WELDING RESEARCH

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Force Characteristics of Resistance Spot Welding of Steels

Force characteristics are presented under various welding conditions, and the mechanism of change is discussed

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ABSTRACT. Welding force is an important parameter of resistance spot welding (RSW). Ideally controlled as constant, the force changes during welding. The change is affected by several factors, including welding schedules and welding machine characteristics. In this article, the welding force change is investigated through experiments. Observations of the force characteristics are presented under various welding conditions, and the mechanism of the change is discussed.

Introduction

Welding force is an important parameter of resistance spot welding because the force functions to ensure electrical contact and to retain weld nuggets from expulsion (Ref. 1). In the process, the force reaches a preset value during the squeeze stage, theoretically remains constant in the weld stage, holds for a short period after the current terminates and is then released — Fig. 1A. In reality, however, the force varies during the weld stage, as depicted in Fig. 1B. From the viewpoint of weld formation, the weld stage is the most important among the four stages. Therefore, force characteristics in the weld stage should be addressed.

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There have been some experimental studies on electrode force. Early studies mainly focused on force measurement (Ref. 2). Researchers later realized the force changed during welding. For example, in 1990, Hahn, *et al.* (Ref. 3), discovered the characteristics of a force curve depended on cylinder types. They stated, however, that the mechanical properties of a welding machine did not affect the follow-up behavior since there was no interruption in the force. Krause and Lehmkuhl (Ref. 4) noticed a slight increase in force due either to the heating caused by the current, or to magnetic forces.

The electrode force has been recognized as important to the welding process and weld quality. Satoh, *et al.* (Ref. 5), found the increase of dynamic force was the main cause for the welding lobe to shift to the high-current side, in the case of a large friction force. Dorn and Xu (Ref. 6) discovered force touching behavior influenced contact electrical resistance and electrode deformation. Similarly, Krause and Lehmkuhl (Ref. 4) indicated force respunse behavior was important because of its influence on electrode life. In 1994, Karagoulis (Ref. 7) showed force was a significant variable, affecting both the size and position of the welding lobes. In 1996, however, De, *et al.* (Ref. 8), did not find any effect on weld strength from force. Through their design of experiments (DOE) for the weldability study of high-strength steels, Gould, *et al.* (Ref. 9), found high forces suppressed centerline-type porosity. In those studies, however, the force behavior during the weld stage was not addressed. To fully understand the complicated influences of the welding force and its change, it is necessary to characterize force behavior and to explore the mechanisms of force change during welding.

KEY WORDS

Aluminum
Electrode
Force Change
Resistance Welding
Steel
Weld Current
Weld Force
Welding Machine

The objective of this study was to explore the force characteristics during the weld stage. In this study, experiments were conducted under various machine setups, welding schedules and sheet metals. Based on the experimental results, attempts were made to explain the force behavior during welding.

Experiment Setup

Equipment

The experiments were carried out on pedestal-type welding machines. The majority of the experiments was con-

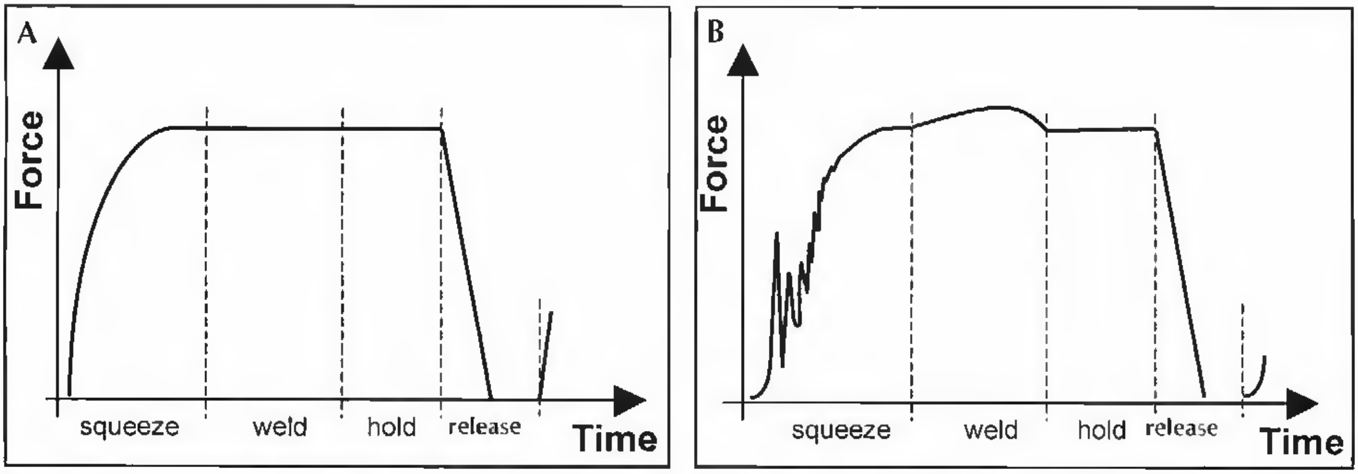

Fig. 1 — Schematic diagram of electrode force in welding. A — Idealized force; B — real force

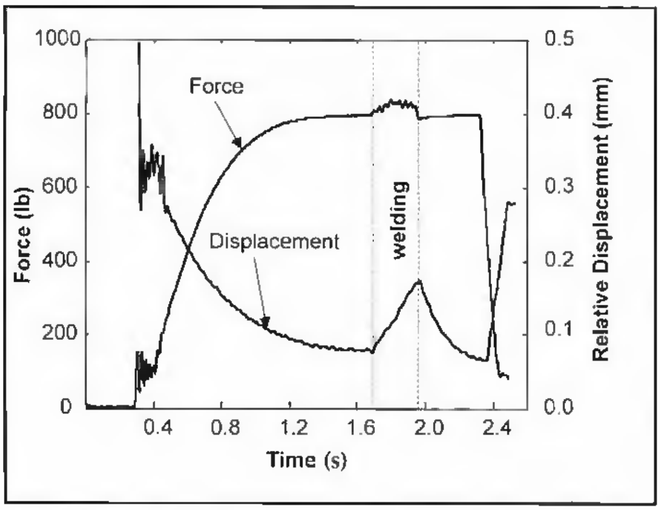

Fig. 2 — Typical measured electrode force and displacement.

