Short-Pulse Resistance Spot Welding of Aluminum Alloy 6016-T4 — Part 2

The influence of pulse shape on weld quality was investigated

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ABSTRACT

In this study, the shape of the current pulse for short-pulse resistance spot welding (RSW) was investigated. In a companion study, it was shown through experiments and simulations that the welding time and total heat input could be reduced without a reduction in final weld size for the resistance spot welding of aluminum alloy AA6016-T4 using medium-frequency direct current (MFDC) welding systems. This study used a variation in current upslope time to vary the current pulse shape, and it used experiments and simulations to analyze the effect of heat input rate on the welding result. Experimental tests were performed on thin sheets (e.g., 1 to 2 mm or 0.04 to 0.08 in.) of AA6016-T4. The size and quality of the welds were evaluated by pull-out testing, ultrasound, and metallography. Resistance and electrode position profiles were evaluated through in-line parameter measurements. An increase in heat input rate was shown to reduce the current level necessary for welding nugget formation and decrease scatter in nugget size for low sheet thicknesses, resulting in a higher process stability. Additionally, significant time and energy savings in comparison to standard practices were obtained. Through an optimized current pulse shape and welding time, the short-pulse MFDC RSW technique can both reduce the current level and overall heat input requirements for satisfactory weld results for this alloy.

KEYWORDS

• Resistance Spot Welding (RSW) • Aluminum Alloys • Automotive Joining Processes

Introduction

Recent developments in automotive body-in-white construction have focused on lightweighting as a strategy for improving vehicle fuel efficiency while maintaining crash performance (Ref. 1). These efforts have led to an increased introduction of aluminum materials to the car body, which provide significant weight-saving potentials (Refs. 1, 2). The use of aluminum is expected to increase further in the coming years (Ref. 2). With this increased introduction of aluminum materials comes an increased focus on the development of robust joining techniques, and resistance spot welding (RSW) has been shown to be a solution for some aluminum joining tasks (Ref. 1). However, challenges in the RSW process for aluminum alloys exist, including weld imperfections and expulsions, achieving process stability, and rapid wear of the welding electrodes (Refs. 3, 4). Despite progress on developing the technology to overcome these challenges, such as through optimization of electrode geometry (Ref. 5), electrode surface condition (Ref. 6), and aluminum sheet surface conditions (Refs. 7–9), further improvement and process understanding is required.

In a companion paper by the same authors, the short-pulse welding technique with medium-frequency direct current (MFDC) RSW systems for aluminum alloy AA6016-T4 was first described (Ref. 10). The influence of the welding time and current level on weld nugget nucleation, growth, and final weld result was investigated. The short-pulse technique produced an equal weld result while gaining improvements regarding energy input and process time. Because the growth of the weld nugget decreased over time during the welding process, it was possible to reduce the overall welding time to 50 ms without changing the necessary current level for acceptable weld results. In the first study, while the influence of welding time and current level was analyzed, the shape of the current pulse was kept constant.

Efforts in the literature to improve the RSW process by adapting the shape of the current pulse have been limited. In Podržaj et al. (Ref. 11), the authors determined that expulsion could be avoided in steel RSW by reducing peak currents while...
maintaining the same root mean square current values. Similarly, the authors in Hwang et al. (Ref. 12) split the welding time into short current pulses to control the heat input and limit expulsion for steel RSW. However, both studies used rectangular pulse forms. In Hajavifard et al. (Ref. 13), the laser spot welding process was analyzed for aluminum alloys with diverse pulse shapes with respect to time, including current downslope times. The authors determined that pulse shapes of the same total energy produced welds with different penetration depths based on the pulse shape used. In addition, the pulse shapes with downslope times were successful in controlling the heat input such that surface cracks and porosity in the welds were avoided. One study by Rusch et al. focused on capacitive discharge (CD) welding systems for the RSW of 5000 series aluminum alloys, utilizing nonrectangular pulse forms (Ref. 14). Here, the durations and energy levels of multiple-pulse weld schedules were investigated. These initial tests using CD systems for RSW applications showed that the shape of the weld nugget could be influenced by the high heat input rates that are possible with CD systems.

