C. T. Ji,
Professor

Y. Zhou,*
Visiting Professor

Department of Materials Engineering,
Nanchang Institute of Aeronautical Technology,
Nanchang, Jiangxi, 330034, P.R. China
e-mail: ctji@niat.edu.cn

Dynamic Electrode Force and Displacement in Resistance Spot Welding of Aluminum

Dynamic electrode displacement and force were characterized during resistance spot welding of aluminum alloy 5182 sheets using a medium-frequency direct-current welder. It was found that both electrode displacement and force increased rapidly at the beginning of the welding stage and then at a reducing rate. Rates of increase in electrode displacement and force were both proportional to welding current. And both electrode displacement and force experienced a sudden drop when weld metal expulsion occurred. However, the rate of increase in electrode displacement did not reach zero during welding even for joints with sufficient nugget diameter, while electrode force peaked when a large nugget diameter was produced. Possible strategies for process monitoring and control were also discussed. [DOI: 10.1115/1.1765140]

1 Introduction

In resistance spot welding (RSW), the size of the weld nugget formed during welding is generally correlated to the joint strength, and therefore, it is used as a key quality criterion in production [1]. As a result, any on-line process monitoring and/or control system must look at some phenomena or characteristics, which occur or change as a result of the formation and growth of a nugget [2]. Dynamic electrode force and displacement, both being responses to nugget formation and growth, are two important parameters to monitor [3–9].

Electrode displacement (separation) occurs during welding as a result of thermal expansion of the weld region, including the solid expansion, the expansion due to the phase transformation from solid to liquid (melting) and liquid expansion beyond the melting point [6]. However, it may be interrupted by weld metal expulsion if heat generation is excessive [8]. On the other hand, the change in electrode force is a response to the thermal expansion under mechanical constraints. This force change can also be affected by other factors, such as the overall stiffness of the sheets between electrodes [5] and electromagnetic force (caused by welding current) acting on electrode arms [10]. For example, the dynamic force would begin to drop as a result of plastic deformation of the weld region [6].

Electrode displacement due to thermal expansion during RSW, mainly on steels [e.g., 4, 7], has been the subject of intense research and development work since the early 1940s [2]. Early work used a control strategy based on adjusting the rate (slope) of thermal expansion at the beginning (say 25%) of the welding stage and terminating the welding current when the total expansion reached a pre-determined value [2]. However, the absolute expansion will be affected by many variables such as machine characteristics and sheet thickness. To overcome this disadvantage, Janota [4], in a study on low carbon steel sheets of 0.6-1.5 mm, proposed a new approach, in which the rate of expansion was again controlled first but the current was terminated when the rate of expansion approached zero (corresponding to maximum expansion) rather than monitoring the absolute expansion. Janota [4] found that the instant of thermal expansion maximum did not depend on thickness, and probably, neither on quality (within certain limits) of the welded sheet, nor on the welding process character. Cho and Chun [7], in an investigation on RSW of mild steels, developed a control system in which electrode displacement was used as a feedback variable to adjust welding current in order to track a desired electrode displacement curve that was experimentally predetermined for good weld quality. The characteristic values of the curve, such as the rates of the expansion and the peak values, were well correlated with joint strength [7]. Haefner et al. [9] developed a real time control system, based on the rate of change of displacement, which would incorporate variations caused by electrode wear.

The dynamic electrode force, i.e., the change of electrode force from the value preset at the start of the weld sequence, would be affected by electrode displacement and hence is also a potentially useful variable for process monitoring or control. In simplest form, the force-displacement relationship measures the effective stiffness of the welding machine-electrode assembly. In most real cases, the force-displacement relationship of RSW process equipment will have significant nonlinear and time/rate-dependent characteristics, which need to be kept in mind when force is monitored. In previous research, the change in electrode force during RSW has been investigated but to a much smaller extent. Chien and Hannatey-Asibu [5] characterized the dynamic electrode force during RSW of 0.8-mm-thick galvanized steel sheets and found that electrode force during welding increased until it reached a peak due to thermal expansion. It then began to decrease, after the nugget started to form (note: not necessarily after a sufficiently large nugget was formed), due to a reduction in overall stiffness of the sheets between the electrodes. Higher current increased the slope of this drop and reduced the time at which the force reached its peak [5]. The force change during welding was affected by welding parameters (e.g., welding current, preset electrode force), welding machine characteristics (e.g., friction, stiffness), and sheet materials (e.g., thickness and physical properties) [6].