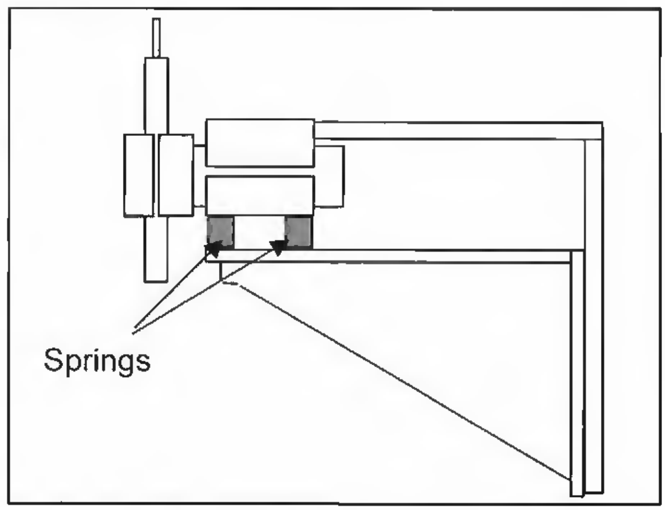

Fig. 3 — Modification of machine stiffness.

ducted on a 75-kVA pedestal welding machine (referred as the "welding machine" hereafter) at the University of Michigan. Some verification tests were done on a 200-kVA pedestal welding machine at the Edison Welding Institute, which will be identified when the results are presented. Truncated-cone electrodes were used in all experiments. To ensure the reliability of experiments, five welds were made under each condition. All welds had normal weld nuggets.

In the experiments, electrode force was monitored by a data acquisition system (DAS). The electrode force was measured by a strain-gauge-based load cell. The electrode displacement was also measured using a linear variable differential transducer (LVDT), which was used to calculate the acceleration of electrodes for the effect of machine moving mass. The typical measured electrode force and displacement in the experiments are shown in Fig. 2. The sampling rate of the data acquisition was set as 5000 Hz, and sampling time for a weld was 2.5 s.

Machine Modifications

The mechanical characteristics of welding machines play an important role in RSW. Because it is a dynamic process, the fundamental characteristics of RSW machines can be identified as machine stiffness, friction and moving mass. It is difficult to change one characteristic while keeping other characteristics constant if different machines are used. Therefore, in this study, the same machine was used and its characteristics, *i.e.*, stiffness, friction and moving mass, were modified individually. The magnitudes of the modified characteristics were selected within practical ranges.

Machine Stiffness

The stiffness of the pedestal welding machine was altered by adding cast springs, which reduced the stiffness of the lower structure, as shown in Fig. 3. In the experiments, two levels of stiffness were considered: 1.67 kN/mm (with springs) and 15.0 kN/mm (without springs).

Machine Friction

The friction of the welding machine was varied by using a specially designed device, as shown in Fig. 4. The device was mounted between the upper and lower structures of the pedestal welding machine. It could provide about 0.36 kN (80 lb) of friction force when there was a slight movement between the structures. The static friction force of the device was about 0.45 kN (100 lb). Because there

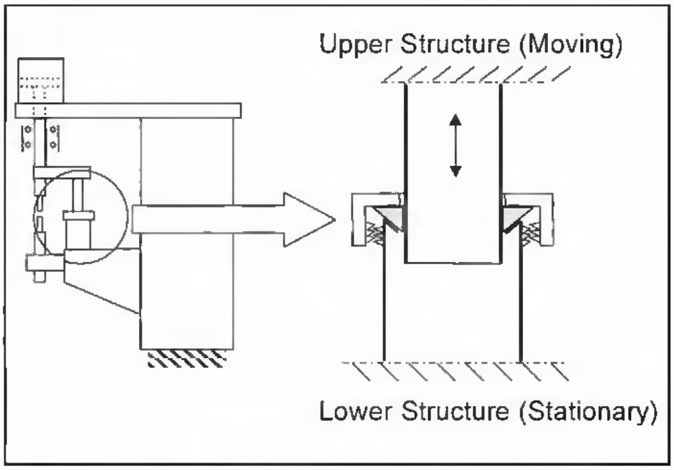

Fig. 4 — Modification of machine friction.

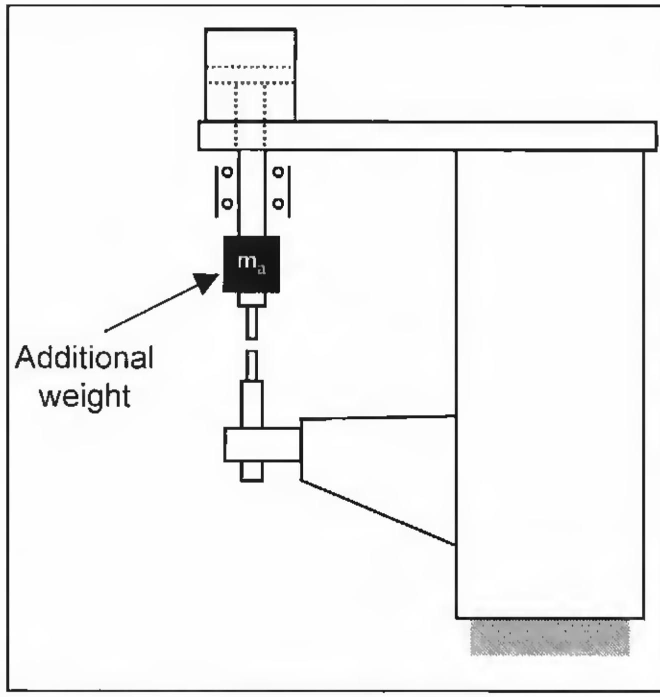

Fig. 5 — Modification of moving mass of the upper structure.

was a movement between electrodes during the weld stage, the effect of static friction was not considered in this study.