This study further develops the short-pulse technique with MFDC systems by examining the shape of the current pulse and its effect on heat input rate and weld quality. The results will show that an improvement in the stability of the RSW process in comparison to standard practices can be realized by optimization of the current profile. Additionally, process time and energy consumption benefits can be obtained. Furthermore, this paper aims to contribute to the understanding of the RSW parameters and highlight their importance in the welding of aluminum alloys with high thermal conductivities.

Materials

As in the previous study (Ref. 10), the alloy of study in this investigation was AA6016-T4, whose composition is presented in Table 1. Sheet thicknesses of 1.0, 1.5, and 2 mm (0.04, 0.06, and 0.08 in.) were studied. All material tested underwent surface treatment for passivation and consistency in the surface oxide layer before welding. Surface pretreatment was completed according to German standard VDA 239-200, Aluminum Sheet Material (Ref. 15). After pretreatment, forming oil was applied to the material surface in accordance with company standards.

Experimental Methods

Experimental welding tests were conducted on a RSW Bosch Rexroth BRC7000 system. Transformers and power rating data correspond to “welding system 1” in the companion study (Ref. 10). As in the previous study, welding current levels up to a maximum of 47 kA were tested. A Düring C-shaped weld gun was used, representative of a normal gun construction used in production. Standard aluminum RSW electrodes were used: Luvata copper-chromium-zinc electrodes with an
A0-type geometry and a 20 mm (0.8 in.) diameter.

The sample geometry for welding tests was a two-sheet combination with sheet measurements 500 \( \times \) 88 mm (19.4 \( \times \) 3.5 in.). The welding sample geometry is illustrated in Fig. 1. A small offset of the two sheets was present to assist with destructive pull-out testing, which was carried out on an internally designed machine. Welding samples contained 30 weld spots, of which five replicates were made for each parameter. A weld spacing of 30 mm (1.2 in.) was used according to internal standards to reduce shunting effects. Electrode surface consistency was realized by automatic mechanical cutting (electrode dressing) after 15 welds.

Parameters of the study were a variation of current pulse shape with either fixed welding time or fixed heat input. A change in electrode force was not considered as a part of this investigation, and thus a constant electrode force of 7 kN was used for all tests. This force value was chosen to prevent expulsions and weld imperfections. The current profile was split up into two phases. The first current phase, referred to as the “upslope time,” was the phase in which current rose from zero to the set current level. The length of this phase altered the slope of the current rise and thereby also the current pulse shape. The three pulse shapes studied in this investigation included upslope times of 0, 50, and 100 ms.

The 100-ms upslope time shape was considered “standard” practice, whereas shorter upslope times were chosen to investigate the effects of steeper current rises. The second phase was referred to as the “welding time,” during which the current level was constant. In the first set of welding experiments, welding time was 50 ms. In the second set of experiments, welding time was increased for shorter upslope times to achieve an approximately constant total heat input. The total heat input was calculated using current and resistance measurements from the experiments using a constant welding time of 50 ms. The welding times for 0 and 50 ms upslope time pulse shapes were then adapted for the constant total heat input tests using the previous resistance measurements. Then, new resistance measurements were used to ensure that an approximately constant total heat input value was obtained for all three pulse shapes. Thus, a total of five current profiles were used: 0-, 50-, and 100-ms upslope time under fixed welding time (50 ms), and the same upslope times under fixed total heat input (80-, 65-, and 50-ms welding times).

As previously mentioned, the same welding time was used for the 100-ms upslope time for the tests with constant welding time and constant total heat input. The current profiles are illustrated in Figs. 2 and 3.

Weld results were analyzed with regard to nugget diameter: the size of the fractured weld nugget after destruction by pull-out testing. Five types of fracture modes were observed, which were classified according to Fig. 4, recorded, and measured by the size of the fractured weld nugget. An acceptable weld result was obtained when the measured nugget diameter was greater than \( 5\sqrt{t_{\text{min}}} \), where \( t_{\text{min}} \) was the minimum sheet thickness of the sheets in the joint. Current and voltage signals were recorded during welding with a Ma-
tuschek SPATZMulti04 welding recorder, which was used to calculate electrical resistance and heat input. The positions of the moveable gun arm were recorded using the Bosch Rexroth PRC7000 weld controller. This signal is used for process monitoring purposes due to the information on heating and nugget formation contained in the signal.

