Image analysis of electrode degradation in resistance spot welding of aluminium

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A study was carried out of the characteristics of electrode degradation in resistance spot welding of aluminium, and its influence on weld quality. Based on analysis of electrode life test results, an imaging approach was developed to determine quantitatively the status of electrode degradation, in which three parameters were defined to represent the tip surface characteristics, namely, relative radius, edge concentration, and eccentricity. This image analysis revealed a clear relationship between these defined electrode surface features and the weld quality, based on which a reasonable understanding was achieved of the causes of weld quality deterioration in electrode life tests. STWJ/404

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INTRODUCTION

Aluminium is perceived as an alternative to steel for next generation automobiles aiming at high fuel efficiency. However, resistance spot welding (RSW) of aluminium is still problematic from the production point of view. Two major reasons are inconsistent weld quality and short electrode life.[1] Electrode life in RSW of aluminium varies considerably depending on conditions such as electrode design (including copper alloy selection,[2,3] coating,[4] and configuration[3,5]) and sheet and electrode surface conditions.[6–8] For a given electrode, sheet material, and process settings, the weld quality varies along with electrode degradation. Degradation of electrode tips in RSW of aluminium is much more severe and faster than that in RSW of steels. Fukumoto *et al.*[9] reported an electrode life range of 420–920 welds in RSW of AA5182 of 1·5 mm thickness using a medium frequency direct current (dc) power supply although welding conditions were kept constant.

Previous studies on electrode degradation in RSW of aluminium have also focused on the electrode wear mechanisms,[10,11] and the relationship between the electrode wear and the weld quality or electrode life.[5,9,12] For example, a qualitative analysis was conducted on the relationships between the dynamic resistance and the electrode wear and weld size.[12] However, a direct relationship between the electrode wear and the weld size has not been discussed. It is generally accepted that the growth of the electrode tip contact area in RSW of steels will result in reduction of welding current density, which is unfavourable to weld quality. Similar trends were also found in RSW of aluminium.[5,9] However, more complex features, in addition to the growth of the outside radius of the contact area, also appeared to influence the weld quality.[9] These features would affect the distribution of electric current and weld force during welding. An image processing approach was therefore developed in the present paper to characterise the evolution of tip surface condition and tip surface features.

ELECTRODE LIFE TESTS AND TIP SURFACE CHARACTERISATION

Electrode life tests

The electrode tip surface characteristics in aluminium RSW were studied based on two electrode life tests. One was a typical life test using a pedestal medium frequency dc welder from a previous study,[9] that is, the present analysis was carried out on data originally generated in that study. The other life test was carried out as part of the present study, using a pedestal alternating current (ac) welder. Both were conducted on AA5182 aluminium sheets of 1·5 mm thickness. The tests used Class 1 (Cu–0·15 wt-%Zr) electrodes having a taper angle of 60°, tip face diameter of 10 mm, and radius of curvature of 50 mm. The welding schedules are given in Table 1. Shear tests were performed after welding on five weld samples from every 60 or 110 welds. Carbon imprints of electrode contact surfaces were taken before shear testing of the corresponding weld samples. The electrode life was defined as the number of welds that had been produced by a pair of electrodes at the point when the shear strength of any of the test samples fell to below 80% of the average value at the start of the life test.

Figure 1 shows typical carbon imprints taken during the ac and dc life tests. A carbon imprint actually shows the areas of mechanical contact between electrodes and sheets when the normal electrode load is applied at room temperature. Therefore it may not be an exact representation of the areas of electrical contact during welding, but is normally taken to be a good conservative approximation of the latter. The examination of the carbon imprints clearly showed that the diameter of the nominal contact area at the electrode tip increased during the progress of each life test.

Table 1 Welding schedules for electrode life tests

Parameter	dc	ac
Current, kA	28·5	29·5
Squeeze time, cycles	25	25
Weld force, kN	6	6
Weld time, cycles	5	5
Hold time, cycles	12	12
Welding rate, welds/min	20	20