The interest in high-volume production of aluminum parts for vehicle applications has been growing rapidly in the last decade because of growing pressure from legislation to improve fuel efficiency and reduce vehicle emissions [11]. On the other hand, RSW is one of the most attractive assembly methods because it is simple in operation and low in cost. Therefore, there is an increased research emphasis on high-volume RSW of aluminum alloys (mainly on issues such as electrode life and joint properties [12–14]), to support its use (to replace steels) in production. However, aluminum alloys have about three times the thermal and electrical conductivities of steels, which means about two to three times the amount of current and about one-quarter the welding time are needed during resistance spot welding of aluminum alloys compared to steels [1].

In contrast to work on steels, there has been very limited work

*Department of Mechanical Engineering, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada, e-mail: nzhou@uwaterloo.ca

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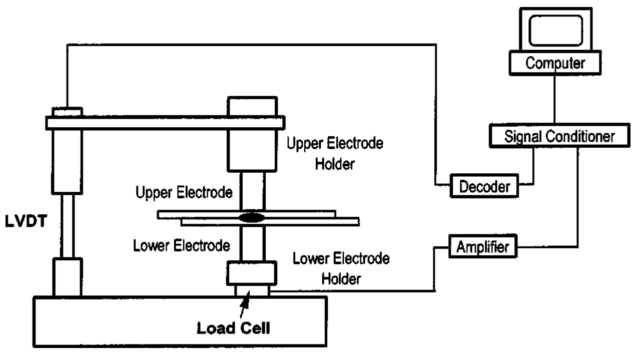

Fig. 1 Schematic of data acquisition system

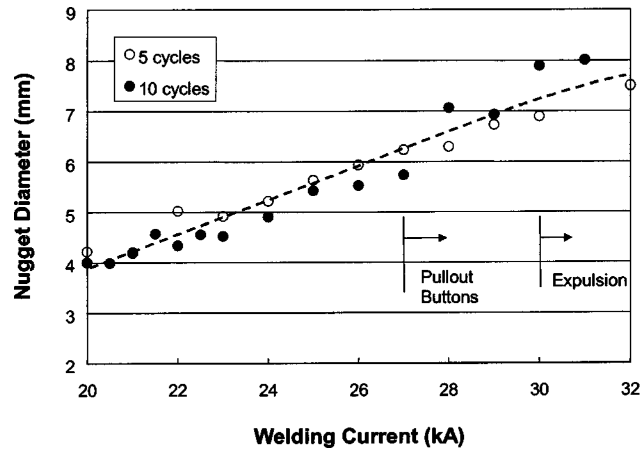

Fig. 2 Nugget diameter versus welding current on the 1.5-mm-thick sheets.

on dynamic electrode force and displacement, process monitoring and control in RSW of aluminum [6,8,15]. The objective of this work was to characterize dynamic electrode displacement and force during RSW of aluminum alloy 5182 sheets using a Medium Frequency Direct Current (MFDC) welder. Possible strategies for process monitoring and control were also discussed.

2 Experimental

All experiments were performed on 1.0- and 1.5-mm-thick, electrolytically cleaned sheet aluminum alloy AA5182 using a MFDC press-type resistance welder of 170 kVA rated power and 1200-Hz transformer frequency. This welder was specially designed and manufactured by Centreline (Windsor) Ltd. for laboratory use with very short arm length (or throat depth, which is about 180 mm from the terminal of the transformer to the center of electrode), high stiffness, low friction and inertia. Electrode force is generated by a pneumatic-hydraulic pressure intensifier (OHMA Piercing Cylinder) that provides a reproducible, constant static force but relatively large dynamic stiffness during the welding sequence. In this actuator design, operation of the cylinder to apply the welding load locks a fixed volume of hydraulic oil in the operating cylinder and necessitates overcoming friction and inertia of the intensifier piston before the loading ram can move in response to rising load.

