

Influence of Lubricants on Electrode Life in Resistance Spot Welding of Aluminum Alloys

One lubricant was found to extend the electrode life to almost double that of the unlubricated surface

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ABSTRACT. Rapid electrode tip degradation and inconsistent joint strength are two major problems associated with resistance spot welding of aluminum alloys. A new approach of lubricating the contact between electrode and aluminum sheet to influence and perhaps extend the electrode life was examined. Different metal-working lubricants were placed between the electrode and aluminum sheet to produce different surface conditions. Keeping all weld conditions constant, electrode life experiments were conducted for both lubricated and unlubricated conditions. Joint shear strength values were periodically measured as hundreds of welds were made until either explosion/sticking occurred or a drop in the shear strength indicated the end of the effective electrode tip life. For the same welding conditions and failure criterion, one "good" lubricant was found to extend the electrode life to almost double that of the unlubricated surface (as received). A second set of experiments was performed to examine the action of the good lubricant. These experiments involved a variety of smaller studies including scanning electron microscopy, x-ray diffraction, hardness measurements, and electrical resistance measurements. The results of this second set of experiments suggested that the good lubricant thinned the surface oxide layer, thus reducing the heat generation at the electrode-worksheets interface. This lower heat generation reduced alloying and pitting rate, thus increasing electrode tip life. Future work on improving the good lubricant was contemplated.

Introduction

Because of their light weight and high strength-to-weight ratio, the use of aluminum alloys in automotive bodies is gaining popularity. The advantages of weight savings (up to 46% (Ref. 1)) and corrosion-resistant properties are considerable. Aluminum Alloy 5182 is particularly developed for automotive bodies with low surface preparation cost (Ref. 2) and is very popular in Japan (Ref. 3). Resistance spot welding (RSW) is one of the most popular sheet metal welding processes in the automotive industry because of its low cost, easy automation, and minimum skill requirements (Ref. 4). Resistance spot welding of aluminum alloys has two major problems: short electrode tip life and inconsistent weld quality (Ref. 5). An electrode can be considered to have failed, thus ending its effective life, if it produces a weld with a shear strength that drops below a certain percentage of the initial value. In some cases, even if the weld shear strength remains high enough to avoid being classified as failed, the electrode starts sticking to the worksheet surface and may produce holes in it accompanied by an arc plus an explosion during the weld process. If this condition is reached, the electrode is not safe for operation and is thus considered to have failed (Ref. 6). Electrode life, then, depends on its ability to produce strong enough welds and to permit welding to proceed without serious

operational disturbances. Electrode life in RSW of aluminum alloys depends on welding parameters (current, time, and force) (Refs. 4, 7) along with electrode design features such as copper alloy selection, coating of the tip, and the macro geometry (Refs. 3, 8, 9). These parameters have received considerable research attention, but electrode life also depends on certain initial tribological features of both the worksheet (Refs. 10, 11) and the electrode (Ref. 12).

Much is known about the electrode degradation behavior (tribology of progressive electrode wear) that eventually ends electrode life during RSW of aluminum. It starts with local alloying of electrode and sheet material during the current cycle. The alloying causes irregularity in both the current and contact pressure distribution, which in turn results in material pickup and pitting of the electrode (Refs. 13-16). Based on these findings, electrode life can be divided into four stages (Ref. 14) and the variation of joint strength can be explained in terms of the contact area between the electrode and the worksheet and pitting of the electrode (Fig. 1) as follows.

Stage I: Contact area grows without any significant pitting; joint strength increases.

Stage II: Joint strength reaches maximum as contact area continues to grow with incipient pitting of electrode.

Stage III: Joint strength starts decreasing as contact area continues to grow but, at the same time, the pitting of the electrode becomes significant and continues to form large cavities.

Stage IV: Joint strength reaches the failure criterion as large cavities appear on the tip surface of the electrodes.

The alloying at the electrode-worksheets (EW) interface is triggered by the excessive heat generation caused by the

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high electrical resistance at the contact. However, it must also be remembered that this type of heat generation is responsible for the actual RSW at the faying surfaces (FS) of the aluminum alloy sheets and thus cannot be avoided (Refs. 17, 18). Consequently, the electrical contact resistance at both these interfaces (EW and FS) is of great importance to the RSW of aluminum alloys. While heat generation at the faying surface governs the actual weld nugget formation, heat generation due to electrical contact resistance at the EW interface can influence nugget growth (Ref. 17) and cause the sequence that leads to electrode tip failure as mentioned previously.

The electrical contact resistance at the EW interface and thus the degradation of the electrode tips can be influenced by various tribological features. In particular, the surface microstructure involving oxide layers, surface roughness, and the presence of a lubricant at the EW interface affects the degradation and ultimately the current flow to the FS interface where the spot weld is formed. The oxide layer (Al_2O_3) on an aluminum surface is often considered to be a uniform ceramic coating or layer. While this may be close to reality for high-purity aluminum, the oxide layer on the aluminum alloy sheets for automotive bodies is much more complex (Refs. 2, 19). The oxide layer is important because its thickness is an influential parameter in the electrical resistance (Ref. 20). Surface roughness, along with the elastic-plastic properties of the materials, also influences the electrical contact resistance (Ref. 21). Finally, the use of a lubricant to change the contact tribology has been considered to a limited extent (Refs. 22, 23).

Some research efforts have been made to alter the tribology of the contact at the EW interface by either periodically cleaning (dressing) the electrode tip (Ref. 14) or coating it with other materials (Ref. 8). However, such procedures may interrupt the manufacturing activity that involves RSW. In the present study, a different but somewhat similar approach is adopted. Since autobody sheets go through several manufacturing processes (rolling, stamping, etc.) before being placed in the vehicle and different lubricants are used for these processes, instead of using a material coating, a thin layer of lubricant is placed at one side of the aluminum sheet that touches the electrode (i.e., only at the EW interface). The strategy behind this approach is to alter the contact resistance at the EW interface without altering any feature of the FS, thus altering the tribological sequence of alloying, pickup, pitting, and eventually electrode tip failure. This approach has the merits of being sim-

ple and flexible and not interrupting the RSW manufacturing activity, and hence is more practical for the industry. The objectives of the present study are to continue and expand the previous research efforts of Rashid et al. (Ref. 6) in order to quantify the effect of using various lubricants and to eventually find an optimal lubricant for improving electrode life. The focus was given to investigate the change in electrode life and pitting behavior under similar weld conditions by changing only the surface feature of the worksheet at the EW interface. The EW surfaces are studied both physically and chemically, and the inevitable scatter of results in this complex process is dealt with by a statistical analysis. In addition, some analytical arguments are presented to explain some of the results.

