The Aluminum Spot Weld

Fatigue strength is dependent on nugget diameter rather than the absence of porosity and expulsion

BY P. H. THORNTON, A. R. KRAUSE AND R. G. DAVIES

ABSTRACT. Weld conditions which promote long tip life for aluminum spot welds are not necessarily associated with high weld quality in terms of freedom from defects such as porosity, cracks and expulsion. Schedules which produce good weld nuggets in terms of the peel test and long tip life may not produce a good response in terms of fatigue life. The fatigue life range is optimized by maximizing the weld nugget diameter, *i.e.*, by employing a weld schedule which may lead to expulsion and weld porosity. Weld strength, in both peel and overlap shear configurations, was found to be linearly dependent upon weld diameter. In the peel test, the strength was also dependent upon the base metal thickness, in that for a given thickness, there is a critical diameter for the transition between weld fracture and nugget pull-out. For a given nugget diameter, if pull-out is observed then the strength is greater than if fracture occurs through the weld. In the shear test, the opposite response was observed, the strength for nugget pull-out being less than that for weld shear failure. Weld pull-out was found only for the thinnest base metal thickness tested and the shear load depended only upon the weld diameter over the range of thicknesses tested. Maximum strength in an aluminum spot weld is obtained by maximizing the weld nugget diameter for that thickness of material.

Introduction

The increase in interest in the use of aluminum in the construction of automobiles has led to a need to characterize the mechanical properties of the spot weld in aluminum alloys. The spot weld is currently the joining method of choice in the automobile industry for economic reasons, and this advantage was recognized many years ago by the aerospace industry (Ref. 1). Because today steel is the primary material of construction in the automobile, its mechanical properties, and in particular the fatigue properties of steel spot welds, have been extensively investigated (Ref. 2). In comparison, there is comparatively little published work on the fatigue properties of aluminum spot welds. Early work on the mechanical properties of aluminum alloy spot welds tended to be focused upon the very high-strength alloys of interest to the aerospace industry. The results indicated that spot-welded construction would not equal the best riveted construction with regard to fatigue resistance unless the spot welds were produced to very high standards (Refs. 3, 4). For those alloys which are of interest to the automobile industry, such fatigue information is now becoming available (Refs. 5, 6).

Other information on the strength of the aluminum spot weld tends to be restricted to the shear strength of overlap joints. Bulletins (Refs. 7–10) give recommendations on the spot welding parameters, based upon the expected shear strength of the joint for a given alloy and gauge of material. Most other references on the spot welding of aluminum focus on the interrelationships between the various spot welding parameters, *e.g.*, weld current, electrode force, material gauge, surface condition, etc., which contribute to electrode tip life (Refs. 11–22). While some of these refer to weld shear strength as a measure of weld quality (Refs. 15, 17, 19), a few also include a reference to the nugget diameter as well (Refs. 18, 20–22). The data on the strength of spot welds in aluminum alloys were summarized in terms of load/spot-weld diameter (Refs. 3, 15), although it had been realized that the strength also depends upon the geometry of the spot weld as well as the metallurgical characteristics of the alloy (Ref. 21).

Much of the early work on the spot welding of aluminum alloys focused upon the defects in the weld nugget (Ref. 23) and the factors in the welding process which produced them. The shear test was the basic method used to quantify weld quality. Hess, *et al.* (Ref. 24), identified a change in failure mode from weld shear failure with smaller diameter weld nuggets to weld pull-out (tearing of the base metal) with larger diameter weld nuggets; the change in failure mode was

KEY WORDS

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Fatigue Life
Weld Strength
Nugget Diameter
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Peel Test
Shear Test
Weld Pull-Out
Base Metal Thickness

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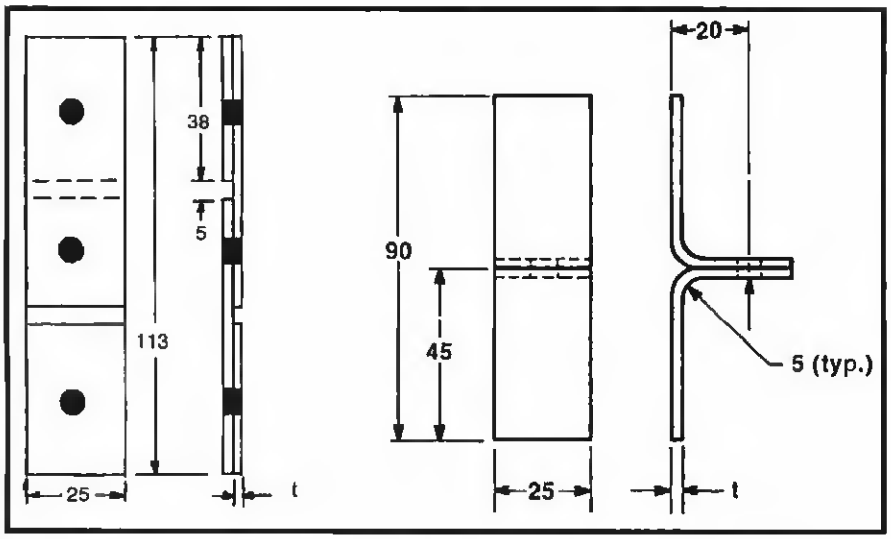


Fig. 1 — Overlap shear (left) and coach peel (right) specimens. All dimensions in mm.

accompanied by an increase in the weld load-bearing ability. It is presumed that failure in all other tests was by weld pull-out rather than by weld failure. The presence of defects, e.g., porosity, cracking, segregation, distorted fusion zone shape, in the spot welds can be recognized by radiography (Refs. 1, 23). Since many of these welds were made under production conditions, it might also be presumed that the welds contained cracks, etc. (Ref. 23). Thus, it may be inferred that such defects do not impair the overall shear load-bearing capability of the joint if the failure is by nugget pull-out.