All welds were made on test coupons about 200×30 mm using Cu-0.15% Zr electrodes with a taper angle of 60°, a tip face diameter of 10 mm and radius of curvature of 50 mm. Nugget diameter was determined from that of pullout buttons in peel testing. The preset electrode force was 5783 N (1300 lbs) and 3559 N (800 lbf), respectively for 1.5- and 1.0-mm-thick sheets. The weld time was 5 or 10 cycles: the MFDC welder uses "cycle(s)" to program all time variables and one cycle equals 1/60 s or 16.7 ms. Other welding conditions included 180-lb close gun electrode force, 50-cycle squeeze time, and 30-cycle hold time.

Electrode displacement and force were measured using a linear variable differential transducer (LVDT) and a piezoelectric load cell (Fig. 1), respectively, each at a sampling speed of 25 kHz. Data collected from the data acquisition system was processed in a personal computer with MATLAB.

3 Results

3.1 Electrode Force. Figure 2 shows nugget diameter versus welding current for the 1.5-mm-thick sheets. Extending weld time from 5 to 10 cycles did not increase nugget diameter, which is understandable considering the different properties of aluminum alloys compared to steels. Because the bulk electrical resistance of aluminum is much lower than that of steel, it is the contact resistance between aluminum surfaces (with surface oxides under production conditions) that produces the heat required to form a weld between the two workpieces. This heat generation would be only effective for the first few cycles because of the intensive cooling caused by the relative high thermal conductivity of aluminum compared to steel [1]. It was observed in peel testing, that when welding current was above 27 kA (with nugget diameters about 6 mm), all joints failed as pullout buttons. Weld metal expulsion started to occur when welding current reached 30-31 kA. The automotive industry specifications generally require that a joint must fail in pullout button mode in peel testing and the nugget diameter must be above $4\sqrt{t}$ (where t is sheet thickness), which produces 4.9 mm for required nugget diameter in this case. Therefore, welding currents of 27-30 kA (with nugget diameters at about 6-7 mm) are evidently required to produce pullout buttons without expulsion.

Dynamic electrode force curves collected at weld time of 10 cycles for the 1.5-mm-thick sheets (Fig. 2) are shown in Fig. 3. At each current, from the start to the end of welding current, dynamic electrode force increased very rapidly at the beginning of the welding stage and then at a reducing rate. The initial rate of force increase (the slope of force curve at initial stage of welding) was proportional to welding current with the average rate over the first two cycles at about 13,300 to 18,700 N/s when the current increased from 25 kA to 31 kA. It also appears that this rate of increase in force did not approach zero during the welding stage until the welding current reached 26 kA. At higher currents, the force started to drop before the current was terminated, which resulted in a force peak (Fig. 3). It is interesting to note that the joints made at currents above 27 kA produced both force peaks and pullout buttons. The force peak also appeared to shift to earlier time as the current increased. When the current was at 31 kA, a large downward spike occurred after the force peak (Fig. 3), which indicated weld metal expulsion. Tests performed on 1.0-mm-thick AA5182 also indicated similar electrode force characteristics.