Materials and Methods

Aluminum Alloy 5182 sheets (Table 1) of 1.5 mm thickness were used for the entire study. All welding was performed using a 170-kVA, medium-frequency direct current (MFDC) spot welding machine (pedestal type, custom made for University of Waterloo by Centerline Ltd., Windsor, Canada). The electrodes were Class I (Ref. 7) type made from copper and 0.15% zirconium. These electrodes were truncated type (taper angle 60 deg) with spherical tip of face diameter 10 mm and radius of curvature of 50 mm — Fig. 2. Since EW interface was the focus of the work, all experiments were performed on an aluminum alloy surface that was either (mill finished) as received or lubricated with one of six lubricants (L1-L6) that had been developed for various other metal-

Table 1 — Chemical Composition of the Aluminum Alloy (AA 5182)

Element	wt-%
Mg	4.71
Mn	0.32
Fe	0.19
Si	0.08
Cu	0.05
Cr	0.01
Zn	0.01
Ti	0.02
Al	Bal

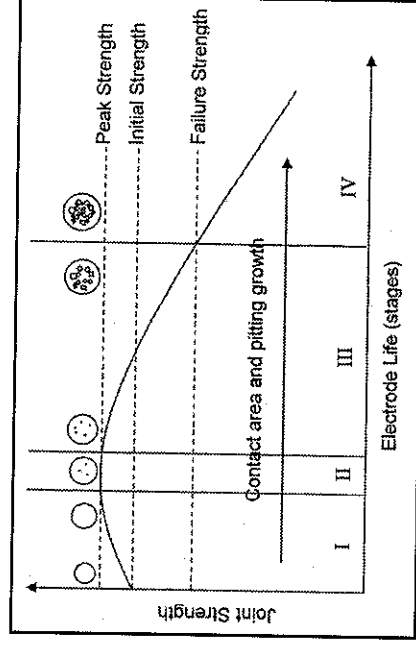


Fig. 1 — Schematic illustration of the four stages of electrode life; correlating the joint strength with contact area between electrode and worksheet and pitting of electrode.

working processes. A surface (or A) indicates those experiments where all four sheet surfaces (sheet surfaces at the top and bottom EW-interfaces and FS) were used in "as-received" conditions while Lx-surface (or Lx-, where x denotes the particular lubricant, 1, 2, .6) represent those experiments where sheet surface at the top and bottom EW-interfaces were lubricated while FS was kept "as received." For example, an L2 surface (or L2-) represents a condition where sheet surfaces at the top and bottom EW interfaces were lubricated with lubricant L2 and FS was kept "as received." The welding parameters, including current, time, and weld (normal) force had been selected based on preliminary investigations on the A surface and kept unchanged for all surfaces.

Electrode Life

Since the present approach was relatively new and not much information was available in the literature, an initial screening test was performed (Ref. 6) that contributed directly to the methodology of the present study. The screening test involved 100 spot welds on each of the Lx-surfaces and A surface. Lubricants were applied only to one side of the aluminum

Table 2 — Welding Parameters (1 cycle = 16.67 ms)

Weld Schedule	Squeeze	25 cycles
	Weld time	5 cycles
	Hold time	12 cycles
Welding Parameters		
Weld (Normal) force	6 kN	
Current	29 kA	
Welding rate	20/min	

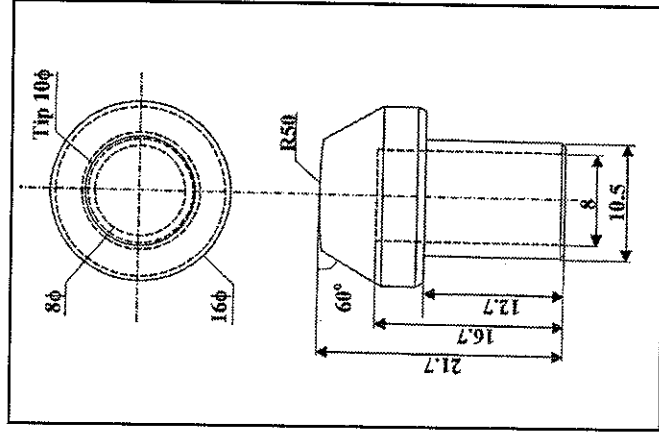


Fig. 2 — Schematic of RSW electrode (all dimensions in mm).

alloy worksheet that touches the electrode (top and bottom) and kept away from the FS. The lubricant was first spread on the worksheet surface using saturated cotton wipes and then allowed to “soak in” for various times (10–30 min) depending on the manufacturer’s recommendations. The L6 lubricant was an exception because it formed a solid layer that became harder with time and so the spot welding was started 2–4 min after surface application. Following the soak-in period, the worksheet surfaces were wiped with soft tissues to leave a very thin, uniform film of lubricant. Since the focus of the study was the EW interface, two of these lubricants were selected for detailed investigation by considering their influence on the electrode degradation behavior. Details of this selection will be presented in the Results and Discussion section of this paper.

Electrode life tests were conducted for L2 surfaces, L6 surfaces, and A surfaces; three life tests were performed for each surface condition. In these electrode life experiments, resistance spot welds were performed on standard welding “coupons” (10 spot welds on 50- \times 400-mm aluminum strips with 35-mm gap between

them). For joint strength measurements, resistance spot welds were performed on overlapped (shear test) specimen of size 30 \times 120 mm with an overlap of 30 mm — Fig. 3. Instron tensile testing machine (Model-4206, Canton, Mass.) was used to measure the shear force of these specimens. Five of these specimens were welded with an interval of 50 spot welds on standard coupons (i.e., measuring weld numbers 1–5, 56–60, 111–115, etc). Each of these life tests also included several sets of carbon imprints of the electrode surface at various stages, all taken by putting carbon paper between electrode and worksheet and applying the same weld force (6 kN) but without any current passing through the contact. These carbon prints showed the contact areas and some gross topographic features such as pitting and material transfer (pickup).

Since the purpose of the study was to investigate the effect of the lubricant, the same failure criterion was set for all surfaces on the basis of the A surface. A tip life failure criterion was specified as a “drop in weld shear strength below 3.92 kN,” which was about 80% of the initial weld shear strength of the A surface. A second criterion was also set in which the electrode tip was considered to have failed if “excessive sticking or explosions occurred” as mentioned previously in the Introduction section. These allowed a definitive end point for the electrode life tests and permitted a comparison of the influence of the lubricants.

Features of L-Surface RSW

A second set of experiments was performed that involved RSW on the two selected lubricated surfaces (mostly concentrating on the L2 surface that performed the best in the electrode life experiments) and the A surfaces. The intent was to determine how the lubricants influenced electrode life. Four identical experiments were performed to explore the repeatability of the results. Each experiment consisted of performing RSW on overlapped (shear test) specimen (Fig. 3) alternatively five each on L2 surfaces and A surfaces with the same pair of electrodes. All conditions were kept the same and the electrodes were wiped with methanol between each spot weld. In this manner, the influences of the subtle differences between

electrode surfaces on RSW were much reduced and only the influences of the surface characteristics of the worksheet at the EW interface on RSW were highlighted.

