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Effects of Sheet Surface Conditions on Electrode Life in Resistance Welding Aluminum

The surface of aluminum sheet was cleaned with three different methods, then each surface was tested as to its effect on electrode life

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ABSTRACT. The relatively short electrode life in welding aluminum sheets has been a bottleneck for large-scale production of aluminum vehicles. The rapid deterioration of electrodes during resistance welding aluminum is the collective consequence of high pressure, high temperature, and a rapid metallurgical (alloying) process. This study systematically investigated the effects of sheet surface conditions on electrode life. Using 2-mm 5A02 aluminum sheets, a schedule conducive to electrode life was used for testing the effects of sheet surface conditions. A three-phase, direct-current pedestal-type resistance spot welding machine was used, and the electrodes lasted for about 200 welds for sheets with untreated or original surfaces, up to 1700 welds when they were electric-arc cleaned, and more than 2000 welds if the sheets were degreased or chemically cleaned. This investigation also shows that the appearance of an electrode after a small number of welds provides useful information on the electrode life using the same welding schedule.

Introduction

With the advantages of high specific strength, low density, high corrosion resistance, and low-energy formability, aluminum has been widely used in almost every aspect of daily life. The constantly increasing demands in weight reduction for fuel economy, and emission control have led to a wider application of aluminum sheets in automobile manufacture. Many automakers have attempted to replace steels with aluminum. For instance, Audi has successfully produced all-aluminum Models A2 and A8 cars.

Resistance spot welding has been the major joining process in automotive body construction because of its low cost, robustness, and many other advantages. However, the experience obtained in welding steels is not readily transferable to welding aluminum, mainly due to the significant physical and metallurgical differences in both the bulk material and surfaces. Because aluminum has higher electrical and thermal conductivities than steels, high electric current and short weld time have to be used in welding aluminum alloys. For example, a current of about 10,000 A may be needed to weld a 2-mm to 2-mm steel sheet combination, but more than 40,000 A are usually required to weld similar combinations of aluminum sheets (Ref. 1). Such a high current produces high temperature in the weldment and at the interfaces between aluminum sheets and copper electrodes. This greatly affects the electrode life considering the metallurgical reaction between aluminum and copper. Aluminum has a high chemical affinity for copper to form a brittle alloy (bronze) with lower electrical and thermal conductivities than copper. The oxide layer, which is inherent to aluminum sheets, also plays an important role. An Al_2O_3 layer on the surface of an aluminum sheet at the as-fabricated state is usually not uniform and may break under an electrode force during welding. As a ceramic, Al_2O_3 is highly insulating with a high melting temperature. A nonuniform or broken Al_2O_3 layer on a sheet surface results in uneven distribution of electric current, with very high electric current density at low resistance locations, and produces significantly localized heating or even melting on the surface (Refs. 2, 3). The electrode face deteriorates rapidly due to alloying and material depletion under high pressure (electrode force) and high temperature. In a continuous welding process, a repeated and accelerated (due to accumulative alloying and material depletion) deterioration of the electrode surfaces makes electrode life so short that such electrodes and sheets cannot directly be used in automated, large-volume automotive production.

Controlling aluminum sheet surface conditions is the key to increasing electrode life as it determines the heating of the interface between a copper electrode and an aluminum sheet. A surface without the Al_2O_3 layer is preferred concerning electrode life. Or, if that is difficult to achieve, a thin, uniform layer can be tolerated as it will result in a uniform heating. According to the German Standard DVS 2929 (Ref. 4), a stable welding process with uniform weld nuggets can be achieved if the sheet-sheet contact resistance is controlled between 20 and 50 $\mu\Omega$. Such contact resistance can only be achieved if the sheet surface is properly

KEYWORDS

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Surface Condition

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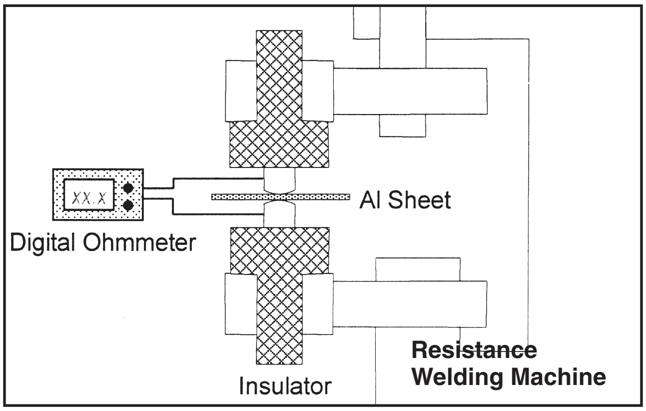

Fig. 1 — Setup for contact resistance measurement.

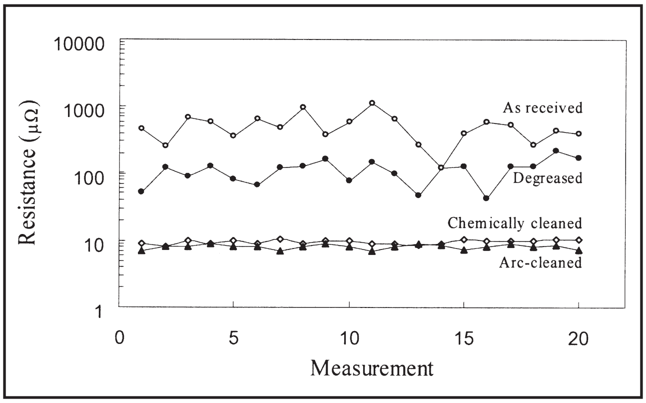

Fig. 3 — Resistance measurement of various surface conditions.