The drop in electrode force after peaking during welding has also been observed in RSW of both bare and galvanized steels [5,6]. This was believed to result from the reduction in overall stiffness of the sheets between the electrodes after the weld region experienced plastic deformation. Chien and Hannatey-Asibu [5] indicated that the force started to decrease even when the nugget just began to form. To further investigate the relation between the force peak and nugget formation in this work, the nugget diameter and force curves at different weld times were investigated (Figs. 4 and 5). It was noted the force started to drop after 3 cycles (Fig. 5), which indicates that the force peak occurred when the nugget had grown to a sufficient size (Fig. 4), and that extending weld time after the force peak did not increase nugget size significantly. This can also be seen in Fig. 2 and is consistent with the general

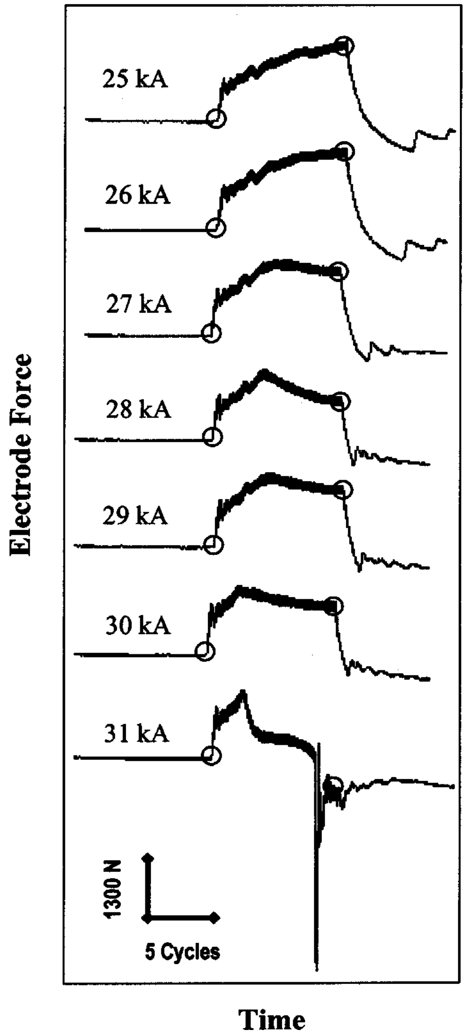

Fig. 3 Electrode force curves at different welding currents on the 1.5-mm-thick sheets. For each current, the first and second points marked (circled) indicate the start and end of welding current, respectively.

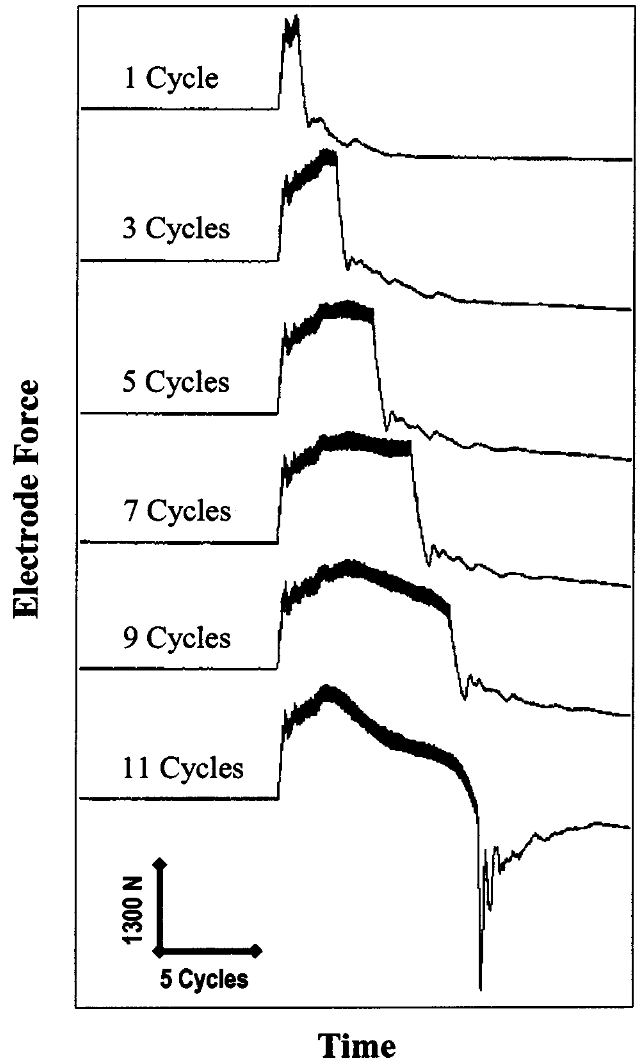

Fig. 5 Electrode force curves at different weld times on the 1.5-mm-thick sheets (with the current at 30 kA)

observations that the high electrical conductivity of aluminum requires about two to three times the amount of welding current and about one quarter of the weld time compared to RSW of steels [1]. This characteristic feature of the dynamic electrode force curve, i.e., the timing of the force peak, would provide a useful base for process control to get a sufficiently large nugget. This process control strategy will be discussed in details in Section 3.3.