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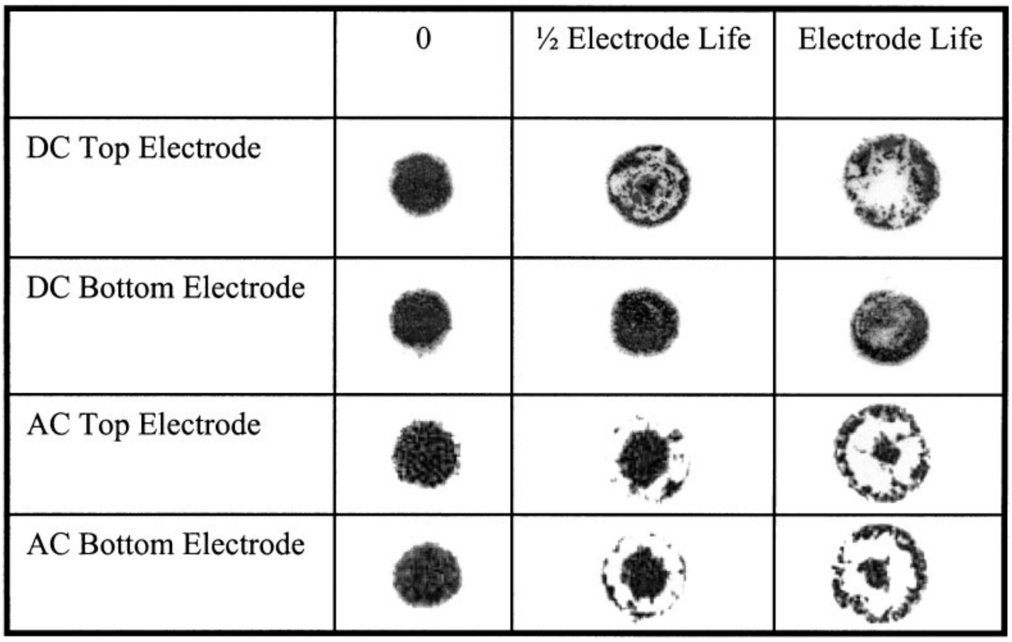
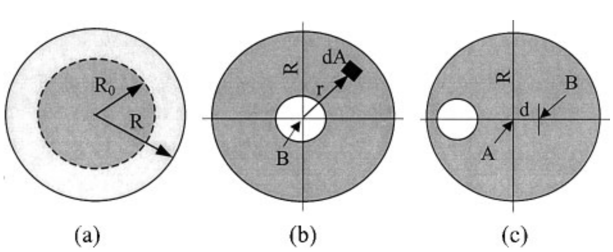


1 Change of electrode tip surfaces during life tests

As increasing numbers of welds were produced, the outside diameter of the contact area showed a progressive increase.

In addition to the growth of the outside diameter of the contact area, the distribution of contact points on the tip surface (based on the areas of contact shown by carbon imprinting) was found to vary greatly during the electrode life tests. Physical (and presumably also electrical) contact was concentrated initially around the centre of the electrode tip surface. As additional welds were made, patches of the original electrode surface were removed by pitting (white areas on imprints), the main mechanism of electrode degradation in aluminium spot welding.[11] The pitting began at the outer periphery of the original contact surface, individual pits progressively connecting together in a ring which then grew towards the centre of the electrode tip. Therefore, for much of the electrode life, the electrode contact points were concentrated mainly in two areas: a central zone of reducing diameter at the electrode axis, and a peripheral ring of contact spots located mostly outside the original contact area.

Figure 1 shows that the progress of electrode degradation in the ac electrode life test was different from that in the dc test. Both electrodes in ac welding suffered surface degradation and wear at a similar rate. The ac electrode wear also developed mainly in an axisymmetric pattern. In other words, the centroid of the area of tip contact points coincided closely with the electrode axis. In dc welding, the wear of the positive (top) electrode was faster than that of the negative electrode. The distribution of contact points became significantly non-symmetric as the electrode approached the end of its life, producing large off centre areas of non-contact. It was also noticed that there was no contact at the centre of the tip surface at the end of life of the dc electrode.



2 Characterisation of electrode tip contact area in terms of *a* relative radius R_r, *b* edge concentration *EC*, and *c* eccentricity *ECC*

Tip surface feature definitions

Based on the analysis of the imprints from electrode life tests, the following electrode tip surface features were defined. They provided a procedure for image processing to investigate the relationship between the tip surface condition and the weld quality.