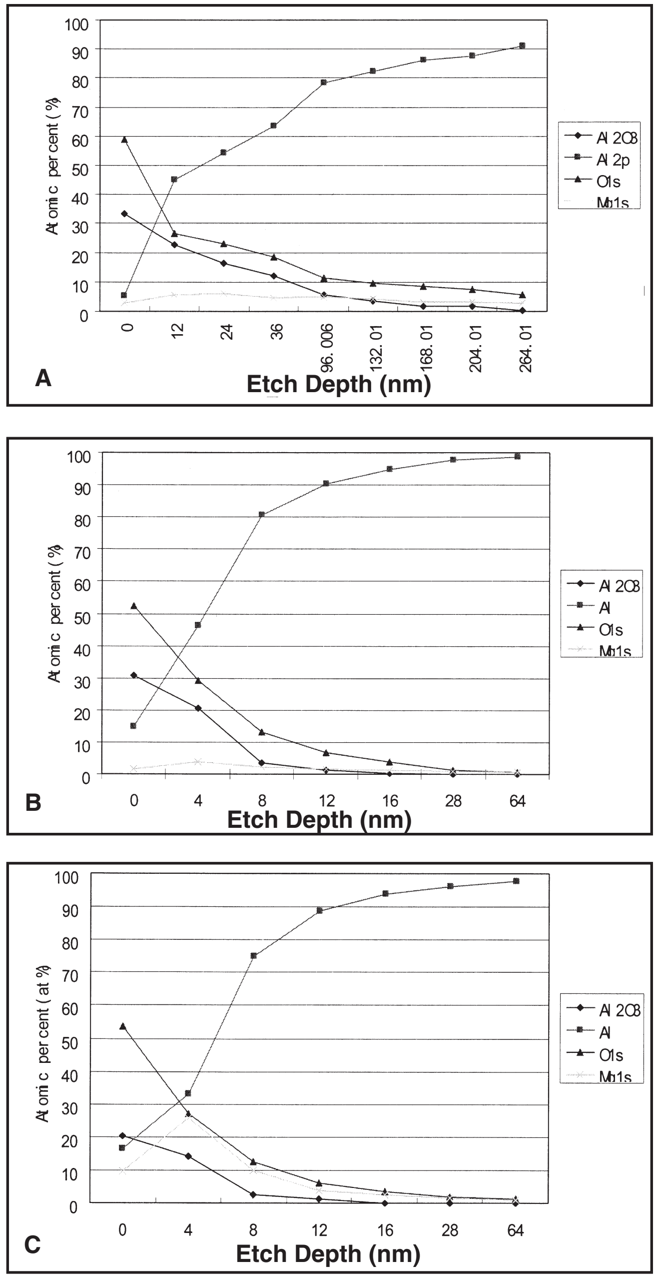

Fig. 2 — Profiles of atomic-percent of various elements in the surface layers after cleaning. A — Degreasing; B — chemical cleaning; C — electric-arc cleaning.

Table 1 — Chemical Composition of 5A02 Aluminum Alloy (wt-%)

Si	Fe	Cu	Mn	Mg	Ti	Al
0.40	0.40	0.10	0.25	2.5	0.15	balance

treated. An early representative work performed by Patrick et al. (Ref. 3) has revealed that different outer and inner surfaces (sheet-electrode and sheet-sheet interfaces) are needed for optimal welding. It is reported that when the inner surface is conversion coated (using a chromium phosphate to achieve uniform resistance and chemical stability) and the outer is arc cleaned, an electrode life of more than 7000 welds can be achieved. This research highlighted the importance of surface conditions in affecting electrode life, although such conditions are difficult to achieve in production. Differential surfaces were also proposed and investigated by Leone and Altshuller (Ref. 5). A parabolic relationship between the number of welds and differential oxide thickness was established, and a differential of about 400 Å in oxide thickness produced the highest number of welds.

Thornton and Newton's experimental study revealed that an electrode life of up to 1000 welds can be achieved if the sheets are properly degreased or chemically cleaned when welding a 2-mm sheet (Ref. 6). A similar electrode life was obtained using aluminum sheets covered by a specially designed thin film (Ref. 7). An electrode life of more than 2000 welds without dressing has been the target for many industrial practitioners.

The electrode degradation was characterized in four steps prior to eventual failure: aluminum pickup, electrode alloying with aluminum, electrode tip face pitting, and cavitation (Ref. 8). In that work, detailed investigation of the metallurgical interactions between the copper electrode and aluminum alloy sheets was carried out with a focus on electrode pitting in welding aluminum sheets. Pitting can be controlled, and electrode life extended, if aluminum pickup and alloying are limited.

The objective of this work is to understand how electrode deterioration is affected by aluminum sheet surface conditions, and therefore, to determine electrode life for welding aluminum sheets.

Experiment

The material selected for this study was 2-mm 5A02 aluminum alloy sheets. 5A02 is nonheat treatable with a composition similar to AA5754. The as-received sheets were in H1 temper condition, with the chemical composition listed in Table 1. Commercially available, dome-shaped Cu-Cr-Zr (Cr: 0.25~0.65%; Zr: 0.08~0.20%; Cu: balance) electrodes of face radius of 100 mm, and 20 mm in diameter were used for contact resistance measurement and for welding. The electrodes had a hardness of HRB = 75, electrical conductivity ≥ 45 MS/m, and a heat treatment of 950°C for 2 h and 500°C for 1 h. The electrodes were (room temperature) water-cooled during testing. A 300 kVA, three-phase DC pedestal welding machine was chosen for this study. A Hobart Cyber-Wave 300S arc welding machine was used for electric arc surface cleaning. The sheet surface contact resistance was measured using a setup as shown in Fig. 1 with a digital micro ohmmeter.

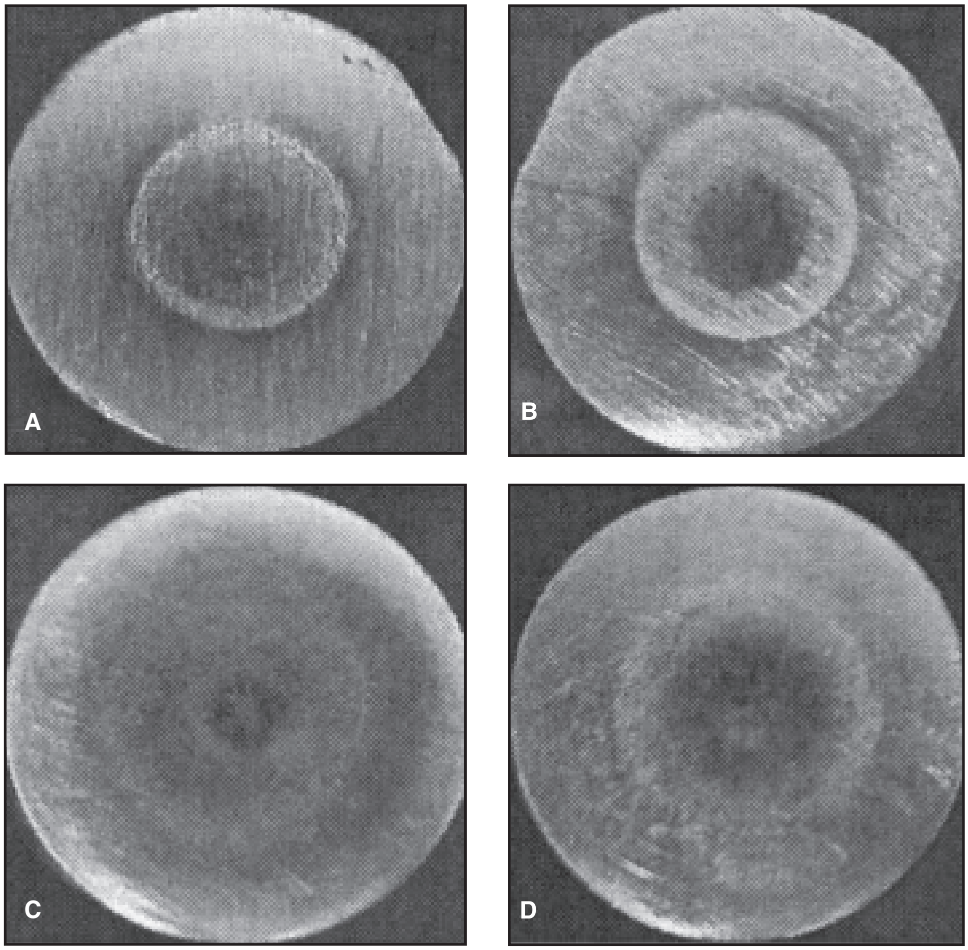

Fig. 4 — Electrode surfaces after making 60 welds on sheets of different surface conditions. A — Chemically cleaned; B — degreased; C — electric-arc cleaned; D — untreated.

