in the aluminum alloy — Table 2.

Results

Effect of Weld Discontinuities

Standard series welds showed satisfactory nugget penetration with some lack of symmetry. There was substantial porosity in the nugget although the periphery was clear, as shown in Fig. 3A. Increased porosity was present in the low-electrode force welds with a central pore usually 2–3 mm in diameter and often associated with cracks — Fig. 3B. The deeply indented spot welds (series K) had 40 to 50% indentation at the center and greater than 1.2-mm sheet separation 10 mm from the weld edge. However, there was no porosity in the narrow weld nugget — Fig. 3C.

The results of the static tests for the standard series (H) and series I, HP and K are given in Table 3. All the cross-tension tested welds gave a button/plug failure, although the welds with excessive porosity or deep indentation were significantly weaker than the standard series. The shear test samples were of a similar strength except for the drilled out welds, and interface failures occurred in all but the deeply indented welds. In many cases the normal scatter of results exceeded the effect of the discontinuities or of welding conditions.

The fatigue test results are shown in Figs. 4 to 6 for comparison of the effect of discontinuities with the standard series. The welds with excessive porosity failed at

Table 3 — Static Test Results in the Study of Discontinuities

	Standard Series (H)	Excessive Porosity (I)	I/H	Drilled Spots (HP)	HP/H	Deep Indentation (K)	K/H	High Force (P)	P/H
CT failure mode	button/plug	button/plug		button/plug		button/plug		button/plug	
CT failure force, kN	2.30 (0.15)	1.82 (0.22)	79%	2.46 (0.06)	107%	1.52 (0.18)	66%	2.32 (0.07)	101%
Weld diameter, mm	6.35 (0.13)	6.18 (0.10)	97%	6.46 (0.15)	102%	6.21 (0.28)	98%	6.47 (0.31)	102%
$d/\sqrt{t}$	5.8	5.6	97%	5.9	102%	5.7	98%	5.9	102%
TS failure mode	interface	interface	—	interface	—	button/plug	—	interface	
TS failure force, kN	3.93 (0.45)	4.15 (0.22)	106%	3.61 (0.22)	92%	4.17 (0.36)	106%	4.09 (0.46)	104%
Interface splash	sometimes slight	always all around	—	sometimes slight	—	always heavy	—	sometimes slight	

CT — cross-tension.
TS — tensile-shear.
Failure forces shown as mean (standard deviation).

Table 4 — Static Test Results in the Study of Weld Size and Comparison with Steel

	Small welds (L)	Standard series (H)	Large welds (M)	Steel series (T)
CT failure mode	button/plug	button/plug	button/plug	button/plug
CT failure force, kN	1.69 (0.29)	2.30 (0.15)	2.68 (0.16)	3.31 (0.30)
Weld diameter, mm	4.63 (0.29)	6.35 (0.13)	7.93 (0.10)	5.21 (0.27)
d/√t	4.2	5.8	7.2	5.8
TS failure mode	interface	interface	button/plug	button/plug
TS failure force, kN	2.33 (0.46)	3.93 (0.45)	5.55 (0.10)	4.32 (0.16)
Interface splash	none	sometimes slight	slight or heavy	none

CT — cross-tension.
TS — tensile-shear.
Failure forces shown as mean (standard deviation).

a slightly lower load than the standard series (1.1 kN compared to 1.3 kN at 10^6 cycles) but within the scatter band showing 90% chance of failure — Fig. 4. In addition, the failure mode was similar in each case, with a crescent-shaped crack growing through the thickness from the edge of the nugget. The results for the drilled out samples gave the same fatigue performance as the standard series — Fig. 5.

As a means of checking the effect of force on fatigue properties, some untested low-force welds were pressed cold between the welding electrodes at 4 kN. This treatment improved the fatigue properties as the test results for these samples (*e.g.,* 1.5 kN at 10^6 cycles) were within the scatter band for the standard series. Furthermore, additional welds made at an even higher force of 6.5 kN, using domed electrodes, gave a higher load than the standard series at 10^6 cycles of 1.5 kN, on the upper limit of the scatter band — Fig. 4.

The deeply indented welds (Fig. 6) failed at a substantially higher load (1.9 kN at 10^6 cycles) than the standard series (1.3 kN). In addition, the fatigue cracks started in the base metal 2–5 mm outside the notch at the interface.

