The Mechanism of Expulsion in Weldbonding of Anodized Aluminum

Expulsion is caused by excessive current density in localized spots and can be prevented by increasing the electrode force and up-slope time

BY K. C. WU

ABSTRACT. In resistance spot welding of anodized aluminum through an adhesive, expulsion can occur during the early stages of the welding cycle, even at relatively low current values. On the other hand, in the resistance spot welding of spot-weld etched aluminum, expulsion occurs at the end of the welding cycle and at peak current values. This difference implies that different expulsion mechanisms exist in the two cases.

Since expulsion is undesirable in a weldbond joint, a program was initiated to determine the mechanisms by which the two types of expulsion occur in order to develop a welding schedule to prevent expulsion. Scanning electron microscopy was used throughout this program to determine the effect of electrode force on the thickness of oxide, the location of the weld nugget initiation, and the effect of the current slope rate on the occurrence of expulsion.

Evidence shows that expulsion occurs on an anodized aluminum surface due to an excessive current density in localized areas. To prevent expulsion, high electrode and forge forces and a low slope rate must be used. With a low slope rate, the welding current takes more time to rise to a given value.

Introduction

Weldbonding is a relatively new joining process. It combines spot-welding with adhesive-bonding to improve the load-carrying capacity of the joint. Initially, weldbonding was conducted with spot-weld etched aluminum, but this surface treatment provided poor bondline durability in the presence of moisture and under stress. To improve durability, not only does the original beta oxide have to be removed, but a corrosion-resistant alpha oxide needs to be deposited on the aluminum surface. However, the oxide produced by anodizing has a high electrical resistance* and the oxide causes expulsion to occur when conventional welding schedules for aluminum are used.

Expulsion is a phenomenon which can occur during the resistance spot welding of all metals. Expulsion usually occurs near the peak of the welding current when the current is too high and/or the electrode force is too low. However, during the welding of anodized aluminum through an adhesive, expulsion can occur at an early stage of the welding cycle at low current values. Therefore, it was believed that the expulsion associated with normal spot-welding was caused by a different mechanism than that which occurs during weldbonding. The development of a method to prevent expulsion while weldbonding anodized aluminum is contingent upon understanding the expulsion mechanism.

**Average contact resistance of a 1.5 V phosphoric acid/sodium dichromate anodized aluminum is about 500 to 600 μΩ as compared to 50 to 100 μΩ for a spot-weld etched aluminum surface.*

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Objective

The objective of this program was to determine the mechanism of expulsion which occurs during the weldbonding of phosphoric acid/sodium dichromate anodized aluminum coated with modified epoxy adhesive so that corrective measures could be taken to eliminate the expulsion.

Materials and Experimental Procedure

Three surface preparations were used during the complete investigation. The baseline work used the standard spot-weld etched surfaces on bare 7075-T6 aluminum sheets of 1.6 mm (0.063 in.) thickness. Earlier in the program, some samples were prepared using the Forest Products Laboratory (FPL) etch plus a 60 min sodium dichromate seal. Finally, the weldbond surface specimens were anodized in a phosphoric acid/sodium dichromate (P/SD) solution at 1.5 V for 20 min (see Appendix). Welding was conducted on lap joint specimens containing a modified epoxy paste adhesive[1] in the faying surfaces.

Both a single-phase, AC spot-welding machine and a three-phase, frequency converter spot-welding machine were used. Welding current form was recorded on a standard direct-ink oscillograph and the maximum value of the welding current was registered on a low-cycle secondary current meter. Electrode force was measured with a cantilever force gage having a sensitivity of 222 N (50 lb).

A linear differential voltage transformer (LDVT) was installed on the single-phase spot-welding machine to measure the upper electrode movement which indirectly detected nugget expansion during welding. The amount of electrode movement was recorded on an oscillograph. When expulsion occurred, the movement of the upper electrode was interrupted momentarily. This interruption was observed on the oscillograph recording.

The test program was designed to first study the effects of various electrode forces on the anodized oxide structures. This was done to learn where and how the welding current penetrated the oxide layer. Next, a series of samples was welded using different numbers of current cycles so that the total weld cycle was interrupted at various times before the complete weld nugget was formed. These partial weldments were then broken apart for examination.

In this portion of the work, welding was conducted for the P/SD anodized aluminum on a single-phase spot-welding machine, for the P/SD anodized aluminum on a three-phase spot-welding machine using three different slope rates and for the spot-weld etched aluminum on the three-phase spot-welding machine using a maximum slope rate. A modified epoxy adhesive was used in the faying surface throughout this program. The welded lap joints were broken apart to inspect the nugget size and to determine the sequence of nugget formation. In most cases, the adhesive was removed with a solvent before the scanning electron microscopic (SEM) examination was performed.