Surface Cleaning

Three types of surface cleaning methods were employed to create sheets with different surface conditions. They were degreasing, chemical cleaning, and electric-arc cleaning. Untreated sheet surface condition was considered in the experiment to provide a baseline comparison.

1) *Degreasing*. Aluminum sheets were soaked in a water solution of a metal degreasing detergent for five minutes, wiped using cotton, and then water-rinsed three times. The sheets were air-dried afterward.

2) *Chemical cleaning.* Sheets were cleaned first following the degreasing procedure as described in 1. Then they were soaked in a water solution of 5%NaOH at 60°C for four minutes. After being water-rinsed for three times, they were soaked in 30%HNO_3 for two minutes at room temperature, then water rinsed three times before being air dried.

3) *Electric-arc cleaning.* The cleaning was performed manually using a Hobart Cyber-Wave 300S arc welding machine with a tungsten electrode. An electrical current of 30 A and 26 V was applied for 10 s to create a cleaned surface of about 15 mm in diameter. Two different types of cleaning were made for contact resistance measurement and for electrode life tests. For contact resistance measurement, the single sheet used was cleaned, using the arc welding machine on both sides, which were to contact with the electrodes. A circular area of about 15 mm in diameter was cleaned on each side. For the sheets used for welding, only the side of a sheet that was to be in contact with the electrode during welding was cleaned. The sheet-sheet interface was not cleaned as it was found in a preliminary experiment that the welding quality was not consistent when both sides of a sheet were cleaned. Care was taken during cleaning to avoid melting the Al sheet surface.

Surfaces cleaned by these three methods were then characterized using X-ray photoelectron spectroscopy (XPS, ESCALAB 250 by Thermo Scientific), similar to the analysis conducted by Leone and Altshuller (Ref. 5). Using a specimen of 10×10×2 mm in size, the probe detected the atomic count of each element, and therefore, revealed the composition of the surface. In addition, the probe depleted the surface layer at an etching speed of 0.2 nm/s, providing the distribution of elements through the thickness of a surface layer.

Contact Resistance Measurement.

In Al welding, it is widely believed that an interface generates more heat due to the contact resistance, which is significantly higher than that of the bulk Al. Therefore, the deterioration of electrodes due to alloying between Cu and Al is largely affected by the contact resistance at the electrode-sheet interfaces. The experimental setup, using a resistance spot welding machine, for contact resistance measurement is shown in Fig. 1. The measurement followed German Standard DVS 2929 (Ref. 4) using an electrode force of 7.5 kN. The same electrodes were used for measurement and for welding. The measurement order was randomized with 20 measure-

Table 2 — Welding Schedules for Rapid Electrode Life Determination

Surface Condition	Untreated	Degreased	Electric-arc Cleaned	Chemically Cleaned
Welding Time and Current	4 cycl. 27.21 kA	4 cycl. 29.1 kA	6 cycl. 34.3 kA	5 cycl. 32.7 kA

Note:Electrode force was 9 kN for all welding tests.

