Contact Resistance of Aluminum

Roughening the electrode tip and the aluminum workpiece surface appears to extend the weld tip life and improve weldability

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

ABSTRACT. The electrode–workpiece and faying surface contact resistances were measured for a variety of aluminum alloys having various surface finishes. The measured value of each contact resistance was dependent upon the imposed current and the surface roughness, R_a, of both the workpiece and the electrode. With sufficiently high currents, often much less than those suggested in various spot welding specifications, electrical breakdown of the contact could occur. An increase in electrode tip life can be associated with higher workpiece surface roughness, R_a. Lower electrode–workpiece contact resistance is also associated with higher values of R_a. Although faying surface contact resistance measurements have not proven successful in identifying long weld tip life behavior, possibly because such determinations often are made with high currents that can produce surface changes, measurements of contact resistance made with a low current, and that are associated with high values of R_a, may provide a means for quality control in the spot welding of aluminum alloys. This current should be kept to a value that prevents the potential drop across the faying surfaces from exceeding 0.15 V to avoid changes in the surface characteristics of the aluminum.

Introduction

Contact resistance is a variable of considerable interest for the electric resistance spot welding of aluminum. The surface of an aluminum sheet can exhibit a wide range of characteristics, depending upon the processing and storage conditions as well as the alloy content. Various methods for measuring the contact resistance of such sheets have been described (Refs. 1–7), several being embodied in specifications and standards. The intent of these latter is to ensure that the aluminum sheet to be spot welded meets a particular surface cleanliness criterion. The German standard (Ref. 4), for example, stipulates that the contact resistance must not exceed 200 μΩ and that the desirable contact resistance is in the range of 20–50 μΩ. To attain such levels, the aluminum surface must be cleaned, either by etching or abrading, and to prevent further contamination, the spot welding must take place fairly soon after this preparation.

Several of these specifications (Refs. 1, 4, 6) appear to have been derived from aerospace requirements. For automobile manufacturing use, it is impractical to clean aluminum sheet to such standards and, furthermore, such sheet is often coated with lubricant for stamping purposes, leading to possible contamination with dirt, etc. Aluminum alloy sheet for automobile use may have been subjected to a conversion coating treatment to stabilize the surface for adhesive bonding purposes. This, together with the lubricant, can produce a contact resistance that greatly exceeds the low values stipulated in welding standards, and yet such material can be spot welded in a satisfactory manner (Ref. 5).

KEY WORDS

Contact Resistance
Resistance Spot Welding
Surface Roughness
Weld Tip Life
Weldability
Faying Surface
Tip–Workpiece Interface

The techniques described to determine contact resistance for spot welding purposes generally are based upon the spot welding process itself, *i.e.*, a similar weld-tip setup is arranged, a current is passed and a potential drop recorded from which the contact resistance is derived using Ohm's Law. In studies of the change of contact resistance during the spot welding process, the approach is similar. The contact resistance that is recorded in both cases often is that across the weld tips and thus includes the electrode tip–workpiece contact resistance as well as that of the faying surface.

In virtually all studies of the spot welding process, the focus has been on the change occurring at the faying interface and the development of a strong spot weld. However, weldability for automobile use is dictated by weld tip life. Although there have been many papers discussing the changes occurring during the spot welding process, there has been very little published work on the deterioration of the weld tip during spot welding, in particular the spot welding of aluminum. Davis and McMaster (Ref. 8) showed that effective tip cooling, together with optimum tip loads and tip geometry, increased tip life, which was defined as the first visible onset of the transfer of electrode material to the aluminum workpiece. An increase in tip roughness can enhance electrode tip life, particularly when accompanied by other procedures, such as chemical surface treatment of the aluminum alloy (Ref. 9) or nickel plating of the electrode (Ref. 10). Newton (Ref. 5) has recorded values of ~20 ± 10 μΩ for the electrode tip–workpiece contact resistance and between 10^2–10^4 μΩ approximately for the total weld-tip to weld-tip contact resistance for several aluminum alloys that have been subject to a conversion coating treatment and/or are coated with lu-

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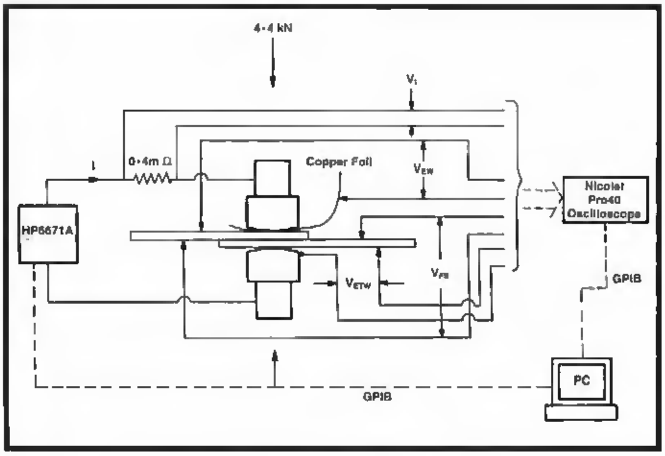

Fig. 1 — Experimental arrangement for measuring quasi-static change of contact resistance with current. V_{ew} = electrode–workpiece voltage, V_{etw} = electrode tip–workpiece voltage, and V_{fs} = faying surface voltage.

bricant. Newton (Ref. 5) also found that the electrode contact resistance for lubricated sheet was lower than that for unlubricated sheet

The currents to he used in the determination of contact resistance according to the various standards cover a wide range of values, from a few milliamps (Ref. 3) to 100 A (Ref. 7). Newton (Ref. 5) used a current of 3.3 A; the German standard (Ref. 4), which was of concern in that work (Ref. 5), indicates a minimum current of 10 A. A previous report (Ref. 11) has indicated that electrical breakdown effects can occur across spot-weld-type contacts at quite low currents, so that the values for the contact resistance that are determined may be affected by the imposed current.

Thus there appear to be two items of concern in the measurement of the contact resistance and its relation to spot weldability. One is the current that should be used in the determination. The ASTM specification (Ref. 3) stipulates that the applied voltage and current should not exceed 20 mV and 100 mA, respectively, for the dry circuit testing of contacts, to avoid surface changes such as oxide film breakdown that can invalidate the results. Thus the high currents used in these various spot welding contact resistance standards can result in changes to the surfaces being investigated, invalidating the resistance values. There is some evidence that contact resistance values obtained using high current methods show little correlation with weldability (Ref. 12), *i.e.*, a high current contact resistance method has not been able to discriminate between aluminum alloy stocks with regard to their effect upon weld tip life. The other item is the electrode tip–workpiece interface, because this is the contact that is affecting weldability. In addition to the increase in electrode life that can be produced by roughening of the electrode tip, electrode life also may be extended by using an aluminum workpiece surface that has been roughened by abrasion or shot blasting (Refs. 13, 14).

In the present work, the changes in contact resistance with current for both the electrode–workpiece interface and the faying surface were examined for a variety of aluminum alloys with different surface treatments but with particular reference to the surface roughness at the electrode interface.