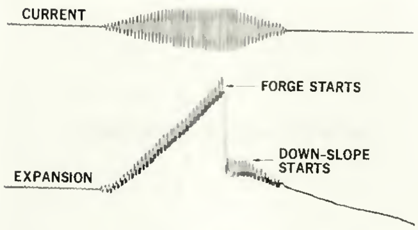


Fig. 1—Current and nugget expansion traces showing no expulsion

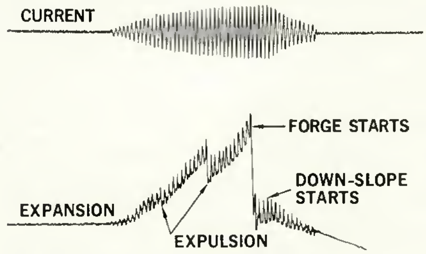


Fig. 2—Current and nugget expansion traces showing expulsion

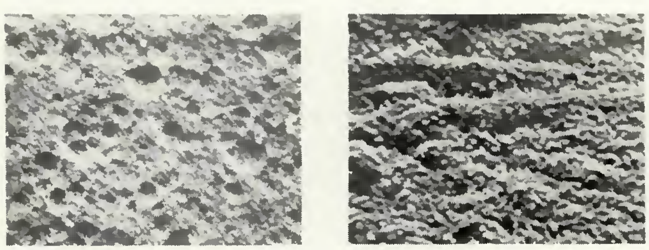
Since the SEM used in this program has a resolution of 70 Å, a residual oxide on a "clean" surface could not be over 70 Å thick without being detected. To measure the thickness of the oxides, the anodized specimens were prepared for SEM examination using a 90 deg bend technique. With this technique, the specimen, approximately 3.2 mm (0.125 in.) by 25.0 mm (1 in.) by 1.6 mm (0.063 in.) thick, was bent to an angle of about 90 deg or until the aluminum surface began to fracture. During this bending process, the more brittle oxide coating cracked but remained attached to the aluminum surface. After coating it with a thin layer of gold (approximately 100 Å) to ensure proper specimen grounding and to enhance the secondary electron emission of the surface, the specimen was inserted in the SEM for examination.

A "top view" examination along the direction normal to the surface revealed information on the surface cleanliness and uniformity of the surface coating. "Side view" examination along the direction parallel to the surface showed the coating thickness as well as the cross-sectional structure of the oxide. This method was used throughout this program to ensure proper surface treatment.

Discussion and Results

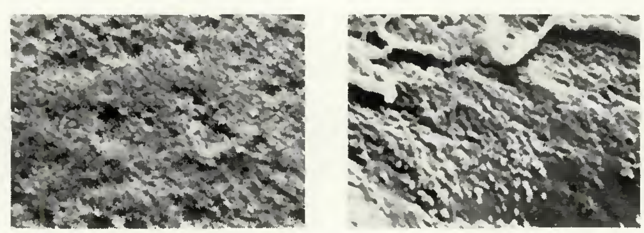
Premature expulsion was observed during the weldbonding of anodized 7075-T6 aluminum on a single-phase, AC spot-welding machine. A linear differential voltage transformer (LDVT) had been installed to monitor the upper electrode movement to evaluate the correlation between the nugget expansion and spot strength.

The nugget expansion trace of a weld without expulsion is shown in Fig. 1. When expulsion occurs, molten aluminum, aluminum oxide, and adhesive are expelled from the nugget. The expulsion of these substances interrupts the normal upward movement of the electrode which is produced by nugget expansion. Figure 2 shows the interruption of the electrode move-



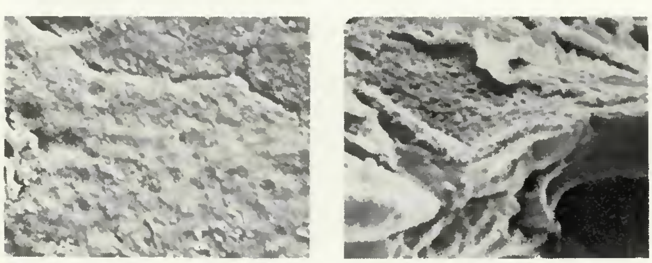
(A) TOP VIEW 2KX (B) SIDE VIEW 20KX

Fig. 3—Anodized surface without compression: (A) top view—normal to surface; (B) side view—parallel to surface (reduced 60% on reproduction)