Additional analysis was conducted by ultrasonic testing and optical microscopy of cross-sectioned samples. Ultrasonic testing was completed using an AmsTech mini scanner device, which utilizes scanning pulse-echo technology to image the weld zone and measure the fusion area. Cross-sectioned samples were sectioned, mounted, and polished using standard metallography techniques. Samples were etched in 5% sodium hydroxide solution for 60 s to reveal the fusion and heat-affected zones. Optical microscopy was performed using a Leica DMRM microscope.

Numerical simulations of the welding process were done with SORPAS® 2D welding software from SWANTEC using the two-dimensional, axisymmetric model and material properties as in the previous study (Ref. 10). In the companion study, electrical resistance properties of the alloy of study were calibrated and tested against experimental results (Ref. 10). Simulated weld sizes showed good agreement with experimental results, and the same model was utilized for this study. Simulations were used to analyze the effect of pulse shape on weld size and compared to experimental results.

**Results**

**Nugget Diameter and Failure Mode as a Function of Pulse Shape for Fixed Welding Time**

The initial welding tests were performed on 1.0-mm sheet thickness with a fixed welding time of 50 ms, and a strong influence of the current pulse shape on the weld result was seen. Results are presented in Fig. 5, where it is seen that when using the standard current pulse with upslope time of 100 ms, the required nugget diameter was not achieved even at the maximum allowable current level. This pulse shape also produced a large inconsistency in the weld result. This is evident by the large scatter of the data, with error bars showing maximum and minimum nugget diameter values. When upslope time was decreased to 50 and 0 ms, significant increases in nugget diameter were achieved, especially at current levels greater than 37 kA. Furthermore, a reduction in the variation in weld result and higher process stability was seen.

Failure modes gave additional insight into the process stability. These results are listed in Table 2. A high level of consistency in the failure mode was present in the case of 0-ms upslope time. In fact, beginning at 37 kA current level, 100% pull-out failure was obtained. Pull-out failure mode is considered advantageous because of its superior joint me-
Heat-affected zone (HAZ) size made between pulse shapes. As with the results from pull-out testing, fusion shapes. However, the areas of no fusion within the nugget area were largest with longer upslope time. At 41-kA current level, a large difference in nugget shape was seen. While a full, round fusion area had been formed with 0-ms upslope time, only partial nugget formation occurred for other pulse shapes. As with the results from pull-out testing, fusion zones were larger for the cases of shorter upslope time. At high current levels, although full nugget formation occurred for all pulse shapes, a difference in final fusion zone size still remained. For each current level tested, the largest fusion zone size was obtained with the shortest upslope time. Furthermore, the welding conditions which showed large areas of no or partial fusion within the fusion zone area in ultrasonic images corresponded to those which had a larger degree of variation in the failure mode obtained. Therefore, it is clear that welding conditions for which complete nugget formation occurs promote a higher consistency in the failure mode obtained.

Cross-sectioned samples were inspected at a single current level of 41 kA and a comparison of fusion zone and heat-affected zone (HAZ) size made between pulse shapes. The results are seen in Fig. 7, where a clear difference is visible in size and shape of the fusion zone as well as the size of the HAZ. The weld with 0-ms current upslope time resulted in an increased fusion zone height and a more round and symmetric fusion zone shape. The fusion zone height for this welding condition was 1.02 mm (0.04 in.). For the condition of 100-ms current upslope time, fusion zone height was 0.51 mm (0.02 in.). With respect to fusion zone diameter, a decrease from 3.84 mm (0.15 in.) to 1.90 mm (0.07 in.) was seen as upslope time was increased from 0 to 100 ms. Notably, a larger HAZ size was also produced by the condition of 100-ms upslope time (Fig. 7C). While heating of the material clearly occurred in this region, no melting occurred and the region did not contribute to the strength of the joint. The longer upslope time welding conditions therefore heat the material in a less efficient manner.