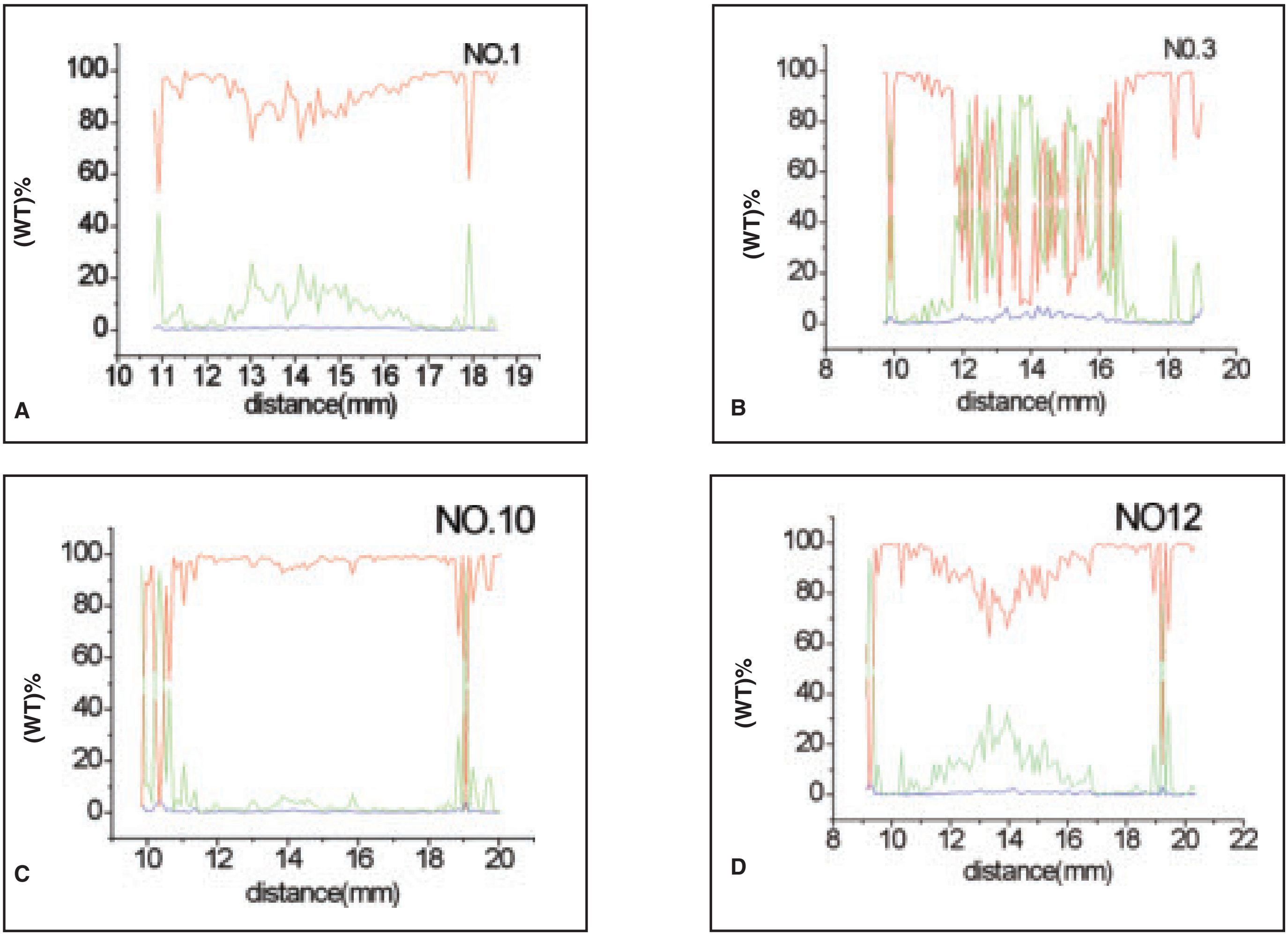

Fig. 5 — Composition profiles of electrode surfaces after 60 welds using the schedules of A — F = 4.5 kN, τ = 60 ms; B — F = 4.5 kN, τ = 180 ms; C — F = 9.0 kN, τ = 60 ms; D — F = 9.0 kN, τ = 180 ms. The red line is for Cu, green is for Al, and blue is for Mg.

ments taken for each surface cleaning condition. In order to make consistent measurements, the electrodes were cleaned after each measurement using the same grit sandpapers.

Rapid Electrode Life Determination

Before conducting electrode life tests, a set of electrodes was used to make a small number of welds, i.e., 60 welds under each of the four surface conditions. The electrodes were then compared with those tested for life, and such a comparison may provide a possibility of determining electrode life after making 60 welds only.

An electrode life is closely related to the welding parameters used. For instance, high electric current or long welding time generates more heat at the electrode-sheet interface, and promotes the formation of bronze through the accelerated diffusion between Cu and Al, and therefore, shortens electrode life. However, such unfavorable conditions cannot be avoided in spot welding aluminum as a certain level of welding current and welding time is necessary to produce an acceptable weld nugget. An experiment was conducted first to determine appropriate welding schedules, as listed in Table 2, with the minimum weld size of $5\sqrt{t}$ (t is Al sheet thickness in millimeters) maintained for each surface condition during the first 60 welds. The unit of welding time was 50 Hz cycles, i.e., 1 cycle = 20 ms. An identical electrode force of 9 kN was used for all welding, and welding times of 4, 5, or 6 cycles were chosen with appropriate welding current levels in order to achieve stable and sizeable weld nuggets.

Electrode Life Tests

Using the same schedules as listed in Table 2, electrode life tests were conducted on sheets with four different surface conditions. The test coupon size was 40×500 mm. All welds were peel-tested to measure the weld size. A "failure" was defined as when there is no weld or a weld produced is smaller than $3.5\sqrt{t}$. When 5% or more of 100 welds failed, the end of an electrode life was reached. For specimens of chemically cleaned, electric-arc cleaned, and degreased, one of every 100 welds was tensile-shear tested, and one of every 50 welds was tested on specimens with untreated surfaces.

Results and Discussion

The various surfaces were characterized first by their composition, depth, and contact resistance. The electrode life was then evaluated through measuring the quality of the welds on the aluminum sheets with various surfaces. The surface features of the electrodes were linked to the measured electrode life in order to predict electrode life by making a small number of welds.

Surface Layers after Cleaning

The profiles of atomic-percent measured by XPS are shown in Fig. 2A–C. The thickness of a surface layer after cleaning can be easily determined in Fig. 2 through

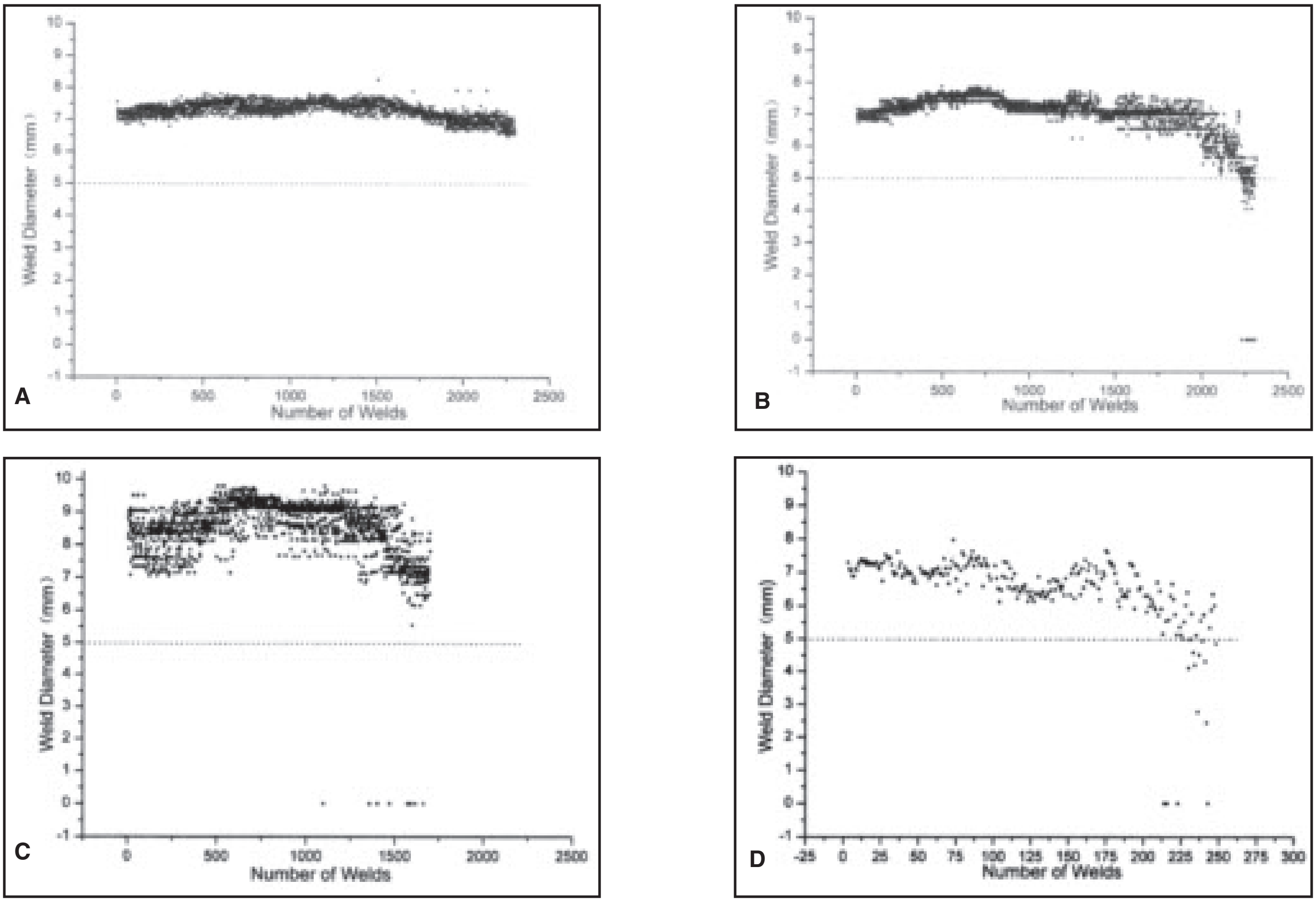

Fig. 6 — Electrode life testing results. A — Chemically cleaned; B — degreased; C — electric-arc cleaned; D — untreated surfaces. The dashed lines represent the minimum weld diameter ($3.5\sqrt{t}$) for the sheets.

