# Experimental simulation of surface pitting of degraded electrodes in resistance spot welding of aluminium alloys

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**A novel experimental technique, using specially designed electrodes (with machined annular and circular pits, and central cavities), was developed to simulate the effects of pitting morphology of the electrode tip face on weld nugget size and joint strength in resistance spot welding of aluminium alloys. Results of the experimental simulations indicate that the distribution of electrode contact areas and their alignment between top and bottom electrodes both affect weld quality. A complete understanding of the correlation between tip face features and weld nugget formation would require three-dimensional numerical modelling; this work has provided well organised experimental data in support of future modelling work. MST/6141**

**Keywords**: Resistance spot welding, Aluminium alloys, Electrode pitting and degradation, Experimental simulation, Weld nugget size, Joint strength

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## Introduction

Short and inconsistent electrode tip life is one of the major issues in resistance spot welding (RSW) of aluminium alloys.[1–6] For example, electrode life was found to range between 400 and 900 welds in RSW of aluminum alloy 5182 using a medium frequency direct current (MFDC) power supply even though the welding conditions were intentionally kept constant.[1,7] In these tests, after the electrodes failed, continued welding produced joints of widely fluctuating strength, showing from time to time, production of good quality welds.[7,8]

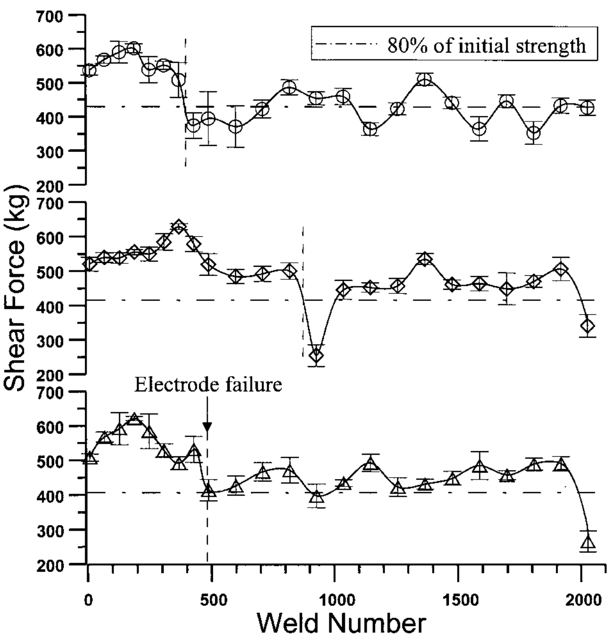
Electrode life tests coupled with detailed mechanical testing, metallurgical examination, and computer simulations, have been used to understand electrode degradation mechanisms and to develop techniques to improve electrode life in RSW of aluminium alloys.[1,7–11] However, because of the complexity and irregularity of the electrode pitting process (involving electrical, mechanical, and metallurgical interactions), it has proven very difficult to infer positive conclusions from the results of conventional electrode life tests. Also, because of this, even with the increased power of modern computers, the use of numerical simulation has been limited since it has proven hard to develop numerical models directly comparable to experimental observations. In this connection, limited experimental trials with specially designed electrodes to simulate electrode pitting in conventional electrode life tests[8,11] appeared to be an alternative to help isolate the factors that affect electrode life, and also possibly to provide better organised experimental data for numerical simulations.

In this present study, electrodes with premachined rings and holes were used in experiments to investigate the effects of electrode tip face features on weld nugget size and joint strength in RSW of aluminium.

## Electrode degradation and tip face features

### ELECTRODE LIFE TESTS

Much research work has been performed to investigate electrode degradation and its effect on weld quality in RSW of aluminium alloys.[1,3–13] For example, a number of electrode life tests were conducted on RSW of aluminum alloy 5182 using Cu–0·15Zr electrodes with both MFDC (at 1200 Hz) and AC (alternating current) power supplies.[1,7–9] Three typical plots of the shear force (as an indication of joint strength) versus the number of welds when using an MFDC power supply are shown in Fig. 1.[7] Detailed mechanical testing coupled with metallurgical examination using scanning electron microscopy/energy dispersive X-ray spectroscopy and X-ray diffraction indicated that electrode degradation proceeded in four basic steps: aluminum pickup, electrode alloying with aluminum, electrode tip face pitting, and cavitation.[7,9] This electrode degradation process led to an increased contact area and