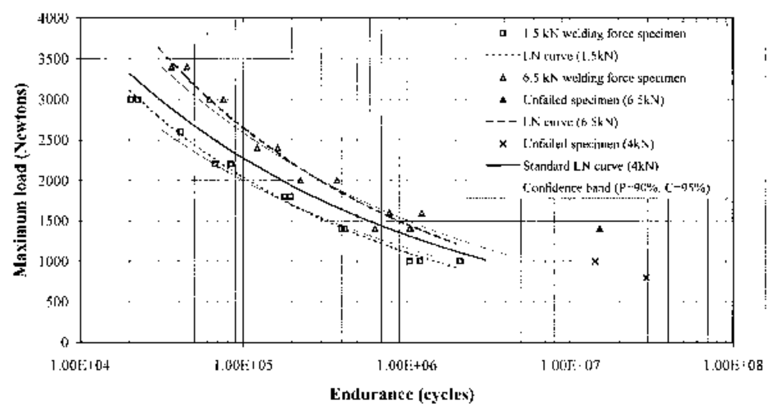

Fig. 4 — L-N curves for specimens with excessive porosity (1.5-kN electrode force, series I) plus comparison with standard specimens in aluminum and welds made with high force (6.5 kN).

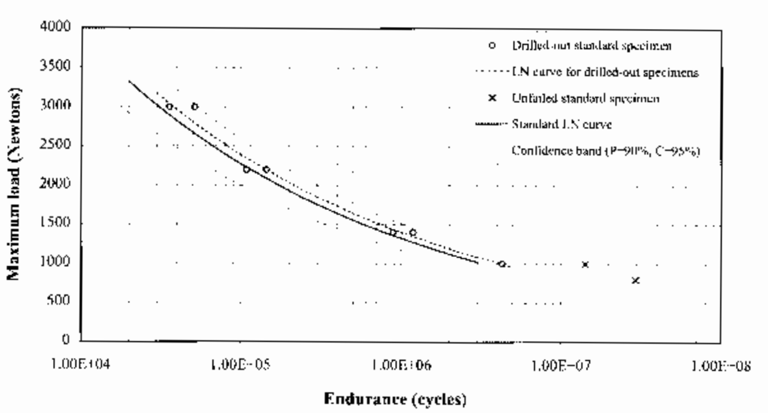

Fig. 5 — L-N curves for drilled-out spot welds (series HP) and comparison with standard specimens in aluminum.

Effect of Weld Size

Series L and M were welded at the standard conditions but with the welding current adjusted to give weld diameters in the target ranges of 4.5–5 mm and 7.5–8 mm.

The radiographs and metallographic sections (Fig. 7) showed that weld splash and porosity in the nugget increased with weld size. However, the periphery of the nugget was clear in each case and it was shown above that the porosity within the nugget had little effect on the mechanical test results. Thus, these tests gave a true comparison of the effect of weld size.

Table 4 summarizes the static tests in comparison with the standard series. As expected, the static strength was highly dependent on weld size. Increasing weld size from the approximately minimum

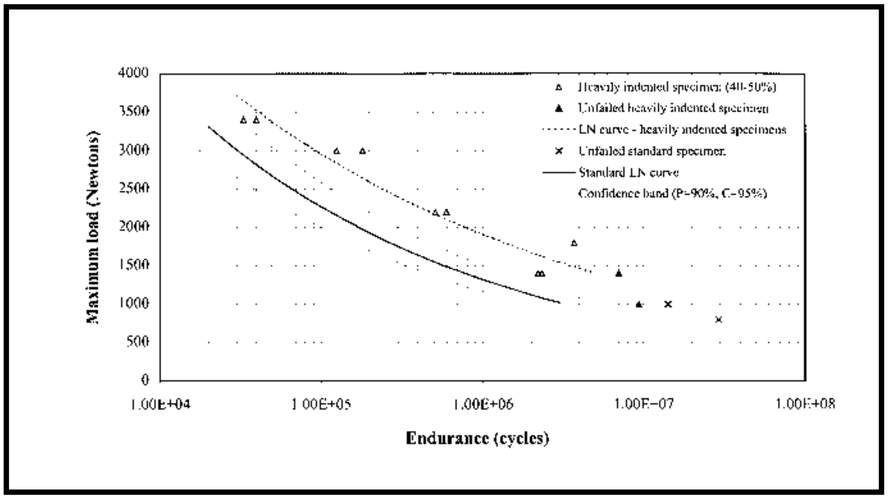

Fig. 6 — L-N curves for heavily indented specimens (series K) and comparison with standard specimens in aluminum.