the changes in atomic-percent of Al_2O_3 along the etching depth. The thickness of the Al_2O_3 layer is estimated around 170 nm for the degreased surface, and it is about 12 nm for both the chemically cleaned and electric-arc cleaned. It can be seen that the percent of aluminum increases approaching the base metal as the amount of Al_2O_3 decreases with depth. The amount of oxygen changes in a similar manner as Al_2O_3. However, oxygen also exists in Mg oxides, in addition to Al_2O_3, although at a much smaller portion. In general, the chemically and electric-arc cleaned surfaces have much thinner and more uniform Al_2O_3 layers than a degreased surface does. The uniformity of aluminum oxide layers was tested by measurements at different locations on a treated surface.

Contact Resistance

The measured resistances of various surface conditions are plotted in Fig. 3, using a setup as shown in Fig. 1. As shown in the figure, there is a significant difference in contact resistance among the sheets of different surface conditions. Electric-arc cleaning resulted in the lowest contact resistance, possibly due to the fact that the layer of grease and oxides on the surface was burned off under the intensive heat of the electric arc. The base metal was exposed and little oxidation occurred after cleaning as the cleaning was performed under the protection of Ar gas. The time elapsed between cleaning and measurement (and welding for the tests on electrode life) was a few hours in which only a thin layer of Al_2O_3 was expected to form as revealed in Fig. 2A–C by XPS measurement. Softening of the base metal in the cleaned surface area occurred under the electric-arc heat. In fact, measurements showed that the hardness of an electric-arc-cleaned surface (Vickers hardness of 60) is about two-thirds of that of a degreased surface (Vickers hardness of 90). This makes the contact area between the electrode and sheet larger than would be for untreated sheets or treated by other means.

The resistance of chemically cleaned surfaces is fairly uniform with a magnitude slightly higher than those electric-arc cleaned. Degreased surfaces have a higher contact resistance, which is still significantly lower than that of untreated surfaces. The contact resistance of degreased and untreated surfaces is not as uniform as those chemically or electric-arc cleaned. The resistance values for chemically cleaned, degreased, and untreated surface conditions are consistent with those published in literature.

Rapid Electrode Life Evaluation

The electrode faces after 60 welds using the schedules listed in Table 2 on four different surface conditions are shown in Fig. 4. The upper and lower electrodes after 60 welds under each condition had very similar appearances, and therefore, only the upper electrodes were used to characterize the influence of surface conditions on electrodes, as shown in the

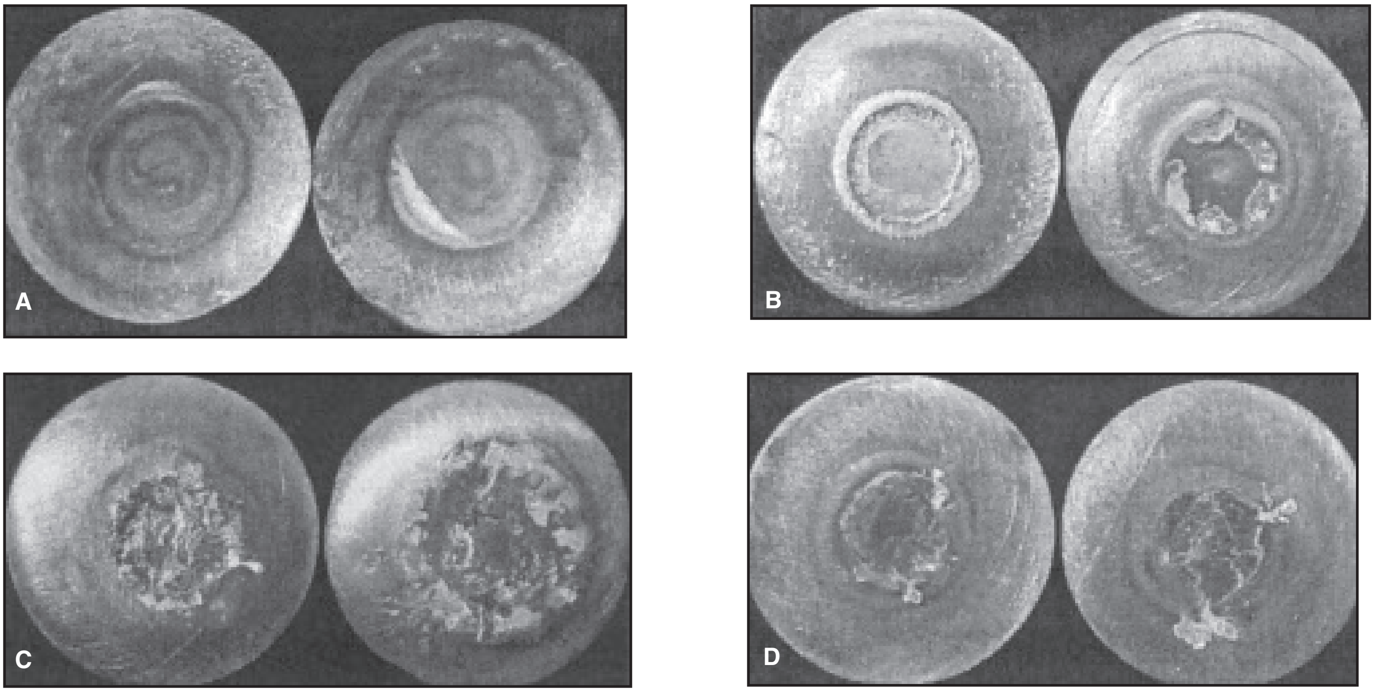

Fig. 7 — Electrode surface morphology after life tests. A — Chemically cleaned; B — degreased; C — electric-arc cleaned; D — untreated aluminum sheets. The electrodes on the left side are from the lower arm of the welding machine (negative), and those on the right side are from the upper arm (positive).

figure. These electrodes show a clear region of metallurgical changes on their faces, due to an intensive heating and a pressurized contact with the Al sheets. In such a zone, a silver-colored ring of aluminum pickup is visible on all electrodes. However, the appearance of such a ring is different in the four electrodes used to weld the sheets with four different surface conditions. The ring is thin and clear with the chemically cleaned surfaces, thicker, yet still clear, with the degreased. The ring becomes blurry and thicker for electric-arc cleaned, and very fuzzy and thick for that with untreated condition. The change of the electrode surface is a direct result of metallurgical reactions occurring during welding, and therefore, the appearance provides a possibility of understanding the metallurgical processes and the trend of electrode deterioration if the electrodes are to be used for more welding using the same schedule. A thick and blurry ring of Al pickup may represent an unstable electrode-sheet contact during a continuous welding process, as resulting from alloying between Cu and Al and removing the resultant bronze from the electrode surface at many locations.