### Numerical Simulations

Fixed welding time tests were accompanied by numerical simulations, and the comparison to experimental results is shown in Fig. 8A–C. Nugget diameter sizes predicted by simulations are comparable to experimental results for the 0-ms upslope time condition. As upslope time is lengthened, the agreement between results decreases, especially for 100-ms upslope time condition. The conditions where less agreement is obtained correspond to conditions that exhibited incomplete fusion from the ultrasonic results (Fig. 6). The same conditions showed a large degree of inconsistency in nugget diameter (Fig. 5) and failure mode (Table 2) in pull-out tests. Therefore, a larger disagreement between simulation and experimental results can be expected for welding conditions that produce welds with incomplete fusion. These conditions include very short welding times and low current levels, as shown in the companion paper (Ref. 10), as well as longer upslope times, as in Fig. 8.

### Table 1 — Chemical Composition of AA 6016-T4 by wt-%

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>V</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>96.4–98.8</td>
<td>≤ 1.50</td>
<td>≤ 0.50</td>
<td>≤ 0.25</td>
<td>≤ 0.40</td>
<td>≤ 1.00</td>
<td>≤ 0.15</td>
<td>≤ 0.30</td>
<td>≤ 0.25</td>
<td>≤ 0.15</td>
</tr>
</tbody>
</table>

### Table 2 — Failure Mode Data For Pull-Out Tests for 50-ms Welding Time

<table>
<thead>
<tr>
<th>Welding Current (kA)</th>
<th>0-ms Current Upslope Time</th>
<th>50-ms Current Upslope Time</th>
<th>100-ms Current Upslope Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Interfacial (100%)</td>
<td>Interfacial (60%)</td>
<td>Mixed (60%)</td>
</tr>
<tr>
<td>27</td>
<td>Interfacial (80%)</td>
<td>Interfacial (60%)</td>
<td>Mixed (100%)</td>
</tr>
<tr>
<td>29</td>
<td>Interfacial (80%)</td>
<td>Interfacial (80%)</td>
<td>Mixed (60%)</td>
</tr>
<tr>
<td>31</td>
<td>Interfacial (60%)</td>
<td>Ring (60%)</td>
<td>Ring (60%)</td>
</tr>
<tr>
<td>33</td>
<td>Pull-Out (100%)</td>
<td>Pull-Out (100%)</td>
<td>Mixed (40%)</td>
</tr>
<tr>
<td>35</td>
<td>Pull-Out (80%)</td>
<td>Pull-Out (80%)</td>
<td>Pull-Out (40%)</td>
</tr>
<tr>
<td>37</td>
<td>Pull-Out (100%)</td>
<td>Pull-Out (80%)</td>
<td>Pull-Out (40%)</td>
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<tr>
<td>39</td>
<td>Pull-Out (100%)</td>
<td>Pull-Out (80%)</td>
<td>Pull-Out (60%)</td>
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<td>Pull-Out (100%)</td>
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<td>47</td>
<td>Pull-Out (100%)</td>
<td>Pull-Out (100%)</td>
<td>Pull-Out (100%)</td>
</tr>
</tbody>
</table>
Influence of Sheet Thickness

When sheet thickness was increased, the effect of the pulse shape on nugget diameter was greatly reduced. Results from pull-out testing for a sheet thickness of 1.5 mm are presented in Fig. 9. It can be seen that the largest nugget diameters were still obtained with a shorter upslope time, as with sheet thickness of 1.0 mm (Fig. 5). However, the difference in nugget diameter between the three sets of parameters was far less significant. While for the 1.0-mm sheet thickness differences of more than 2 mm in nugget diameter were observed between pulse shapes, the differences in diameter for the 1.5-mm sheet thickness were only approximately 1 mm. Longer upslope time also still produced larger variation in nugget diameter.