acceptable 4.2√t to the large 7.2√t gave a 2.4 times-increase in shear failure load and a 1.6-times increase in cross-tension failure load. The cross-tension tests failed by button/plug failure except for some of the small welds, which broke around the nugget rather than through the sheet thickness. In shear, the largest welds failed by forming a button/plug, whereas the standard and small welds failed across the interface.

The fatigue results showed less difference between the weld sizes than did the static results — Figs. 8, 9. At low endurance, the small welds withstood a lower fatigue load than the standard series scatter band. At these conditions, the L-N curve for the large welds was slightly better than the standard series, but remained within the scatter band. In all except the small welds, which failed across the interface, classical failure occurred. This comprised a crescent-shaped crack, starting from the edge of the weld or bonded zone and propagating through the material thickness. At high-cycle/low-load conditions, there was no significant difference between the weld sizes. All of these welds showed the classic failure mode, described above.

The results for the large welds were also very similar to the standard series with individual values lying within the scatter band over the whole test range. All of these welds showed the classic failure mode, with the crescent-shaped crack starting from the edge of the weld or bonded zone and propagating through the thickness.

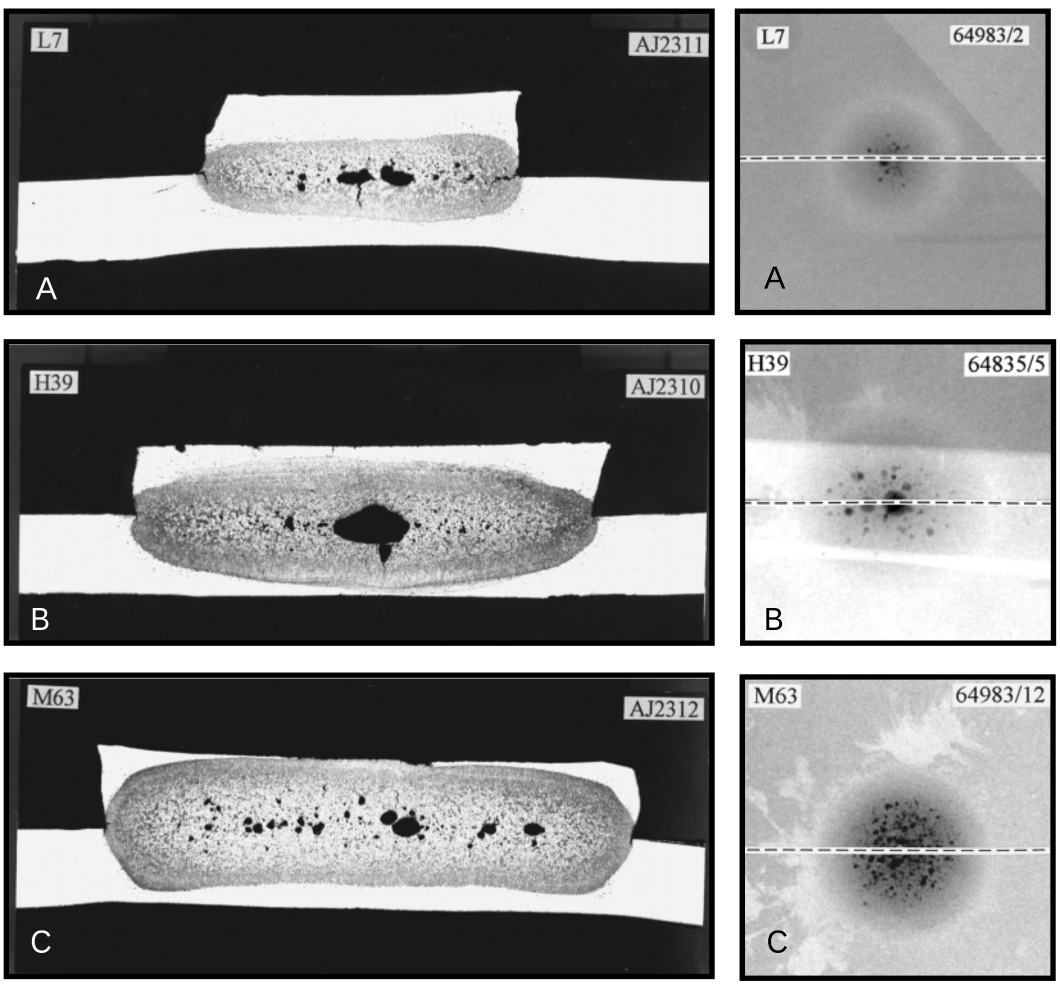

Fig. 7 — Metallographic sections of aluminum alloy spot welds comparing weld size. Radiographs show the plan view, as-welded, and are marked to show the position of the subsequent section taken after cross-tension testing. A — Small weld (L), weld L7, 21.3 kA, 4.3-mm diameter; B — standard series (H), weld H39, 26.7 kA, 6.35-mm diameter; C — large weld (M), weld M63, 34.8 kA, 7.9-mm diameter.

Comparison of Steel and Aluminum Alloy

In order to provide a representative comparison between the aluminum alloy and steel on the basis of sheets with similar stiffness, a 0.8-mm, zinc-coated steel was chosen. The 1.2-mm aluminum alloy was still 50% lighter weight than the steel, despite being 50% thicker. The 5.2-mm weld size in the steel was the same proportion of the sheet thickness as for the aluminum (nominally 5.8√t). Similar static and fatigue tests were conducted as for the aluminum alloy and the results are shown in Table 4 and Fig. 10.