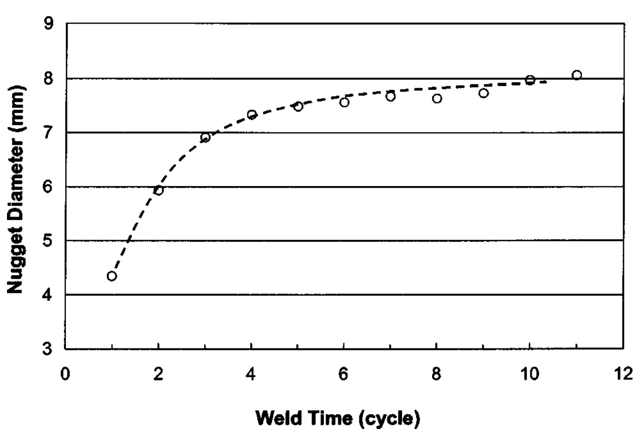

Fig. 4 Button diameter versus weld time on the 1.5-mm-thick sheets (with the current at 30 kA)

Tang et al. [6] reported that dynamic electrode force decreased during RSW of aluminum alloy 5754 of 1 to 2 mm in thickness, rather than increased, even at the beginning of the welding stage, which is obviously the opposite to the observation in this work. While the exact reason(s) for these different observations are unknown, it is believed that this discrepancy was caused by different welding conditions (such as welding machine characteristics, welding process parameters and materials properties of workpieces). For example, Fujimoto et al. [10] have shown that the electromagnetic force, caused by high welding current, tends to force the electrode arms apart and provides an opposite effect to the thermal expansion produced at the weld region. This electromagnetic force, proportional to the square of the current and electrode arm length, could result in a net decrease in dynamic electrode force during welding. In this connection, the welder used in this work, deigned specially for laboratory use, has very short electrode arm length (about 180 mm) compared to most commercially made welders (with arm length much longer than 450-600 mm).

3.2 Electrode Displacement. Dynamic electrode displacement curves collected at weld time of 10 cycles for the 1.5-mm-thick sheets (Fig. 2) are shown in Fig. 6. At each current, the