Machine Moving Mass

Some parts of the upper structure of the pedestal welding machine moved during a welding operation. So, in the experiment, a 20-kg weight was added to the upper structure of the welding machine, as shown in Fig. 5. As a result, the moving mass of the welding machine was increased from 40 to 60 kg.

Force Characterization

General Observation

A typical force curve of steel welding is shown in Fig. 6. The welding schedule chosen was 5.3 kN (1200 lb) force, 9.6 kA current and 16-cycle (267-ms) welding time for 2-mm-thick bare steel.

The following observations can be made by examining the figure. First, during the weld stage, the actual force was larger than the preset one. This was consistent for several experiments of steel welding. Second, the force increased rapidly at the beginning of welding current application. The force reached its maximum value before the current terminated under this condition. However, the force would continue increasing if the welding time was set shorter, e.g., ten cycles.

Description of Force Change

The force signal has strong noise during the weld stage due to electrical-magnetic interference. However, the major trend of the force change, rather than the oscillation due to noise, is important to present force behavior. To describe the trend, the force profile was represented by a curve fitting. Because the force change was nonlinear, an exponential function of the following form was employed:

$$F = A + Be^{-(t-t_0)} + C(t-t_0)e^{-(t-t_0)} \quad (1)$$

where, A, B and C are coefficients; t is time; and t_0 is the beginning of the weld stage. For simplicity, let $t_0 = 0$. Therefore,

$$F = A + Be^{-t} + Cte^{-t} \quad (2)$$

The maximum force can be expressed as

$$F_m = A + Be^{-t_m} + Ct_m e^{-t_m} \quad (3)$$

where, t_m is the time when maximum force is achieved, or

$$t_m = \frac{C-B}{C} \quad (4)$$

For the experimental data shown in Fig. 6, the force can be represented as $F = -1918 + 3121e^{-t} + 3928te^{-t}$, which is shown in a solid line in the figure. Its maximum value is 5695 N (1280 lb), and it occurs at 205 ms (12 cycles) from the time welding current starts.

This exponential model was used to analyze all experimental data of steel welding. With the exponential model, the force change trend became clear. The change can also be described by five characteristic parameters: preset force (F_0), maximum force (F_m), the time of the maximum force (t_m) and the start (t_0) and end times (t_w) of the weld stage — Fig. 7.

Results and Discussions

In this section, the results of various experimental investigations are presented to show the influences of machine characteristics, welding schedules and material properties on the force characteristics. Attempts were made to scientifically explain the experimental observations.

Table 1— Force Change under Various Preset Forces

Preset Force (lb)	600	800	1000	1200
ΔF (lb)	13	36	60	76
$\Delta F/F_0$ (%)	2.3	4.7	6.0	6.1

Influences of Machine Mechanical Characteristics

Force analysis is fundamental to understanding the roles of the machine characteristics, *i.e.*, stiffness friction and moving mass, which play different roles in influencing the welding force. Thus, the force analysis is presented first, followed by experimental observations and further discussions.

Force Analysis

An electrode force is composed of three components based on a free-body-diagram analysis: cylinder force (F_c), dynamic force (F_d) and friction (F_f) — Fig. 8. These components satisfy the following relations:

$$\sum F = F_e - (F_c + F_d + F_f) = 0 \quad (5)$$

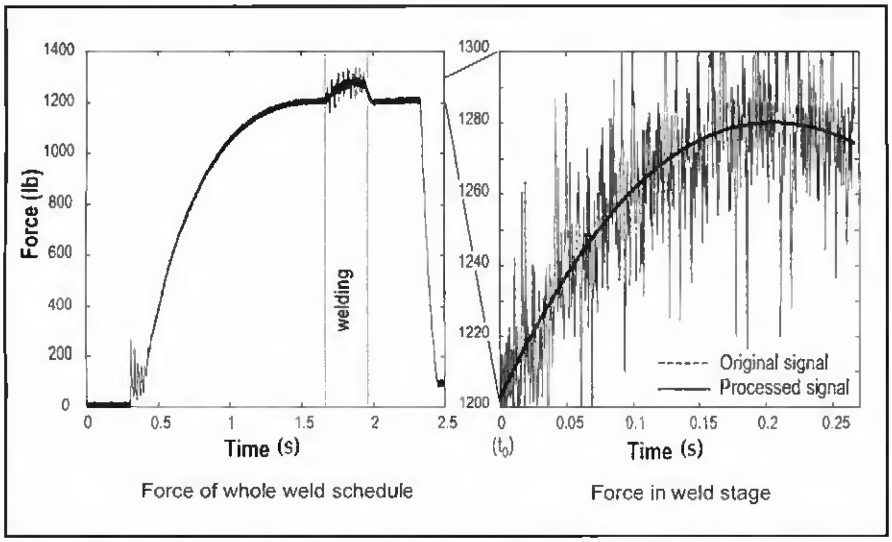

Fig. 6 — Typical force profile for welding steel.

Table 2 — Comparison of Material Properties between a Mild Steel and an Aluminum Alloy (ASM International, 1990)

	E (GPa)	σ_y (MPa)	Hardness	T_m (°C)	α (10^{-6}/K)	λ (W/cm K)
Steel	207	350	40 HRC	1538	11.8	0.802
Al Alloy (5454)	70	115	62 HB	660	23.1	2.37
Ratio	0.34	0.33	—	0.43	1.96	2.96

Table 3 — Welding Schedules for 1.5-mm Steel and Aluminum Sheets (Davies, 1993; AWS, 1997)

	Force (N)	Current (kA)	Time (cycle)
Steel	3560 (800 lb)	12.0	14
Aluminum	5118 (1150 lb)	33.2	8

The friction includes two components: one is from the inside of the cylinder of a welding machine and the other is from its guideway, marked as F_{fc} and F_{fs}, respectively — Fig. 9. Evidently, $F_f = F_{fc} + F_{fs}$, and the forces, F_{fc} and F_{fs}, work in the same direction. An important characteristic of the friction during welding is its change from static friction to kinetic friction. Because electrodes are stationary before applying welding current and move after it is applied, the force change due to the friction is nonlinear, and the change should be significant at the beginning of the weld stage.