On the other hand, a clearly defined and narrow silver band may be the result of a consistent contact between the electrode and the sheets, with a lesser amount of material removed from the surface. Oxidation of Cu is also observed on the electrode faces. Fig. 4A and B appears less oxidized than Figure 4C and D. The surfaces of the electrodes show a significant roughening (in the form of small craters) on those using untreated and electric-arc cleaned sheets, while the electrodes used on chemically cleaned and degreased sheets are much smoother.

Figure 4 clearly shows that welding using sheets of different surface conditions creates distinctively different appearances of electrode faces. Recognizing such differences may help in predicting electrode life after making only a small number of welds. This is possible by linking the features of these electrodes to their respective electrode lives produced in electrode life tests.

Effect of Welding Schedules

The alloying between copper electrodes and aluminum sheets is also influenced by electrode force and welding time. As shown in Fig. 5, the profiles of Cu, Al, and Mg along a line through the electrode center, measured through a line scanning of chemical composition, depend on both factors. Low electrode force (4.5 kN) and long welding time (180 ms) generate more heat at the electrode-sheet interface, and therefore a larger amount of alloying with Al and Mg (Fig. 5B) than with a shorter welding time — Fig. 5A. A similar effect of welding time is also observed with higher electrode force (9.0 kN, as in Fig. 5C, D), but the severity of alloying is significantly lessened with high electrode force, as can be seen by comparing Fig. 5A with 5C, and 5B with 5D. A large electrode force creates low contact resistance, and therefore less heat generation and alloying at the electrode-sheet interface. Thus, a large electrode force is preferred for electrode life.

Effect of Surface Conditions on Electrode Life

The electrode lives determined by welding using sheets of four different surface conditions are shown in Fig. 6. In welding chemically cleaned sheets more than 2300 quality welds were produced; the electrodes were slightly worn and they were still far from the end of their lives as shown in Fig. 6A. Electrodes used to weld degreased sheets have a life of more than 2000 welds — Fig. 6B. In this case, the variation of weld diameters grows large at the end of the electrode life, but is significantly smaller than those for electric-arc cleaned and untreated sheets — Fig. 6C, D. As shown in Fig. 6C, the electrode life is about 1700 welds when sheets were electric-arc cleaned. When untreated sheets were used, the electrode life is about 200 welds, which is significantly

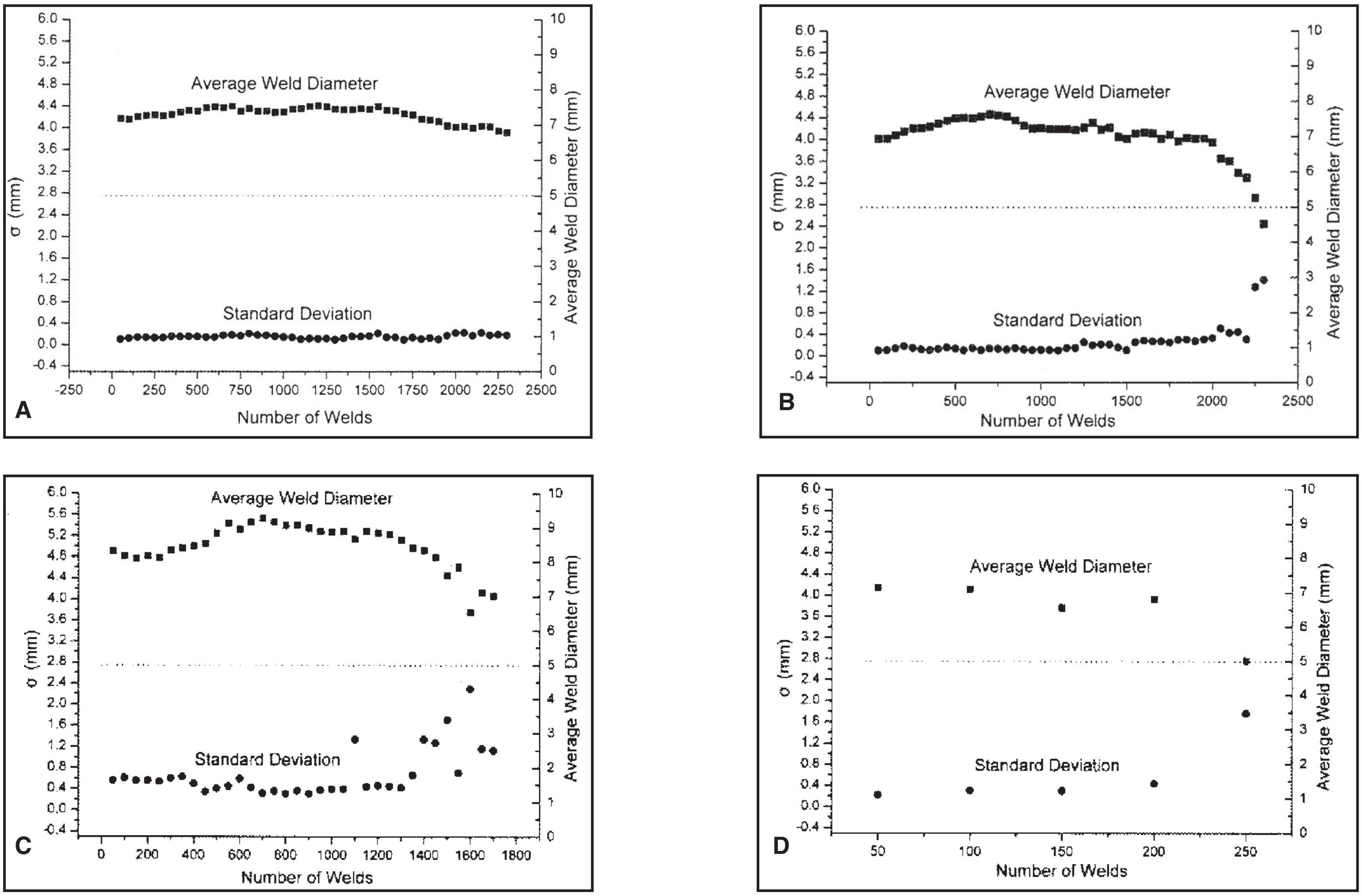

Fig. 8 — Average diameters and standard deviations of welds. A — Chemical cleaning; B — degreasing; C — electric-arc cleaning methods; D — untreated sheets.

shorter than any of those treated sheets. Therefore, the surface condition of sheets plays a key role in determining electrode life in welding Al..