As in the electrode life experiments, a tensile testing machine was used to determine the joint shear strength but this time optical microscopy was also used to measure the weld nugget diameter after the shear strength test as well as the diameter of indentation of the upper electrode into the worksheet. Spot welds on L2 surface and A surface were sectioned longitudinally and observed with optical microscopy to explore weld nugget geometry. Also, hardness measurements were performed prior to the welding using a standard Vickers hardness tester (LECO MHT-200 Vickers microhardness tester, Wilson Instrument, Canton, Mass.) with a load of 50 kg, on L2 surface and A surface to explore the change in hardness of the worksheet surface with the application of lubricant (L2). The various differences between the L2 surface and A surface were assessed with an elementary statistical analysis (student’s t-test with a 0.05 significance level).

In order to obtain some higher resolution images along with energy-dispersive x-ray analysis (EDX), scanning electron microscopy (SEM) was used with a Jeol-840 microscope (Jeol Ltd., Tokyo, Japan) at an accelerating voltage of 20 kV. To analyze some of the adherent surface layers on both the A surface and L2 surface, electron spectroscopy for chemical analysis (ESCA) were used (ESCALAB-250, VG Scientific, East Grinstead, UK). In addition, the alloys formed on the electrode tips were identified using x-ray diffraction (XRD) performed with a Siemens D-500 powder diffractometer (Berlin, Germany). All surfaces were cleaned with methanol before being placed in the various high-vacuum chambers.

Electrical contact resistance (static) of the EW interface was also measured to investigate the influence of lubricants on the surface regarding heat generation. Ten additional aluminum sheet specimens of 50- \times 40-mm size (to avoid the shunting problems that would occur in the longer standard coupons) were prepared for each of the L2 surfaces and A surfaces so that the resistance across the EW interface could be measured along with surface roughness of the aluminum sheet. Using the MFDC

Table 3 — Significant Events for Each Life Test

Electrode Condition	A surfaces			L2 surface			L6 surface		
	1	2	3	1	2	3	1	2	3
Visible pit initiation on electrode	65	96	180	395	49	81	12	2	4
Pitting visible in carbon imprint	110	110	220	440	110	110	53	33	33
Peak strength	110	110	165	445	225	225	108	35	35
Electrode fail	420	325	435	775	720	700	198	37	58

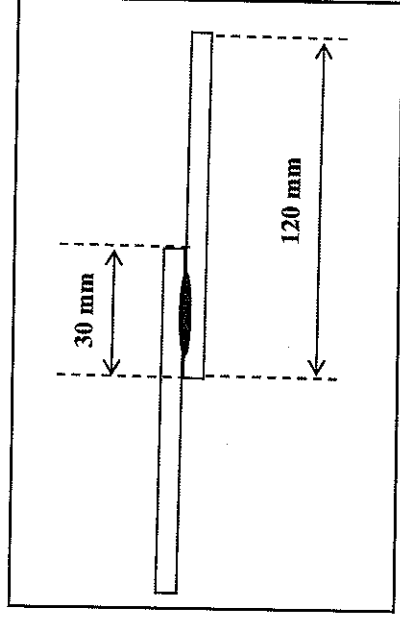


Fig. 3 — Sample geometry for overlapped specimen for joint strength measurements.

spot welding machine, the specimens were clamped between the electrodes with the same welding force (6 kN) that was used for the RSW. The contact resistance of EW interface was measured at room temperature by measuring voltage drop while passing a 10-A current through the electrodes (Fig. 4, (Ref. 24)) using a digital low resistance ohmmeter (DLRO-10X, AVO International, Scunthorpe, UK). The centerline-average surface roughness (Ra) of the worksheet was also measured with a direct contact profilometer (Surtronic +3, Taylor Hobson Ltd, Leicester, UK).

Results and Discussion

Electrode Life Test

Results from the initial screening tests (Fig. 5) showed that all these lubricants influenced RSW (Ref. 6). Optical stereoscopic views of the top (positive) electrodes at low magnification showed that most of the lubricants sustained combustion due to high heat generation at EW interface. Consequently, electrode degradation occurred even more rapidly than for the A surface that did not have any lubricant. However, the electrodes for the various lubricants degraded at different rates. Welding on the L2 surface produced an almost clean electrode tip surface while welding on the L6 surface showed the heaviest degradation of electrode. Both these lubricants were water-based synthetic lubricant used for metalworking of ferrous and nonferrous (including aluminum) alloys. These two lubricants then selected for further investigation as “good” and “bad” lubricants for RSW of aluminum alloys.

Although the results were somewhat scattered, the electrode life experiments showed that, for the same welding conditions, the “bad” lubricant (L6 surface)

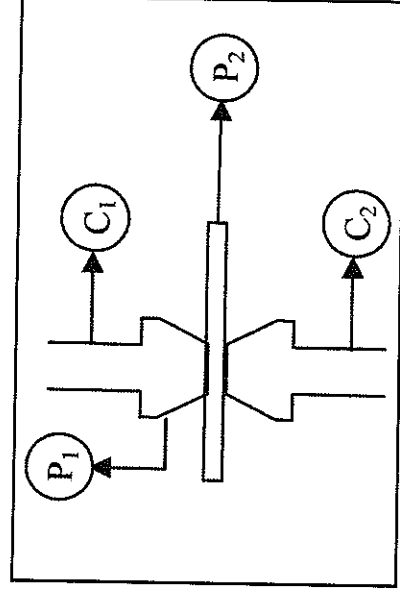


Fig. 4 — Layout for static resistance measurement (four-point method).

caused electrode failure at very early stages, while the “good” lubricant (L2 surface) extended the electrode life to almost double the electrode life of the A surface. Figure 6 shows the electrode life results for A and L2 surfaces in terms of joint shear strength plotted against weld spot numbers. The straight line (dashed) represents the failure load at 3.92 kN as described earlier. All these curves followed the four stages of electrode life, i.e., joint shear strength increased initially and reached a peak before dropping down to the failure mark (as shown in Fig. 1). The average electrode life for L2 surfaces was 730 welds (range: 700–775) while the average electrode life for A surfaces was only 393 welds (range: 325–435). In the case of the L2 surface and A surface, the declining joint strength defined failure while for the L6 surface, electrode sticking and explosion defined failure. In all three tests with L6, the electrode started pitting at a very early stage. Then, the electrodes started sticking to the work surfaces and producing explosions so that the average electrode life was 98 welds (range: 37–198). Thus, it was very clear that lubricants on the worksheet surface could influence electrode life.

The sequence of significant events in electrode life included detection of pitting, peak joint shear strength, and failure (Table 3). The degradation of the electrode surfaces was illustrated by carbon imprints taken at various stages — Fig. 7. While welding on L6 surfaces, significant physical damage to the electrodes occurred. For L2 surfaces and the A surfaces, it was alloying, pickup, and pitting that were the main indicators of electrode degradation (Table 3). However, different alloying and pitting rates occurred for these surface conditions. In general, an early start of pitting caused early failure of the electrode; however, based on the pre-

sent observations, it was discovered that the rate of alloying and pitting should also be considered for predicting electrode lives. In two out of three tests of both the L2 and the A surfaces, pitting started at around 110 welds but for all of the L2 surfaces, the rate of pitting was slower with large central portions not pitted and remaining in contact until about 500 welds compared with about 200 welds for the A surfaces. The larger number of welds needed (Table 3) for the L2 surfaces to reach the peak joint strength (Stage II) supported this view of the importance of pitting rate.