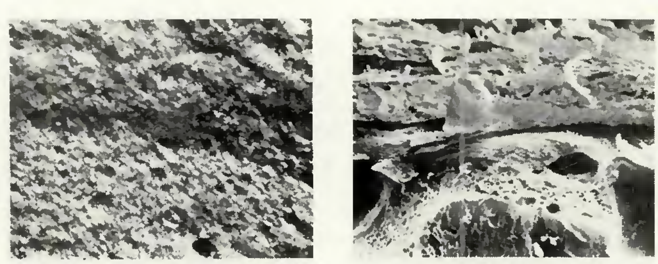
(A) TOP VIEW 2KX (B) SIDE VIEW 20KX

Fig. 4—Anodized surface compressed with a 4,450 N (1,000 lb) force: (A) top view—normal to surface; (B) side view—parallel to surface (reduced 60% on reproduction)



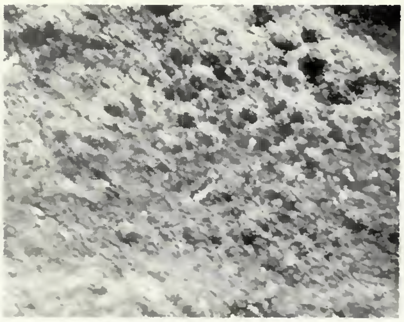
(A) TOP VIEW 2KX (B) SIDE VIEW 20KX

Fig. 5—Anodized surface compressed with an 8,900 N (2,400 lb) force: (A) top view—normal to surface; (B) side view—parallel to surface (reduced 60% on reproduction)

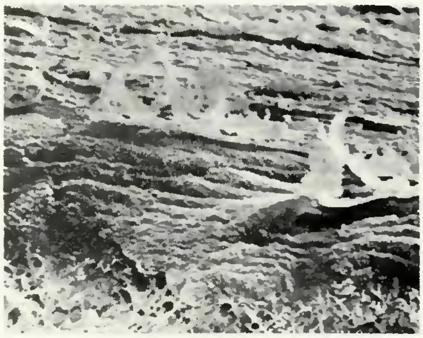


(A) TOP VIEW 2KX (B) SIDE VIEW 20KX

Fig. 6—Anodized surface compressed with a 17,800 N (4,000 lb) force: (A) top view—normal to surface; (B) side view—parallel to surface (reduced 60% on reproduction)

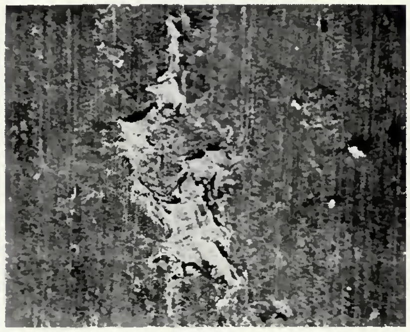


(A) TOP VIEW 2KX

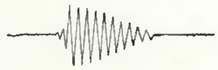


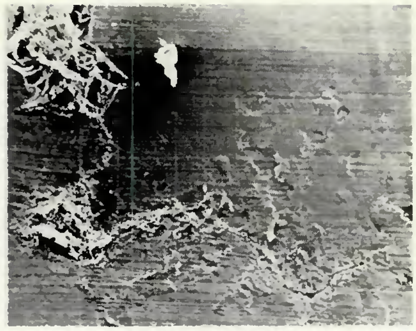
(B) SIDE VIEW 20KX

Fig. 7—Anodized surface compressed with an 8,900 N (2,000 lb) force and then with a 17,800 N (4,000 lb) forge force: (A) top view—normal to surface; (B) side view—parallel to surface (reduced 45% on reproduction)

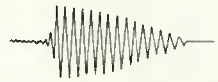


(A) 10 CYCLES 13.2KA 100X

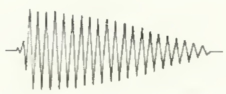




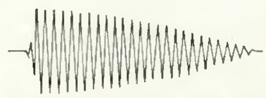
(B) 15 CYCLES 15.4KA 100X

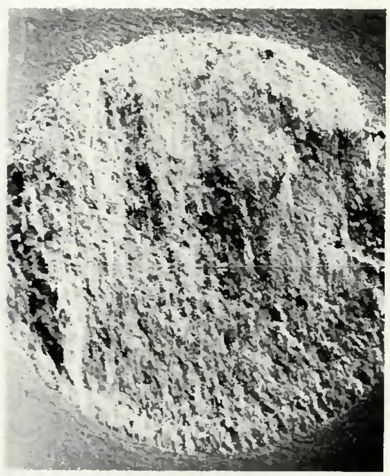


(C) 20 CYCLES 16.6KA 20X



(D) 25 CYCLES 17.2KA 20X





(E) 38 CYCLES 20.2KA 14X

Fig. 8—Formation of weld nuggets, single-phase AC spot-welding machine: (A) 10 cycles; (B) 15 cycles; (C) 20 cycles; (D) 25 cycles; (E) 38 cycles. Reduced as follows on reproduction: A to D—46%; E—51%

ment on the recording trace.