In comparison to steel spot welds, those in aluminum alloys are comparatively weak. Hoglund and Bernard (Ref. 15) pointed out that the spot weld in aluminum alloys is a zone of cast metal intimately bonded with the unmelted metal of the parts joined. Patrick and Sharp (Ref. 5) indicate that the expected shear strength of a spot weld in a variety of aluminum alloys is only 40–60% of that of a mild steel spot weld in similar gauge material.

The shear load, P, for aluminum spot welds appeared to depend upon the weld diameter, d, according to the following relationship (Ref. 21):

$$P = 120d^2 \qquad (1)$$

where P is in N and d is in mm. The results of McMaster, *et al.* (Refs. 1, 23), also could be interpreted by a similar relationship between shear load and the square of the nugget diameter. Dewey and Mapes (Ref. 22) found a more complex relationship between the shear load, nugget diameter and base metal thickness.

Bonding at the corona interface, the boundary zone surrounding the weld nugget, can provide a significant contribution to the load-carrying capacity of the spot weld under certain circumstances. In Alclad®[1] 2024 sheet, the corona diameter was found to be ~1.5d and to have an estimated shear strength of 45 MPa (Ref. 21). McMaster and Begovich (Refs. 25, 26) found that the corona bond, which can provide up to 40% of the strength of the weld, is most likely to form on freshly cleaned surfaces, and provides a decreasing contribution to the total weld strength with an increase in time between cleaning and welding. Because of the variability of the strength of the corona bond, with its dependance on production variables such as relative cleanliness, elapsed time between cleaning and welding, etc., it was considered good practice to ignore the corona bond contribution to weld shear strength and to accept that the corona bond did not augment the tension strength of the spot weld, since it was observed that the tensile failure load may remain constant while the shear load increases (Ref. 1). The corona bond effect has been identified as the cause for the wide scatter in spot weld strength results, which can make the qualification of machine performance very difficult (Ref. 27).

Expulsion and weld porosity occur when there is insufficient weld pressure to contain the melt (Refs. 25, 26). However, once the melt is contained, any further increase in pressure has little effect upon weld shear strength, but merely results in an increase in the tip penetration. The onset of expulsion can be controlled by the geometry of the weld electrode tip. To eliminate expulsion with Alclad 2024 material, the optimum tip radius was found to be ~230 mm (~9 in.); with smaller radii, sufficient force could not be applied to prevent expulsion (Ref. 25). The timing and magnitude of the weld forging force must also be controlled to prevent weld cracking. The time span over which the forge force can be applied increases with an increase in the force level (Ref. 26). Overall, there is a small window of weld parameters that will permit the production of defect-free welds (Refs. 14, 26).

Much of the early work (Refs. 3, 7) was focused upon the production of defect-free welds. This requirement necessitates close monitoring of the weld parameters, which may only be possible under low production schedules. Furthermore, the application of high electrode forces for postweld forging, etc., may not be practical with the mobile welding units often employed on automobile assembly lines.

The purpose of the present work was to examine the strength of spot welds made under nonideal conditions in which weld defects, for example, expulsion and weld porosity, would arise, and thus to answer the question, "Is a weld which contains visible defects really a bad weld?"

Experimental Procedure

The alloys studied were the nonheat-treatable 5754 and the heat-treatable Alloys 6111 and X613 (Alcan equivalent of 6111). Coach peel and overlap shear specimens were made according to the dimensions shown in Fig. 1 in aluminum Alloys 5754-O and X613-T4 supplied by Alcan Ltd. in 1-, 2- and 3-mm (0.04-, 0.08- and 0.12-in.) thicknesses. This material is normally supplied with a proprietary conversion coating finish to provide consistent surface resistivity and is coated with a dry lubricant for stamping purposes. The surfaces were not treated in any other way prior to spot welding.

Preliminary fatigue tests were made on overlap shear specimens made by Alcan Ltd. from 2-mm 5754 aluminum alloy according to the company's welding specifications, and on 1.6-mm (0.063-in.) 6111 aluminum alloy, supplied by Alcoa, and welded in-house using AC equipment. Cross-tension tests were made upon 1.6-mm 5754 aluminum alloy samples welded by Alcan Ltd.

Overlap shear and coach peel samples were prepared from heat-treated material as required, placing the material

1. Alclad is a registered trademark of Alcoa Inc.

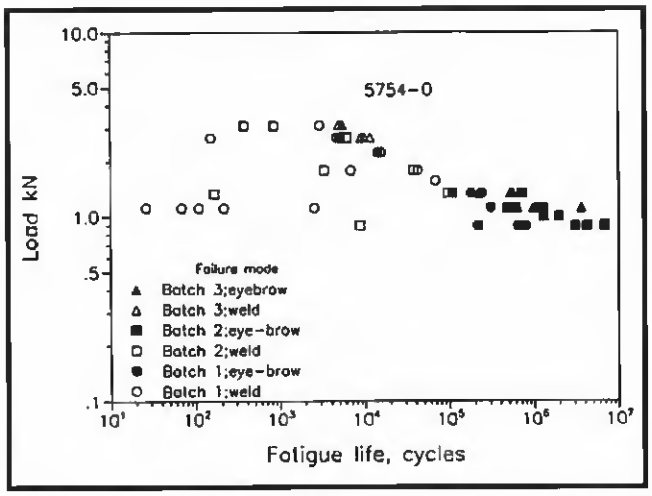


Fig. 2 — Fatigue life of aluminum Alloy 5754-O subject to different welding schedules.