1 **Typical conventional electrode life tests in RSW of aluminum alloy 5182**

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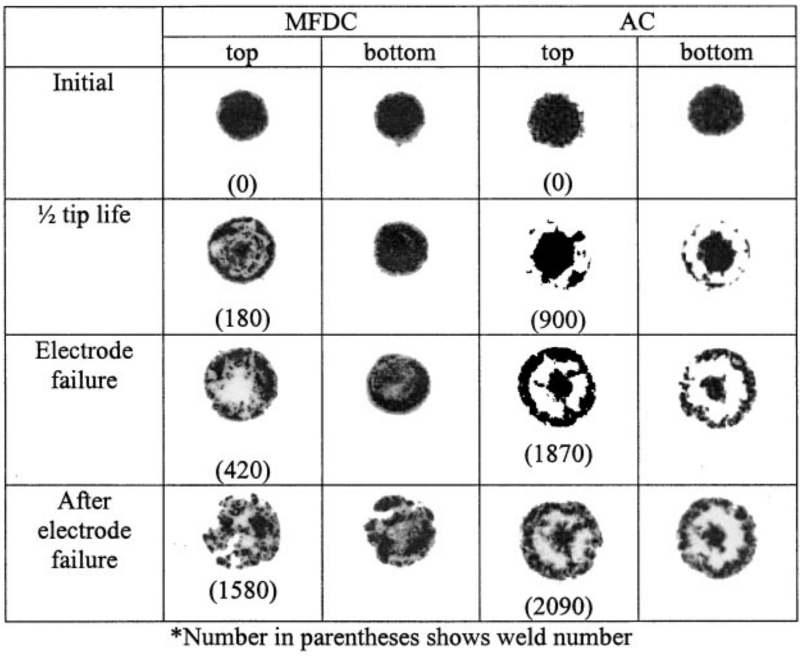



**2 Typical carbon imprints of electrode tip faces in RSW of aluminum alloys 5182 using MFDC and AC welding machines**

hence a reduced current density at faying surfaces, which in turn led to undersized weld nugget formation and hence reduced joint strength.[1,8] However, this generalised observation of reduced 'nominal' current density, although it can account for the point of electrode failure, could not explain why, after the deemed end of electrode life, the joint strength fluctuated, showing from time to time production of good quality welds (Fig. 1). Further work is obviously required to study electrode tip face features (e.g. the distribution of electrode contact areas) and how the evolution of these features affects weld quality (see Fig. 2 for typical carbon imprints of electrode tips in conventional electrode life tests).

In previous work as noted above, electrode life ranged from 400 to 900 welds when a MFDC welding machine was used, although welding conditions were intentionally kept constant. An AC welder gave a much longer electrode life, at about 1900 welds.[1,7,8] This difference in electrode life was attributed to the fact that positive electrodes degraded much faster, due to the polarity effect,[8,14] than negative electrodes when the MFDC welding machine was used (Fig. 2). In other words, the electrode life when using an MFDC welding machine is mainly determined by degradation of the positive electrode, while in the case of RSW of aluminum alloys using AC power supplies, both electrodes degrade at a similar rate. It was observed that electrode pitting generally initiated at the edge regions of the electrode tip faces and, eventually, the pits grew and connected to each other forming roughly an annulus with a central contact area, as shown in Fig. 2.[1,7–9] This central contact area was lost when the MFDC electrode was deemed to fail[1,7–9] while a part of the central contact remained even after electrode failure in the electrode life test using an AC welding machine.[8] It was, therefore, believed that a central cavity was a much worse form of electrode pitting than an annulus pitting pattern. A finite element analysis (FEA) also indicated that the diameter of this central cavity had a significant effect on current distribution and hence nugget formation.[11] It has also been suggested that many other electrode tip face features (such as the asymmetric distribution of the contact areas and overlap of these contact areas on top and bottom electrodes) would affect weld quality.[8]

### ELECTRODE TIP FACE CHARACTERISTICS

Based on the carbon imprints taken during electrode life tests, three descriptors of electrode tip face features have previously been introduced to investigate the effects of face conditions on weld quality.[8]