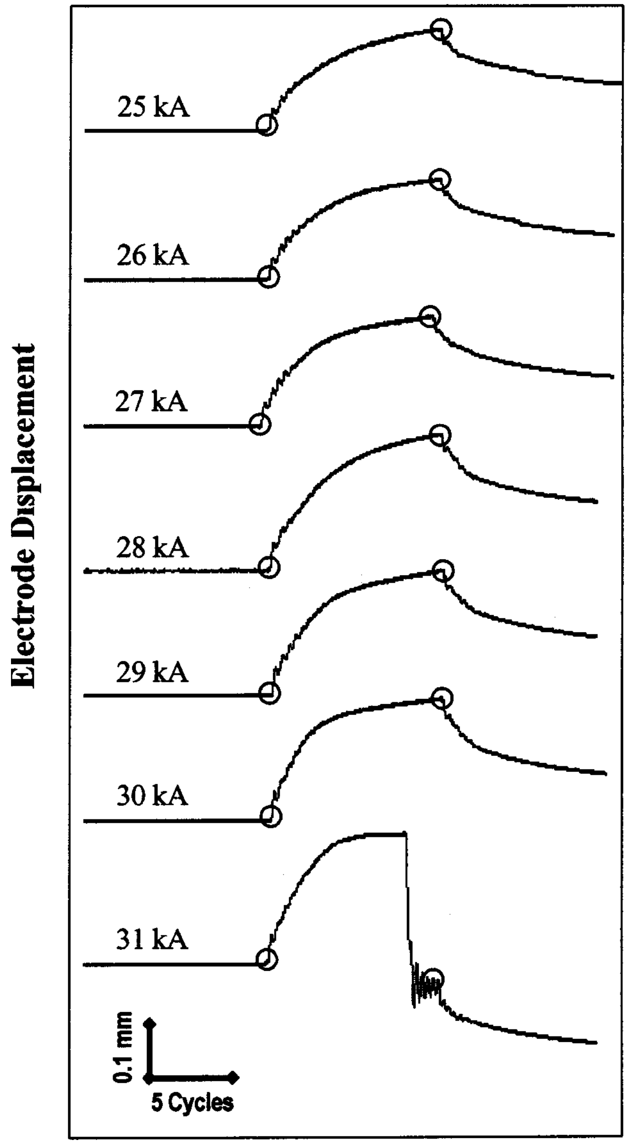

Fig. 6 Electrode displacement curves at different welding currents on the 1.5-mm-thick sheets. For each current, the first and second points marked (circled) indicate the start and end of welding current, respectively.

displacement increased rapidly at the beginning of the weld stage and then at a reducing rate until the current was terminated. However, the rate of change of displacement did not drop to zero under the normal welding conditions, except for the curve where expulsion occurred because the current was too high. When expulsion occurred at welding current of 31 kA, electrode displacement experienced a sudden drop before the current was terminated. The initial rate of expansion (the slope of displacement curve at initial stage of welding) was proportional to welding current. For example, the average rate over the first two cycles was about 3.2 to 5.1 mm/s when the current increased from 25 kA to 31 kA.

Janota [4], in a study on low carbon steel sheets of 0.6-1.5 mm in thickness, found that the approach of the rate of thermal expansion (really the increase in displacement) to zero coincided with the end of significant nugget size expansion. However, as shown above, this is not the case in this work for aluminum. Although the nuggets grew most of their diameter in the first 3 cycles in this work (Fig. 4), the electrode displacement increased continuously until the current was terminated. This may be because thermal

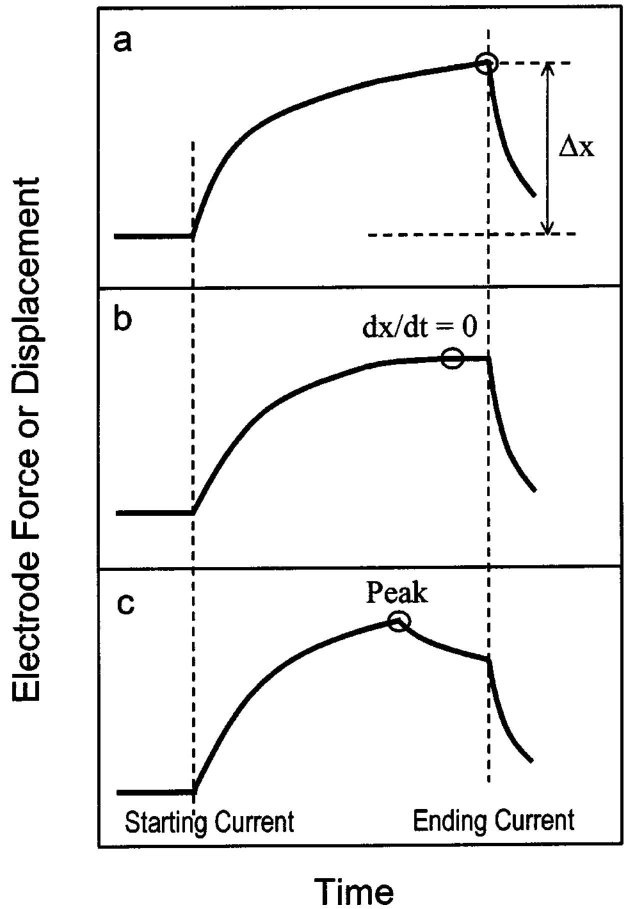

Fig. 7 Schematic of the change in electrode force or displacement

equilibrium (i.e., a steady state of the temperature field) was not reached within the measuring system comprising electrode holders, electrodes and sheet workpieces when the temperature field between sheets was close to equilibrium.