Figure 2 also shows that the first expulsion occurred at the 13th cycle of the total of 30 cycles of up-slope and welding time. At the 13th cycle, the current was about ⅔ of the peak value, and the heat energy was only ¼ of the total energy used to make a weld. These results indicate that the mechanism of expulsion which occurred with anodized aluminum is somewhat different than that in spot-weld etched aluminum where expulsion occurs at or near peak current.

Based on the observations just described, a hypothesis was formulated on the mechanisms of expulsion in the spot-weld etched aluminum and P/SD anodized aluminum.

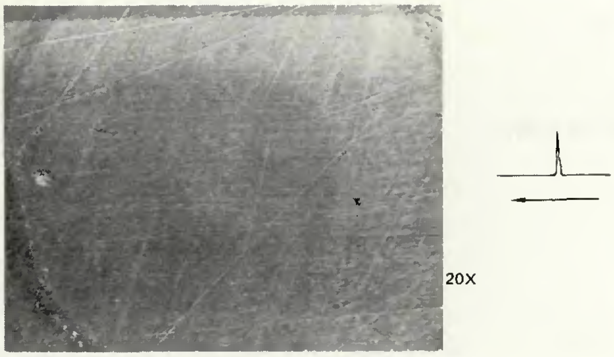
Hypothesis

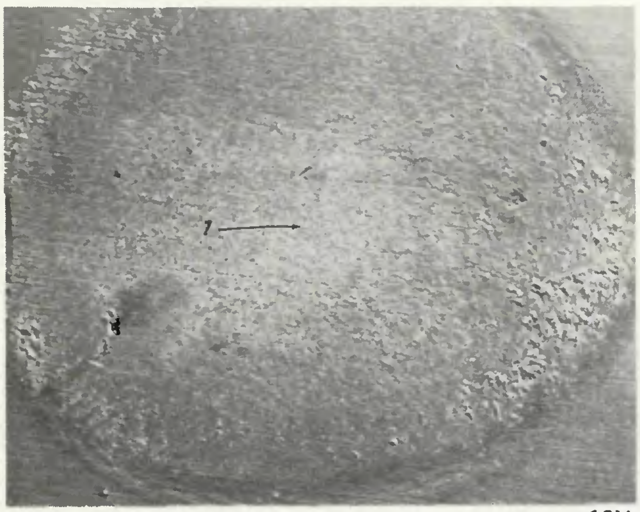
The oxide layer is less than 70 Å thick on spot-weld etched aluminum surfaces and, under the electrode force, the center of the faying surface has the lowest electrical resistance. Thus, melting is probably initiated in the center and spreads outward to form a nugget. Expulsion occurs only when the welding current reaches its peak, i.e., the current density is extremely high, and the electrode force is too low to contain the molten nugget.

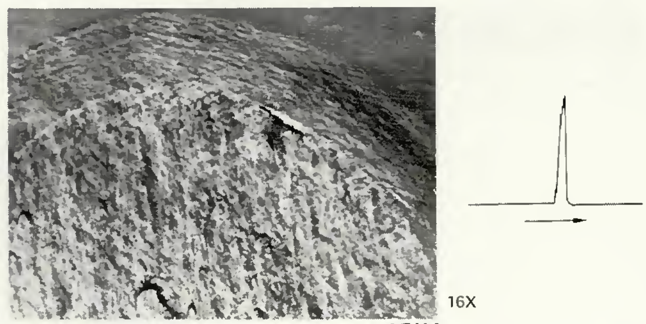
The oxide thickness on the aluminum surface anodized in the P/SD solution at 1.5 V for 20 minutes is approximately 500 to 700 A. Because of this thickness, the oxide is not perfectly uniform, and the lowest electrical resistance region is not necessarily located in the center of the faying surface under the electrode. During welding, therefore, the welding current initially flows through a few small spots where the electrical resistance is the lowest, and expulsion occurs when the localized current density exceeds some limit. This results in premature expulsion and irregularly shaped weld nuggets, as has been observed.[2]

Effect of Electrode Force

Evidence of the thinning of the oxide layer with a high electrode force is shown in Figs. 3 through 7. Figure 3(A) shows the rough anodized surface (top view), and Fig. 3(B) shows







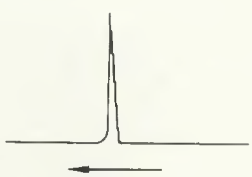


Fig. 9—Spot-weld etched sheet, welded on three-phase spot-welding machine; (A) 1 cycle; (B) 2 cycles; (C) enlargement of area 1; (D) 3 cycles. Reduced as follows on reproduction: (A)—42%; (B) and (C)—14%; (D)—43%

the profile of the oxide layer characterized by typical spherical particles (side view). When a 4,450 N (1,000 lb) electrode force was applied on the anodized 7075 sheet, dimples in the faying surfaces were flattened (Fig. 4(A)) and layers of oxide were compressed (Fig. 4(B)). This became more pronounced when an 8,900 N (2,000 lb) electrode force was applied to the anodized sheet, as shown in Fig. 5.