Another interesting observation from electrode life tests (Fig. 6) was the joint strength for these surfaces. Though there was considerable overlap in the data, the joint strength of the L2 surfaces, during the initial stage of the life, were slightly lower than that of A surfaces. However, after the first few welds, the joint strength of the L2 surfaces starts exceeding that of the A surfaces and remains higher to produce longer electrode life. Since welding conditions, failure criterion, and FS characteristics were kept the same for all these surfaces, the difference in pitting rate and, hence, electrode life occurred due to change of the only variable, i.e., the surface characteristics of the worksheet at the EW interface. This effect was further investigated in the following sections.

Features of L-surface RSW

A detailed investigation was conducted to explore the possible reasons for the different performance of the two lubricated surfaces (L2 and L6 surfaces) compared with the A surface. The focus of this investigation was on the “good” lubricant (L2). As mentioned earlier, there was a very slight difference between the initial joint strength of A and L2 surfaces,

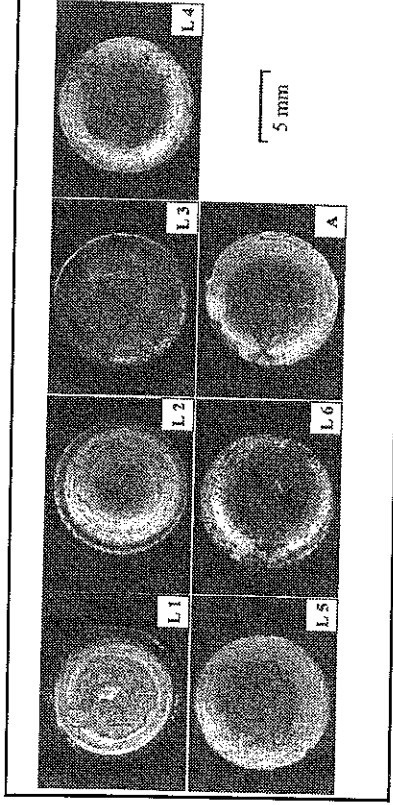


Fig. 5 — Optical stereomicroscope images of the electrode surfaces for different lubricants in the screening test after 100 welds (Ref. 6).

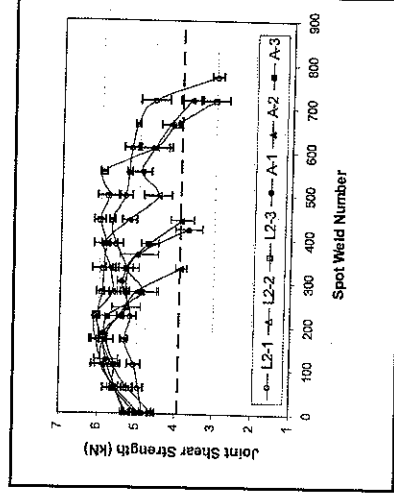


Fig. 6 — Electrode life tests for L2 and A surfaces with horizontal (dashed) line representing the failure strength.

tial joint shear strength in more detail, a second set of experiments was performed (as described previously) and included measurements of weld nugget diameter as well as the diameter of the indentation of the electrode tip into the worksheet surface.

Initial Joint Shear Strength

When planning this second set of experiments, it was realized that it was not possible to provide exactly the same electrode (even if they are selected from the same batch) or worksheet surfaces (even if they are from the same sheet). Small variations in microstructure and roughness of the surfaces were essentially inherent in them, and they could significantly influence the tribological interaction of the surfaces and thus the weld strength and ultimately the electrode tip life. However, as described previously, if the same electrodes were used for small numbers of successive welds of the A surface and the L2 surface, the variable nature of the electrode tip could be eliminated and the variable nature of the worksheet surfaces could be tested.

Four sets of joint strength experiments were performed; in each set five over-

Surface	Test 1		Test 2		Test 3	
	Weld No.	Imp. No.	Weld No.	Imp. No.	Weld No.	Imp. No.
L2-surface	0	0	0	0	0	0
	165	110	110	110	110	110
	440	220	220	220	220	220
	550	330	330	330	330	330
	660	485	485	485	485	485
A-surface	0	0	0	0	0	0
	120	108	162	162	162	162
	180	152	216	216	216	216
	300	216	270	270	270	270
	360	270	378	378	378	378
L2-surface	420	324	432	432	432	432
	0	0	0	0	0	0
	165	110	110	110	110	110
	440	220	220	220	220	220
	550	330	330	330	330	330
L2-surface	660	485	485	485	485	485
	770	715	715	715	715	715
	0	0	0	0	0	0
	165	110	110	110	110	110
	440	220	220	220	220	220
L2-surface	550	330	330	330	330	330
	660	485	485	485	485	485
	770	715	715	715	715	715
	0	0	0	0	0	0
	165	110	110	110	110	110

Fig. 7 — Carbon imprints of the upper (positive) electrode during life tests, showing the development of surface pitting and cavity formation.

though there was considerable overlap. The average initial joint shear strength for each of the three tests of the L2 surfaces was 4.88 ± 0.32 kN, whereas for the A surfaces, it was 5.06 ± 0.26 kN and for the L6 surfaces it was even higher at 5.57 ± 0.23 kN. These differences, though not huge, provided some insight into the tribological mechanisms that were eventually responsible for the increased electrode tip life with the L2 surfaces. So, to explore the ini-

lapped specimens each from A surface and L2 surface were welded alternatively with the same pair of electrodes. Each of these sets showed higher values of joint shear strength for A surface compared with L2 surface — Fig. 8. For same surfaces (A surface or L2 surface), the variability between these sets were related to randomly distributed differences between these surfaces inherent to these kind of experiments. However, within one set, where the surface variability of the electrode tip was removed, the differences in joint shear strength of spot welds for the A surfaces compared with the L2 surfaces were related to the lubricant action. So, two sets of data were assembled, one containing all of the L2 surface data and the other containing all of the A surface data. The average joint shear strength for the L2 surface was 5.01 kN was lower than the average shear joint strength for the A surface of 5.37 kN. Although, the difference is not huge in terms of strength, it was statistically different ($p < 0.005$).