Experimental Procedure

Standard spot weld electrode tips with a 50-mm-radius spherical contact surface were inserted in stainless steel holders attached to the top and bottom crossheads of an Instron testing machine. The tip holders were designed so that the electrode tips could be internally water cooled. The sheet samples, 50 x 25 mm, were placed upon a micarta loading guide mounted on the bottom electrode holder at such a

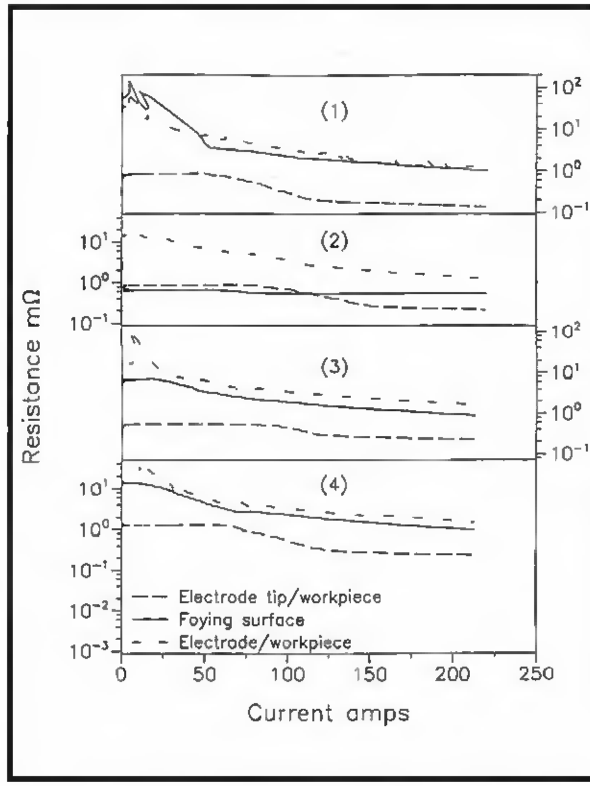

Fig. 2 — Sequence of four successive contact resistance measurements on 6111 aluminum alloy with Z255 lubricant.

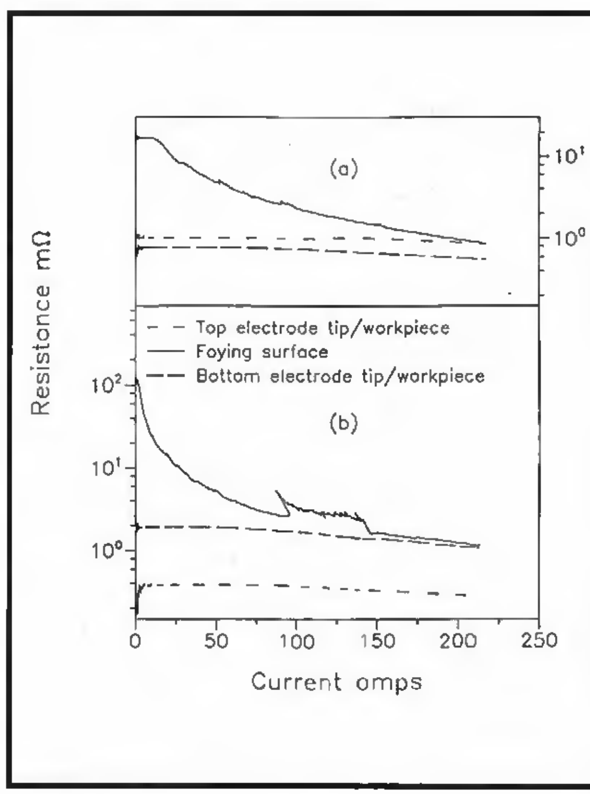

Fig. 3 — Effect of electrode polarity on contact resistance for 6061 aluminum alloy. A — Bottom electrode negative, top electrode positive; B — top electrode negative, bottom electrode positive.

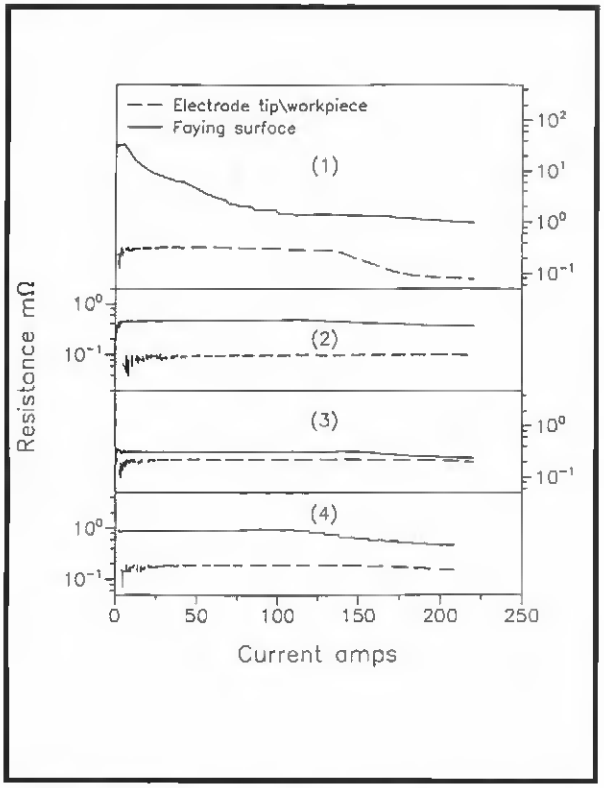

Fig. 4 — Sequence of four successive contact resistance measurements using a freshly abraded (600 grit) tip for each test on 6111 aluminum alloy with AZ55 lubricant.

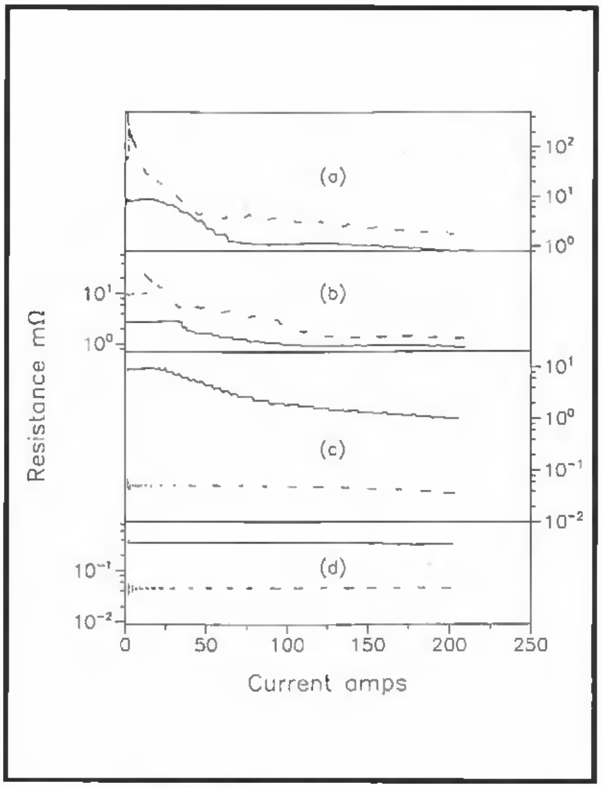

Fig. 5 — Effect of surface abrasion of copper electrode on contact resistance on 6111 aluminum alloy with Z255 lubricant. A — Copper foil, as received; B — copper foil, abraded with 12 µ SiC paper; C — copper foil, abraded with 600-grit emery paper; and D — copper foil abraded with 180-grit emery paper.

height that the samples lay flat and parallel to one another on the bottom electrode tip with 25-mm overlap. The top specimen could be lowered onto the bottom specimen without any sliding motion that could have generated erroneous readings. Several contiguous readings could be taken on a given sample.

The experimental arrangement is shown schematically in Fig. 1. Current was passed between the electrodes through cables attached to the electrode tips. The contact voltages at the electrode–workpiece and faying interfaces were detected via alligator clips that had one insulated jaw. Where appropriate, the clip was attached with the uninsulated jaw in contact with the surface of interest. A load of 2.2 kN was applied to the electrodes prior to the attachment of the alligator clips to simulate the load applied during conventional spot welding. This load also prevented extraneous relative movement from occurring between the specimen pieces while the alligator clips were being attached.