As opposed to the other sheet thicknesses, a longer current upslope time resulted in larger nugget diameter for the case of 2.0-mm sheet thickness (Fig. 10). Likely, this result is due to the larger overall heat input for 100-ms upslope time. While the rate of current input had a large effect on the weld result for thin-sheet thicknesses, the pulse shape seemed to have little to no effect on the weld result for the thicker sheets. Instead, increased total heat input from the upslope phase contributed to further nugget growth. The amount of variation in result was also largely unaffected by the pulse shape for this sheet thickness.

Pulse Shape with Constant Total Heat Input

For a more complete understanding of the influence of heat input rate on nugget formation, which is directly affected by the current slope, experiments were carried out using three additional parameters (Fig. 3) with nearly equal total heat input. It was determined that welding times of 80, 65, and 50 ms were necessary for the upslope times of 0, 50, and 100 ms, respectively, to achieve equal total heat inputs. Tests were performed on 1.0-mm sheet thickness due to the larger influence of pulse shape on the welding result for this thickness.

As anticipated, the same trend was obtained as in the previous section. The pulse shape with lowest current upslope time produced the largest nugget sizes. Extending the welding time for 0- and 50-ms upslope time cases had little impact on the nugget size compared with previous tests.
with 50-ms welding time. Results are presented in Table 3. For each of the three current levels tested, the 0-ms upslope time parameters led to the largest nugget diameter. In addition to the measurement of nugget diameter, total heat input ($Q_{\text{total}}$) and maximum heat input rates during welding ($Q_{\text{max}}$) were calculated for each case. Heat input was calculated as a cumulative heat generation according to the Joule heating law (Equation 1), and heat input rate was calculated according to Equation 2 (Ref. 17). The total heat input remained approximately constant ($\pm$300 J) between pulse shapes for the given current level. The 0-ms upslope time corresponded to both the highest maximum heat input rates and largest nugget diameters for each current level.

\[
Q_{\text{total}} = \int_{t_i}^{t_f} I^2 R dt (1)
\]

\[
Q = P(t)R(t) (2)
\]

**Discussion**

Pulse shape has a large impact on weld size, although this effect is less pronounced with increasing sheet thickness. The heat input rate during nugget formation varies greatly when pulse shape is changed, and this is an important consideration when welding this alloy in thin sheet thicknesses. The heat input rate increases rapidly during the initial stages of current application, reaching its maximum value early in the process due to large resistances present. Because the heat input rate is proportional to the square of the welding current (Equation 2), the maximum heat input rate does not occur until the current has also reached its maximum value. Therefore, the speed of the current rise has a large influence on heat input rate. Heat input rates throughout the welding process for three pulse shapes of equal current level and total heat input are shown in Fig. 11. Slower current rises due to long upslope times result in greatly reduced maximum heat input rates. This reduction is because the maximum current level is achieved later in the process, when significant decrease in resistance has already taken place. Figure 5 shows that the pulse shape had a significant impact on the current level needed for a satisfactory weld result. Likely, this is related to the differences in heat input rate during the early stages of the weld process when the nugget is formed. Aluminum alloy AA6016-T4 has a high thermal conductivity value of approximately 190 $W/mK$ (Ref. 18). Therefore, large heat input rates are necessary for heating at the joining interface before heat is conducted away to the base material. The relationship between heat input rates and the weld result suggest that heat losses from the joining location have a large influence on the final weld result and that a large enough heat input rate must be present for nugget formation to occur.

Heat input rates, however, had significantly less influence on the weld result when the sheet thickness was increased, evident by the results in Figs. 9 and 10. An explanation for this trend can be the difference in proximity of the water-cooled electrodes to the joining interface and the resulting differences in heat transfer conditions. The heating at the joining interface is influenced by cooling to a lesser degree when sheet thickness is increased. Therefore, when sheet thickness is increased, the heat input rate is less critical due to reduced heat losses via electrode cooling. This observation is consistent with the study by Kim et al. (Ref. 17), who studied RSW of galvanized steels. The authors in this study concluded that electrode cooling and heat transfer through the electrodes impact nugget growth to a greater degree for thin-sheet welding.