Relative radius (Fig. 2a)

Relative radius is the ratio of the radius of the outer edge of the contact area R to the initial value R_0 when the electrode is new, defined as

$$R_r = \frac{R}{R_0} \qquad (1)$$

Edge concentration (Fig. 2b)

Edge concentration models the degree of distribution of contact points away from the centroid (B) of the actual contact area. It is defined as

$$EC = \frac{3}{2} \times \frac{\sum \left(\mathrm{d}A \times \frac{r}{R_{eq}} \right)}{\sum \mathrm{d}A} \qquad (2)$$

where dA is a small contact patch, r is the distance of this small patch from the centroid of the whole contact area of which R is the radius, and R_{eq} is equivalent radius of a circle having the same area as the whole actual contact area.

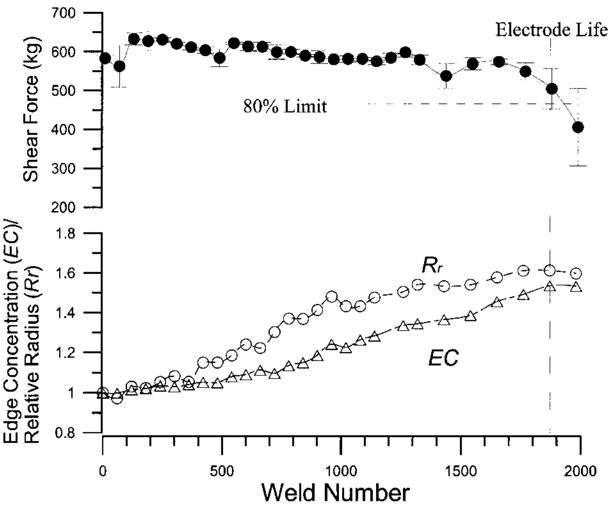
For example, for a solid circular contact area of radius equal to R ($R=R_{eq}$)

$$EC = \frac{3}{2} \times \frac{\int_0^R \frac{r}{R} \times 2\pi r \mathrm{d}r}{\pi R^2} = 1$$

EC, representing the result of pitting accumulation, is normally larger than 1.

Eccentricity (Fig. 2c)

Suppose A is the geometric centre of the whole contact area, B the centroid of all the contact points, and d the



3 Weld property and electrode surface features in ac life tests

distance separating A and B: the eccentricity is then defined as

$$ECC=\frac{d}{R} \quad (3)$$

Since pitting usually occurs at a location away from the electrode tip centre, a marked increase or change in *ECC* would indicate the occurrence of heavy pitting.

A set of image processing programs was developed, based on the formulae above, using MatLAB Image Processing Toolbox (MathWorks, Natick, MA, USA). Image processing was then performed on carbon imprints of electrodes.

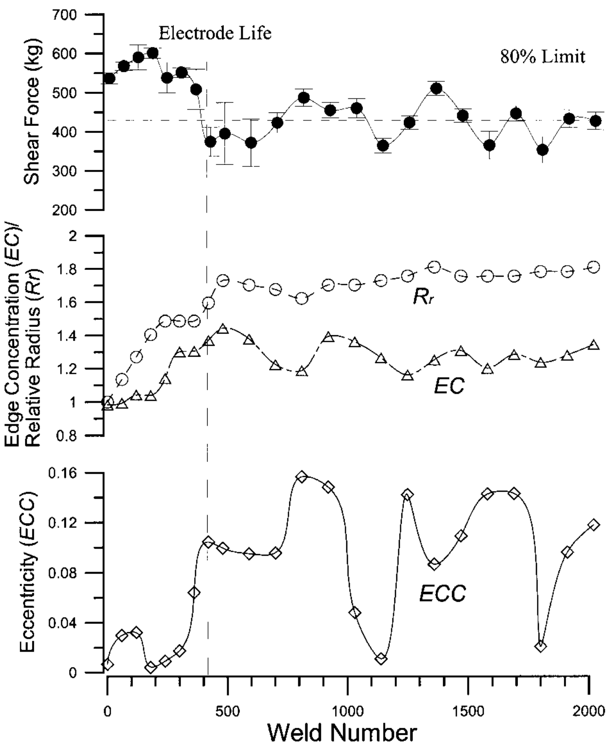
IMAGE PROCESSING AND SHEAR TEST RESULTS

The electrode tip surface features and shear test results from the ac electrode life test are shown in Fig. 3. Average values of the top and bottom electrode tip surface features are used because both electrodes were worn out in a similar manner and at a similar rate. The following are observations from the ac life test results:

(i) electrode life was reached at 1870 welds
(ii) *ECC* stayed at a low level (0·05–0·06) throughout the ac life test (Table 2). This was due to the symmetrical distribution of the pitting (and hence the remaining contact points) on the tip surface
(iii) before 1600 welds, R_r and *EC* increased steadily to 1·54 and 1·39 respectively – nevertheless, the associated change in weld strength (shear force) was relatively small
(iv) after 1600 welds, *EC* continued to increase while there was little variation in R_r – a sharp decrease in shear force occurred during this period, which indicates an unfavourable influence of *EC* on weld quality.