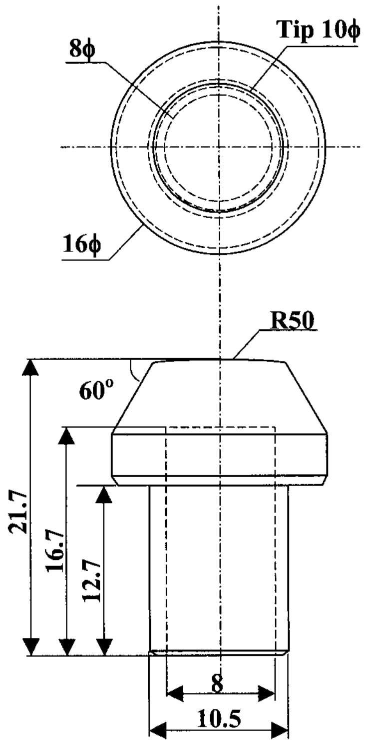
1. Relative radius $R_r$: this is the ratio of the radius of the outer edge of the nominal contact area to the initial value when the electrode is new.
2. Edge concentration *EC*: this models the degree of distribution of contact areas away from the centroid of the actual contact area.
3. Eccentricity *ECC*: this shows the eccentricity of centroid of all the contact areas against the geometric center.

While $R_r$ affects the nominal current density, *EC* and *ECC*, indicating uneven distributions of contact areas on electrode tip faces due to electrode pitting, determine the current distribution.

The descriptors $R_r$, *EC*, and *ECC* have been shown to determine weld quality as defined by weld nugget size and joint strength.[8] The results of image analysis studies of these features have indicated that while the growth $R_r$ and *EC* led to a decrease in joint strength, the effect of *ECC* was too complicated to be generalised. One limitation of these conventional electrode life tests is that clear and conclusive correlations between the tip face features and nugget formation were very difficult to derive because of the complexity and irregularity of the tip face morphology. On the other hand, it has been shown that, based on very limited trials, specially designed electrodes (with predrilled central holes to simulate the central cavity) coupled with FEA allowed much improved understanding of the effects of electrode degradation on weld nugget formation.[11]

## Experimental simulation

The welding was carried out on 1·5 mm thick ($t$), electrolytically cleaned sheet aluminium alloy 5182 with Class I (Cu–0·15%Zr) electrodes. Original electrodes in conventional life tests have a taper angle of 60°, tip face diameter of 10 mm and radius of curvature of 50 mm




**3 Configuration of electrodes used in conventional electrode life tests (unit: mm)**

(Fig. 3). The electrodes used in this work were designed with an electrode tip face diameter of 8 mm as shown in Fig. 4 to simulate the actual degraded electrodes with no pit, annular pit, central cavitation or random pits (Fig. 2). The radius of tip surface curvature of these experimental electrodes was also modified to 300 mm to reflect the fact that the radius increases with increasing weld number during electrode tip life tests as a consequence of electrode degradation. The tip faces of the experimental electrodes were machined to have:

(i) type A: a central hole of 4·5 mm in diameter
(ii) type B: an annular pit with an outer diameter at 6 mm and inner diameter at 4 mm. Both types A and B had the same pit area of 15·8 mm$^2$
(iii) type F: no pits
(iv) type D and E: two small circular pits of 3 mm in diameter, but with different geometrical arrangements, both with the same pit area of 14·1 mm$^2$.

The depth of the machined portion on all electrodes was about 0·5 mm. However, it should be kept in mind that, in practice, electrode pits vary in depth and shape dynamically (Fig. 2). Some pits may grow in area and/or depth and even join each other, and others disappear as a result of filling due to alloying and deformation.

It was the intention that Type A and B electrodes had the same *ECC* values but different *EC* values, while type D and E electrodes had the same *EC* but different *ECC* values. Actual *EC* and *ECC* were calculated using MatLAB Image Processing Toolbox based on the carbon imprints that were taken from the electrode tip faces under the actual welding force but without current flowing.[8] For each simulation test series, a new pair of appropriately machined electrodes was employed to make only 15 test welds, and therefore any metallurgical effects, such as alloying between electrode tip and aluminium sheet[9] during testing was minimised.

To avoid the complication of the polarity effect, a press type AC weld machine was used in the experimental simulations. This machine was specially designed and manufactured for laboratory use with very short arm length (or throat depth, which is about 180 mm from the terminal of the transformer to the centre of the electrode), high stiffness, low friction and inertia. Electrode force is generated by a pneumatic–hydraulic pressure intensifier that provides a reproducible, constant static force but relatively large dynamic stiffness during the welding sequence.