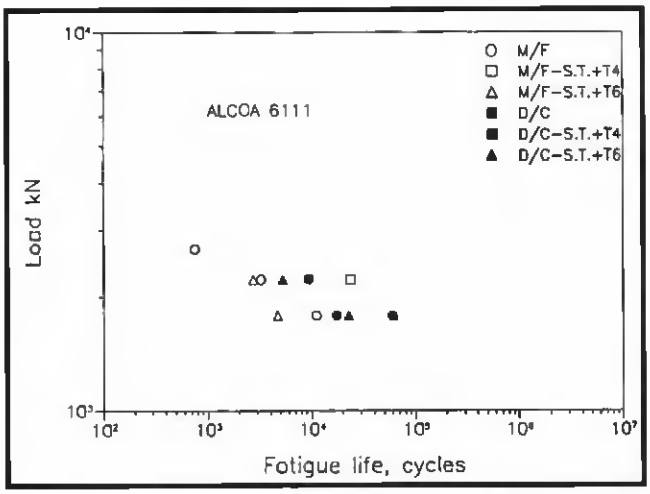


Fig. 3 — Fatigue life of aluminum Alloy 6111. M/F: mill finish (T4 condition); D/C: degrease and clean (T4 condition); S.T. + T4: mill finish, solution heat treat, room-temperature age; T6: mill finish + 1/2 h 175°C

into either the annealed, T4 or T6 condition. In-house welding used electrodes with a tip radius of 76 mm (3 in.), a nominal 4500 N load and 8 cycles of current. The spot weld diameter was changed by altering the weld current over the range of 20–32 kA.

Some shear tests were made in the customary way by simply loading the shear test samples in tension to the point of failure. With the thinner base metals, the samples deformed during the test, so that the shear test tended to be transformed into a peel test. Therefore, shear tests also were made after restraining plates were fastened to the specimen on either side of the spot weld under test, to restrict the tendency of the sample to deform and so to maintain the shear loading as long as possible. The shear and coach peel tests were performed in an Instron Model 1125 machine at a crosshead rate of 2.5 mm/min. The fatigue and high rate cross-tension tests were made in MTS electohydraulic machines.

Results

Fatigue and Tension Tests

Figure 2 shows the wide range in fatigue results, extending over four orders of magnitude with little change in applied load, which can be observed in spot welds made by Alcan Ltd. The Batch 1 samples were made to a schedule that gives a nominal good weld as judged by the peel test. The fact that many of the failures were within the weld, rather than in the base metal, which is the typical fatigue failure mode in steel spot welds, indicates that the conventional welding procedure is not adequate. It was only by changing the weld conditions to the point of expulsion and beyond, Batches 2 and 3, respectively, that consistent fatigue lives could be obtained, with minimal scatter and with significant lives in the low load, long life region. Similar results with regard to weld failure were obtained with samples of 6111, welded in-house according to nominally optimum conditions — Fig. 3. The tensile characteristics of the spot welds produced by nominally correct conditions also showed considerable scatter. Figure 4 shows the response of cross-T spot welds, made with welding currents below that of the expulsion limit, tested at different loading rates. The weld buttons exceeded the minimum recommended diameters (Ref. 7). Metallographic examination revealed some porosity within the weld nugget — Fig. 5.

Shear and Peel Tests

Figure 6 shows the results for overlap shear and peel tests made on 5754 aluminum alloy in three thicknesses. The range of weld nugget diameters was obtained by varying the weld current. In the case of the overlap shear tests, most of the samples fractured through the weld. The exceptions were those made in the 1-mm sheet. The samples in this thickness, unless they were restrained from distorting by the supporting side plates, tended to fail by nugget pull-out. When restrained, the fracture was generally by shear through the weld. The support plates appeared to have little effect on the shear results for the thicker samples. For the peel tests, a transition was found between nugget pull-out, for the 1-mm thickness and for the larger-diameter nuggets in the 2-mm thickness, and weld shear failure for the remainder. For the present tests, over the range of nugget diameters investigated, a simple linear relationship between load and nugget diameter can be drawn — Fig. 6. Results for Alloy X613 are shown in Fig. 7. Only one thickness of material was examined in this alloy. Similar to the behavior of the 2-mm 5754 material, the peel samples of the X613 alloy with the smaller nugget diameters fractured

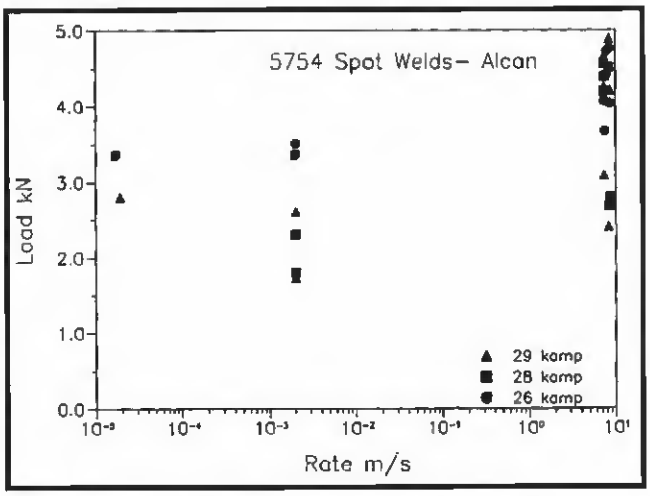


Fig. 4 — Cross-tension test results at different loading rates.