The effects of a 17,800 N (4,000 lb) electrode force and the combination of an 8,900 N (2,000 lb) electrode force and a 17,800 N (4,000 lb) forge force on the appearance of the oxide are shown in Figs. 6 and 7, respectively. It is apparent that, regardless of the preload, a 17,800 N (4,000 lb) forge force created more cracks and resulted in a smoother oxide surface appearance (top view). The high electrode forces compressed the oxide into thin layers. Therefore, when the sheet was bent, the compressed oxide layers were flaked off from the surface (side views). Figures 6 and 7 clearly show that the oxide sheets were penetrated in various locations and their thickness was greatly reduced by the 17,800 N (4,000 lb) force.

The evidence cited above substantiates the hypothesis that high forces are required to reduce the contact resistance in the faying surfaces. However, high forces alone cannot eliminate expulsion, as evidenced in the following experiments.

Formation of Weld Nugget

Anodized Surfaces Welded on a *Single-Phase Machine:* A single-phase, AC spot-welding machine was used to eliminate expulsion from weld nuggets made with a 7075-T6 aluminum which was FPL etched and given a 60 min sodium dichromate seal. In this early work on up-slope time, 30 cycles was used (Fig. 1). This long up-slope time prevented the welding current density in the melting spots from exceeding the limit that causes expulsion. The current recorded in Figs. 1 and 2 shows a complete welding cycle for this system consisting of a 30-cycle up-slope, an 8-cycle weld, and a 12-cycle down-slope. This schedule was also used for 7075-T6 aluminum treated with the 1.5 V P/SD anodize as described below.

Figure 8 shows the sequence of weld nugget formation using a single-phase spot-welding machine for the indicated welding times. At the end of 10 cycles, as shown in Fig. 8(A), a weld nugget about 0.3 mm by 0.6 mm (0.012 by 0.024 in.) was formed. Scattered melting spots were observed in the weld, which was formed in 15 cycles, as shown in Fig. 8(B).

Four spots which melted around a 2.54 mm (0.1 in.) diameter circle in 20 cycles are shown in Fig. 8(C). A welding time of 25 cycles caused these melting areas to grow into large spots (3.4 mm or 0.15 in. in diameter) which were connected together over one-