The dynamic force (F_d) exists because of the acceleration of nugget expansion. Based on D'Alambert's principle, $F_d - ma = 0$, that is, the dynamic force is determined by the equivalent moving mass (m) and its acceleration (a). The acceleration of nugget growth exists at the beginning of the weld stage. If the acceleration is large, the dynamic force may be considerable.

The cylinder force (F_c) may be assumed constant if the air pressure (p and p') is controlled precisely by regulating valves. However, because of the imperfection in pneumatic and mechanical systems, F_c can in fact vary within a small range. Accordingly, the cylinder force may be considered as two parts: preset constant force (F'_c) and force variance (F_v), that is,

$$F_c = F'_c + F_v \qquad (6)$$

When the force change is within the control accuracy of pneumatic and mechanical systems, the cylinder can provide a slightly larger or smaller force than the preset one. Generally, the force variance (F_v) is small in a short interval and varies with machines and air sources. In this study, the force variance was ignored.

Machine Friction

The experimental conditions for the friction investigation were 1.8-mm bare steel specimen, 4000-N (900-lb) force, eight-cycle welding time and 8.8-kA electrical current. Comparing experiments between cases with and without the additional friction, three observations were made — Fig. 10.

1) When electrodes touched workpieces, force oscillation was reduced by the additional friction because the machine with greater friction had a stronger damping capacity. In addition, the touching was delayed.

2) The total force was smaller before welding when friction was greater because the friction opposes and cancels out some of the cylinder force.

3) Friction force applied toward the nugget and added more to the total force because the nugget expanded and pushed the electrodes away. Thus, the force in the case with additional friction increased more significantly than that without additional friction.

Friction can be considered the main source of force change during welding. The friction force is proportional to the normal force on contact surfaces. The normal force, furthermore, is in proportion to the preset force because of the bending moment of machine structures and the imperfect alignment of electrodes. In other words, the friction force is proportional to the preset force. It is expected, therefore, that the force change is more significant when the preset force is greater.

Machine Stiffness

Figure 11 shows the experimental data with higher and lower machine stiffnesses. It can be seen from Fig. 11A that the measured forces are different only during welding. The increment of the force under lower stiffness is 133 N (30 lb), while 334 N (75 lb) under higher stiffness.

Unlike friction and dynamic force, the machine stiffness provides an indirect influence on the force change. Different machine stiffnesses provide different constraints to nugget growth. The nugget expansion is more difficult under higher stiffness and it causes a greater reaction force on the electrodes. Therefore, greater stiffness results in a greater change of electrode force.

Machine Moving Mass

No significant force change was observed during the weld stage under different moving mass. Typical force curves obtained from the experiments are shown in Fig. 12.

As discussed previously, the effect of the moving mass can be seen only when the nugget volume expands with acceleration. The acceleration may be derived

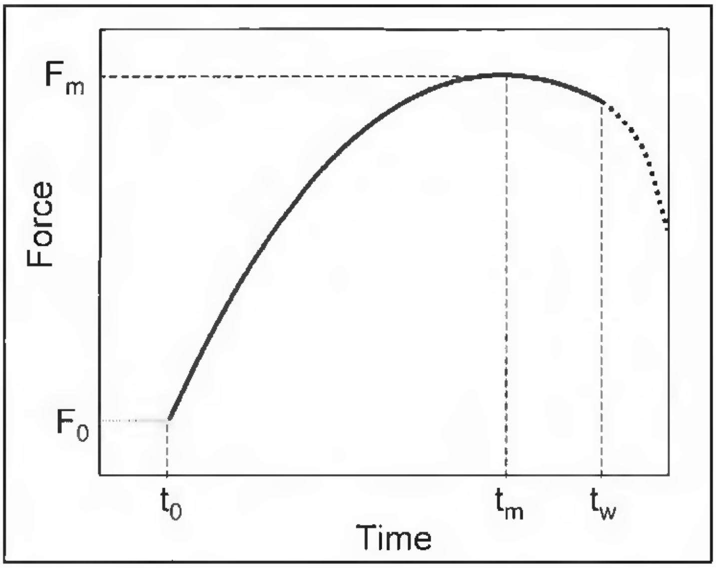

Fig. 7 — Representation of force characteristics during the weld stage.

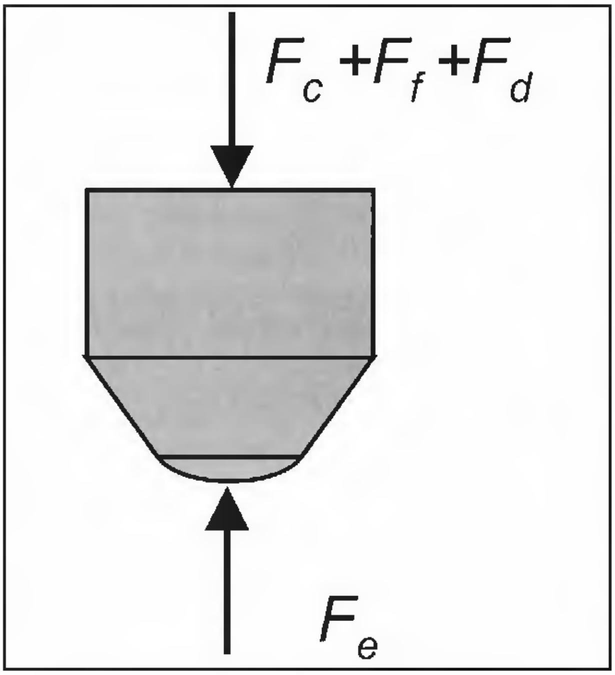

Fig. 8 — Equivalent forces on the upper electrode.