3.3 Discussion on Process Control Strategies. Thermal expansion is really a physical response to the temperature rise due to the accumulation of total energy in the weld region during welding [6,9]. This expansion will level off or start to drop if the temperature reaches its maximum or starts to decrease. Electrode displacement, driven by thermal expansion, will be also affected by the deformation (both elastic and plastic) of the weld region. The change in electrode force, on the other hand, is a mechanical response to the constraint of thermal expansion. The mechanical constraint is in turn affected by the welding process, e.g., plastic deformation of the weld region [6]. The change in electrode displacement and force would be further complicated by the electromagnetic force [10] and by any nonlinearity in response of the welder's loading system. Unfortunately, there is no quantitative description of both electrode force and displacement because of the complex nature of RSW. Dynamic electrode force and displacement will be affected by many variables, such as machine characteristics, properties of sheets, sheet thickness and process parameters [2,6,8]. Therefore, until more fundamental understanding is developed to mathematically describe the behavior of the two parameters, direct measurements may be the only ways available if the process is to be monitored and controlled based on these parameters.

Based on the experimental observations in this work, possible strategies for process control in RSW of aluminum alloys could be proposed, similar those in RSW of steels, depending on the char-

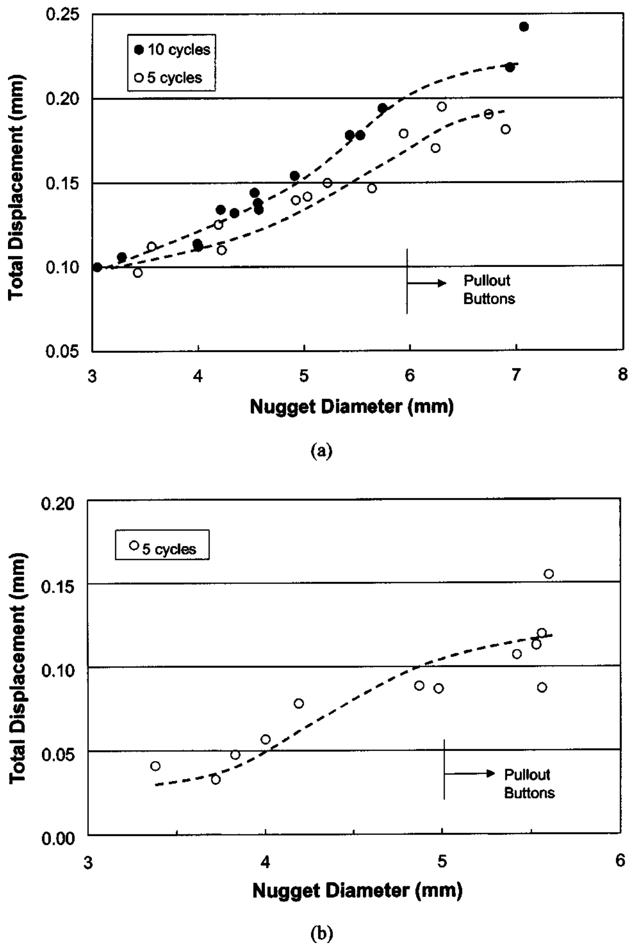

Fig. 8 Electrode displacement versus nugget diameter on the 1.5-mm-thick (*a*) and 1.0-mm-thick sheets (*b*)

acteristics of dynamic electrode displacement and/or force (Fig. 7). All the strategies include two steps. The first step is to adjust welding current to achieve an experimentally-determined rate of electrode displacement or force at the beginning of the welding stage. For example, in this work, a targeted initial rate of increase in displacement or force could be about 4.3 mm/s or 16,500 N/s (based on the results of welding current at about 29 kA). After the target rate is achieved, the second step is to keep the current constant until the total change in electrode displacement/force reaches a desired value (again prescribed by experiments), or the rate of change in electrode displacement/force reaches zero or starts to drop (Fig. 7). These three situations in the second step are discussed as follows in details.