The faces of electrodes after electrode life tests using various surface conditions are shown in Fig. 7, arranged in the same order as their electrode lives — Fig. 6. The electrodes used in welding untreated sheets (Fig. 7D) appear less worn than others. However, they were used to make only about 200 welds, while the others made 1700 welds (electric-arc cleaning, Fig. 7C) or more than 2000 welds (chemical cleaning, Fig. 7A; and degreasing, Fig. 7B).

The effects of surface conditions on electrode life can be evaluated by considering the magnitude and uniformity of contact resistance between the electrode and sheet. The contact resistance can be directly measured, or it can be indirectly estimated using the linear relationship between the contact resistance and oxide thickness established by Leone and Altshuller (Ref. 5). Chemically cleaned surfaces have the thinnest oxide layer (Fig. 2), and therefore, the lowest contact resistance, as shown in Fig. 3, and they produced the longest electrode life. On the other hand, untreated sheets exhibited the highest contact resistance and yielded the shortest electrode life.

The impact of contact resistance is clearly shown by the appearance of the electrodes at the end of their respective lives in Fig. 7. Low contact resistance benefits the electrode life primarily due to less oxidation and alloying, which results in less heating at the contact interface and long electrode life. The electrodes used to weld chemically cleaned sheets have slight alloying and oxidation on the surface after the life test, and those for degreased sheets have craters due to depletion of bronze, and a large area of Cu-Al alloying. The electric-arc cleaned sheets deteriorated the electrodes the most, as evidenced by the large number of craters and Al pickup/alloying on the electrode surfaces.

The consistency and uniformity of electrode-sheet contact play an important role in determining electrode life. As discussed in previous sections, nonuniformly distributed contact resistance on a sheet surface induces uneven, localized heating between the sheet and a Cu electrode during welding. Severe oxidation and alloying may occur at these locations, resulting in a nonuniform distribution of surface resistivity on the Cu electrode face, which in turn, affects subsequent welding. Oxidation and alloying occur on the electrode surface during every welding cycle. An accumulative effect of such a process is the continuous deterioration of the electrode surface. As a result, the current distribution changes from weld to weld and produces inconsistent welds if the electrode surface damage is severe enough.

Although Fig. 3 shows that electric-arc cleaned sheets have a lower, and more consistent contact resistance than degreased sheets, it is not always possible to create a uniform and consistent surface by electric-arc cleaning, especially when it's performed manually while trying to achieve sufficient cleaning without melting the surface. The rough surface of the electrode after 60 welds shown in Fig. 4C may be the result of the inconsistently arc-cleaned sheet surfaces. This explains that electric-arc cleaning produces lower contact resistance but shorter electrode life

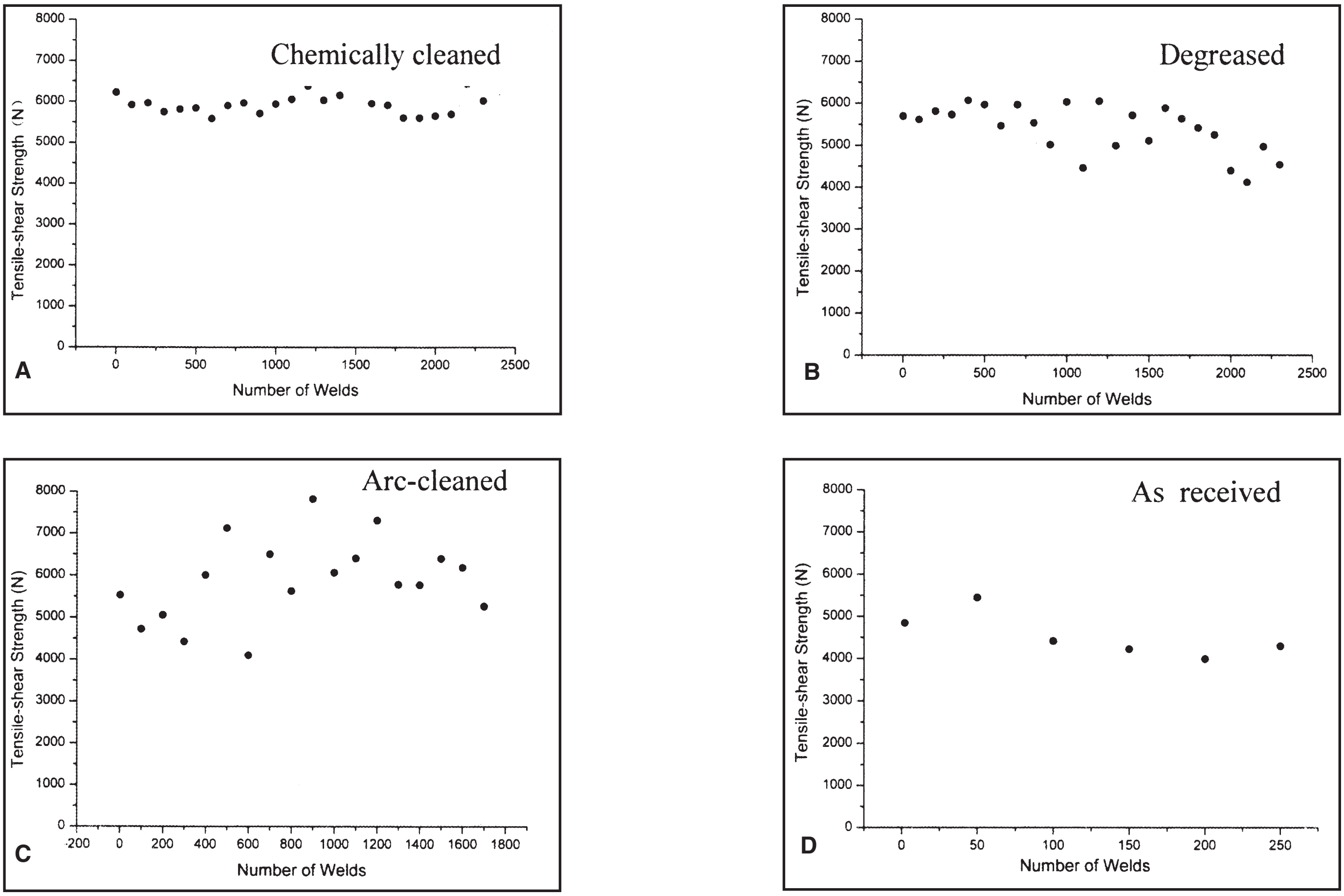

Fig. 9 — Tensile-shear strengths of welds. A — Chemically cleaned; B — degreased; C — electric-arc cleaned; D — untreated sheets, taken during electrode life tests.

than degreasing. Another possible reason is that the thin aluminum oxide layer remaining on the sheets after degreasing would serve as a protection layer, which prohibits the interdiffusion between Cu and Al, while not producing much localized heating in the contact area.