An electrode–workpiece interface was created in two ways. One was with the bottom electrode tip itself. The voltage contact in this case was a fine wire soldered to the tip on the outside surface where it joined to the radius contact surface. This electrode tip was cleaned prior to each test by being ahraded with 600-grit emery paper wrapped around a tool contoured with the same radius as the tip (Ref. 15). The other way of creating the electrode–workpiece interface was by inserting a short length of copper foil (0.1 mm thick by ~5 mm wide) between the upper electrode tip and the sample. This was done for two reasons: a) to provide a fresh, uncontaminated surface for each successive measurement, and b) to eliminate any contribution of the bulk resistance of the electrode tip to the voltage measurement. Samples of the copper foil were cleaned by lightly etching in diluted nitric acid and rinsing in water after being cut from the roll. Except where otherwise stated, these samples were used with the

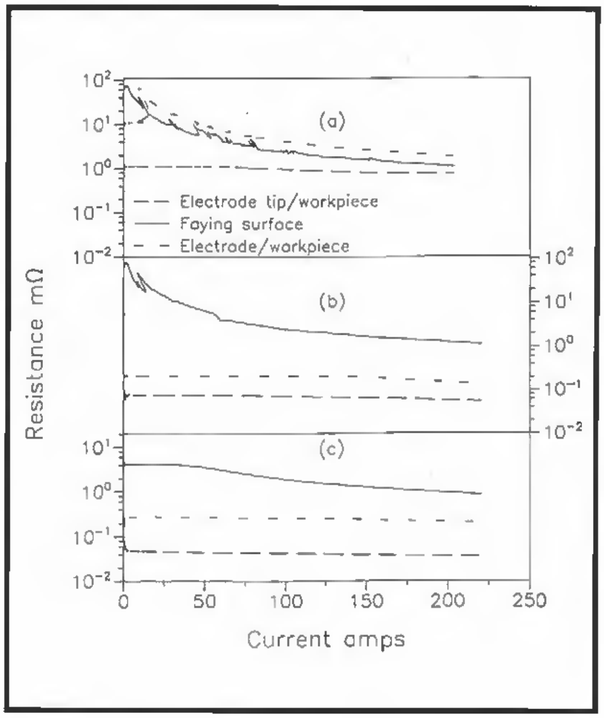

Fig. 6 — Effect of surface abrasion of electrode contact surface of workpiece on contact resistance. 2024 aluminum alloy. A — As received; B — freshly abraded 600-grit emery paper; and C — freshly abraded 180-grit emery paper.

Table 1 — Materials Used for Contact Resistance Measurements

Material	Thickness (mm)	Lubricant
2024-T3	2.2	—
5182-O	2	—
5754-O	2	Unknown
6061-T4	2.2	—
6111-T4	2	Z231
6111-T4	0.9	Z242
6111-T4	0.95	Z249
6111-T4	1.8	Z255
6111-T4	3	Z266
6111-T4	1	UCIS
6111-T4	0.95	AL070
6111-T4	2	Unknown

Table 2 — Effect of Electrode Polarity on Contact Resistance

Electrode Contact Resistance	Number
+ < −	8
+ ~ −	2
+ > −	2

natural patina that then developed upon standing in the normal laboratory atmosphere. Care was taken not to touch the contact surfaces by hand. In the case of this copper foil electrode, the voltage developed between the copper strip and the workpiece was measured.

Most tests were made with the electrode strip-electrode tip pair, the copper strip forming the one (upper) electrical contact with the workpiece and the spot weld electrode tip forming the other (lower) electrical contact with the workpiece. In the description of the results, the former is referred to as the "electrode–workpiece" combination and the latter as the "electrode tip–workpiece" combination. A few tests were made in which the upper electrode had the same configuration as the bottom electrode, *i.e.*, it was a spot weld electrode tip with an attached wire for the voltage connection.

Direct current was supplied from an HP6671A programmable power supply capable of providing up to 220 A. The current was incrementally step ramped from ~0.1 A up to the maximum output of the power supply in a period of ~75 s. The magnitude of the current was determined by the potential drop across a 0.4 μΩ shunt resistor. This voltage and the contact voltages were recorded on a Nicolet Pro40 digital oscilloscope for subsequent data reduction.

Contact resistance measurements were made upon various aluminum alloys between 1 and 3 mm thick. Samples were tested in the as-received condition or after degreasing in acetone if they had been coated with lubricant. Some samples were annealed to produce a thick oxide film and others were given a chromate coating treatment. The materials used are listed in Table 1. Surface roughness profiles of the sample surfaces were determined on a UBM surface profiling system.

Results

The variability of the results obtained in any sequence of contact resistance measurements has been well known for many years (Ref. 16). The values can show a wide variation in magnitude, and they may not even show a consistent decrease with an increase in the contact load (Ref. 11). In practice, the results generally are expressed as an average of a number of measurements. For this present work, only a comparatively small number of tests, between three and ten, were performed in any given sequence. Although individual results demonstrate considerable differences from others in the sequence, the observations do illustrate trends that can be identified. Figure 2 shows the variations that typically are seen in any series of results. The actual value of the contact resistance can vary over several orders of magnitude, depending upon the interface and current, and the response with change of current can differ from test to test, as seen for the upper two sets of curves in Fig. 2. Two particular trends that can be identified in Fig. 2 are that the resistance of the elec-

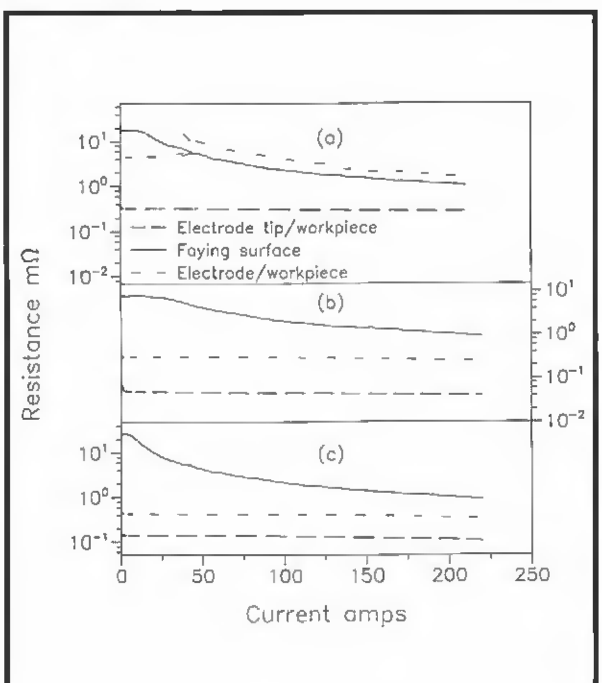

Fig. 7 — Effect of surface finish of electrode contact surface of workpiece on contact resistance on 2024 aluminum alloy. A — Annealed 3 h at 400°C, furnace cooled; B — abraded 600-grit paper, annealed 1 h at 150°C; C — abraded 180-grit paper, annealed 1 h/150°C.

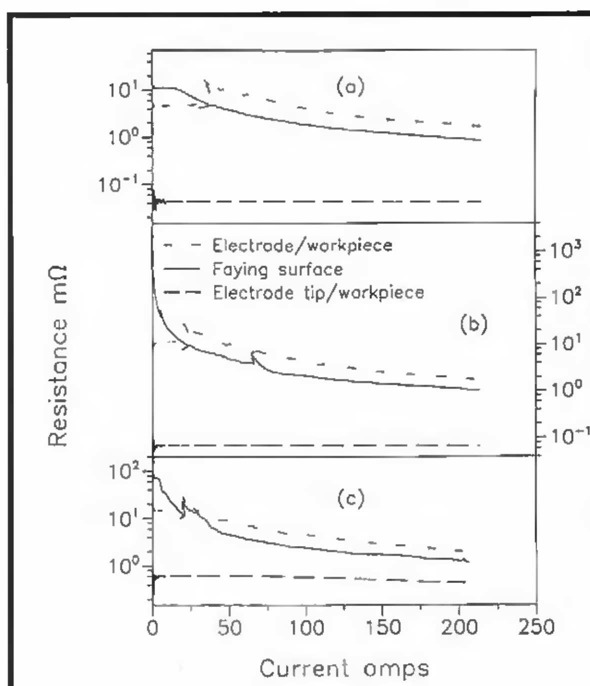

Fig. 8 — Contact resistances for unlubricated aluminum alloys. A — 5182, as received; B — 5754, degreased; and C — 5754, chromate conversion coat.