Nugget and Indentation Diameter

For good quality weld, joint shear strength was considered very likely to be related directly to the nugget diameter. And, therefore, it was decided to investigate the nugget diameter in order to validate its relation with the joint strength as well as the weld quality. As expected, the nugget diameter distributions (Fig. 9) looked very similar to the joint shear strength distributions (Fig. 8). Using the same assumptions as before, two sets of data were assembled, one containing all of the L2-surface data and the other containing all of the A-surface data. The average nugget diameter for the L2 surface of 6.57 mm was statistically smaller than the average nugget diameter for the A surface of 6.78 mm ($p < 0.001$). In the process, it was also found interesting that

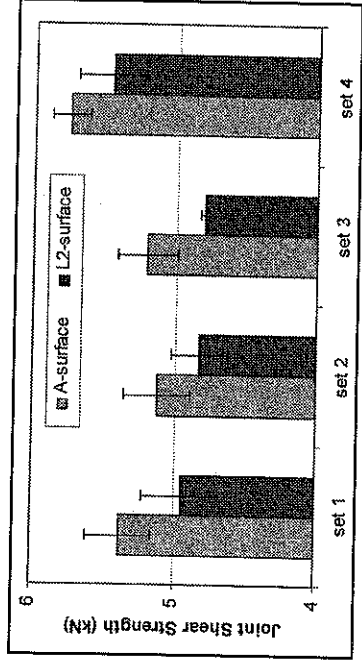


Fig. 8 — Joint shear strength (each set welded with the same pair of electrodes).

the two surfaces showed a difference in the diameter of indentation of the upper electrode into the worksheet surface — Fig. 10. The same data assembly was performed as described in the previous two paragraphs. The average indentation diameter for the L2 surface of 8.30 mm was again statistically smaller than the average indentation diameter for the A surface of 8.42 mm ($p < 0.001$). The implications of these findings are discussed in the next section.

Heat Generation at the EW Interface

One possible explanation for different initial joint shear strengths (or nugget diameters) of the L2 and A surfaces was related to the heat transfer from the FS through the EW interface to the cooling water that was circulated within the electrode. During the current cycle, heat was generated at the FS and melted the surrounding material to form the weld nugget that grew until the end of solidification (Refs. 17, 18). The electrodes were water cooled and the majority of the heat generated at the interfaces (EW and FS) was transferred to the cooling water through the EW interface. Clearly, the rate of heat transfer from the FS to the cooling water would be directly influenced by the heat generation at the interposed EW interface. Since lubricants were applied only at the EW interfaces and not at the faying surface, for the same amount of current and time, the heat generation at the faying interface is always the same. However, a lower heat generation at the EW interface would allow

a faster rate of heat transfer from the FS. This would result in lowering the time of solidification and hence a smaller weld nugget. Thus, the smaller average nugget diameter, reported in the previous section for the L2 surfaces compared with the A surfaces, indicated that there was less heat generation (lower temperature) at the EW interface for the L2 surfaces.

This smaller nugget diameter was illustrated by typical longitudinal sections of the L2- and A surface welds — Fig. 11.

There was further support for the concept of less heat generation and lower temperature at the EW interface for the L2 surface. Vickers hardness testing of the L2 and A surfaces were conducted prior to any welding. It was observed that the hardness of the aluminum worksheet did not change with the application of lubricant L2 to its surface. However, the results presented in the previous section indicated that, during the RSW, the average diameter of the indentation of electrodes into the sheet surface was smaller for the L2 surface compared with the A surface — Fig. 10. Since both these surfaces started

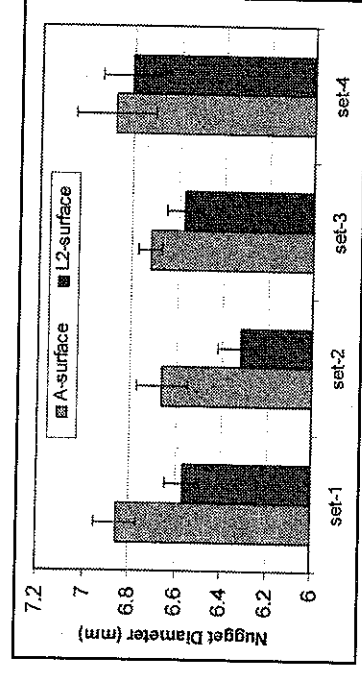


Fig. 9 — Nugget diameter (each set welded with the same pair of electrodes).

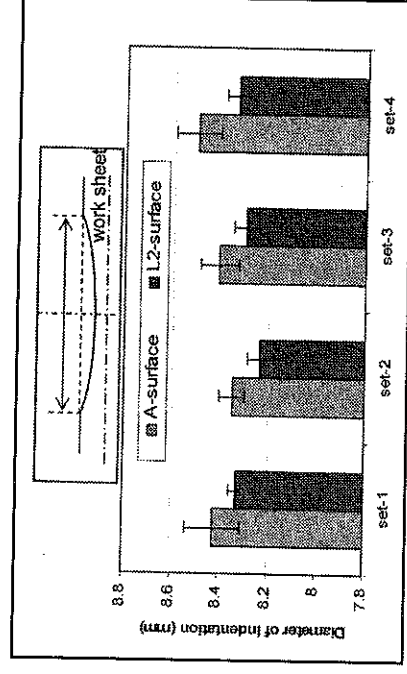


Fig. 10 — Diameter of indentation of the worksheet (each set welded with the same pair of electrodes).

with the same hardness level, one plausible explanation for different indentation was related to the heat generation at the EW interface. Since thermal softening of metals and alloys occurs at high temperature (Ref. 25), less penetration of electrode into worksheet for L2 surfaces suggested less thermal softening hence lower heat generation at this interface compare to A surface.

Having obtained support for the idea that the temperature at the EW interface was lower for the L2 surface than for the A surface, the next step was to find the reason for this lower temperature.

Surface Oxide Layer

A lower surface temperature would

Table 4 — Intermetallic Reactions for Different Cu-Al Phases (Ref. 27)

Reaction	Temperature (°C)
$L \leftrightarrow Al + \theta$	548.2
$L + \eta_1 \leftrightarrow \theta$	591
$L \leftrightarrow (Cu) + \beta$	1032
$\beta \leftrightarrow (Cu) + \gamma_1$	567
$\gamma_0 \leftrightarrow \beta + \gamma_1$	780
$\gamma_0 + \epsilon_1 \leftrightarrow \gamma_1$	873

Table 5 — Electrical Contact Resistance (Static) of the EW Interface and Centerline Average Surface Roughness (Ra) of the Worksheet (Ref. 6)

	A surface		L2 surface	
	Roughness (μm)	Resistance ($\mu\Omega$)	Roughness (μm)	Resistance ($\mu\Omega$)
Lowest	0.30	10.3	0.28	7.8
Highest	0.52	13.5	0.34	9.4
Average	0.34	11.2	0.31	8.6
Std Dev	0.06	1.0	0.02	0.5

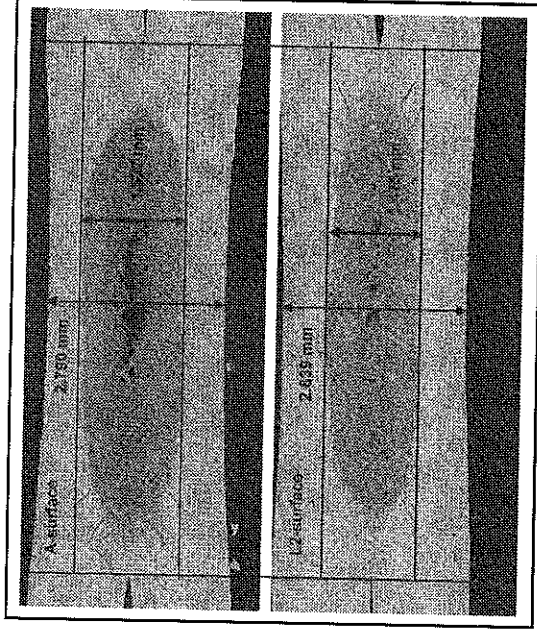


Fig. 11 — Typical nugget cross section (A surface and L2 surface).