For the first situation (Fig. $7(a)$), the displacement or force keeps increasing until the current is terminated; therefore, only the total change during welding can be used for process control. This is the case for displacement in this work (Fig. 6). However, the disadvantage of this control strategy is that the absolute change in displacement or force may be affected by many variables (such as weld time and sheet thickness). The relation between the total displacement (between the start and end of welding current) and nugget diameter for the joints without expulsion is investigated in the present work (Fig. 8). It was found that the total displacement correlated well with nugget diameter but was also affected by weld time and sheet thickness. This indicates that, for the purpose of process control, the target displacement will have to be experimentally determined for each set of experimental/production conditions. In this work, as discussed above, weld time of 5 cycles was sufficient; and therefore, a targeted total displacement at about 0.18 mm could be used to ensure nugget diameters at about 6.5 mm (Fig. 8).

Hao et al. [15], in an investigation on RSW of 1 and 2-mm-thick aluminum alloy 5754, indicated that a relationship existed between final displacement and nugget diameters for 2-mm-thick sheets but not for 1-mm-thick sheets. Although no detailed information was given for the displacement curves, it appeared the displacement dropped before the current was terminated [13], which was not observed under normal welding conditions (when no expulsion occurred) in this work (Fig. 6). Again, it is expected that the characteristics of electrode displacement would be also affected by many variables (such as machine characteristics), similar to electrode force.

If sufficient nugget size can be produced when the rate of change of electrode displacement or force reaches zero, the second situation (i.e., the starting point of $dx/dt=0$ in Fig. $7(b)$) may be a better strategy for process control. However, this strategy is not applicable in this work since the rate of change in displacement did not reach zero until weld metal expulsion occurred (Fig. 6). And the characteristic features of the electrode force curves in this work (Fig. 3) make the last situation of the strategies (Fig. $7(c)$) an alternative for process control. This strategy requires that the timing of electrode force or displacement peaks should be correlated to nugget formation and growth. Figures 4 and 5 shows that by the time the electrode force reached its peak, the nugget diameter has almost reached its maximum in RSW of aluminum alloy 5182.

Summary

Dynamic electrode displacement and force were characterized during resistance spot welding of 1.0 and 1.5-mm-thick sheet aluminum alloy 5182 using a medium-frequency direct-current welder and electrodes with a tip face curvature radius of 50 mm and tip face diameter of 10 mm. The results indicated that both electrode displacement and force increased rapidly at the beginning of the welding stage and then at a reducing rate under normal welding conditions. Rates of increase in electrode displacement and force at initial stage of welding were both proportional to welding current. Electrode displacement and force both experienced a sudden drop when weld metal expulsion occurred. However, the rate of increase in electrode displacement did not reach zero during welding even for the joints with sufficient nugget diameter while electrode force peaked when a large nugget diameter was produced.

Two possible strategies for process control in resistance spot welding of aluminum alloys 5182 were proposed, based on the characteristics of dynamic electrode displacement and force observed in this work. The first step of the strategies is to adjust welding current during process to achieve initial rates of change in electrode displacement or force at about 4.3 mm/s or 16,500 N/s for sheet thickness of 1.5 mm. Once the welding current is set, the second step is to keep the current constant until the force reaches its peak or the total displacement reaches an experimentally predetermined value, which is 0.18 mm at weld time of 5 cycles. Both would produce sufficient nugget diameters at about 6.5 mm for 1.5-mm-thick sheets. However, it should be kept in mind that other welding conditions (such as machine design and materials properties) would affect these control variables. For example, the targeted total displacement will change depending on welding conditions (such as sheet thickness and weld time).

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