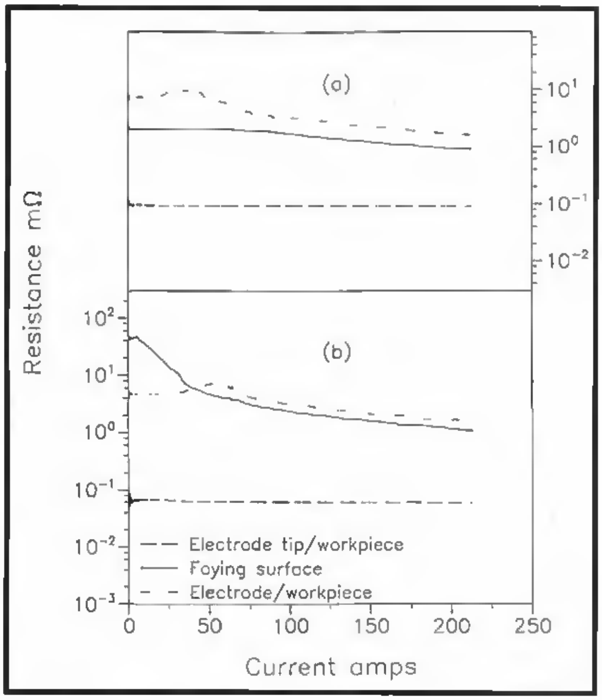

Fig. 9 — Contact resistances for unlubricated 6111 aluminum alloys. A — 6111, degreased; B — 6111/Z255, degreased.

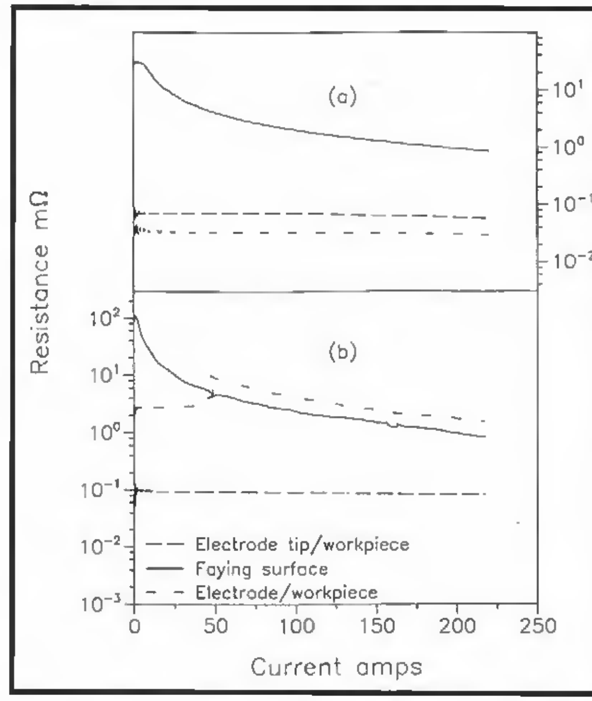

Fig. 10 — Contact resistances for unlubricated 6111 aluminum alloys. A — 6111/UCIS, degreased. B — 6111/AL070, degreased.

trode tip–workpiece contact was significantly less than that of the electrode–workpiece contact and the value of the contact resistance does depend upon the current. The possible causes of these trends will be discussed in another section. The variability demonstrated in Fig. 2 between each successive run of the sequence is typical of that observed for all of the other sequences, from which just one example was chosen for the purposes of illustration. All examples chosen for illustration were selected at random from the results in their respective sequences.

Effect of Electrode Polarity

All of the experiments involved the passing of a direct current across three metallic interfaces, two of which involved the dissimilar metals, copper and aluminum. Because the current was carried across the interfaces by just a few metallic junctions (Ref. 17), local current densities could be high, causing localized high temperatures to be developed, and hence possibly significant thermal voltages. These thermal electromotive forces (EMFs) could enhance or diminish the measured potential drop across the interface, depending upon the direction of the applied current with regard to the interface in question. Tests were done on several different aluminum alloys in which the current direction, and hence the polarity of the electrodes, was reversed for different tests. Because of the scatter between individual tests, a precise duplication of results cannot be expected. However, if the thermal EMFs are significant, then this should be reflected by the overall level of the resistance values obtained. For these tests, a similar electrode tip–workpiece configuration was employed for both electrodes. Typical results for 6061 aluminum alloy are shown in Fig. 3 and the results for all of these tests are summarized in Table 2. The negative electrode tends to display a higher contact resistance than the positive electrode. Although the thermal EMFs may be contributing to this effect, the actual cause is not clear. The EMF generated by a copper-aluminum junction is ~3 mV at 600°C (Ref. 18). The EMF generated across a resistance of ~1 mΩ, which is a value typical of the electrode–workpiece contact resistances observed in this particular sequence of tests, with a current of 10 A is ~10 mV. The actual voltages observed at these current levels and below, particularly when the contact resistance is even lower than 1 mΩ, are masked by signal noise, as shown in Fig. 3. With an increase in current, above 100 A in particular, there is some decrease in contact re-

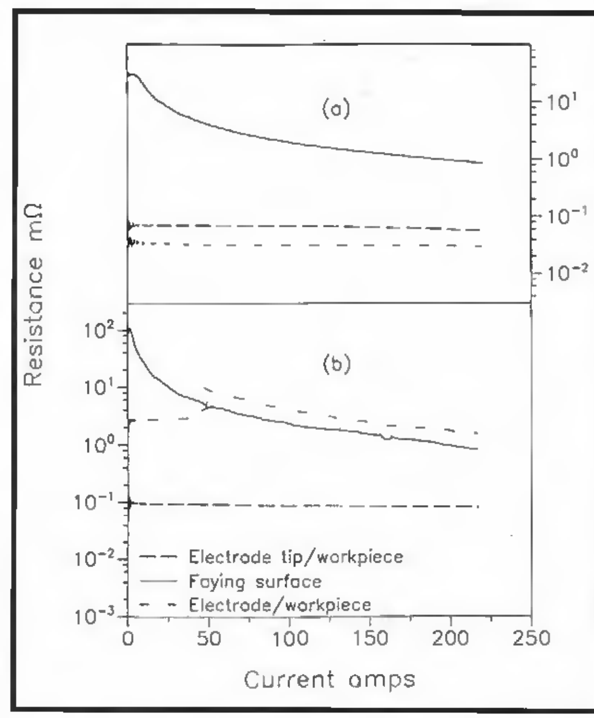

Fig. 11 — Contact resistances for lubricated 6111 aluminum alloys. A — 5754, as received; B — 6111/Z255 lubricant, as received; and C — 6111/Z266 lubricant, as received.

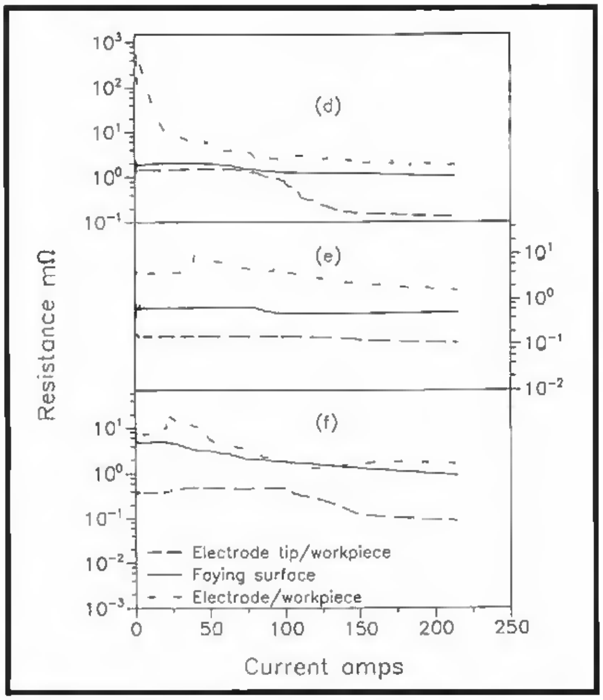

Fig. 12 — Contact resistances for lubricated 6111 aluminum alloys. A — 6111/Z231 lubricant, as received; B — 6111/Z242 lubricant, as received; and C — 6111/Z249 lubricant, as received.