Although the steel sheet was double the weight of the aluminum sheet, the static shear strength of the steel spot welds was only about 10% higher than that of the aluminum spot welds.

The benefit of the aluminum alloy was less pronounced when considering fatigue performance. At 10^6 cycles, the fatigue load for the two spot aluminum alloy samples was 1.3 kN, compared to 2.2 kN for the steel spot welds. However, load distribution and joint stiffness can influence the fatigue properties of a joint. Thus, the actual load per spot is dependent on joint design and material thickness in a structural component.

Discussion

Significance of Discontinuities

Two categories of discontinuities occur in resistance spot welding of aluminum. Those caused by incorrect choice of welding conditions or machine setup include stuck welds, surface splash, deep surface indentation and sheet separation, but are easily avoided. Certain discontinuities are intrinsic in aluminum alloy spot welds, particularly shrinkage porosity and cracking in the weld nugget. If these become severe, surface cracking or a shrinkage pipe can form in the center of the electrode indentation. Although not a discontinuity as such, weld splash is common. It was intended that the extreme conditions assessed in this work represented those beyond normal quality standards in production.

The excessive porosity and drilled out welds indicated that cavities up to 40% of the weld diameter had no significant effect on joint performance. The welds produced with excessive indentation of 40 to 50% showed an actual increase in fatigue performance compared with the standard welds. However, static cross-tension strength was lower than standard welds as the base metal was thinned at the edge of the weld.

Influence of Electrode Force

Although, fatigue properties of welds were fairly insensitive to the discontinuities studied, electrode force appeared to play a more important role. It would appear that higher electrode force, or a postweld squeeze, improved the fatigue performance. This may be because the higher forces modify either the residual stress at the edge of the weld, where the fatigue cracks initiate, or reduce the sharpness and stress concentration at the notch. The radial residual stress in this zone, due to the cooling of the weld, was