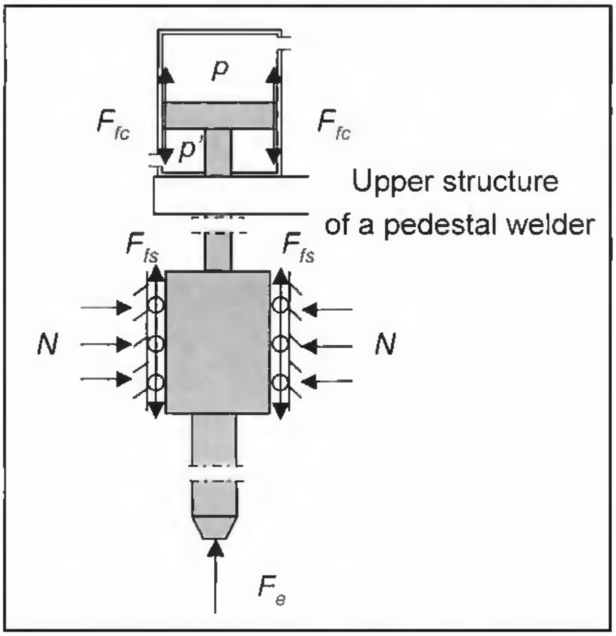

Fig. 9 — Friction forces in the upper structure of a pedestal welding machine.

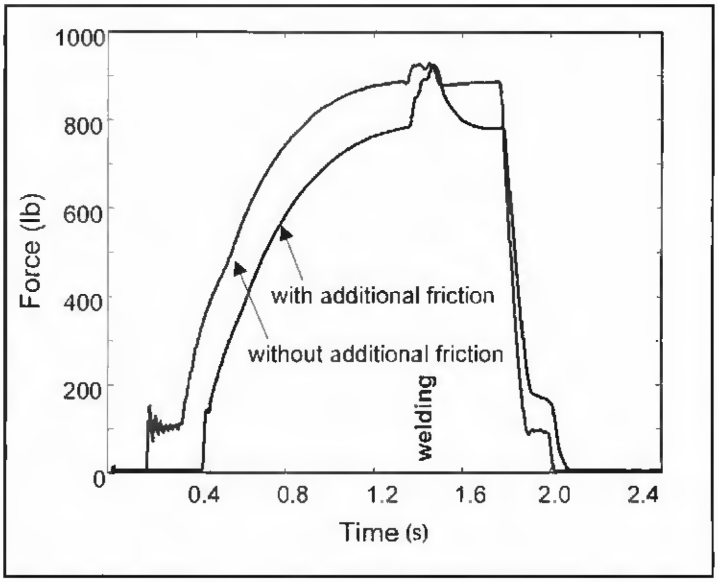

Fig. 10 — Force profiles with different friction.

from the measured electrode displacement. Under this experimental condition, the acceleration was about 0.23 m/s² during the first welding cycle, but almost zero afterward. If the upper structure weight of the pedestal welding machine was 40 kg, the calculated dynamic force was only 9 N (2 lb). Considering 3000-N (675-lb) welding force, it is understandable that the moving mass played an insignificant role in the force behavior.

Influences of Process Parameters

Force Change with Current and Time

Welding current and welding time are two very important process parameters of RSW. The experimental results showed the force increment (ΔF) decreased when the current increased — Fig. 13. Moreover, the time needed (t_m) for the force to reach its maximum value was shorter when the current was larger.

The welding time, however, showed a different effect on the force increment. The force change (ΔF) increased with time — Fig. 14. Under this welding condition, the force reached the maximum value (F_m) at or near the end of the weld stage.

The above observations can be understood from the governing equation of RSW,

$$H = kI^2Rt \quad (7)$$

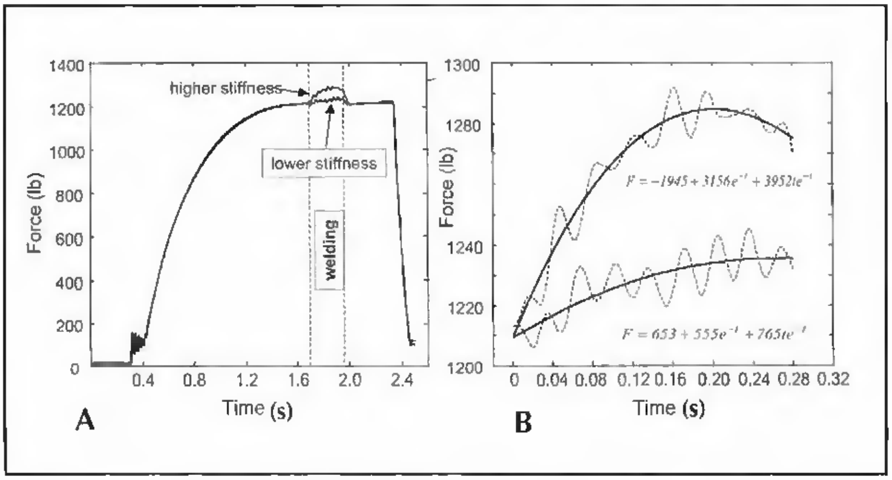

Fig. 11 — Force profiles with different machine stiffnesses. A — Force during entire welding process; B — force during the weld stage.

where H is the heat generated, k is heat loss factor, I is welding current, R is the resistance of the weldment and t is welding time.

This equation illustrates the fundamental relationship between the heat and welding parameters. A large current causes the temperature of the weld area to increase quickly, because the heat is proportional to the square of the current. Thus, the nugget volume softened earlier using a larger current than when using a lower current. Accordingly, the force began to drop to a lower level at an earlier stage, which was consistent with other experimental observations. Moreover, increasing welding time also increased heat input when other conditions were unchanged, but only linearly. Compared with current effect, therefore, the workpiece softened less and the force change took longer.