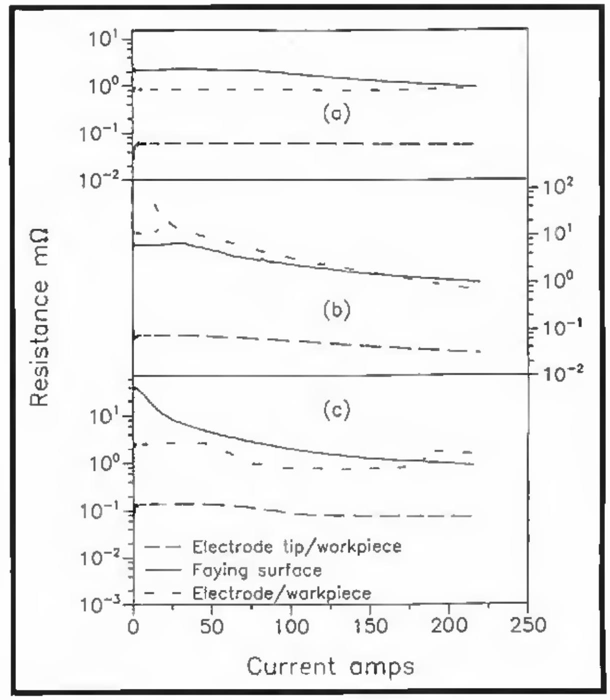

Fig. 13 — Contact resistances for lubricated 6111 aluminum alloys. A — 6111, lubricant unknown, as received; B — 6111/UCIS lubricant, as received; and C — 6111/AL070 lubricant, as received.

sistance for both electrodes. Because the change is in the same direction and of the same amount for both electrodes, the thermal EMFs do not seem to be effective in this current regime either.

Because of the high currents involved in the present work, it was not experimentally convenient to reverse the current polarity during a particular test. Preliminary experiments with mechanical relays to effect this current reversal showed that the variable and erratic changes in the resistances of the relay contacts themselves affected the current flowing and thus caused large voltage changes across the electrode–workpiece contacts. Therefore, attempts to effect current reversal during a test were not pursued further. For all of the results reported, the experimental arrangement was maintained with the (bottom) spot weld tip electrode, the electrode tip–workpiece combination, having negative polarity, and the (top) copper strip electrode, the electrode–workpiece combination, having positive polarity.

Surface Roughness of the Electrode

This sequence of tests was done on Alcan 6111-T4 aluminum alloy coated with Z255 lubricant to determine if any effects could be discerned with regard to the surface roughness of the electrode contact itself upon the contact resistance.

Direct Electrode Tip Contact

Figure 4 shows the variation of contact resistance with current for a series of tests in which the contact resistance of the electrode tip itself, *i.e.*, the electrode tip–workpiece combination, freshly abraded with 600-grit emery paper for each measurement, was examined. The initial faying surface resistance, *i.e.*, at low current levels, is seen to vary in magnitude from ~0.5 mΩ to nearly 50 mΩ. A change in resistance can occur with an increase in current. If the initial resistance is ~1 mΩ, it occurs at ~100 A, and if it is ~30 mΩ, at ~10 A.

The initial electrode tip–workpiece contact resistance not only was significantly lower than that of the faying surface, but the variation also was lower, in the range 0.1–0.5 mΩ. Again, with an increase in current, the contact resistance remained essentially constant, until the magnitude of the current reached a certain level, beyond which the contact resistance decreased. When the electrode–workpiece contact resistance was ~0.3 mΩ, this change occurred at ~140 A.

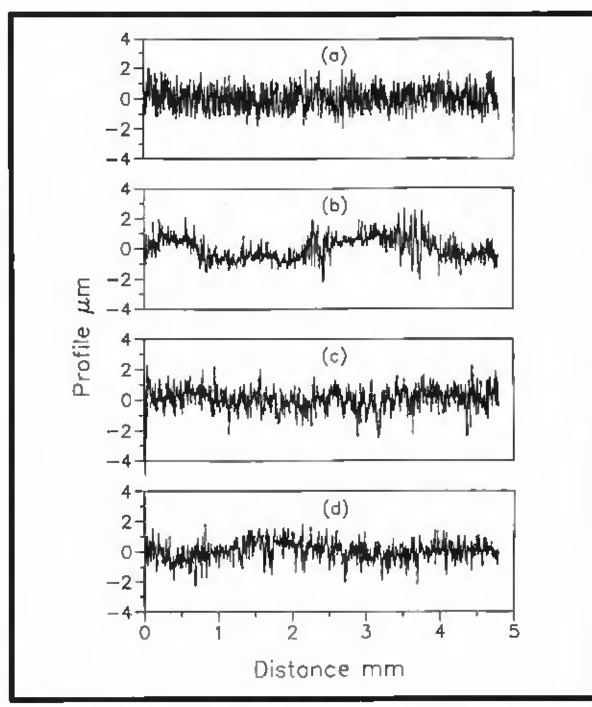

Fig. 14 — Surface profiles of aluminum alloys. A — 2024, transverse to rolling direction; B — 2024, parallel to rolling direction; C — 5754, transverse to rolling direction; and D — 5754, parallel to rolling direction.

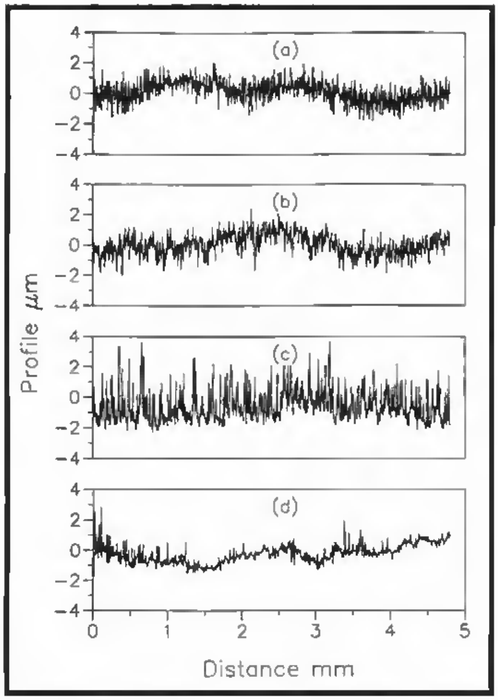

Fig. 15 — Surface profiles of aluminum alloys. A — 6111/Z255, transverse to rolling direction; B — 6111/Z255, parallel to rolling direction; C — 6111/UCIS, transverse to rolling direction; and D — 6111/UCIS, parallel to rolling direction.

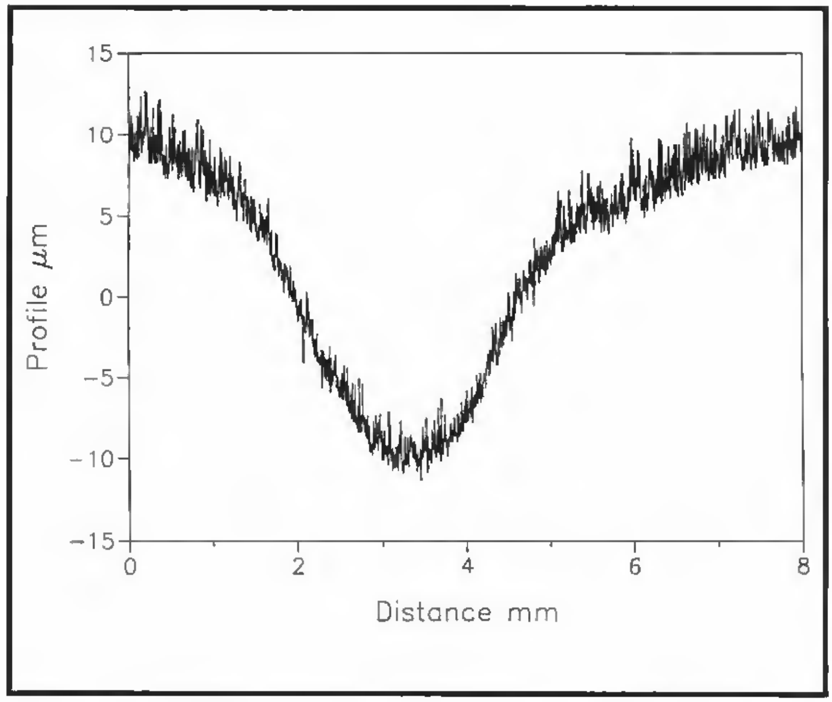

Fig. 16 — Surface profile of workpiece indentation at electrode contact. 6111/UCIS, transverse to rolling direction.