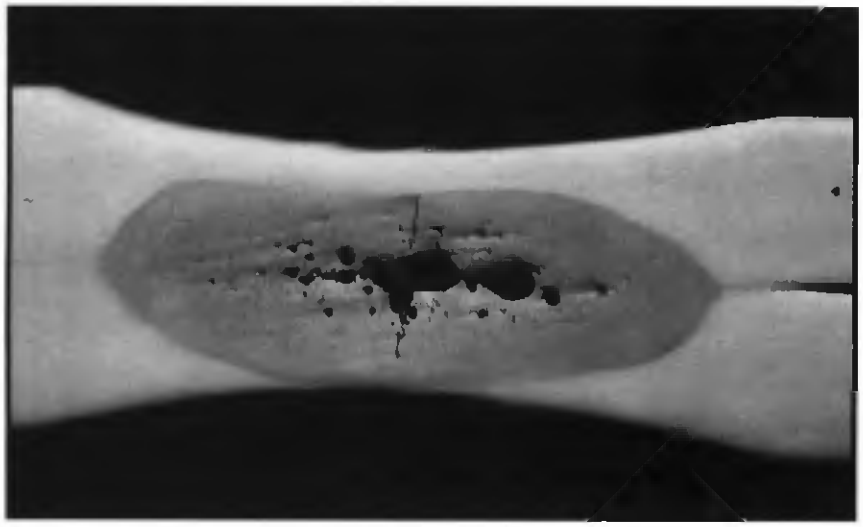
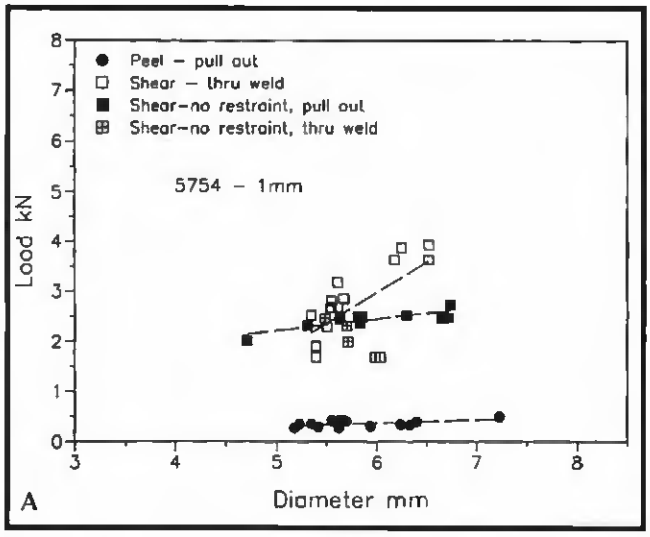


Fig. 5 — Porosity in weld nugget of 5754 aluminum alloy.

through the weld, while those with the larger diameters underwent nugget pullout. Again, over the more limited range of nugget diameters investigated, there was a linear relationship between load and nugget diameter.

In order to determine the scatter which could be experienced in the coach peel tests, two batches of material were made from the 2-mm 5754 alloy sheet. The first batch consisted of five groups, each of 15 samples, made using weld currents from 22 to 30 kA. The second batch, made at a different time, consisted of three groups, each of five samples, made with three weld current settings. Figure 8 shows the coach peel test results for these samples. The results for the first batch are presented as average values, with scatter bars. Because the second batch contained fewer specimens, the individual results are shown. All of the samples, except for those with the smallest diameter welds in the second batch, failed by weld nugget pullout. Much of