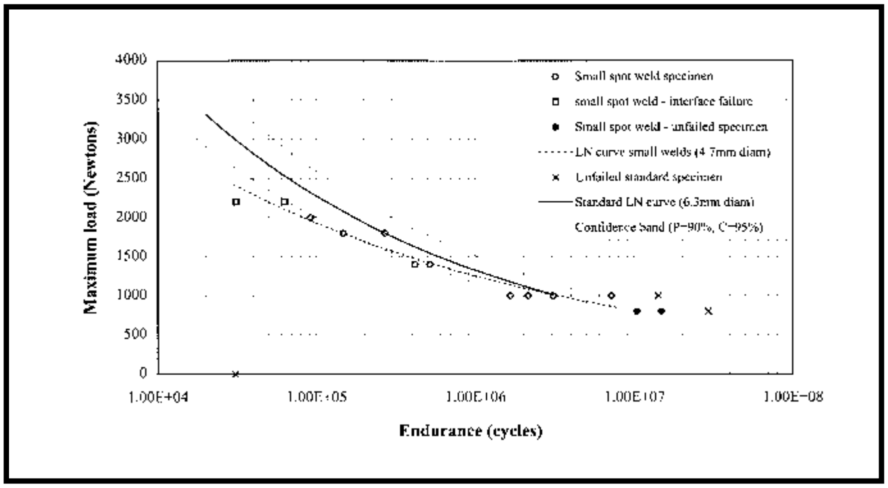

Fig. 8 — L-N curves for small spot welds (series L) and comparison with standard specimens in aluminum.

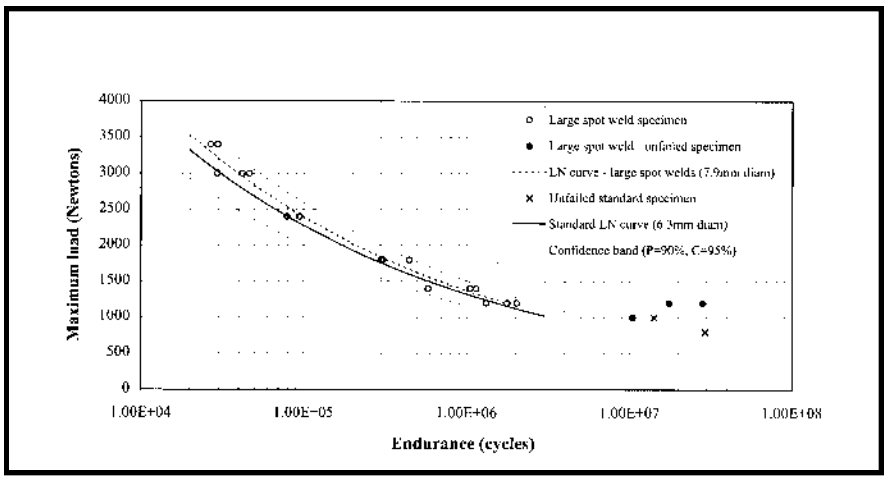

Fig. 9 — L-N curves for large spot welds (series M) and comparison with standard specimens in aluminum.

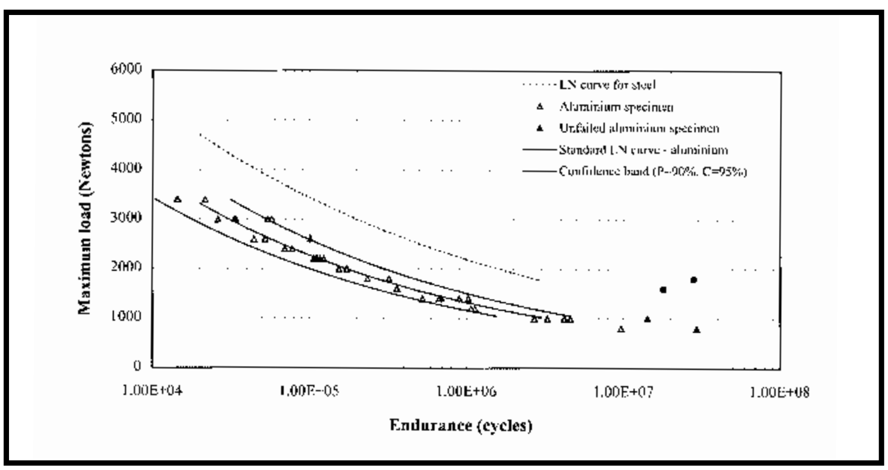

Fig. 10 — L-N curves for standard spot welded specimens in galvanized steel and in aluminum alloy (series H and S).

shown to be tensile and close to the material yield stress to aluminum (Ref. 13). Furthermore, mechanical treatment of welds (Ref. 13) was shown to increase fatigue life tenfold, although thermal treatment gave no improvement. Postweld compressive loading of spot welds in steel is a recognized means of improving fatigue performance by introducing compressive stresses at the edge of the weld.