Maximum heat input rate was shown to partially indicate weld quality for 1.0-mm sheet thickness. However, total heat input was not relatable to weld quality. In Table 3, the maximum heat input rates and corresponding nugget diameter values were shown for constant heat input conditions. In all cases except for one, a maximum heat input rate of 100 kW or higher produced a weld of acceptable size. Therefore, the maximum heat input rate was relatable...
to the weld result. However, the case of 0-ms upslope time and 33-kA current level resulted in a maximum heat input rate of 159 kW but a nugget size of only approximately 3 mm (0.12 in.). In this case, although the maximum heat input rate was large, the current level was too low to produce a weld of sufficient size, possibly due to low total heat input. Therefore, although heat input rate has an influence on the weld result, the data suggests that it is not the only factor determining the weld result.

Total heat input, however, was a far less reliable indicator of the weld result. This was evident by comparing the nugget diameter data for welds of varying total heat input from the fixed welding time conditions — Fig. 12. Results included three different pulse shapes represented as a separate data series. It can be seen in Fig. 12 that welding conditions with similar total heat input values produced welds of vastly different sizes. In fact, welding conditions with a low total heat input but the 0-ms upslope time produced larger nugget diameters than conditions with a much higher total heat input but longer upslope times. Although conventional logic dictates that a larger heat input will produce a weld of larger size, this was shown to be untrue for these conditions and heat input rate tended to be a more influential factor. As previously discussed, these relationships are valid given the proper heat transfer conditions, specifically the RSW of thin sheets with materials of high conductivity. For these conditions, electrode cooling is in close proximity to the joining interface, and the heat losses via cooling added to heat losses via conduction through the sheets result in a large influence of the heat input rate on the welding result.

Simulations predicted an effect of pulse shape on the welding result, however to a lesser degree than observed in experiments. Simulation results for fixed welding time conditions were shown in Fig. 8A–C. Although smaller nugget diameters were predicted for the longer upslope time conditions, the differences in nugget diameter between pulse shapes were notably less than those observed in experimental tests. Generally, the nugget size was overestimated by simulations for the conditions of 50- and 100-ms upslope times. To investigate this difference, electrode to electrode resistances measured during experiments were compared to simulation outputs, shown in Fig. 13A–C. As seen in Fig. 13B and C, resistance values were much higher during the first approximately 10 to 25 ms of welding in the simulations than were measured experimentally. This difference resulted in a larger heat generation during the nugget nucleation stage in simulations than in experiments and may explain the overestimation of nugget size in the simulations for these conditions. While nugget sizes were in good agreement for the case of 0-ms upslope time, there was also a difference in the resistance curves between simulation and experiments for this condition during the first approximately 10 ms of current application. In this case, however, the resistances in simulations were far less than in experimental measurements. The reason for this difference in resistance signals is unclear. It is also unclear why better agreement in nugget size is obtained despite differences in resistance signals. However, it is clear that simulations and reality differ during the initial nugget nucleation stage. This is likely a result of the changing surface layer and contact properties occurring during this time but requires further investigations.

Inhomogeneous surface layers and more accurate contact properties are likely necessary for more accurate modeling of the nugget nucleation stage of the welding process. To obtain more accurate modeling of the contact resistance breakdown and nugget nucleation stage and thereby improve agreement between simulation and experimental results, it is likely that the surface contact properties must be defined in more detail. The numerical model considered temperature-dependent electrical resistivity values for surfaces of the workpiece and electrodes. Therefore, the contact resistance was already modeled dynamically during the welding process. However, the resistivity properties were considered uniform along the surfaces of the parts, as is standard in RSW modeling. However, it is evident by ultrasonic images (Fig. 6) that nugget formation does not occur uniformly along the joining interface but rather at localized points of electrical contact. The small molten zones then proceed to grow together to form a full nugget as the contact resistance breaks down, except in cases of slow heat input rate when no further nugget growth occurs and a partially formed nugget remains. Because of this inhomogeneous nugget formation, it is likely that the inhomogeneity of the surface properties plays a role in nugget formation and final weld result. Variations in thickness and compo-

Fig. 13 — Comparison of electrode/electrode resistances in simulations to experimental measurements for: A — 0-ms upslope time; B — 50-ms upslope time; C — 100-ms upslope time. Results for 10-mm sheet thickness, 41-kA current level, and 50-ms welding time.
position of the aluminum oxide layer, pores and cracks in the oxide layer, and other factors could all affect the local resistivity values along the surface. Although incorporating this into a numerical model involves considerable effort, and no efforts have been made in this direction to the knowledge of the authors, an improvement of the modeling of the surface layers is an area of potential improvement for aluminum RSW modeling. A more detailed representation would assist in modeling of the contact resistance breakdown during the nugget nucleation stage, which influences the final welding result for certain welding conditions.