Force Change with Preset Force

To find the influence of the preset force value on the force characteristics during the weld stage, experiments were conducted under several preset forces with other parameters held constant. Force profiles monitored are shown in Fig. 15. A general observation was that the force increase became greater with a larger preset force. For example, the increment was about 338 N (76 lb) for a 5339-N (1200-lb) preset force. The force changes (ΔF) and the change ratio ($\Delta F/F_0$) are shown in Table 1.

The force constrains the thermal expansion of the nugget volume. When a larger force is applied, the thermal expansion suffers from a stronger constraint and creates a larger reaction force. Therefore, larger force change is expected.

Influences of Workpiece Material Properties

The previous observations and discussions pertain to steel welding. As an important alternative to steel, aluminum alloys have found their increasing use in automobile bodies for weight reduction. An all-aluminum car body has just been produced. Because aluminum alloys have very different material properties, different force characteristics are expected.

Experiments of aluminum welding. The main difference in the force change between aluminum welding and steel welding is the direction of the force change. The force decreases, rather than increases, for aluminum welding. Figure 16 shows a typical force behavior for aluminum welding, under the welding conditions of 4000-N (900-lb) force, 20-kA current and eight-cycle welding time for 1-mm aluminum sheets.

To prove the consistency of the above observation, various experiments were conducted under different welding schedules, on different workpiece thicknesses and using different machines. All observations on these experiments were consistent, as shown in Figs. 17 and 18. That is, the force always decreased in the weld stage for aluminum. The force decrement correlated well with current increment. The figures also show the thickness of sheet metal is another influential factor for the force change.

Impact of material properties. Aluminum alloys act much differently from

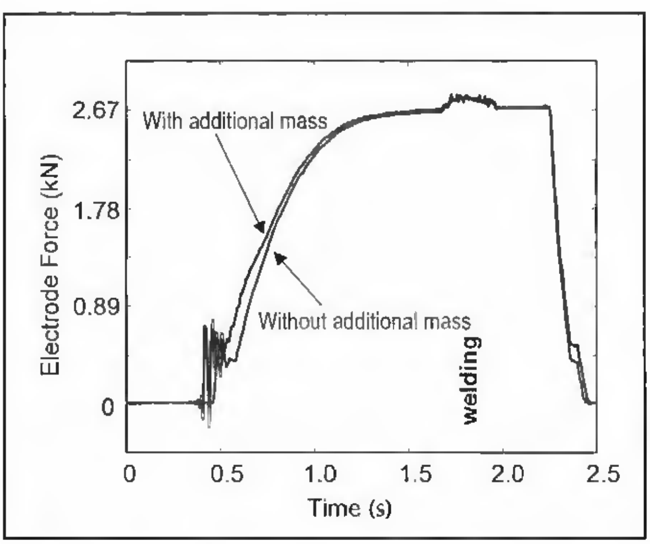

Fig. 12 — Force profiles with different moving mass.

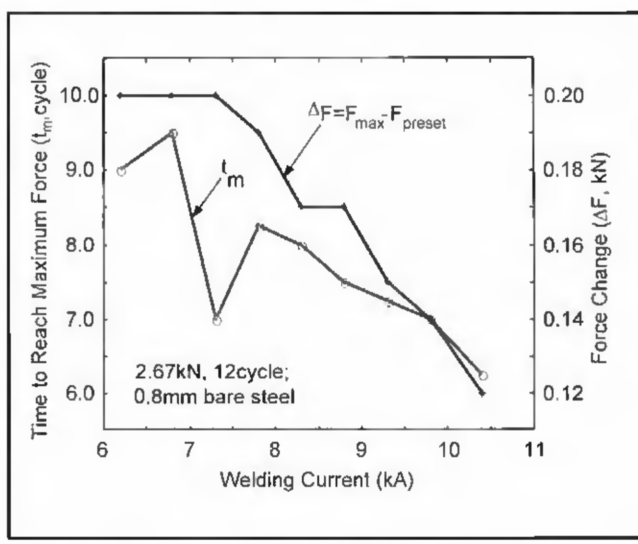

Fig. 13 — Force change vs. welding current (constant preset force and time).

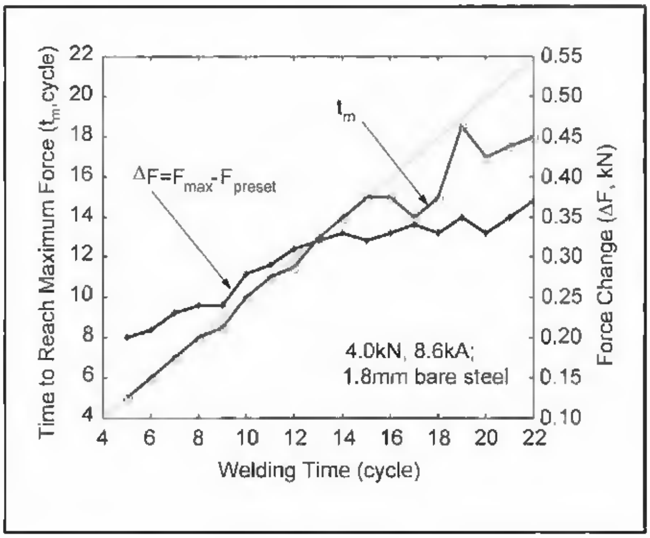

Fig. 14 — Force change vs. welding time (constant preset force and current).