Combinations of either type A or B as top the electrode, with type F as the bottom electrode were designed to study the effects of central cavity and annular pit on weld nugget size and joint strength. Combinations of types D and E for both top and bottom electrodes were designed to study the effects of the distribution, and more importantly, the alignment of contact areas from top and bottom electrodes. Welding conditions used (Table 1) were derived using type F electrodes to produce a plug (i.e. pullout button) diameter in excess of $5t^{0·5}$ without weld metal expulsion, as determined by peel testing. The maximum shear force was recorded as an indication of joint strength in tensile-shear testing using an Instron tensile testing machine with a crosshead speed of 0·33 mm s$^{-1}$. The averages and standard deviations were calculated based on five weld samples made with each electrode arrangement.

Nominal and actual electrode tip face areas were defined, respectively, as the area based on the outside diameter of the carbon imprint, and the nominal area less the pitted area, also measured from carbon imprints. The contact area at the sheet/sheet (S/S) interface and weld nugget area were measured from fractured faying surfaces of failed specimens after shear testing, in which the S/S contact area was based on the outside diameter of the indentation produced by the S/S interactions during welding. All the area measurements were done using a computer based image analyser.

## Results and discussion

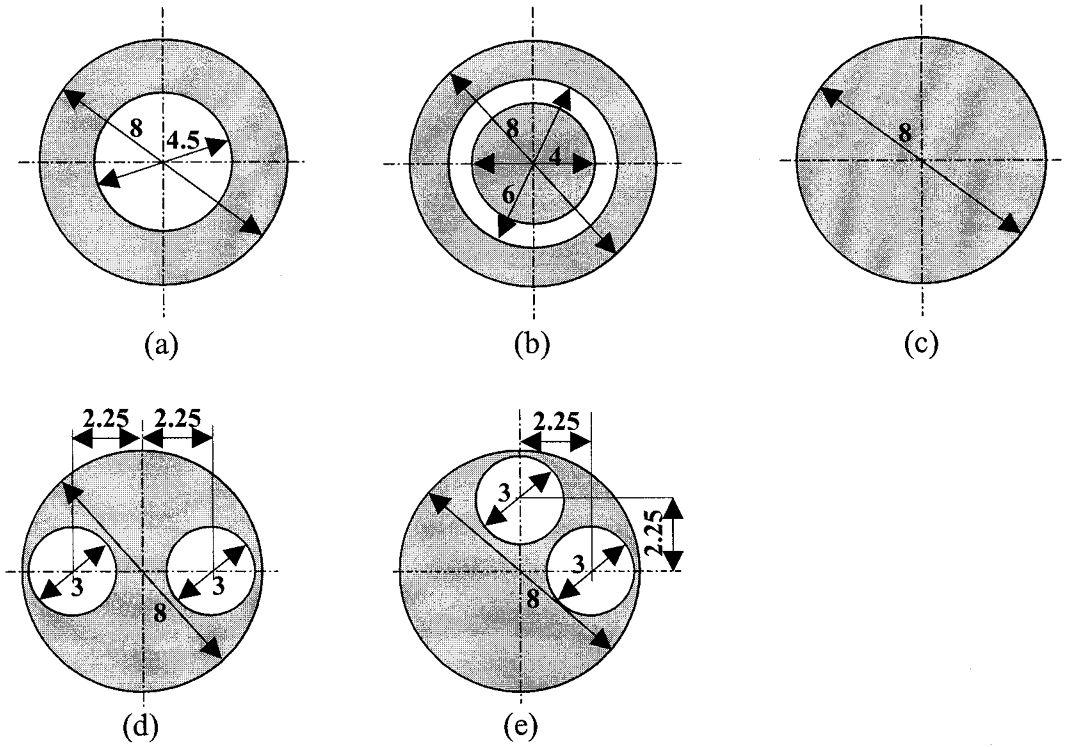
Plots of the shear test results in experimental simulations with each of the different electrode designs (Fig. 4) followed a simple linear relation between the shear force and nugget area (Fig. 5). This is similar to that observed in conventional electrode life tests,[1,15] which indicates the basic relevancy of the simulations in this work.