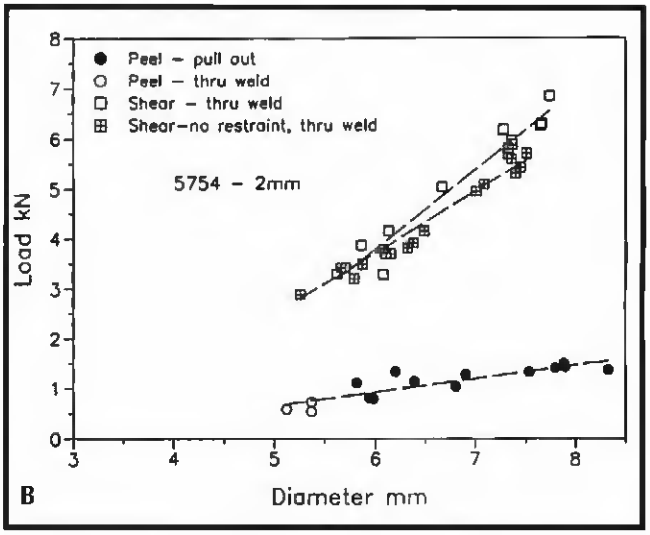
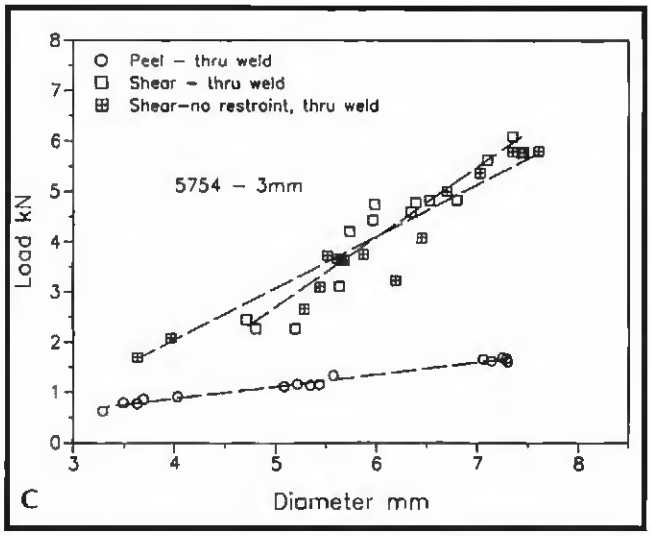


Fig. 6 — Overlap shear and coach peel test results for 5754-O aluminum alloy. A — 1 mm; B — 2 mm; C — 3 mm.



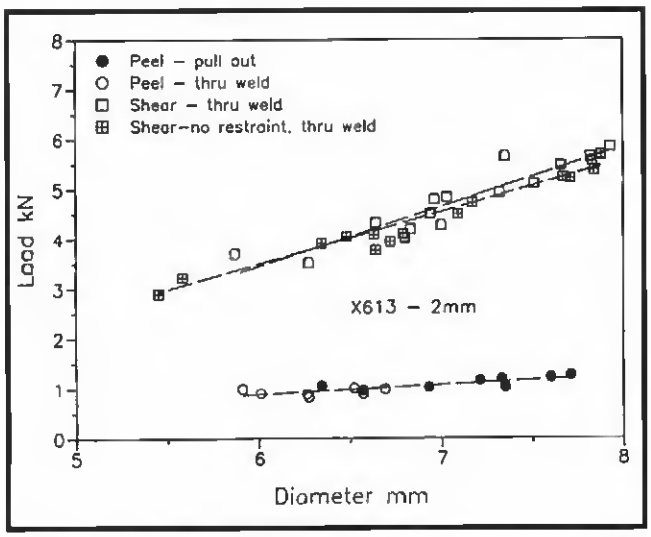


Fig. 7 — Overlap shear and coach peel test results for 2-mm X613-T4 aluminum alloy.

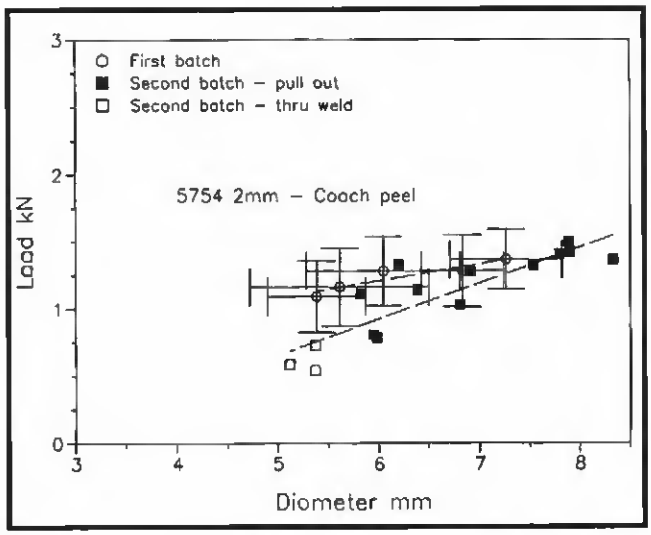


Fig. 8 — Spread in load values for coach peel tests on two different batches of 5754-O aluminum alloy.

the error in this work arises from the difficulty in obtaining a reliable value for the nugget diameter since the remnant of base metal that remained attached to the nugget prevented a reliable second measurement of the diameter from being obtained. For the remainder of this report, the individual values for each sample will be given, the samples being made with five specimens per group, and with each group at one nominal current setting, as in the second batch described above.

Hardness Tests

Microhardness traverse tests were made upon spot welds in the 5754 and X613 materials. Figure 9 shows the hardness values obtained from weld nuggets made at three different welding currents in the 5754-O alloy. It is seen that there is virtually no change in hardness between the weld material and the base metal in this alloy. A change in weld current, although it produced a change in the nugget diameter, essentially did not affect the hardness of the weld zone. Some scatter is to be expected in these results because of the weld porosity.

If the base metal was one of the heat treatable alloys, differences were found between the base metal hardness and that of the weld nugget. For the X613-O alloy, some hardening of the weld nugget relative to the base metal occurred (Fig. 10), whereas for this alloy in the T4 and T6 tempers, the weld nugget was significantly softer than the base metal. However, if the weld nugget was subjected to a solution heat treatment and age cycle, its hardness was restored to approximately that of the base metal — Fig. 10. For the three X613 base metal tempers, O, T4 and T6, the weld nugget hardness was approximately the same. Thus, although some of the alloying elements segregate during solidification of the weld nugget, enough remain in solution to cause some subsequent aging response.