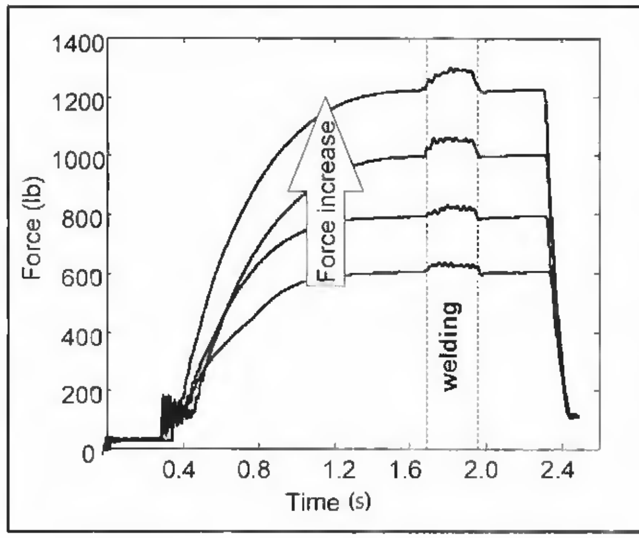

Fig. 15 — Force profiles vs. present forces.

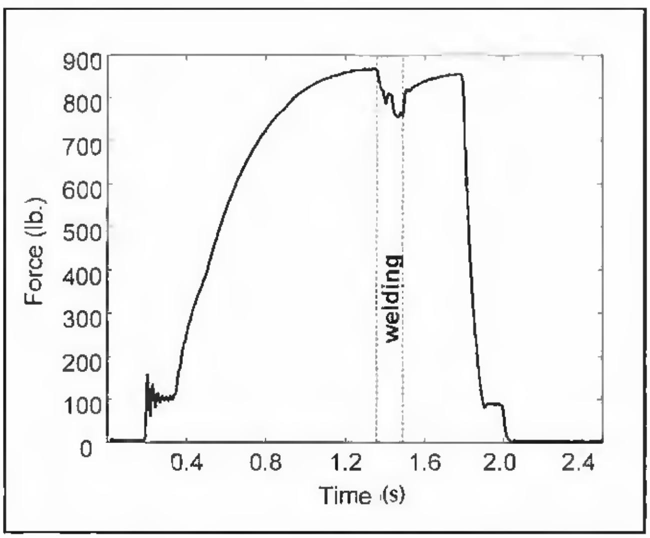

Fig. 16 — Force change of aluminum welding.

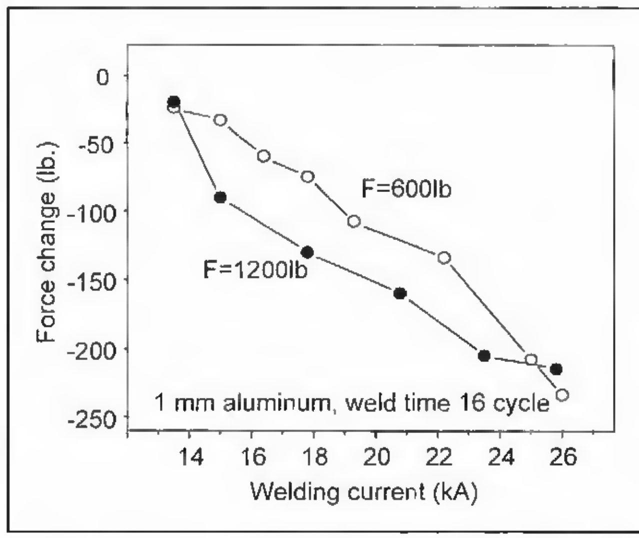

Fig. 17 — Force changes for aluminum on a 75-kVA pedestal welding machine.

steel because of their distinctive physical properties. The comparison of material properties between a mild steel and an aluminum alloy is listed in Table 2, where the property ratio is that of the aluminum alloy over that of steel.

Accordingly, the welding schedules for aluminum were different from steel. A comparison of welding schedules is listed in Table 3 for 1.5-mm sheets. For example, the preset force for aluminum welding was about 1.5 times larger than that for steel welding.

If the electrode face is 6 mm in diameter for steel welding, the pressure on the workpiece surface is 126 MPa, which is about 36% of the steel yield stress at room temperature. Comparatively, the pressure is about 133 MPa for aluminum welding with a 7-mm-diameter electrode, which is about 116% of the aluminum alloy's yield stress. Even at room temperature, the aluminum alloy yields under normal working conditions. At high temperatures, the workpiece deforms plastically. Consequently, the measured force declines.

Further Discussions on Force Change

The basic reason for the force change is the thermal expansion of the weld area due to Joule heating. The expansion may be simplified into three steps: solid thermal expansion, phase transformation from solid to liquid and liquid expansion beyond metal melting point. In all three phases, the volume of the weld area expands. Quantitatively, the volume changes of a pure iron and an aluminum alloy are shown in Fig. 19.

In RSW, however, the expansion of the weld area is much more complex than that shown in Fig. 19. First, the nugget expands during welding. The temperature distribution in the nugget and its surrounding solid is not uniform. Besides, the weld area is constrained by

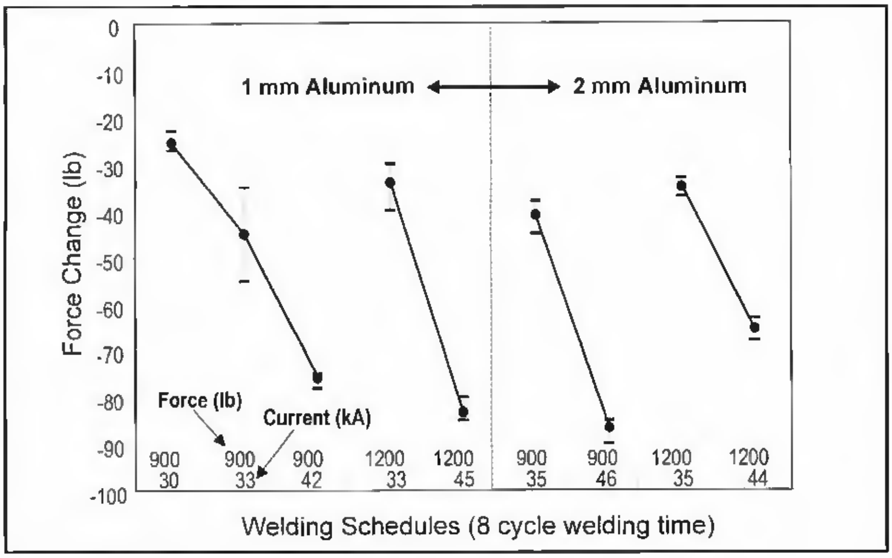

Fig. 18 — Force changes for aluminum on a 200-kVA pedestal welding machine.