### EDGE CONCENTRATION OF ELECTRODE CONTACT AREAS

The results of experimental simulations of type A, B and F electrodes, in which the effect on weld quality of an annular pit is compared with the effect of a central cavity, are summarized in Table 2. The nugget area and shear force reduced from the electrode combination FF to BF, and to AF. The *EC* values also increased in the same order although the nominal tip face and S/S contact areas did not show any significant change. A lower and more variable joint strength was obtained using the AF electrode combination compared with BF electrodes (Table 2), which is consistent with the results obtained from conventional electrode life tests. The results suggest that an electrode with the central portion completely pitted away performed much worse than an electrode with annular pit.[8] Examination of welds of similar S/S contact areas but different values of nugget area and shear force (Table 2) indicated that the nominal current density was not sufficient

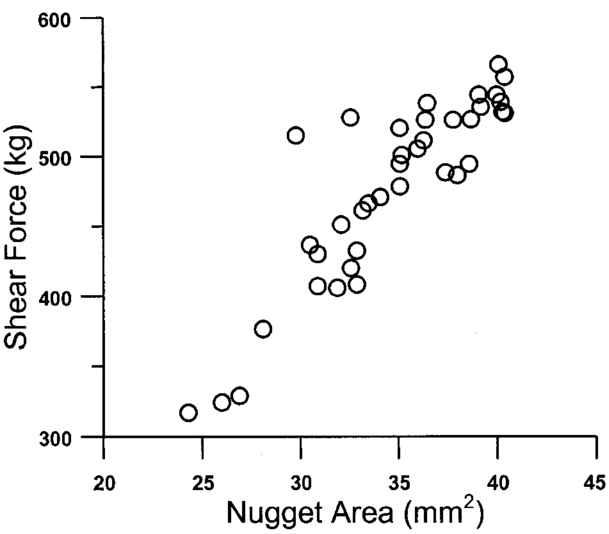
**Table 1 Welding conditions**

| | |
|---|---|
| Squeeze, cycles | 25 |
| Weld time, cycles | 5 |
| Hold time, cycles | 12 |
| Weld force, kN | 5·3 |
| Welding current, kA | 34 |




*a* type A; *b* type B; *c* type F; *d* type D; *e* type E

**4 Design of electrode tip face in experimental simulations (unit: mm)**




**5 Plot of shear force versus weld nugget area for joints made using each of the different experimental electrodes**

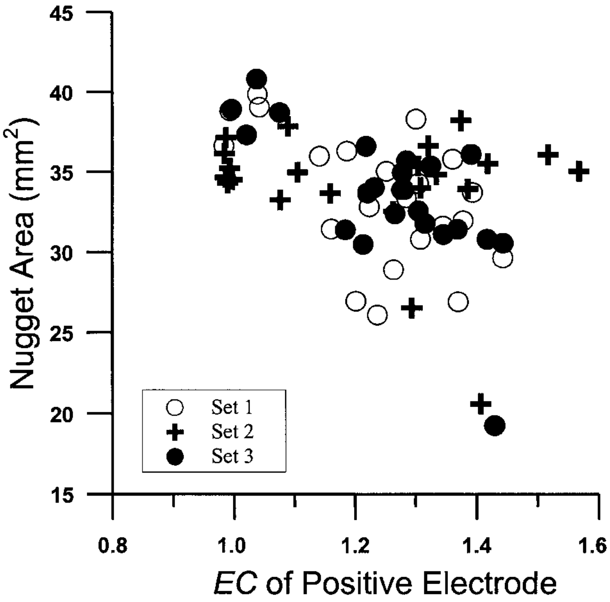
to determine nugget formation and hence joint strength. Instead, these results confirmed the suggestion, based mainly on conventional electrode life tests, that the distribution of contact areas plays an important role in weld quality,[8] e.g. as in this case, the higher the *EC*, the lower the joint strength. A similar trend was seen when all nugget areas were plotted against the *EC* of the positive electrodes in actual electrode life tests determined using MFDC welding,[8] as shown in Fig. 6.