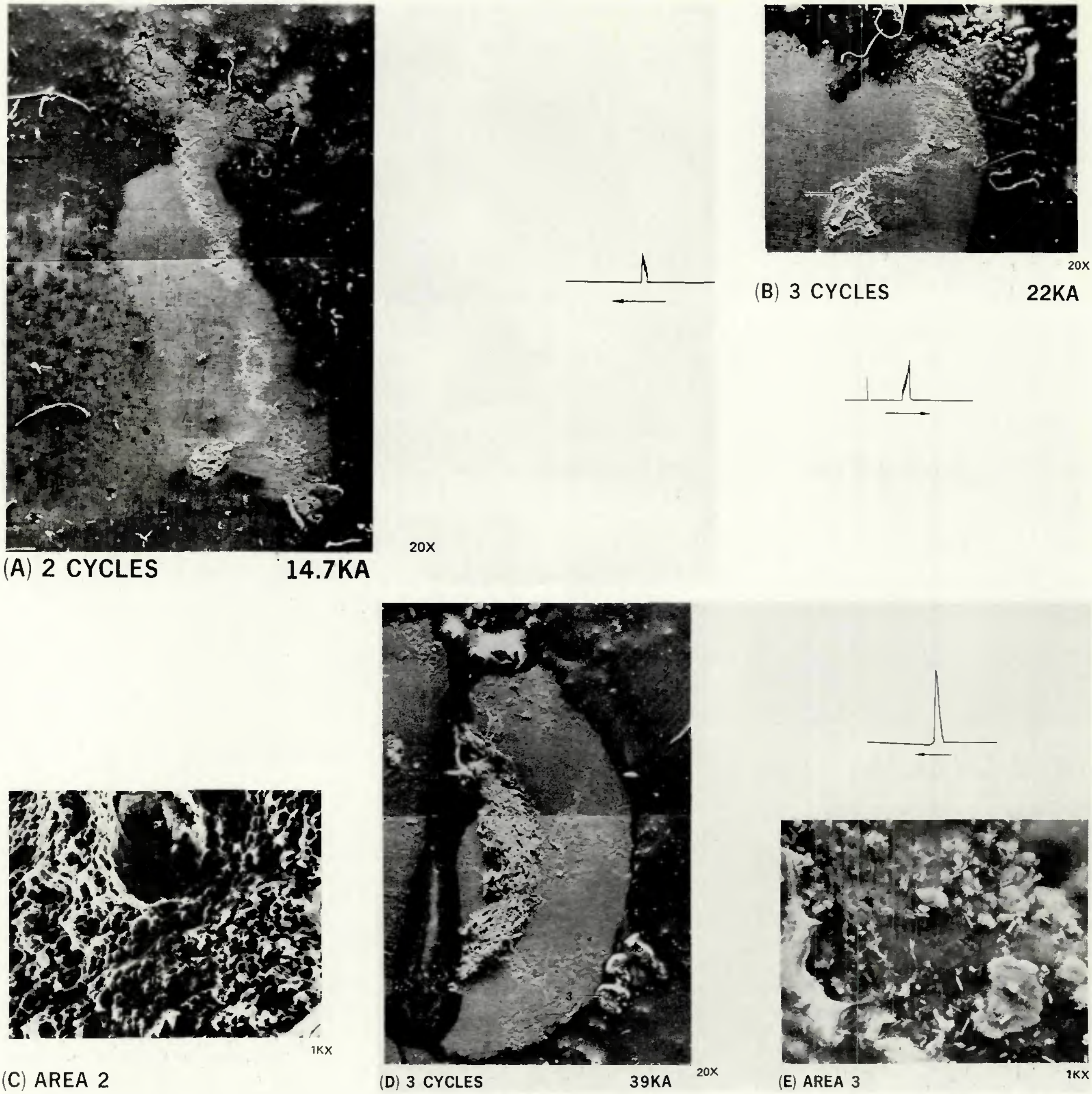


Fig. 10—Anodized surface welded on a three-phase spot-welding machine, high rising rate: (A) 2 cycles 10% rate, 14.7 kA; (B) 3 cycles 10% rate, 22 kA; (C) enlargement of area 2; (D) 3 cycles 5% rate, 39.3 kA; (E) enlargement of area 3. Reduced as follows on reproduction: (A)—40%; (B) and (C)—44%; (D) and (E)—48%

half of the circle (Fig. 8(D)). A complete weld nugget was formed (Fig. 8(E)) when 30 cycles of up-slope and 8 cycles of welding time were used.

Spot-Weld Etched Surfaces Welded on a Three-Phase Machine: A three-phase frequency converter type spot-welding machine was used to examine the process of weld nugget formation and the mechanism of expulsion on spot-weld etched aluminum surfaces.

Spot-weld etched surfaces have a low surface resistance (30–100 $\mu\Omega$). Thus, a short welding time of three cycles with sufficient current to form a weld nugget was used. One-, two-, or three-cycle welding time with a current slope rate of 18 kA/cycle was used to study the nugget formation.[3] The unaffected surface resulting from 1 cycle of welding time is shown in Fig. 9(A). The faying surface is indicated by the dark ring. However, no joining occurred. A 2-cycle welding time allowed some fusion to occur, mainly in the center of the faying surface (Fig. 9(B)). Fusion is evident in area 1, as shown at ×5000 magnification in Fig. 9(C). A complete weld nugget was formed in 3 cycles of welding time. A portion of the nugget is shown in Fig. 9(D).

This series of SEM photos shows that the weld nugget for the spot-weld etched sheets starts at the center of the faying surface and spreads outward in a very short time span.

Anodized Surfaces Welded on a Three-Phase Machine: During this portion of the investigation, the aluminum specimens were anodized with the 1.5 V P/SD treatment. Figure 10(A) shows an irregular weld nugget and expulsion produced by using a current