Figure 4 shows the electrode tip surface features and shear test results from the dc life test. Only the values for the top (positive) electrode are displayed since the major electrode wear happened at the top. The dc life test results give the following observations:

(i) electrode life was reached at 420 welds – the shear force for test welds made after the end of electrode life fluctuated up and down, showing from time to time the development of good quality welds (above the 80% strength limit)
(ii) before the end of electrode life, the shear force started to decrease after *EC* and *ECC* had both obviously increased
(iii) when welding was continued after the electrode life was reached, R_r, *EC*, and *ECC* stayed at high levels (Table 2), the R_r value being relatively constant while *EC* and *ECC* fluctuated at high amplitudes (Fig. 4), indicating that the large variation in shear strength was not strongly linked to the contact area radius – other tip surface features such as *EC* and *ECC* were also evidently affecting the weld quality, but no clear correlation was observed between the shear force variation and the *EC* and *ECC* curves.



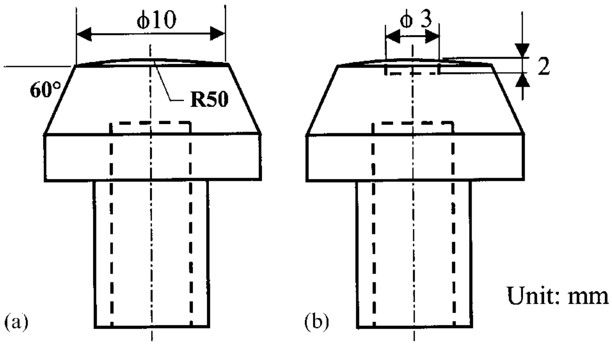
4 Weld property and top electrode surface features in dc life tests

DISCUSSION

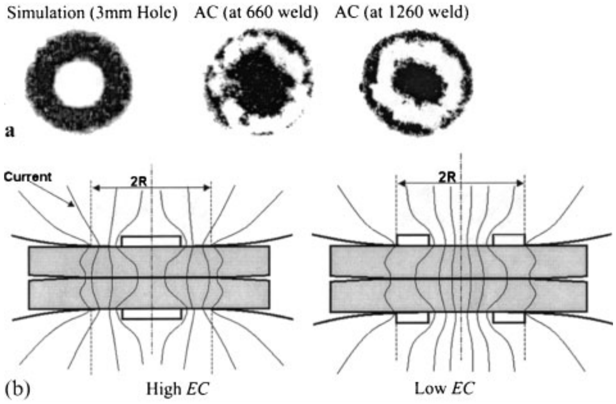
It is widely accepted that the growth of the electrode tip contact area results in a decrease in current density at the faying (sheet/sheet) interface, which eventually leads to undersize weld nuggets and a reduction in weld strength. This is actually the foundation supporting the stepper control strategy in RSW, mainly for steel. In the aluminium RSW life tests reported above, the electrode failures were all associated with a high R_r level (Figs. 3 and 4). However,

Table 2 Electrode tip surface feature changes during life tests

	dc (life=420 welds)			ac (life=1870 welds)		
	R_r	*EC*	*ECC*	R_r	*EC*	*ECC*
Before electrode life (average)	1·32	1·12	0·02	1·30	1·18	0·06
At electrode life	1·59	1·37	0·10	1·62	1·54	0·05
After electrode life (average)	1·74	1·29	0·10	1·60	1·51	0·05



5 Electrode design for simulation test, showing *a* normal electrode and *b* simulation electrode



6 Influence of contact area distribution, showing *a* tip imprints from simulation and ac electrode life tests and *b* influence of edge concentration on current flow

it was difficult to explain, using only the nominal contact area, why some welds of good quality were from time to time produced after the end of dc electrode life while R_r stayed above the level reached at the electrode life (Fig. 4). It was also difficult to explain why in the ac life test the shear strength after 1600 welds decreased sharply whereas R_r was almost constant (Fig. 3). The test results imply that other characteristics of the tip surface played a role in determining the weld quality.