Examination of cross-sections of weld nuggets made using the premachined experimental electrodes (Fig. 7) indicated relatively thinner melt thickness at weld nugget centres formed using AF and BF electrode combinations. This was not the case when using an FF electrode combination. This was attributed to the changes in current distribution due to the presence of pits. The relation between the size of the central cavity and the weld nugget morphology has been estimated using FEA,[11] wherein a doughnut shaped weld nugget is obtained when electrode cavitation reaches a critical diameter. Even though the S/S contact area and hence the nominal current density was similar for all electrodes (Table 2), the current distribution at the faying surfaces was much lower at the centre because

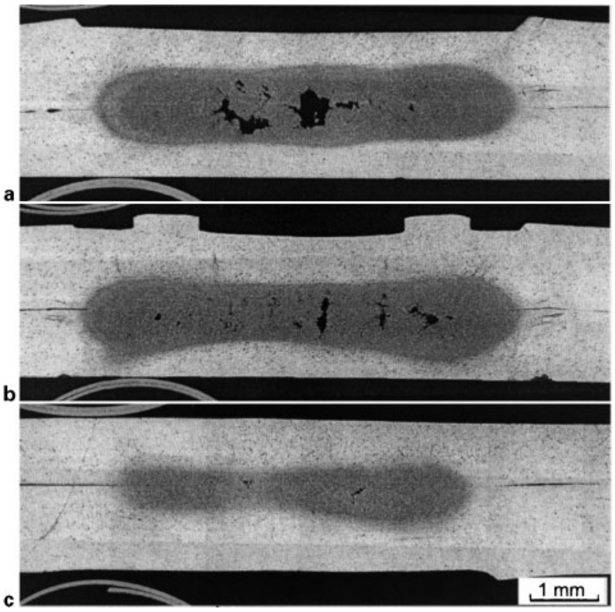
**Table 2 Effect of *EC* on weld nugget area and shear force**

| Electrode type | Top | Bottom | Nugget area, mm$^2$ | Shear force, kg | Nominal contact area, mm$^2$ | S/S contact area, mm$^2$ | *EC** |
|---|---|---|---|---|---|---|---|
| F–F |  |  | 34·4±2·8 | 502±41 | 47·7 | 64·1 | 1·00 |
| B–F |  |  | 33·6±2·2 | 470±36 | 50·2 | 65·1 | 1·31 |
| A–F |  |  | 27·0±2·1 | 372±83 | 48·2 | 63·5 | 1·53 |

**EC* is calculated on top electrode.




**6 Relation between weld nugget area and *EC* of positive electrode in conventional electrode life tests using MFDC welding machine**




electrode combination *a* F–F; *b* B–F; *c* A–F

**7 Cross-sections of joints made with different electrode combinations**

of the central cavity present in A electrodes unless the cavity was really small.[11] In the case of B electrodes, the existence of central contact on the tip face helped to restrict the spread of current, resulting in better weld quality.[8]