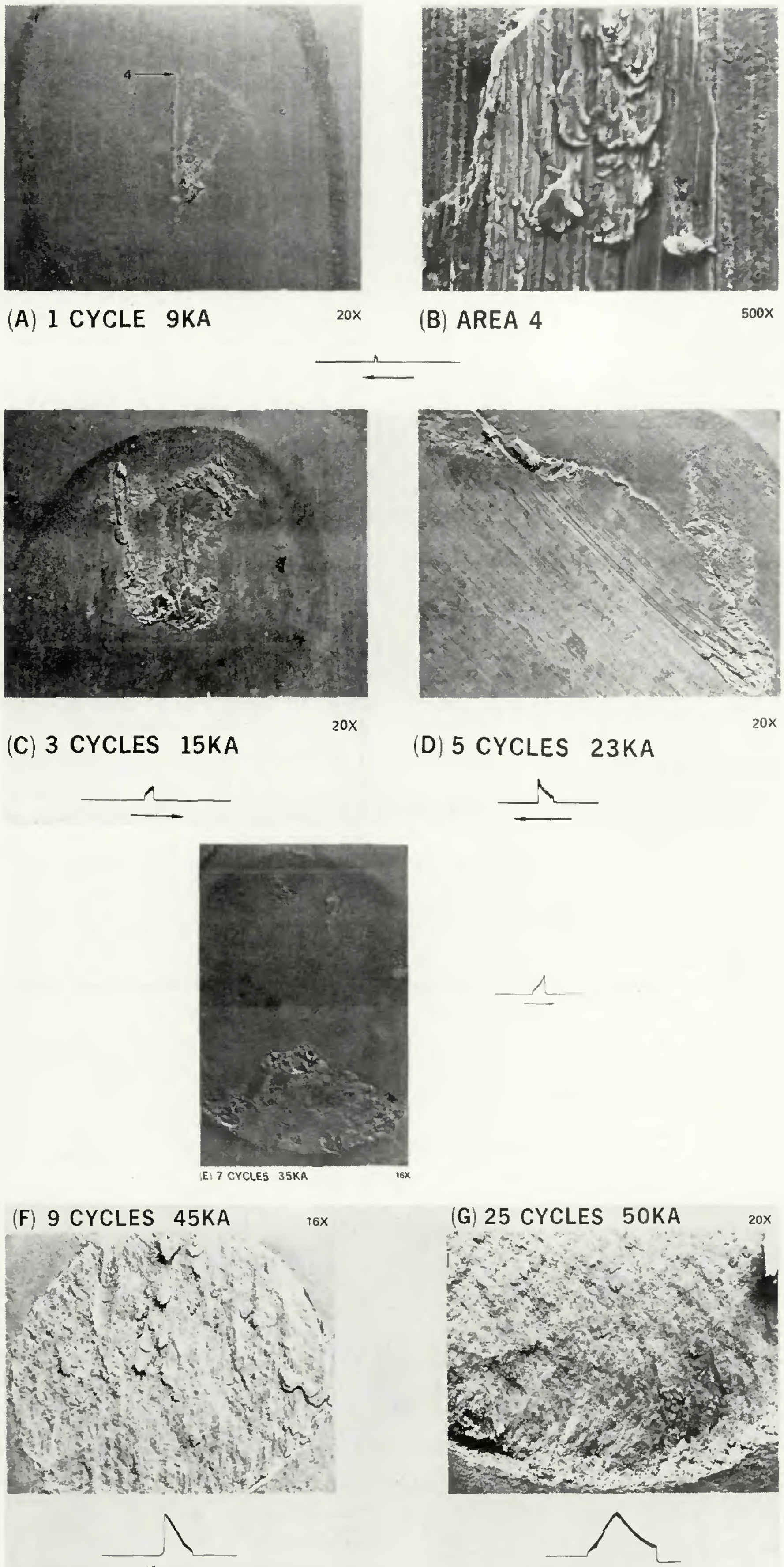


Fig. 11—Anodized surfaces welded on a three-phase spot-welding machine, slow rising rate: (A) 1 cycle; (B) enlargement of area 4; (C) enlargement of area 5; (D) 3 cycles; (E) enlargement of area 6; (F) 5 cycles; (G) enlargement of area 7. Reduced as follows on reproduction: (A) and (B)—46%; (C) and (D)—45%; (E)—32%; (F) and (G)—50%

slope rate of 7.3 kA/cycle and 2 cycles of welding time. The peak current reached in 2 cycles was only 14.7 kA. Expulsion was persistent in the weld made with a welding current of 22 kA at the end of 3 cycles at the same slope rate (Fig. 10(B)). Figure 10(C) is an enlargement of the melting zone shown by the arrow in Fig. 10(B).

A second weld nugget made with a 39.3 kA peak current at a slope rate of 13.1 kA/cycle in only 3 cycles is shown in Fig. 10(D). The melting area in this case is larger and expulsion was observed. The dark streak in the center of the weld is cured adhesive which had not been removed. Figure 10(E) shows that the expulsion material from area 3 (enlarged to ×1000) contained essentially molten aluminum and aluminum oxide.

This series of SEM photos shows that welding current, associated with high slope rates, increases more rapidly than does the area of the melting spots. Thus the current density exceeds the expulsion limit. Therefore, expulsion took place in every case when a high slope rate was used. In addition to the expulsion, irregular shaped weld nuggets were observed in the above three welds.