Electrode life test (ac) – influence of edge concentration

As shown in Fig. 3, the ac life test results after 1600 welds suggest that *EC* should be accountable for the large and relatively sudden quality decrease. That is, an increase in *EC* led to a decrease in shear strength. To help in understanding the influence of *EC*, a physical simulation test was conducted in which the edge concentration was simulated by drilling a hole at the centre of the tip surface (Fig. 5*b*). Both the top and the bottom electrodes in the simulation test had the centre of the electrode tip drilled away. The results of these tests were compared with those of the ac electrode life test, in which the top and bottom electrodes were worn out at a similar rate. In both tests the major changes of the tip surface features were in R_r and *EC*.

The ac result at 660 welds was selected as an example for comparison with the simulation result, because the R_r values for both were very close (Table 3). Figure 6*a* shows their electrode imprints. Supposing that the contact area radius were the only factor affecting the weld quality, the two cases in comparison should have resulted in similar shear strength. However, the shear force for the simulation example was only 292 kg, well below the ac result (613 kg). The difference of the tip surface condition between the two electrodes lies in *EC*. This suggests that the distribution of the contact points played an important role in determining welding quality. The higher the *EC*, the lower will be the shear strength.

The effect of *EC* could be explained with reference to Fig. 6*b*, where *R* represents the radius of the actual contact area. The change in *EC* would affect the distribution of the welding current. In the high *EC* case, the current will flow through a ring at the electrode/sheet interface, resulting in less current flowing through the centre of the faying (sheet/sheet) interface. This relatively wider spread of current would yield low current density and low heating efficiency, leading to an undersized nugget or even no fusion.

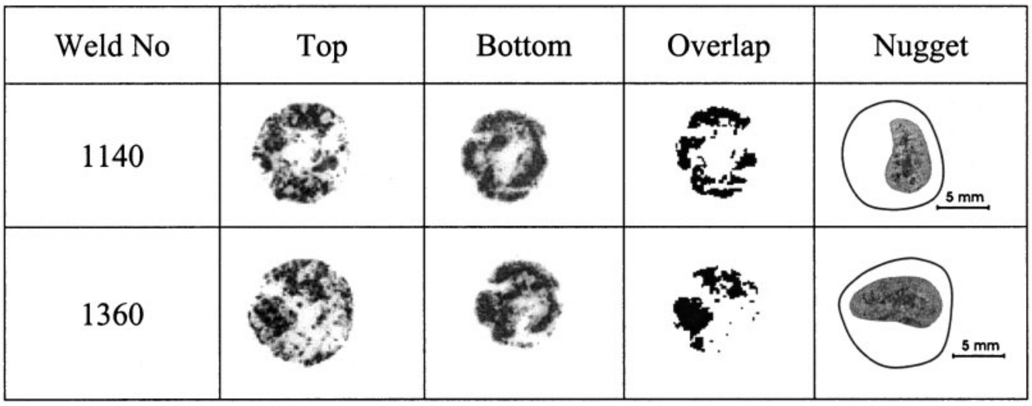
A further comparison between the simulation and the ac life test results shows that during the later part of the ac electrode life, both R_r and *EC* increased above the level of the simulation example but still yielded good quality welds. For example, the R_r and *EC* values at 1260 welds were 1·51 and 1·34 (Table 3), based on which a weld quality worse than that of the simulation sample (R_r=1·21, *EC*=1·33) would have been expected. However, the actual shear force at 1260 welds was found to be as high as 599 kg. The reason is that the distribution of the contact points in the simulation test was not exactly the same as that for the ac sample (Fig. 6*a*) – there was no central contact on the simulation electrodes. The loss of central contact is evidently the most detrimental factor when the contact points concentrate towards the edge of the tip surface. The existence of some significant central contact in the ac life test helped to restrict the spreading of current, resulting in a low sensitivity of the weld quality to the increase in R_r. A relatively consistent shear strength was therefore maintained for quite some time (Fig. 3).