The bonded zone is not normally considered as contributing strength to welds in aluminum alloys, and the cross-tension tested welds showed failure at the edge of the fused zone. However, at low-load fatigue conditions, there is sometimes sufficient strength to promote cracking from the outer edge of this zone.

Conclusions

The static and fatigue properties of resistance spot welds in 1.2-mm 5182-0 aluminum alloy have been studied to establish the effect of weld discontinuities and weld size, and to compare with 0.8-mm zinc-coated low-carbon steel. The following conclusions are drawn.

Excessive porosity, up to about 40% of the nugget diameter, did not affect the static or fatigue performance of the welds in shear when maintaining a constant 6.3-mm weld diameter.

The location of the fatigue cracks were not affected by the porosity or drilled hole.

Increasing the weld diameter from 4.2–7.2 mm produced a large increase in the static properties of welds. However, in fatigue, the weld size had only a small positive effect for high-load/low-endurance conditions and no effect at all for low-load/high-endurance (10^6 cycles).

Electrode force had one of the most significant effects on fatigue strength. The fatigue load at 10^6 cycles was 15% higher when electrode force was increased from 4.0 to 6.5 kN and 15% lower at 1.5-kN electrode force. A postweld squeeze at 4 kN largely restored the fatigue properties of the low-force welds.

Deep surface indentation increased the fatigue strength of welds of the standard size probably due to the higher electrode forces used, which modified conditions at the edge of the nugget.

When showing a 50% weight saving in comparison to steel, the fatigue strength of spot welds in aluminum was lower than the equivalent welds in steel.

References

1. Patrick, E. P., and Sharp, M. L. 1992. Joining aluminum auto body structure. SAE Paper 920282.
2. Kucza, J. C., Butruille, J. R., Hank, E., and Lancrenon, B. 1997. Aluminum as rolled sheet for automotive applications — effect of surface oxide on resistance spot welding and adhesive bonding behavior. SAE Paper 970013.
3. Hoch, F. R. 1978. Joining of aluminum alloys 6009/6010. SAE Paper 780396.
4. Krause, A. R., Thornton, P. H., and Davies, R. G. 1994. Effect of magnesium content on the fatigue of spot-welded aluminum alloys. *Proceedings of the International Symposium of Recent Developments in Light Metals*, Toronto, Ontario, pp. 31–49.
5. Auhl, J. R., and Patrick, E. P. 1994. A fresh look at resistance spot welding of aluminum alloy components. SAE Paper 940160.
6. Rivett, R. M., and Westgate, S. A. 1980. Resistance welding of aluminum alloys in mass production. *Metal Construction* 12(10): 510–517.
7. Leone, G. L., and Altshuller, B. 1984. Improvement on the resistance spot weldability of aluminum body sheet. SAE Paper 840292.
8. Pickering, E. R., and Hart, C. J. 1994. Optimizing resistance spot welding on aluminum-alloy 6111 autobody sheet. SAE Paper 940662.
9. Thornton, P. H., Krause, A. R., and Davies, R. G. 1996. The aluminum spot weld. *Welding Journal* 75(3): 101-s to 108-s.
10. Watanabe, G., and Tachikawa, H. 1995. Behavior of cracking formed in aluminum alloy sheets on spot welding. Toyota Central R&D Labs, Inc., IIW Doc No. III-1041-95, Stockholm, Sweden.
11. Nordmark, E. G. 1978. Fatigue performance of aluminum joints for automotive applications. SAE Paper 780397.
12. Krause, A. R., Thornton, P. H., and Davies, R. G. 1993. The fatigue of spot-welded aluminum alloys. *Light Metals Processing and Applications*, pp. 589–600, International Symposium Light Metals, 32nd Annual Conference Metallurgists, The Metallurgical Society of CIM, Quebec City, Canada.
13. Steffens, H. D., and Kern, H. 1985. Influence of residual stresses and microstructure on the lifetime of resistance spot welded 2024 aluminum. *Proceedings, International Conference, the Effects of Fabrication Related Stresses on Product Manufacture and Performance*, Cambridge, U.K. Paper 50 pp. 269–283.