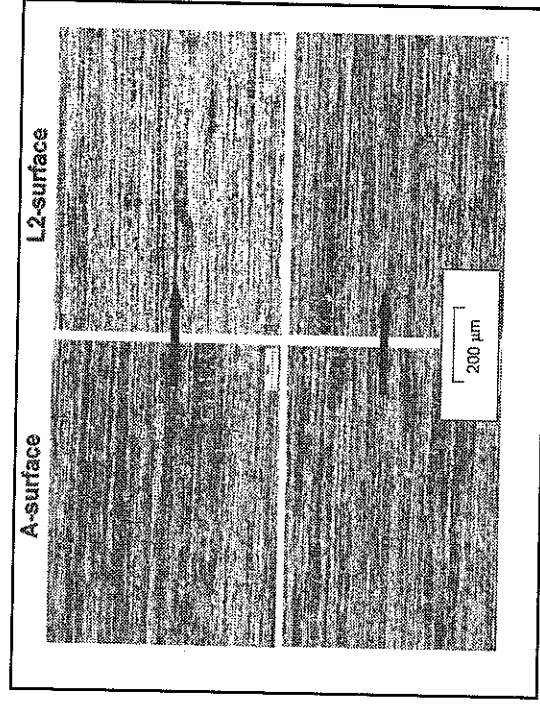


Fig. 12 — Optical microscopy showing the effect of good lubricant (L2) on an unpolished work sheet surface.

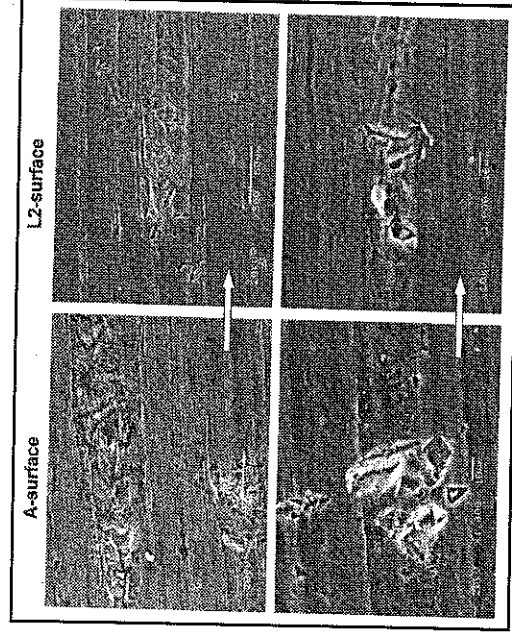


Fig. 13 — SEM shows the effect of the good lubricant (L2) on an unpolished work sheet surface (may not be exactly the same position).

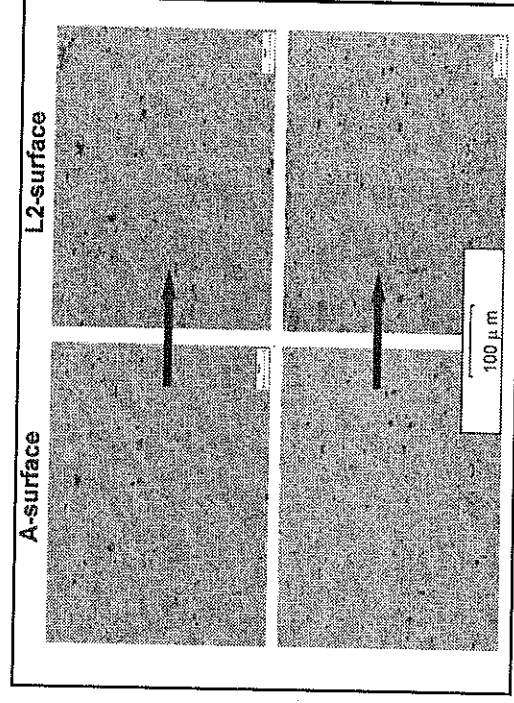


Fig. 14 — Optical microscopy showing the effect of good lubricant (L2) on a polished work sheet surface.

occur at the EW interface if the L2 lubricant acted to decrease the thickness of the surface oxide layer, which would reduce the electrical resistance and thus the heat generation. The possibility of a reduced oxide layer thickness was suggested by the following observation. While applying the L2 lubricant to the worksheet surface, it was found that the color of the white cotton balls turned grey or black whereas for the "poor" L6 lubricant they retained the actual color of the L6 lubricant. This observation suggested that some chemical change occurred at the surface of the aluminum sheet when the lubricant L2 was used and investigations were performed to explore this possibility.

Optical microscopy provided further insight. The same points on a rough alu-

minum worksheet were examined before and after application of L2 lubricant — Fig. 12. All these surfaces were wiped with methanol before viewing them. The L2 surface appeared lighter in color and seemed to have material removed from the sheet surface. Further support for this finding was provided by higher resolution SEM images of equivalent points on a worksheet surface before and after applying the L2 lubricant — Fig. 13. However, when this procedure was repeated for freshly polished surfaces (Fig. 14), there was no apparent change in the appearance of the L2 surface. This finding was consistent because the oxide layer would be much thinner after the polishing and would have needed considerable time to develop an increased thickness (Ref. 2).

In order to provide further proof that the oxide layer had thinned with the application of lubricant L2, one sample each from the A surface and the L2 surface were examined by ESCA. Specimens were cut in 6 mm × 6 mm size and were cleaned with methanol before being placed into a vacuum chamber. Both samples were placed into the same chamber at the same time. The results were plotted for the intensity (count per second or CPS) of radiation of both aluminum and oxygen, presented in the surface oxide (Al₂O₃) layer, against sputtering time — Fig. 15. More intensity (CPS) at the same sputtering time suggests more concentration of that particular element on the surface. Similarly, longer sputtering time to achieve the same intensity level suggests a thick sur-

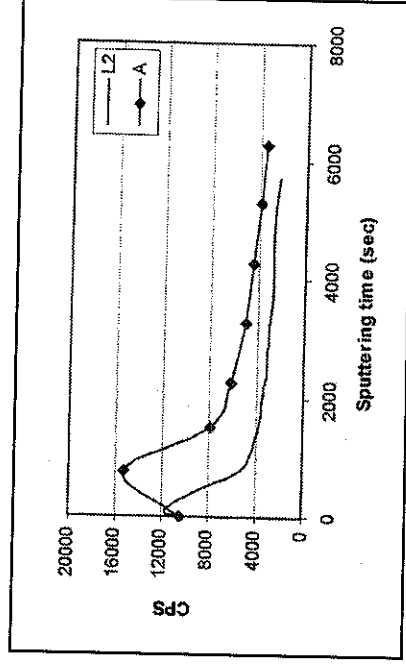
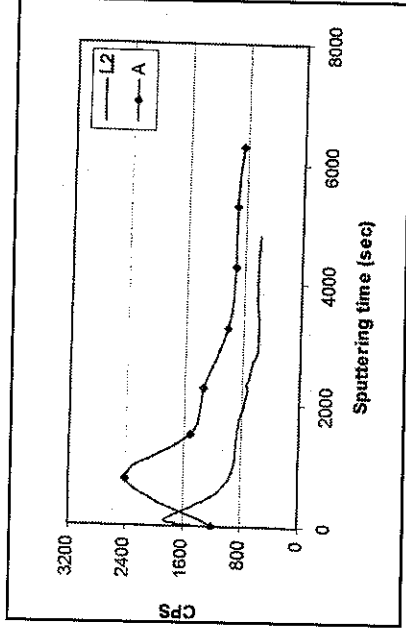