## ALIGNMENT OF CONTACT AREAS BETWEEN TOP AND BOTTOM ELECTRODES

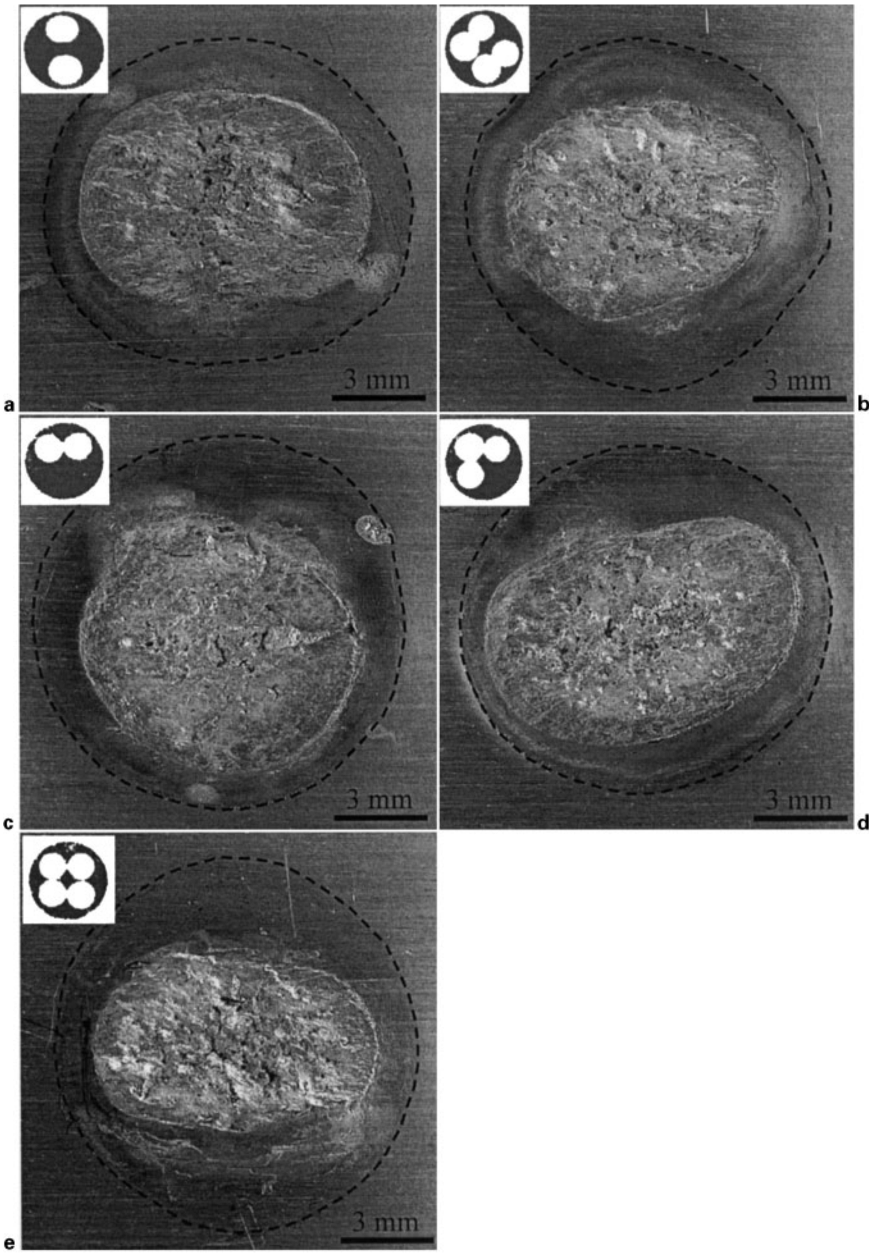
The results of experimental simulations made with type D and E electrodes, in which all *EC* values were similar but *ECC* was different, are summarised in Table 3. In this test, type D and E electrodes, with symmetrical and asymmetrical distributed contact areas on the electrode tip faces, were arranged differently to investigate the effects of alignment of contact areas between the top and bottom electrodes. For example, both DD-1 and EE-1 electrode combinations had perfect top/bottom electrode alignment but the latter had contact areas off the centre of the tip faces. Electrode combinations DD-2 and EE-3 had worse alignment of the contact areas between the top and bottom electrodes than the EE-2 electrode combination.

Electrode combinations DD-1 and DD-2, with the same *EC* and *ECC* values, had similar S/S contact areas and hence nominal current densities, but very different nugget size and joint strength. This was clearly a result of the alignment or misalignment of the contact areas between the top and bottom electrodes. It is believed that the better alignment in the DD-1 combination would have resulted in a much more concentrated current flow while the misalignment in the DD-2 combination would clearly distort and spread the current flow. These general trends were also observed in the EE combinations. For example, the EE-1 electrode combination were the best aligned and the EE-3 electrodes were the worst with the EE-2 electrodes in between. Therefore, the joint strength of the joints made using the EE-3 combination was much lower than that of the EE-1 combination. Using the EE-3 electrode combination increased the S/S contact area by about 11% compared to that of EE-1 electrodes, which would also contribute to the lower nugget size and hence joint strength.[1] A comparison of the results obtained using the EE-1 and EE-2 combinations indicated that the latter did not reduce

**Table 3 Effect of alignment of contact areas on top and bottom electrodes**

| Electrode type | Top | Bottom | Overlapped area | Nugget area, mm$^2$ | Shear force, kg | Nominal contact area, mm$^2$* | S/S contact area, mm$^2$ | *EC** | *ECC** | Area of overlap, mm$^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| DD-1 |  |  |  | 38·4±1·6 | 536±22 | 53·7 | 66·6 | 1·26 | 0·01 | 34·7 |
| DD-2 |  |  |  | 34·8±1·2 | 487±21 | 53·7 | 66·3 | 1·26 | 0·01 | 26·2 |
| EE-1 |  |  |  | 39·3±1·2 | 513±21 | 55·5 | 66·6 | 1·20 | 0·14 | 39·4 |
| EE-2 |  |  |  | 39·7±0·7 | 542±11 | 55·5 | 65·3 | 1·22 | 0·13 | 31·4 |
| EE-3 |  |  |  | 32·2±0·9 | 415±11 | 56·4 | 73·4 | 1·24 | 0·10 | 26·5 |

*Nominal contact area, *EC* and *ECC* are the average values for top and bottom electrodes.