The other trend of particular note here is the manner in which the observed value of the contact resistance can depend upon the current used for the measurement. High currents, such as those used in some standards (Refs. 6, 7), can effectively modify the surface if the initial contact resistance is sufficiently large.

Indirect Electrode Contact

These tests were performed with the copper strip inserted between the spot weld electrode tip and the workpiece, *i.e.*, the electrode–workpiece combination. The surface of the copper strip was left in either the as-received condition, except for the cleaning operation previously described, or it was freshly abraded just prior to a test.

Figure 5 shows that the faying surface resistance is in the same range of values as those shown in Fig. 4, *i.e.*, 0.5–10 mΩ. Again, a change in contact resistance occurs with an increase in current, the current value at which the change is manifested depending upon the initial magnitude of the resistance. The electrode–workpiece resistance (Fig. 5A) is much higher than that of the electrode tip–workpiece combination — Fig. 4. Initial values of up to 500 mΩ have been seen. It is seen also that an instability can develop in these electrode–workpiece contacts as the current is increased; in Fig. 5A the instability is shown to develop at ~3 A.

By abrading the copper strip electrode before the measurement, the observed electrode–workpiece contact resistance could he reduced and the decrease was dependent upon the coarseness of the ahrasive used. With fine abrasive, 12 µ SiC paper, the initial contact resistance was reduced to the range 0.3–10 mΩ — Fig. 5B. By using coarser abrasives, 600 and 180 grit emery papers, the electrode–workpiece contact resistance could be reduced even more, with values of ~0.05 mΩ being attained by use of the coarser grit papers — Fig. 5C, D. The contact resistances measured after abrading with the 180-grit paper tended to be lower than those determined after abrading with the 600-grit paper.

Surface Roughness of Workpiece

The benefits of ahrading the workpiece surface before spot welding on the electrode life have been well documented (Refs. 13, 14, 19), and Fig. 6 demonstrates the changes that can be experienced. Figure 6A shows the contact resistance for 2024-T3 aluminum alloy in the as-received, mill finish condition and Fig. 6 B and C shows the large decreases in electrode contact resistance caused by abrading the workpiece surfaces that make contact with the electrodes just before the test. Although the initial faying surface contact resistance shown in Fig. 6C is much less than that shown in either Figs. 6A or 6B, this effect is due to the sample-to-sample variations in contact resistance that are always experienced with this type of measurement (as discussed previously and as illustrated in Fig. 2) and not to any effect of abrading. For none of the tests were the faying surfaces abraded.

Table 3 — Surface Roughness Data

Material	Surface Roughness, R_a (µm)
2024	0.456
5182	0.379
5754	0.424
6111/Z231	0.335
6111/Z242	0.148
6111/Z249	0.410
6111/Z255	0.395
6111/Z266	0.388
6111/AL070	0.529
6111/UCI5	0.721
6111	0.320
Copper foil, as received	0.353
12µ	0.368
600 grit	0.664
180 grit	0.721

A sample of 2024-T3 aluminum alloy that had been annealed for 3 h at 400°C showed contact resistances (Fig. 7A) that were similar to those of the as-received

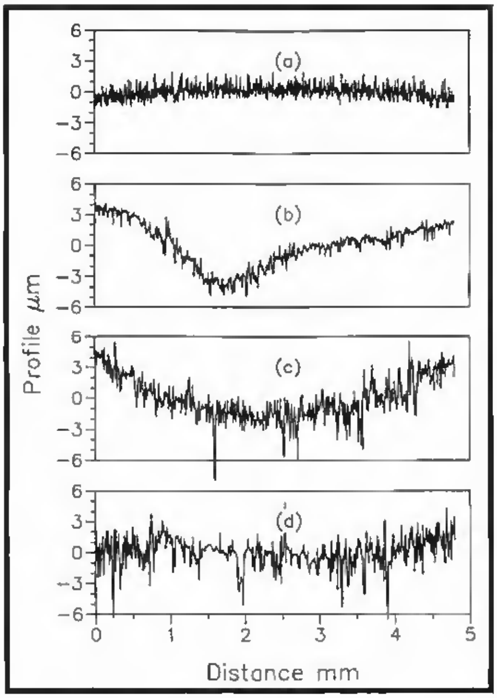

Fig. 17 — Surface profiles of copper foil. A — As received; B — abraded 12-µ SiC paper; C — abraded 600-grit emery paper; D — abraded 180-grit emery paper.

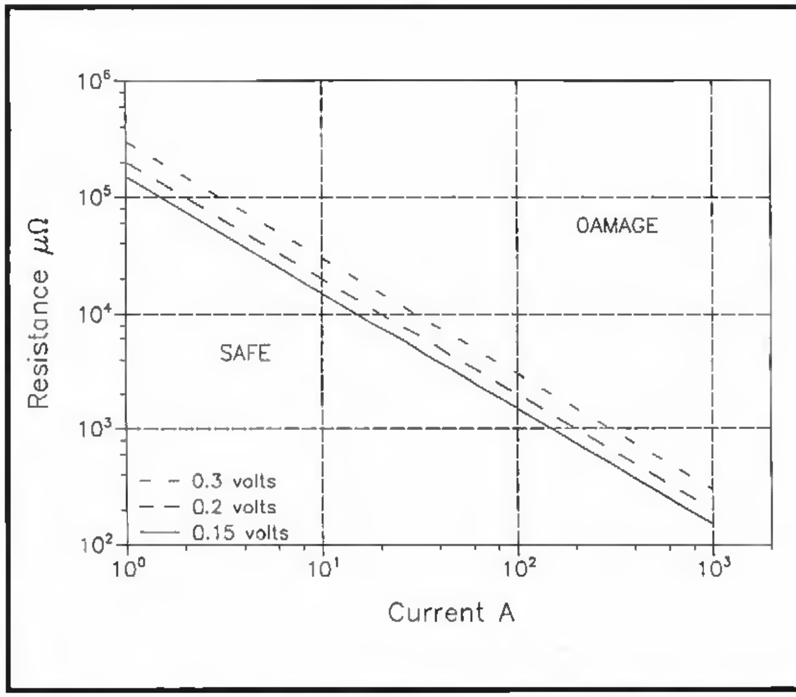

Fig. 18 — Variation of limiting contact resistance with current for various junction potentials.

alloy (Fig. 6A), i.e., the oxide film formed by the annealing treatment had not changed the contact resistance characteristics. In contrast, if the electrode contact surface of the workpiece was abraded before annealing, the contact resistance was low (Fig. 7B, C), comparable to that of the freshly abraded surfaces — Fig. 6B, C. These results imply that sample surface roughness affects the contact resistance to a greater extent than surface contaminants.

Effect of Alloy Composition

Unlubricated Samples

Representative curves demonstrating the change in contact resistance with current for several different aluminum alloys, supplied originally without a surface lubricant, or if lubricated, after having been degreased, are presented in Figs. 8–10. Each of these individual curves is taken from a series of six tests and it must be remembered that in each series, a variation between individual samples such as is illustrated in Fig. 2 was observed, so that specific differences between individual results are difficult to quantify.