The observation in the preceding section indicates that expulsion occurs early in the weld schedule even with low current values during the welding of anodized surfaces. This is in contrast with the expulsion which occurs at the peak welding current during the welding of spot-weld etched surfaces. Thus, it appears that to eliminate expulsion during welding of anodized surfaces, the current density should be maintained below some critical value. To achieve this, the welding current should have a slope rate such that the current increases in proportion to the increased area of the melting spots. Thus, the current density is always below the critical value required for expulsion.

Welding currents having a slope rate of 5 kA/cycle were used on a 3 phase spot-welding machine to weld specimens using an electrode force of 8,900 N (2,000 lb) and a forge force of 17,800 N (4,000 lb) with various welding times. The complete welding schedule consists of 10 cycles of up-slope current and 15 cycles of down-slope current. With these welding parameters, expulsion was prevented. The formation of this type of weld nugget is illustrated in Figs. 11(A) through 11(G).

Figure 11(A) shows an irregularly shaped nugget formed with only 1 cycle of welding time. Evidence of melting is seen in area 4 which is magnified ×500 in Fig. 11(B). As the welding time was increased to 3 cycles, a larger molten nugget was formed and a footprint of the faying surfaces is visible (Fig. 11(C)). An irregularly shaped weld made with a 5-cycle welding time is shown in Fig. 11(D).

A larger footprint and molten nugget were formed in the weld made with a 7-cycle welding time (Fig. 11(E)). In this case, melting was spread around the perimeter of the footprint. A small circular weld nugget was formed at the end of 9 cycles, Fig. 11(F). A full-size weld nugget was formed with the complete 25 welding cycle welding time. Part of this weld nugget is shown in Fig. 11(G).

This series of SEM photos depicts the sequence of weld nugget formation in anodized aluminum. Expulsion was prevented by the combination of high electrode force and low slope rate.

Conclusions

Based on the evidence observed from the SEM photos, it is concluded that:

1. High electrode forces either reduce the thickness of the anodized oxide layer or fracture it, allowing the interface to become more conductive.
2. High electrode forces, in conjunction with low slope-rate welding current, prevent expulsion during the weldbonding of 1.5 V P/SD anodized aluminum.
3. Expulsion in resistance welding of spot-weld etched aluminum occurs at the peak welding current due to a gross excessive current density; whereas, expulsion during the weldbonding of anodized aluminum, when an improper schedule is used, occurs during the early stages of the welding cycle due to microscopic areas which experience an excessive current density.

Acknowledgment

The author wishes to thank Mr. R. R. Wells for his guidance throughout this program and Messrs. H. Miller, H. Langman, and Mrs. S. Feenstra for their contributions in conducting the surface cleaning, welding, and SEM work, respectively.

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Appendix

Forest Product Laboratory Etch Plus 60-Minute Dichromate Seal (FPL + 60)

1. Degrease in trichlorethane vapor.
2. Alkaline-clean 10-15 min in Turco 4215-S solution (6-8 oz/gal or 45-61 gm/l of solution) at 155 F ± 10 F (68 C ± 5.5 C).
3. Spray-rinse in deionized water.
4. Sulphuric-dichromate etch for 10 min, ±1 min, in a solution of sulphuric acid (38.5 to 41.4 oz/gal or 288-311 gm/l of solution) and sodium dichromate (4.1 to 4.9 oz/gal or 31-37 gm/l of solution) at 145 to 160 F (63 to 71 C).
5. Spray-rinse in deionized water.
6. Dichromate-seal for 60 min in a sodium dichromate solution (7.25 oz/gal or 55 gm/l of solution) at 180 to 212 F (98 to 100 C).
7. Spray-rinse in deionized water and oven-dry at 150 F (66 C).

Low-Voltage Phosphoric Acid/Sodium Dichromate Anodize (P/SD)

1. Degrease in trichlorethane vapor.
2. Alkaline-clean 10-15 min in Turco 4215-S solution (6-8 oz/gal or 45-61 gm/l of solution) at 155 ± 10 F (68 ± 5.5 C).
3. Spray-rinse in deionized water.
4. Deoxidize 7 min in nitric acid (6–16% by volume)/Amchem 7 solution (2.7–3.3 oz/gal or 20–25 gm/l of solution) at room temperature.
5. Spray-rinse in deionized water.
6. Anodize at 1.5 V DC for 20–25 minutes in phosphoric acid/sodium dichromate solution (1.4 oz H_3PO_4/gal or 199 gm/l of solution and 1% $Na_2Cr_2O_7$ by weight) at room temperature.
7. Spray-rinse in deionized water and oven-dry at 150 F (66 C).