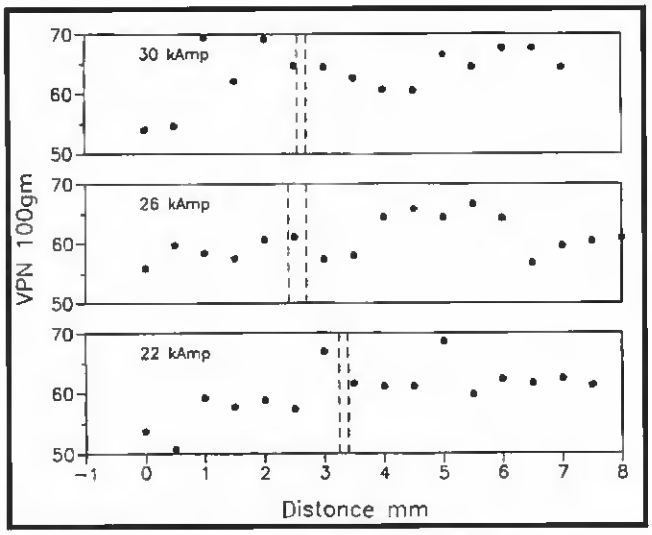


Fig. 9 — Hardness traverse results for spot welds in 5754-O aluminum alloy for welds made with different currents. Traverse starts within weld nugget. Dotted lines denote boundary between weld and base metal.

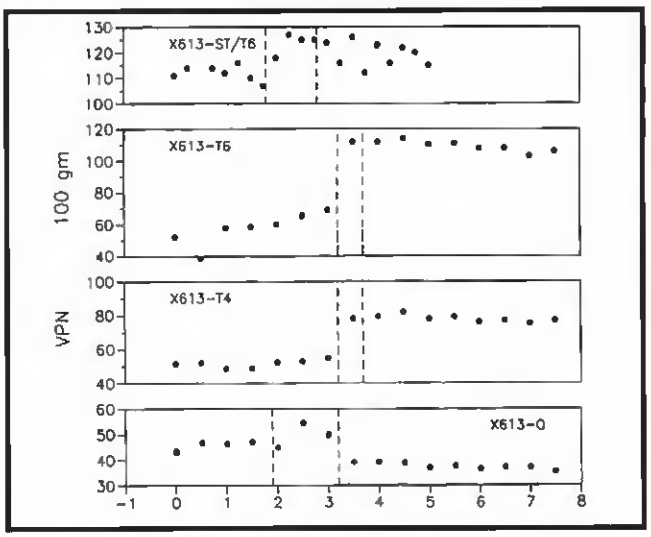


Fig. 10 — Hardness traverse results for spot welds in X613 aluminum alloy for welds made with different currents. Traverse starts within weld nugget. Dotted lines denote boundary between weld and base metal.

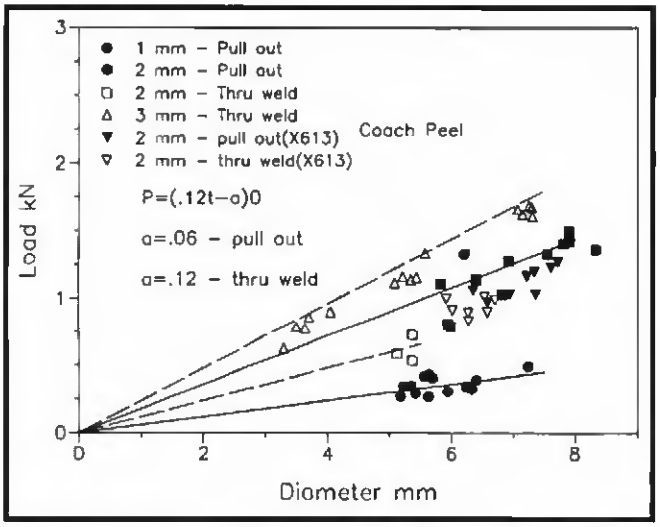


Fig. 11 — Relationship between load and weld nugget diameter for coach peel tests. Alloy 5754 except as noted.

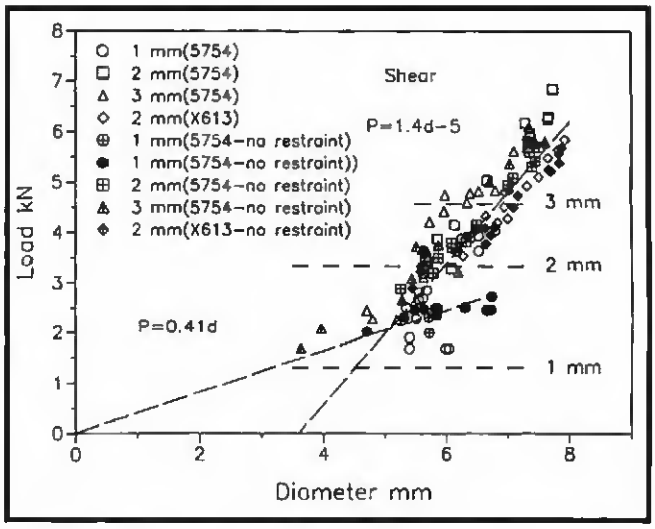


Fig. 12 — Relationship between load and weld nugget diameter for overlap shear tests. Minimum specification loads for different thicknesses shown by horizontal dotted lines. Solid symbols: nugget pull-out; open symbols: weld shear.