The faying surface resistance for all of the samples showed essentially the same response with change of current being ~100 mΩ at low currents and decreasing to ~1 mΩ at high currents. The most significant response is that of the electrode contact resistance. For all of the samples, the contact resistance of the electrode tip–workpiece combination was low, ~0.1 mΩ. In contrast, for all of the samples but one, the contact resistance of the electrode–workpiece combination was high, of the same order of magnitude as the faying surface resistance. This one exception, Fig. 10A, was for a 6111-T4 aluminum alloy sample originally coated with a UCIS lubricant, and in this one case, for all of the samples examined, the contact resistance of the electrode–workpiece combination was consistently low, of the same

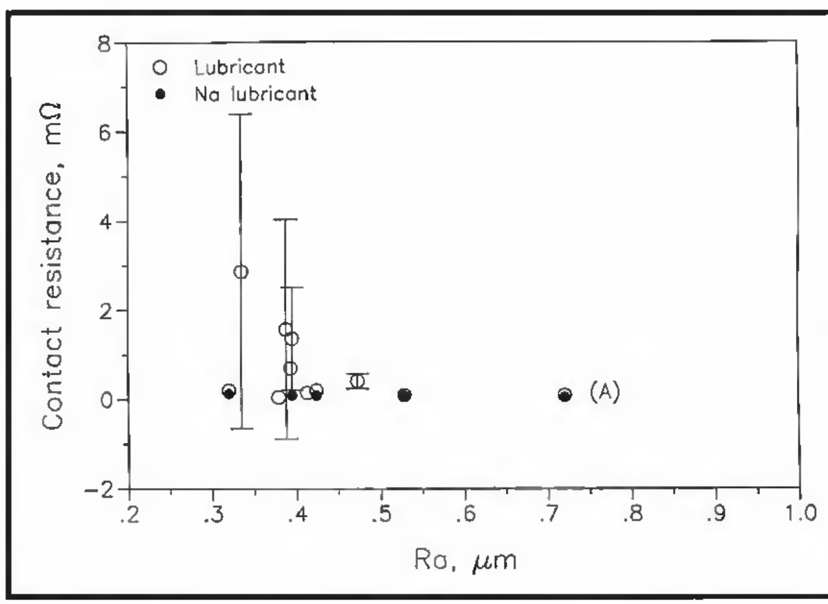

Fig. 19 — Electrode tip contact resistance and workpiece surface roughness. Material (A) passed 2000 weld tip life test.

order of magnitude as that of the electrode tip–workpiece combination.

Lubricated Samples

This group of samples included one of the 5754 aluminum alloy and several of the 6111 aluminum alloy. The nature of the lubricant for the 5754 alloy and for one of the 6111 alloys was not known. Contact resistance curves for these materials are shown in Figs. 11–13. The initial contact resistances for the faying surfaces tended to be lower, and those for the electrode tip–workpiece combination tended to be higher than the corresponding resistances for the unlubricated samples. As a consequence, the electrode tip–workpiece contact resistance showed changes as the current was increased. The contact resistance for the electrode–workpiece combination tended to be higher than the faying surface contact resistance, even for the particular case of the 6111-T4 aluminum alloy coated with UCIS lubricant — Fig. 13B.

Surface Roughness Profiles

Typical surface roughness profiles are shown in Figs. 14 and 15 for several of the aluminum alloys and the surface roughness data are shown in Table 3. The 6111-T4 aluminum alloy coated with UCIS lubricant was the only material that differed significantly from the others — Fig. 15C. The profile displays many large spikes and the surface roughness parameter, R_a, for this particular material had the highest value of the materials examined (Table 3). Figure 16 shows the surface profile across an indentation caused by the radiused electrode tip. Although some flattening of the surface has occurred over the contact region, as seen by a reduction in the amplitude of the spikes, the flattening is not complete. Surface roughness profiles for the copper foil used as an electrode contact are shown in Fig. 17, both for the as-rolled and cleaned condition, as well as after abrading with various grades of abrasive paper.

Discussion

The curves displaying the variation of contact resistance with current show that a change in contact resistance can occur with increase in current, the value of the contact resistance at which this change arises depending upon the magnitude of the contact resistance. This change is manifested by either a decrease in the value of the resistance for the faying surface contact or, usually, by an increase for the electrode–workpiece contact. In this latter case, the increase was usually very sudden and large enough to cause a decrease in the current in the circuit, giving rise to the backward sloping peaks, as shown in Fig. 2C, for example. The effect was manifested when the voltage level across the particular junction pair in question attained a certain level. For the faying surface, *i.e.*, the aluminum–aluminum junction, this level was ~0.2 V, and for the electrode–workpiece surface, *i.e.*, the copper–aluminum junction, ~0.3 V. The change is a result of the potential across the junction reaching a critical value at which the temperature developed across the junction has effectively reached the melting point of the metals in contact. Kohlrausch (Ref. 20) showed that this supertemperature θ is related to the potential difference U across the junction by the relation

$$U = \sqrt{a\theta}(1 + b\theta)$$

where the values of a and b depend upon the thermal conductivity and electrical resistivity of the conductor. The calculated value for U for aluminum is ~0.2 V. The surface resistance depends upon the number of asperities making metallic contact, as described by Holm (Ref. 17), so that the attainment of the critical voltage will depend upon the applied current, as governed by Ohm's Law. The variation of critical contact resistance with applied current is shown in Fig. 18. It is seen that if the contact resistance is >2 mΩ, approximately, local melting at the aluminum faying surfaces will result if the current exceeds 100 A. For the copper electrode–aluminum contact, melting will occur at this current when the resistance is >3 mΩ, approximately. Thus, the change in contact resistance with increase in current, when the current has reached a particular level that depends upon the initial value of the contact resistance, as shown in Figs. 2–13, can be related to the crossing of this damage threshold — Fig. 18.

Figure 18 has particular relevance to the magnitude of the current that is used to determine the contact resistance. As was discussed previously, in practical applications the values that this current has taken cover a wide range of latitude. A current of ~100 A, such as is used in the Ford test (Ref. 7), can cause a significant change in the contact resistance due to local fusion at the contact points and this may be one cause of the observation that contact resistance appears to have little correlation to spot welding performance, particularly as related to electrode life (Refs. 12, 21). To avoid any possible surface modification, the current used for the resistance test should be kept to a value that will not cause the potential across the faying surfaces to exceed, for example, 0.15 V — Fig. 18.

Rivet and Lucas (Ref. 21) concluded that a dynamic resistance value derived from the actual spot welding equipment, using a current of 10 kA, gave a better correlation to electrode life. The values for the dynamic resistance so obtained differed significantly from the static resistance values obtained using a current of 10 A. This dynamic resistance was derived from the voltage and current signals generated during the first half cycle of weld current. Rivet and Lucas (Ref. 21) stated that the current and voltage were in phase during this measurement. Recent work (Ref. 11) has indicated that during this initial half cycle of weld current, the voltage and current can be significantly out of phase, and that, at the earliest time at which a resistance value could be derived, ~0.2 ms after current switch on, the current already can exceed 1 kA for a typical aluminum spot weld, at which point the faying surface contact resistance has decreased to ~50 $\mu\Omega$. Because of the large currents that are flowing when the measurements are being taken in the dynamic resistance method, considerable changes in the surface characteristics caused by local melting at the contact points must have occurred, as would be expected from Fig. 18, so that the values of contact resistance obtained by the dynamic method will have little relationship to those obtained by a low current static method.

Surface roughness of the workpiece has long been known to increase electrode life (Refs. 13, 14, 22) in the spot welding of aluminum, and this has been associated with an enhancement of the oxide breakdown (Ref. 23). The large decrease in the copper–aluminum junction resistance by abrading the workpiece surface just before a measurement is shown in Fig. 6. Especially noticeable is that the contact resistance of the copper foil electrode junction is also reduced by this treatment. Furthermore, reestablishing the oxide film by an anneal does not affect the contact resistance, provided that the surface is sufficiently rough (albeit that the thickness of the film produced in this experiment, an anneal at 150°C, is less than that of the original specimen, which was produced at 400°C) — Fig. 7. It would thus appear that the surface roughness may be the important factor in these surface roughness–life tests, the cleanliness of the surface that results from abrading just before the spot-welding being incidental.