Fig. 15 — Thickness of the oxide layers on A and L2 surfaces from ESCA. A — Aluminum in oxides; B — oxygen in oxides on the sheet surface (Ref. 6).

face layer for that particular element. Interestingly, for both these elements, the intensity at any sputtering time was lower for the L2 surface compared to the A surface; thus showing a thinner (or low concentration of) oxide layer on the aluminum sheet surface that was treated with the lubricant L2.

Alloys on the Electrode Surface

As described previously, 100 spot welds were performed on L2 and A surfaces to investigate the type and properties of intermetallic phases formed during the spot welds and their influence on the subsequent electrode life. This was done by analyzing the top (positive) electrodes with x-ray diffraction (XRD). Since electrodes are made of copper, higher intensities of Cu than Cu-Al phases were expected. However, the occurrence of the intensity peaks for Cu-Al phases were well matched with the standard XRD pattern for that phase — Fig. 16. The Cu_9Al_4 (γ_1 phase) was observed at about 44.2 deg on both electrodes while the intensity peaks for CuAl_2 (θ phase) were found only at the electrode that had been in contact with the L2 surface. These peaks occurred at 42.7, 47.4, and 47.9 deg, which matched the standard XRD pattern for the first peak at 42.6 deg, second peak at 47.3 deg, and third peak at 47.8 deg for this phase (Ref. 26). The match was good enough to believe that the CuAl_2 phase was present on the electrode surface used in welding the L2 surface but not on the electrode surface used in welding the A surface.

Based on the reaction kinetics (Table 4 (Ref. 27)), the CuAl_2 formed at a lower temperature (550–600°C) while the Cu_9Al_4 formed at a higher temperature (780–873°C). Finding Cu_9Al_4 when both the L2 and A surfaces were subject to RSW meant that higher temperatures at the EW interface were present in both

cases. However, finding only CuAl_2 when the L2 surface was subject to RSW meant that some lower temperatures were experienced. This finding was consistent with the idea of lower heat generation at the EW interface for the L2 surface due to the reduction of oxide layer thickness. There was also likely to be a further contributing factor. Aluminum-copper alloys were considered to be electrical insulators compared with pure aluminum or copper. However,

the conductivity of CuAl_2 was almost doubtless that of Cu_9Al_4 (Ref. 16). Thus, once CuAl_2 was present it helped reduce the electrical resistance and keep the interface temperatures lower compared with the regions having Cu_9Al_4 . Presumably, this helped reduce the rate of surface pitting and cavity formation during the electrode life tests for the L2 surface.

Electrical Resistance

During the course of the weld cycle, the contact resistances at the EW and FS interfaces were subject to change due to local melting. However, contact resistance at the top EW interface measured prior to the passage of the high weld current was considered as an indicator of the performance of the electrodes in subsequent RSW (Refs. 24, 28). Thus, contact resistance across the top EW interface was measured for ten L2 surfaces and ten A

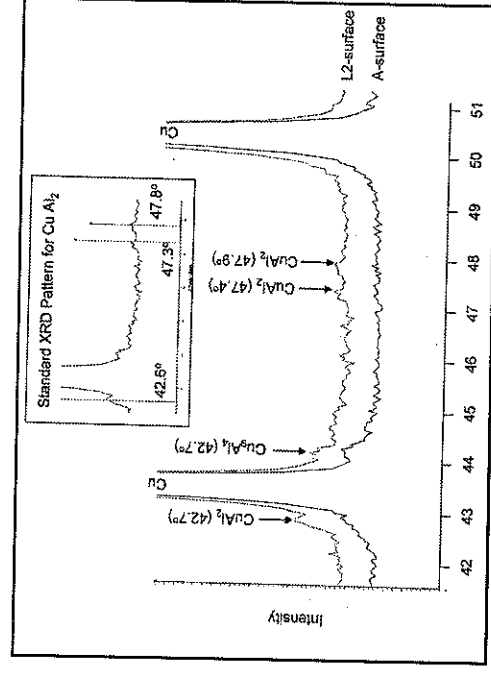


Fig. 16 — Typical XRD intensity spectra showing different Cu-Al intermetallic phases found on the electrode surfaces after 100 spot welds on A surface and L2 surface. Small window is showing the standard XRD pattern for CuAl_2 phase.

surfaces (Table 5). The L2 surface seemed to have a lower average electrical resistance than the A surface. This finding provided additional support for the idea that oxide layer thickness was reduced.

It was also observed that the application of lubricant L2 improved the roughness of the worksheet. In general, a higher surface roughness results in lower contact resistance as more asperities crack under load and produce more fresh metal-to-metal contacts. However, in the case of aluminum, the effect of oxide layer thickness on the contact resistance was more dominating than the roughness (Ref. 23, 28). This effect was investigated in another study (Ref. 28) where contact resistance between electrode and AA5182 sheets (without lubricant), grinded with different grades of sandpapers, were measured. It was found that the EW contact resistance was decreased from 9.1 $\mu\Omega$ for a roughness level 0.24 μm to 7.2 $\mu\Omega$ for a

roughness level of 1.08 μm . The study suggested that the grinded surfaces had a fresh (thin) oxide layer and hence lower contact resistances than ungrinded (as-received) surface (11.6 $\mu\Omega$ for a roughness level of 0.32 μm). In the present study, while comparing the A surface with the L2 surface, the roughness levels were very close to each other (0.34 and 0.31 μm , respectively, Table 5). It was believed that this small variation in roughness was not significant enough to reduce the contact resistance from 11.2 $\mu\Omega$ (A surface) to 8.6 $\mu\Omega$ (L2 surface). Thus, a reduction in oxide layer thickness seemed to be the most likely explanation for the reduced contact resistance and hence lower temperature at the EW interface for the L2 surfaces.

Conclusions

Resistance spot welding of AA5182 was investigated using different metal-working lubricants placed only on one side of the worksheet associated with the electrode-worksheet interface (i.e., top and bottom EW interfaces). Based on a screening test, it was observed that placing a lubricant only at the EW interface can influence the electrode degradation significantly. One lubricant (L2) was identified as "good" for resistance spot welding of AA5182 compared to other lubricants, which showed negative effect on electrode degradation.