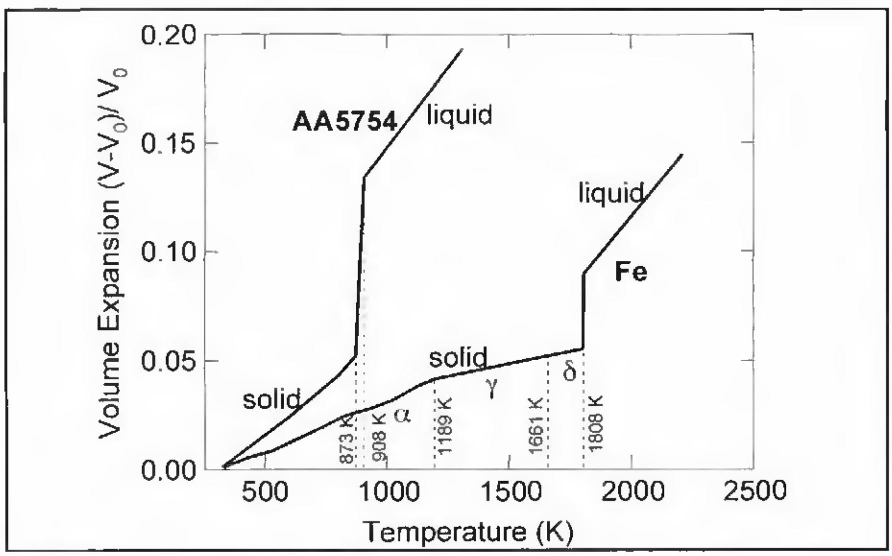

Fig. 19 — Metal volume change vs. temperature (Ref. 1).

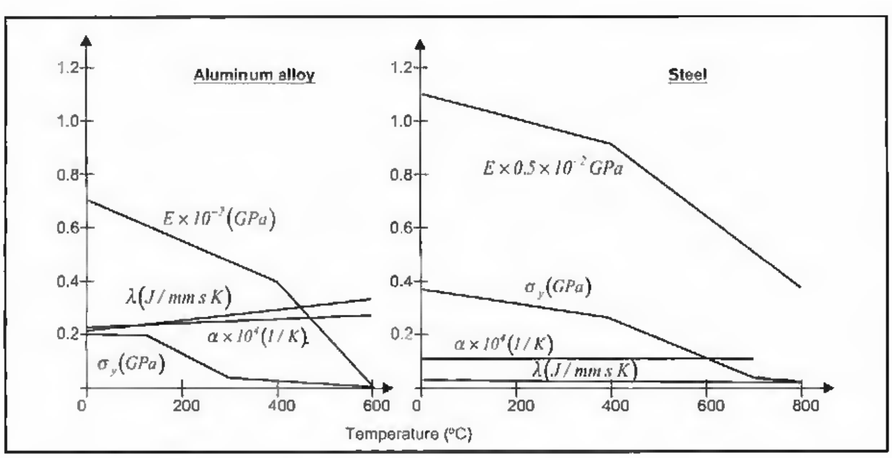

Fig. 20 — Material properties at elevated temperature (Ref. 10).

an electrode force. Therefore, it is extremely difficult to derive a quantitative description of the expansion and corresponding reaction force.

Furthermore, the expansion is significantly affected by the material properties because they are temperature dependent — Fig. 20. For example, yield strength (σ_y) drops dramatically at high temperatures. That means the weld area yields during welding. Under plastic deformation, the weld area softens and has less resistance to electrode squeezing. In other words, after a certain welding time, the force should begin to drop because of the plastic deformation of the weld area at high temperature.

In summary, thermal expansion is the root cause of the force change. The force change during the weld stage is affected by the machine mechanical characteristics, the process parameters and the thermal and mechanical characteristics of the workpiece material. In general, the force increases quickly in the beginning cycles, reaches its maximum (F_m) and then drops after t_m for steel. The yielding of the weld area at a high temperature is the reason for the force decrease after several cycles. For aluminum, force decreases from the beginning of the weld stage.

Conclusions

Experimental observations and analytical discussion of the dynamic electrode force during welding were presented. In general, the force increases during the weld stage for steel and the force change can be represented by an exponential model. The force is affected by machine characteristics, process parameters and workpiece materials. These findings can be beneficial to the design of welding machines, the selection of welding schedules and welding process monitoring and diagnosis.

1) *Influence of machine mechanical characteristics.* Friction is most important to the force change during welding. Friction and the force change are positively correlated. The machine stiffness plays a role as a constraint of the weld area expansion. The force change is larger under higher machine stiffness. However, the influence of the moving mass is insignificant.

2) *Influence of process parameters.* The force change is positively correlated with preset force. The influences of welding current and time are realized through the effects of the thermal-mechanical process. The force monotonically increases for steel with a relatively small current and a relatively short time. The force reaches its maximum value and then drops when the current is large or welding time is long.

3) *Influence of material properties of workpieces.* The yield strength at an elevated temperature is critical to the electrode force change, which may be the root cause for the force decrease at the late weld stage for steel. For the same reason, the force decreases from the beginning of the weld stage for aluminum. Moreover, the thickness of sheet metal also influences the force change through the thermal expansion of volume.

However, because of the complex nature of RSW, it is difficult to quantitatively describe the dependence of force change on these variables. If only a few variables are concerned, quantitative changes may be obtained through special designed experiments. Furthermore, the observations and conclusions of this research focus mainly on steel welding. Therefore, the force characteristics of aluminum welding need more study.

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