The modified surface properties of the electric-arc cleaned sheets may be responsible for the relatively short electrode life. The surface of such a treated sheet is softened by electric-arc heating, which results in a large contact area between the electrode and the sheet under an electrode force of 9 kN. Therefore, welding such sheets needs high electric current in order to achieve a minimum current density for making a weld. As shown in Table 2, welding electric-arc cleaned sheets requires the highest welding current and longest welding time among all surface conditions. The surfaces of the electrodes used to weld electric-arc cleaned sheets in Fig. 7 have significantly more damage than those using other cleaning methods. There are many large and deep craters, large area of Al deposit, and the contact area appears significantly larger than others. When intensive alloying and alloy depletion from an electrode surface occur, the effective contact area between the electrode and a sheet surface becomes unstable — it can be small at one weld and result in a large current density, and it can be large at the next weld and result in very low electric current density producing low weld penetration or an undersized weld. Such changes in contact area are random and produce large variations in the welds created.

Electrical polarity appears to have some effects on the electrode deterioration. Similar effects were discussed by Lum et al. (Ref. 8). In Fig. 7, for each pair of electrodes, the one on the left side was taken from the lower or negative electrode arm. These electrodes appear less damaged than those on the right side, which were taken from the upper, or positive electrode arm. This phenomenon might be explained considering the micro morphology of the contact interface and the dynamics of resistance heating, and is not a subject of this study.

The variability of weld quality in a welding process is an important index in production. It may also provide a useful indicator for electrode life, as a large variability indicates that the welding process becomes unstable, and it may be close to the end of electrode life. In order to understand the influence of surface conditions, both average weld diameters and standard deviations are plotted in Fig. 8. These quantities were calculated on every 50 welds in the electrode life tests. Welding chemically cleaned sheets produced fairly consistent welds and a small, but almost constant standard deviation — Fig. 8A. It can be seen, when welding under other surface conditions, that accompanying a drop in the average weld diameter when an electrode life approached its end, the standard deviation of diameters increased dramatically. From the figure, it can be seen that an increase of about 300% in standard deviation is observed for all surface conditions when the electrode life was reached. The standard deviation before the sudden increase is about 0.4 mm, and it jumps to about 1.4 mm or more, accompanied by a visible drop in weld diameters when it's close to an electrode life. In the case of electric-arc cleaning, the first such increase in standard deviation doesn't correspond to an average weld diameter falling below the desired value. However, this occurrence is fairly close to the end of the electrode life. Therefore, the change in standard deviation of weld diameters during welding can be a useful index for electrode life.

Tensile-shear strengths of the welds of various surface conditions are shown in Fig. 9. One of every 100 welds during electrode life tests was tested, except for untreated sheets for which one of every 50 welds was tested. Chemical cleaning again produced the highest strength with the least variability. Degreasing has lower strength and larger variability, and electric-arc cleaned is quite unstable, similar to those observed in Fig. 6 for measured weld sizes. Such differences can be attributed to the magnitude and distribution of contact resistivity of the sheets cleaned using different methods.

Relation between 60-Weld Electrodes and Electrode Lives

As seen in Fig. 4, the electrodes used to weld sheets of different surface conditions have distinctively different characteristics. The subsequent electrode life tests proved that the electrode lives are different. Therefore, it is possible to predict the electrode life for a particular stack-up of sheets and welding schedule, only after a small number of welds, such as 60 welds, as in this study. By analyzing the features shown in Fig. 4 and linking them to the corresponding electrode lives, the following observations can be made:

1) The border of the reaction area on the electrode face. An electrode of long life tends to have a small, thin, yet clear silver band on the surface after a small number of welds. Such a band indicates a stable contact between the electrode and the sheet. On the other hand, a large, thick, and fuzzy silver band may indicate a short electrode life, as in the cases of electric-arc cleaning and untreated sheets because of the repeated alloying and removal of the alloy.

2) Black oxidation (burning) marks at the center of an electrode face. Inside the silver band there is usually an area of oxidation that is directly related to the cleanness of the electrode-sheet interface. Greases and other organic compounds at the interface may be burned under the intensive heating during welding. As such reaction is due to low conductive or even insulating substances at the interface, it directly reflects the contact resistivity or resistance. Therefore, it affects the deterioration of electrodes and electrode life. By comparing Figs. 4 and 6, it can be seen that small and light burning marks on the electrode face after 60 welds indicate a long electrode life, and large and dark burning marks correspond to a short electrode life.

Such an understanding may help predict the electrode life for a combination of sheets, electrodes, and welding parameters by conducting a small number of welds that produce visible characteristics on the electrode faces, as observed in this study. However, a detailed and quantitative relationship between electrode surface features and electrode life needs a more thorough and well-designed investigation to develop.

Summary

In this study, the effects of sheet surface conditions on electrode life have been investigated. Using four types of surface treatments, namely, chemical cleaning, degreasing, electric-arc cleaning, and original (untreated), drastically different electrode lives were obtained. The effects of surface conditions on electrode life can be attributed to the influences of the magnitude and distribution of surface resistivity, as summarized in the following.

Chemical cleaning. It produced the thinnest and most uniform layer of Al_2O_3 on sheet surfaces. The greases on surfaces are also largely removed in the process. As a result, very little alloying and oxidation occur during welding, yielding a long electrode life (more than 2300 welds, yet far from the electrode life).

Degreasing. It did not change the thickness or the uniformity of Al_2O_3 on sheet surfaces. Welding using degreased Al sheets can produce an electrode life of more than 2000 welds in this study.

Electric-arc cleaning. It produces similar contact resistance compared with chemical cleaning, and a significantly longer electrode life (about 1700 welds) than untreated surfaces. However, electrode life shorter than those using the degreasing cleaning method, which has a higher surface contact resistance.

Original surface. The untreated sheets have both greases and oxides on the surfaces, and the electrode life in welding such sheets was about 200 welds.

In general, the surface condition of Al sheets plays an important role in affecting the electrode life. From this study it can be concluded that welding untreated sheets without dressing the electrodes is not practical. The electric-arc cleaned surfaces produced a shorter life than degreased, and therefore, a low-contact resistance doesn't guarantee a long electrode life. Although chemical cleaning produced desirable electrode life, it is costly, time-consuming, and environmentally unfriendly. Degreasing is more practical than other cleaning methods and it may be adopted in large-volume production, such as automobile manufacture.

The tensile strength of welds tested during electrode life tests shows a similar trend as the weld diameter. This study also shows that together with the average weld diameter, the change in standard deviation of weld diameters provides a feasible indication of electrode life. The rapid electrode life determination method using only 60 welds provides a possibility of selecting appropriate welding schedules, sheet stackups, and surface conditions for prolonged electrode life.

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