Electrode life tests were conducted (three each) for good lubricant (L2 surface), bad lubricant (L6 surface), and as received (A surface). For the same welding conditions, faying surface characteristics, and failure criterion, the presence of lubricant L2 at the EW interface extended the electrode life to 730 welds, which was almost double the electrode life for the A surface (393 welds). This improvement of electrode life was associated with a slower pitting rate, which resulted due to the application of good lubricant (L2) on the worksheet. The bad lubricant (L6) produced very short and inconsistent electrode lives with an early development of pitting.

It was observed, through several analytical arguments, that the slower pitting rate of electrodes associated with the L2 surfaces were due to the lesser heat generation at the EW interface for the L2 surface compared to the A surface.

Physical and chemical analysis of the L2 and A surfaces revealed that the worksheet oxide layer thickness was reduced by the application of good lubricant (L2). This reduction of oxide layer thickness resulted in lower contact resistance at the EW interface and hence slower alloying and pitting of the electrode. This reduction in alloying and pitting led to a longer electrode life.

Future Work

Although the electrode life was substantially extended by using the L2 surface, further improvements might be possible. Thus, future work was needed to find the details of the mechanism responsible for the effectiveness of L2 and to attempt to develop an even better lubricant.

Acknowledgments

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References

1. Wheeler, M. J., Sheasby, and P. G., Kewley, D. 1987. Aluminum structured vehicle technology — A comprehensive approach to vehicle design and manufacturing in aluminum. SAE Technical Paper 870146.
2. Kucza, J. C., Buttrulle, J. R., and Hank, E. 1997. Aluminum as-rolled sheet for application-effect of surface oxide on resistance spot welding and adhesive bonding behavior. SAE Technical Paper 970013.
3. Ikeda, R., Yasuda, K., Hashiguchi, K., Okita, T., and Yahaba, T. 1995. Effect of electrode configuration on electrode life in resistance spot welding of galvanized steel and aluminum alloy for car body sheets. *Advanced Technologies & Processes (Proc. International Body Engineering Conference, IBEC '95)*. pp. 144–151.
4. Browne, D. J., Newton, C. J., and Boomer, D. 1995. Optimization and validation of a model to predict the spot weldability parameter lobes for aluminum automotive body sheet. *Advanced Technologies & Processes (Proc. International Body Engineering Conference, IBEC '95)*. pp. 100–106.
5. Williams, N. T. 1984. Suggested topics for future research in resistance welding. *Welding in the World* 22(1/2). pp. 28–34.
6. Rashid, M., Fukumoto, S., Medley, J. B., and Zhou, Y. 2004. Effect of lubrication on electrode life in resistance spot welding of aluminum alloys. *Sheet Metal Welding Conference XI*. Paper 1-3.
7. Giroux, D., and James, F. D. 1995. *Resistance Welding Manual*. Fourth Edition. Philadelphia, Pa. Resistance Welder Manufacturers Association.
8. Glagola, M. A., and Roest, C. A. 1976. Nickel plated electrodes for spot welding aluminum. SAE paper 760167.
9. Bowers, R. J., Sorensen, C. D., and Eagar, T. W. 1990. Electrode geometry in resistance spot welding. *Welding Journal* 69(2): 45-s to 51-s.
10. Leone, G. L., and Altshuller, B. 1984. Improvement on the resistance spot weldability of aluminum body sheet. SAE paper 840292.
11. Rivett, R. M. 1980. Spot welding electrode life tests on aluminum sheet — Effect of parent metal composition and surface treatment. The Welding Institute 132/1980.
12. Spinella, D. J., Brockenbrough, J. R., and Friday, J. M. 2004. Fundamental effects of electrode wear on aluminum resistance spot welding performance. *Sheet Metal Welding Conference XI*. Paper 1-1.
13. Patrick, E. P., and Spinella, D. J. 1996. The effects of surface characteristics on the resistance spot weldability of aluminum sheet. *AWS Sheet Metal Welding Conference VII*. Paper-B4.
14. Lum, I., Fukumoto, S., Biro, E., Boomer, D. R., and Zhou, Y. 2004. Electrode Pitting in Resistance Spot Welding of Aluminum Alloy 5182. *Metallurgical and Materials transaction A* (35A). pp. 217–225.
15. Fukumoto, S., Lum, I., Biro, E., Boomer, D. R., and Zhou, Y. 2003. Effect of electrode degradation on electrode life in resistance spot welding of aluminum alloy 5182. *Welding Journal* 82(11): 307-s to 312-s.
16. Diththey, U., and Hicken, S. 1998. Metallographic investigation into wear processes on electrodes during the resistance spot welding of aluminum. *Welding and Cutting* (1). pp. 34–40.
17. Xu, L., and Khan, J. A. 1999. Nugget growth model for Aluminum alloys during resistance spot welding. *Welding Journal* 78(11): 367-s to 372-s.
18. Murakawa, H., Kimura, F., and Ueda, Y. Weldability analysis of spot welding on aluminum using FEM. *Mathematical Modeling of Weld Phenomena* 3, pp. 273–280.
19. Patrick, E. P., Auhl, J. R., and Sun, T. S. 1984. Understanding the process mechanism is key to reliable resistance spot welding aluminum autobody components. SAE technical paper 840291.
20. Sun, T. S. 1982. Electrode deterioration mechanisms in resistance spot welding of aluminum. Alcoa Internal Report No. 53-82-3.
21. Dzekster, N. N., and Ismailov, V. V. 1990. Some methods for improving aluminum contacts. *Proceeding of 36th Annual Holm Conference*, Illinois Institute of Technology Chicago, Ill. pp. 518–520.
22. Sugimura, K., and Nagae, A. 1990. Lubricant for some plated contacts. *Proceeding of 36th Annual Holm Conference on Electrical Contacts*, Illinois Institute of Technology, Chicago, Ill. pp. 417–424.
23. Thornton, P. H., Krause, A. R., and Davies, R. G. 1997. Contact resistance of aluminum. *Welding Journal* 76(8): 331-s to 341-s.
24. James, P. S., Chandler, H. W., Evans, J. T., Browne, D. J., and Newton, C. J. 1997. The effect of mechanical loading on the contact resistance of coated aluminum. *Materials Science and Engineering: A* 230. pp. 194–201.
25. Tewari, R., Dey, G. K., Fotedar, P. K., Kutty, T. R. G., and Prabhua, N. 2004. Deformation behavior of Zr₃Al-Nb alloys I: Room-temperature and high-temperature deformation study. *Metallurgical and Materials Transaction A*. Volume 35A.
26. Havinga (XRD Standard Card # 25-0012), 1973. Phillips Research Lab, Eindhoven, the Netherlands.
27. Murray, J. L. 1990. *Binary Alloy Phase Diagram*, Second Edition, Volume 1. Materials Park, Ohio: ASM International.
28. Rashid, M., Medley, J. B., and Zhou, Y. 2006. Effect of surface characteristics on contact resistance and resistance spot welding behavior of 5182 aluminum alloy sheet. *Proceedings of the CSME FORUM 2006*.