The pulse shape affects the resistance profile during welding. A faster current rise speed is characterized by a more rapid breakdown in resistance after current application as well as a higher peak resistance value. In a typical resistance vs. time curve for the aluminum RSW process, high resistances are present at the start of current application due to contact resistances from the aluminum oxide layer and lack of electrical connection between the sheets. This resistance is quickly reduced as current flow begins. As material is heated at the joining interface, a small rise in resistance is visible which then decreases steadily as melting and electrode indentation occur. A variation in resistance signals is seen as a function of pulse shape, shown in Fig. 14. Resistance signals are shown only during current application time, which varies in length based on pulse shape (Fig. 2). When upslope time was reduced and current rise speed increased, a sharp peak in resistance signal became visible, which was followed by a drop to an almost constant value within the first milliseconds of current application. The larger resistance values may correspond to rapid heating occurring at the beginning of current application due to the rapid current rise. The resistance profiles may also suggest rapid formation of the weld nugget, which occurs due to high contact resistances present at the start of current application. However, it is unclear whether these peaks in the resistance signals are directly relatable to the welding result.

In typical process monitoring of aluminum RSW, the resistance signal is not used due to small changes in resistance during the process (Ref. 19). For this reason, the resistance signal typically does not contain enough information on nugget formation to make a determination of the weld quality. Therefore, other process parameters are used for process monitoring, including the force on the gun arm from thermal expansion of the material during welding (Refs. 19, 20) or the electrode position signal when constant force control is used. Electrode position signals for the three pulse shape conditions are shown in Fig. 15. The position signals correspond to the same welding conditions as in Fig. 14. In Fig. 15, the position value of zero corresponds to the electrode position at the start of the pre-welding squeeze time, and changes in position during welding are presented relative to these initial positions. The 0-ms upslope time condition produced an electrode position signal with both a larger slope and larger change in position during welding. Generally, these two factors are used to qualify the weld and are related to nugget diameter. Therefore, the electrode position signals agree with data from pull-out tests (Fig. 5). A large change in position corresponds to large thermal expansion and corresponding force on the gun arm due to heating during nugget formation. It was previously hypothesized that the peaks in resistance curves may also be related to heating and nugget formation. Although the resistance peaks occur at different points of time in the welding process than the electrode position changes, the time delays are logical due to the time needed for controller action and movement of the electrode arm itself. Therefore, it is plausible that the peaks seen in the resistance curves in Fig. 14 may relate to heating and nugget formation, as they match the characteristics of the position curves which are used for process monitoring. However, this relationship requires further investigation over a larger range of welding conditions.

The short-pulse technique results in efficient formation of the welding nugget by increasing the heat input rate. Significant energy and time savings are obtained by lowering current levels and shortening of the main welding time as well as absence of the current upslope phase. Part one of the study on short-pulse parameters for AA6016-T4 (Ref. 10) showed that welding times could be re-
WELDING RESEARCH

Conclusion

This paper has investigated the influence of current pulse shape on the weld result for the RSW of AA6014-T4 using MFDC welding systems. The results have shown that short-pulse welding parameters with an optimized current profile reduce the required welding current levels as well as total heat input necessary to achieve sufficient weld size. The heat input rate is a function of both the welding current level and the pulse shape, and the heat input rate was an important factor for the weld quality of thin sheets. Heat input rate was not an influential factor for increased sheet thicknesses. An increased heat input rate resulted in more efficient heating of the material to be joined and for limiting heat losses to the surrounding material and electrodes during welding. A change in current pulse shape resulted in clear differences in electrical resistance and position signals, the characteristics of which may be related to the weld quality.

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