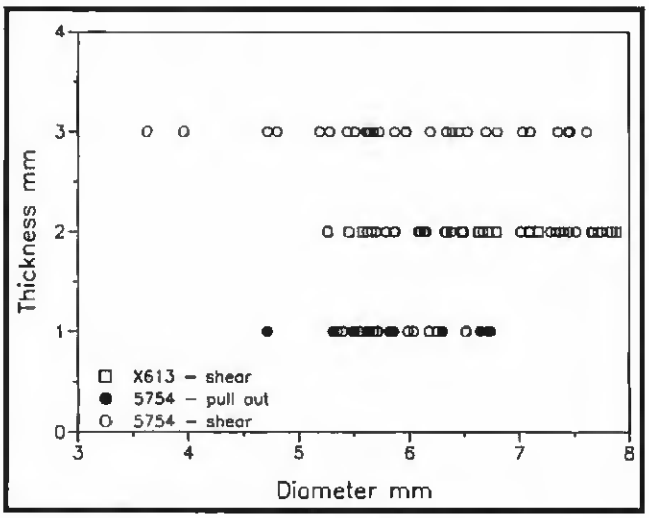
Discussion

The combined results for the coach peel tests in the two alloys tested are shown in Fig. 11. To a first approximation, for the 5754 alloy results, the load can be linearly related to the spot weld diameter for a given thickness by the expression

$$P = (0.12t - a)d \qquad (2)$$

where P is the load in kN, t is the sheet thickness in mm and a is a constant with numerical values of 0.06 for weld pull-out and 0.12 for weld fracture. The trend appears to be for the weld pull-out load to be greater than that for weld fracture for a given weld diameter and thickness in the 5754 alloy. This trend is not followed by the results for the X613 alloy, which fall at intermediate values between the weld failure and nugget pull-out results for the 5754 alloy, and for which both failure modes have the same dependence upon nugget diameter.

For the 1-mm 5754 alloy sheet, a minimum weld diameter for nugget pull-out failure was not established, but from Fig. 11 it can be estimated to be < 5 mm (0.2 in.). For the 2-mm 5754 alloy sheet, the minimum diameter is ~6 mm (~0.24 in.). However, for the 2-mm X613 alloy sheet, a minimum nugget diameter of ~7 mm (~0.28 in.) is necessary. A nugget sufficiently large to produce weld pull-out failure was not made in the 3-mm 5754 alloy sheet, but it would appear to have to be > 7 mm in diameter in order to do so. Minimum weld nugget diameters of 4, 5.7 and 7 mm, approximately, are indicated in the Aluminum Association guidelines (Ref. 8) for 1-, 2- and 3-mm sheet, respectively. These sizes are in agreement with the results shown in Fig. 11 for 5754 aluminum alloy, but not for the X613 alloy, which requires a larger nugget diameter in order to produce weld pull-out failure. Minimum loads for the peel test have not been stipulated in the current welding standards (Refs. 7, 8) for aluminum alloy spot welds. Nevertheless, it could still be possible to produce a satisfactory weld on the basis of



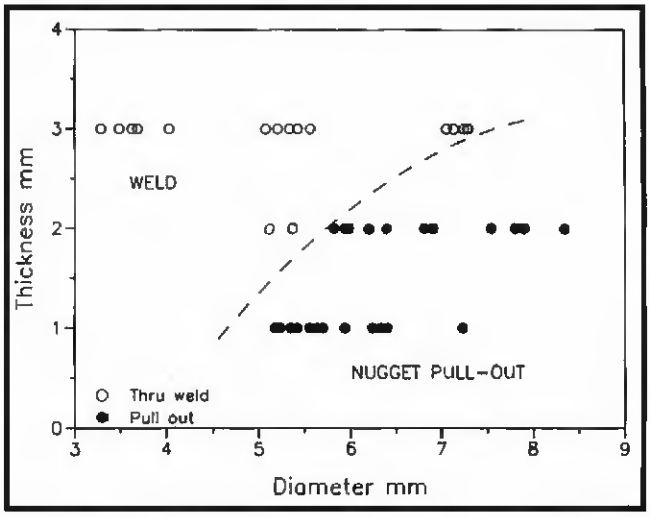


Fig. 13 — A — Failure mode in overlap shear tests for different thicknesses and nugget diameters; B — change in weld failure mode with weld nugget diameter and base metal thickness for coach peel tests.

size and/or peel fracture load, but which failed by weld fracture rather than by nugget pull-out.

Figure 12 shows that for the shear tests, two modes of behavior occur, but for both there is a simple linear relationship with the nugget diameter. If shear failure occurs, the shear load can be related to the diameter by the relation

$$P = 1.4d - 5 \quad (3)$$

whereas if nugget pullout occurs, the relationship is

$$P = 0.41d \quad (4)$$

Only for the 1-mm sheet did the bending distortion affect the shear test results. Probably for thinner gauge material, even the use of restraining plates would not prevent completely the occurrence of nugget pull-out. The minimum shear loads for design purposes for a given base metal thickness (Ref. 8) are seen to be exceeded by all samples with nugget diameters greater than ~3, ~6 and ~7 mm, for the 1-, 2- and 3-mm sheet, respectively.