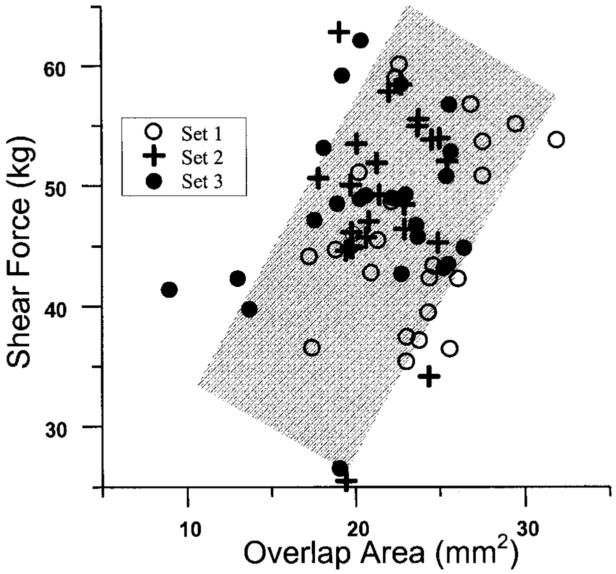

*a* DD-1; *b* DD-2; *c* EE-1; *d* EE-2; *e* EE-3

**8 Fractured surfaces of joints made using different electrode combinations**

the joint strength relative to the former combination, despite the fact that current flow was distorted to a much larger extent when using the EE-1 combination.

It also appeared that weld nuggets tended to form under the overlapped region of electrode contact areas (Fig. 8). This may be related to the suggestion[8] that a larger overlapping region may indicate more concentrated heating rather than distortion and spreading of the current flow. Table 3 shows that the DD-1 and EE-1 combinations, having a larger overlapped area, produced higher joint strength, while the others (DD-2 and EE-3) with a smaller overlapping region produced lower joint strength. Plotting joint strength versus overlapped area in the conventional electrode tip life tests also indicated a similar tendency despite the large scatter (Fig. 9). However, it is also obvious that overlapping alone cannot explain all the results. For example, the combinations DD-2 and EE-3 had almost the same overlapped contact areas, but different joint strength (Table 3). It is believed that the distortion of current flow from one electrode to the other may be smaller in the case of DD-2 compared to EE-3. Three dimensional numerical modelling is definitely needed to better understand how the distribution and alignment of contact areas from the top and bottom electrodes affect weld nugget formation.

In order to get the clearest possible understanding of some of the geometric effects of the electrode tip face features, the metallurgical effects[9] were not considered and in fact were deliberately minimised in this work by limiting the number of welds made with each pair of electrodes. The alloy phases (such as $Al_xCu_y$ and MgO) that form between the copper electrodes and aluminium sheets are relatively high in electrical resistivity and low in thermal conductivity compared to either aluminum or copper alloys.[10] As they build up on the electrode tips in conventional electrode life tests, the heat generation at the electrode/sheet interfaces changes and, in turn, the location and dimension of weld nuggets formed at the faying surfaces is affected.[9,12,13]




**9 Relation between shear force and overlap area in conventional electrode life tests using MFDC welding machine**

## Conclusions

The effects of electrode pitting morphology at the tip faces on weld nugget size and joint strength in resistance spot welding of aluminum alloys have been investigated experimentally using specially designed electrodes with machined annular pits, central cavities and also both symmetrically and asymmetrically distributed circular pits. These simulation results indicated that, besides the nominal current density at the faying surfaces, the current distribution determined by distribution of contact areas on electrode tip faces and the degree of alignment between top and bottom electrodes each affect weld quality. An increased edge concentration of the contact areas reduced weld nugget size and hence joint strength. A distorted current flow from one electrode to the other caused by misalignment of the contact areas appeared to reduce weld quality. For this reason, the overlapped region of the contact areas from both electrodes might be used as an indicator of weld quality. However, a better understanding of the exact correlation between tip face features and weld nugget formation would need three-dimensional numerical modelling. This work has provided well organised experimental data to support future modelling work.

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