Electrode life test (dc)

The relationship between the weld quality and the *EC* and *ECC* values was to some extent revealed by the dc life test results before the end of electrode life (Fig. 4). The shear force before the end of electrode life could be divided into two stages: an initial increase with successive welds (1–180 welds) followed by a falling section (180–420 welds). In the first stage both the *EC* and *ECC* values were low, indicating little pitting. The initial increase in R_r did not result in an unfavourable effect on weld quality. Further investigation of this stage can be found in a previous study.[9,11] In the second stage, the *EC* and *ECC* values increased rapidly, indicating the occurrence of extensive pitting. Both R_r and

Table 3 Simulation and ac life test results

		Life test	
	Simulation (3 mm diameter central hole)	At 660 welds	At 1260 welds
R_r	1·21	1·22	1·51
EC	1·33	1·11	1·34
Average shear force, kg	292	613	599



7 Imprints and nuggets of samples beyond dc electrode life (note that hand drawn circle indicates sheet–sheet contact area)

EC would be expected to contribute to the continuous decrease in shear strength. The increase in *ECC* would cause a shifting of current toward one side of the tip surface. Although this type of current distribution is unwanted, it could occasionally result in a weld with an adequate nugget area and shear strength, especially when an even distribution of the current would lead to a lower than normal current density. However, the effect of *ECC* in the second stage in Fig. 4 is uncertain, in terms of when it is favourable or unfavourable to the weld strength.

The situation of welding beyond the dc electrode life was evidently more complex. The bottom electrode wear must be taken into account if an understanding is to be achieved of the weld quality produced. The approach taken was to estimate the effect of the surface condition of the two electrodes on the current distribution. The analysis was carried out by observing the overlapping area of the imprints of the two electrodes. In the following, two typical cases in Fig. 4 are described, one at 1140 welds with a quality (strength) below the 80% limit, the other at 1360 welds with good quality. Their top and bottom electrode surface features are given in Table 4. Figure 7 shows the electrode imprints, the overlap of the top and bottom electrode contact areas, and the nugget shapes developed. An outstanding difference is that the *ECC* values for the electrodes at 1360 welds were higher (Table 4). Nevertheless, as the actual contact areas of the two electrodes overlapped well (Fig. 7), this led to a concentrated heating, rather than a distortion of the current flow. Sufficiently large nuggets were therefore formed, in spite of the higher R_r value. In the case at 1140 welds, the overlapping contact points scattered toward the edge and there was no central contact, a situation similar to the simulation test. As shown in Fig. 7 a smaller, off centre nugget was thus produced. As generally expected and as found by Fukumoto *et al.*,[9] an increase in nugget area leads to an increase in shear force.

Comparison of ac and dc results

Owing to the Peltier effect, the electrode wear in the dc test was concentrated on the positive electrode side.[9] The start of pitting in the dc test occurred much earlier than that in the ac test. As a result, the increase of R_r and *EC* for the dc positive electrode was much faster than that for the ac electrodes (Figs. 3 and 4). Furthermore, the central contact area on the dc tip surface was found to be lost quickly (Fig. 1). In contrast, a good central contact was maintained in the ac test, which, together with a symmetric distribution of the contact points, kept a good concentration of the current around the centre of the faying interface and a good overlapping of the contact points of both electrodes. These factors worked together, leading to a much longer electrode life in the ac life test.

SUMMARY

The present paper summarises an investigation of the electrode tip surface characteristics in RSW of aluminium, and correlations between the tip surface condition and the weld quality.

Based on the carbon imprints taken during electrode life tests, three aspects of electrode tip surface features were defined, namely, relative radius R_r, edge concentration *EC*, and eccentricity *ECC*: R_r relates to the nominal contact area at the tip surface, and *EC* and *ECC*, which model the effects of electrode tip surface pitting, determine the current distribution at the contact surfaces. Image processing programs were developed to extract these features.

The image analysis of the results of the electrode life tests and a simulation test showed that R_r, *EC*, *ECC*, and tip surface central contact all contribute to weld quality. The increase in R_r and *EC* led to a decrease in weld shear strength. The existence of central contact on the tip surface helped to maintain good weld quality. The effect of *ECC* was complex. These findings provided a reasonable explanation for the longer electrode life that was achieved in the ac life test.

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Table 4 Tip surface features and weld quality of samples beyond dc electrode life

	At 1140 welds					At 1360 welds				
Electrode	R_r	*EC*	*ECC*	Average shear force, kg	Nugget area, mm^2	R_r	*EC*	*ECC*	Average shear force, kg	Nugget area, mm^2
Top	1·73	1·26	0·01	365	29	1·81	1·25	0·09	511	35
Bottom	1·33	1·17	0·02	…	…	1·38	1·10	0·08	…	…

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