Figure 13A shows that the overlap shear test does not discriminate unambiguously between welds which would give shear failure and those which would give nugget pull-out failure. By constraining the overlap shear specimen, welds in the 1-mm-thick 5754 alloy could be induced to fail by shear. If the restraining plates were omitted, the specimen flexed and failure occurred by nugget pull-out. This response was observed over the whole range of nugget diameters examined for the 1-mm material. No change in failure mode due to the absence of the restraining plates was seen for the thicker materials. In contrast, for the peel test, a marked demarcation can be seen between the material thickness, the nugget diameter and the failure mode — Fig. 13B. For 1-mm material, the nugget diameter for the transition zone for nugget pull-out/through weld failure is < 5 mm. As the material thickness increases, the critical diameter increases to > 7.5 mm for the 3-mm material. Thus, the observation of shear failure in a peel test cannot be the sole criterion for an unsatisfactory weld, since material thickness also must be taken into consideration.

These results may be understood more fully in the light of the material characteristics of the spot weld vs. those of the base metal, and the stress concentration that occurs at the spot weld. Kan (Ref. 28) has shown by finite element analysis that a stress concentration forms on the axis of the specimen in the overlap shear test at the nugget/base metal interface and migrates around the nugget as the load increases. In aluminum alloy spot welds, this stress concentration is ~4 (Ref. 29). The material in the spot weld itself has mechanical properties that are significantly different from those of the base metal. In chill-cast 6061 aluminum alloy, the yield and tensile strengths were found to be ~75% of those of the base metal (6061-T4), and the elongation was ~2%, vs. ~20% (Ref. 29). Figure 9 shows that for the 5754 alloy, the hardness of the spot weld is somewhat lower than that of the base metal, and Fig. 10 shows that for the X613 alloy, the spot weld hardness can be significantly different from the base metal hardness, particularly for those alloys welded in the T4 and T6 aged conditions. For these conditions, the hardness of the spot weld material is very similar to that of the 5754 alloy, so that it can be presumed that the other mechanical properties are similar, although in the base metal they are quite different — Table 1. These lower mechanical properties are the key to the behavior of the aluminum spot weld. At lower loads, the plastic strain tends to be localized in the base metal surrounding the nugget, but at higher loads the plastic strain migrates into the weld from the periphery of the nugget (Ref. 29). The low plastic strain capability of the weld material then quickly leads to fracture by shear loading. Base metals with different mechanical properties produce spot welds that fail under similar loads because the spot weld material has similarly low mechanical properties, and the large stress concentration operating at the nugget tends to mask mechanical property differences.

The question which initiated this work was that of weld quality, that is what constitutes a "good weld" and what are the criteria by which it can be judged. The failure mode in the simple peel test, which is the standard shop-floor test for steel spot-welds, is not by itself sufficient for identifying unsatisfactory spot welds in aluminum alloys. Earlier work (Ref. 6) indicated that spot welds produced to specification (Ref. 8) did not have an adequate fatigue performance. Only by increasing the weld diameter could satisfactory fatigue performance be obtained. Such procedures lead to metal expulsion, weld porosity and cracking (Fig. 5), which are grounds for failure according to specification (Refs. 7, 8). Some control over these effects can be obtained by changes in the weld procedure, e.g., by application of higher weld pressures, but such changes carry the burden of introducing effects such as excessive indentation, which by itself could lead to an impairment in the fatigue life or strength because of the thinning of the base metal involved. Internal defects tend to play a relatively insignificant role in the fracture initiation process, since the critical stress concentration is located on the weld periphery, and providing they are contained within the weld, corroding media should not gain access to them. The present results indicate that a weld may have satisfactory shear load performance but unsatisfactory peel test performance, *i.e.*, it fractures through the weld in a peel test in the standard shop floor test. The specification standards (Ref. 8) do not consider failure mode as a critical issue. Based upon the current experimental observations, together with the specification recommendations (Ref. 8), a strength value coupled with a spot weld size value would seem to be more appropriate to determine whether or not a weld is satisfactory.

Table 1 — Mechanical Properties of Aluminum Alloys

Alloy	0.1% Yield MPa	U.T.S. MPa	% Elongation
5754-O	108	236	16
X613-O	68	152	19
X613-T4	153	297	27
X613-T6	337	367	10

This work indicates that, providing that the weld nugget is sufficiently large, the weld will have satisfactory load-bearing capability, in particular for adequate fatigue performance (Ref. 6). Weld defects, such as expulsion, porosity and possibly cracking, at least to the level illustrated herein, should not have a deleterious effect upon the mechanical behavior. This point is important because the weld conditions employed in automobile production (noncleaned surfaces and with focus upon long tip life) are not strictly compatible with those conditions that have been identified with the production of welds for aerospace applications, *i.e.*, freshly abraded surfaces, high forge forces and large tip radii (Ref. 25). As Chihoski (Ref. 27) has emphasized, deviations from traditional constraints can provide more consistent performance, and the presence of defects is not necessarily the criterion for an unsatisfactory weld.

Conclusions

The weld nugget diameter is the most important criterion for weld nugget quality in terms of weld strength and fatigue life for the aluminum spot weld. Porosity, cracks and expulsion, which are nor-

mally considered weld defects for welds produced to military and aerospace applications, do not necessarily lead to lower weld performance. To optimize the strength of an aluminum spot weld, it is necessary to maximize the weld diameter for that thickness of material.

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