Essentially most published work on contact resistance as applied to the spot welding of aluminum has focused on the condition of the workpiece surface (Refs. 14, 19, 22). There is some evidence that an increase in the surface roughness of the electrode surface does increase the weld tip life (Ref. 9). The condition of the electrode contact surface if mentioned at all, is usually in terms of being cleaned and/or abraded (Refs. 4, 5), or of being rotated to ensure good contact prior to a measurement (Refs. 7, 24). The present work has shown that considerable differences can exist at the electrode surface in terms of the contact resistance of the electrode–workpiece junction. In general, the contact resistance of the copper foil–aluminum junction was considerably greater than that of the electrode tip–aluminum junction. Electrical breakdown, as manifested by sudden, large increases in resistance, occurred at low currents for the copper foil–aluminum junction; such breakdowns virtually were never observed at the electrode tip–aluminum junction up to the maximum currents that were used in these experiments, ~220 A. This electrode tip was always abraded with 600-grit paper before a test run. Abrading the copper foil surface reduced the contact resistance (Fig. 5), particularly if the surface roughness was increased. Several descriptions of measuring contact resistance have been given in which the total contact resistance between the electrodes is measured (Refs. 4, 5, 25). This present work has shown that the copper–aluminum junction resistance can exceed that of the aluminum–aluminum junction, particularly if the surface roughness, R_a, of the copper electrode is low, *e.g.*, <0.4 μm, as shown in Figs. 8–10, so that great care must be taken in comparing contact resistances from different sources. Also, as shown in Fig. 5 and in Table 3, the surface roughness, R_a, of the electrode should be ~0.7 μm to produce low electrode–workpiece contact resistances. Figure 5 also shows that merely cleaning a surface is not sufficient to reduce significantly the contact resistance; cleaning the copper foil surface by abrading with 12 μ SiC paper did not change the contact resistance significantly from that of the unabraded copper foil. Significant change resulted only when the foil surface was roughened with coarser-grit paper.

Newton (Ref. 5) has found that the electrode–workpiece contact resistance is ~20 μΩ for a series of lubricated and unlubricated aluminum alloys, using an electrode that was abraded with 600-grit SiC paper and a current of 3.3 A. These contact resistance values are much less than those observed in the present work. The difference possibly arises from the different electrode mounting configurations employed. Newton (Ref. 5) used a scissor-type welding gun, whereas in the present work, the electrodes were mounted between the crossheads of the testing machine. A welding gun has less rigidity than the testing machine arrangement employed in the present work, so there is the possibility that the electrode tips could have skidded on contact with the workpiece, thus ensuring better contact. In the present work, the electrode tips were held rigidly, with very little possibility of skidding. Also, the difference in the rate of closure of the electrode tips may have made some contribution. Closure of the electrode tips in the welding gun was done pneumatically, whereas that in the testing machine was manual, *i.e.*, much more slowly. These experimental differences did not make any significant difference in the magnitude of the values obtained for the faying surface resistances. Thus, in establishing comparisons of electrode–workpiece contact resistance, attention should be given to the electrode mounting methods.

In comparing Figs. 9 and 10 to Figs. 11–13, a lubricant appears to decrease the faying surface contact resistance and to introduce some instability into the copper–aluminum contact resistance. It does not significantly change the magnitude of the resistance if the copper surface is relatively smooth (the copper foil electrode), but it does seem to increase that for the electrode tip combination. The one exception to these observations is that provided by the 6111 aluminum alloy coated with UCIS lubricant. This particular material is of great interest because it is the one of the group of 6111 materials examined that passed the 2000 spot weld life test (Ref. 7). Figure 10 A shows that in the degreased condition, both types of electrode possessed a low contact resistance. In the lubricated state, the contact resistance for the smoother copper foil contact was increased, but that for the rougher electrode tip maintained a low value — Fig. 13B. The overall behavior appears to be related to the surface roughness of this particular batch of 6111 material (Table 3).

Contact resistance, as determined by the faying surface contact resistance, thus is not the sole criterion by which the suitability of the material for spot welding should be judged. In other investigations, this particular contact resistance has been the focus of attention. From the present results, surface roughness, of the workpiece as well as the electrode, plays a significant role in the determination of the contact resistance. More attention should be given to the electrode–workpiece contact resistance because it is this contact that deteriorates in use and that governs weld tip life and weldability. Figure 19 shows the average electrode tip contact resistance as determined from each sequence of tests, plotted against the surface roughness of the workpiece. The contact resistance taken is the initial, low current value. The error bars show that considerable scatter was experienced in these determinations. The three observations that can be made from Fig. 18 are 1) the lubricant does increase the electrode–workpiece contact resistance; 2) low electrode–workpiece contact resistance may be associated with low workpiece surface roughness; and 3) the one material that passed the 2000 spot weld life test had the highest surface roughness as well as a low electrode–workpiece contact resistance. These observations are made for an electrode that had a rough surface finish, R_a = ~0.7 μm. For an electrode that has a smoother surface finish, the roughness of the workpiece can control the contact resistance, and if R_a is too low, ~0.4 μm, for example, then electrode–workpiece contact resistance breakdown can occur at quite low currents. A contact surface is one where the junctions in the two surfaces are made at random by projecting spikes, as depicted in Figs. 14–17. Under load, extensive plastic deformation occurs locally within the spikes, reducing their amplitude, as well as that which occurs globally over the contact area of the bulk metal, as shown in Fig. 16. Extensive uniform contact as often depicted over the whole contact surface area, as in Fig. 6, Ref. 14, for example, does not occur. It is this extensive, localized plastic deformation within the spikes, with the rubbing together of adjacent surfaces that removes surface oxides, lubricants and other contaminants, that provides metallic contact. Wefers (Ref. 23) has shown that an increase in surface roughness enhances oxide breakdown. An increase in R_a effectively increases this local plastic deformation, overcoming the masking effects that these surface contaminants produce, and thus increasing the conduction. However, these surface constituents can provide load bearing capability in addition to that which is provided by the surface spikes in contact. This will tend to reduce the plastic deformation imparted to the spikes under load and hence increase the contact resistance. A rougher surface contributes spikes of greater height that can penetrate such surface constituents and generate a lower contact resistance.

A key question still remains as to whether dynamic or static resistance gives a better correlation to electrode life. Rivet and Lucas (Ref. 21) concluded that dynamic resistance was better than static resistance. In the discussion above it was pointed out that the large currents applied during the measurement in the dynamic method quickly change the surface characteristics. However, a method using a large current (100 A) to measure static resistance has found acceptance for quality control in the spot welding of aluminum (Ref. 7). This method, too, must change the surface characteristics during the test in many instances. The present work indicates that a fairly simple test, involving only low currents, when combined with knowledge of the surface roughness of the materials in question, may give an adequate indication of tip life.

Conclusions

The contact resistance between electrode and workpiece is affected by the surface roughness, both of the electrode surface and the workpiece surface. A low contact resistance can be obtained by a surface of low R_a, but this may not be associated with other desirable characteristics such as a long weld tip life. For a long weld tip life, a workpiece surface roughness of ~0.7 µm can be identified with weldability. Breakdown of the copper electrode–aluminum workpiece junction occurs at lower currents, ~10–20 A, with electrode surfaces of lower roughness, e.g., R_a ~0.4 µm. When R_a is ~0.7 µm, breakdown was not observed for currents up to 220 A. The improvement in weld tip life noted after abrasion may be due to the increase in surface roughness, rather than just an increase in surface cleanliness. Nonrigid electrode tip mounting methods that are found with the typical weld guns can lead to lower electrode–workpiece contact resistance values, possibly due to the skidding on making contact. The current used for contact resistance measurements should take into consideration the expected magnitude of the contact resistance. If the latter is too high, then local fusion at the contact can occur with sufficiently high current, effectively changing the contact resistance of the surface. The value of the current used should not cause the potential drop across the aluminum faying surfaces to exceed 0.2 V, and should be less, if practical. Low current resistance measurements, associated with surface roughness determinations, could provide a means for material quality control in the spot welding of aluminum alloys.

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