Influence of Welding Machine Mechanical Characteristics on the Resistance Spot Welding Process and Weld Quality

How machine stiffness, friction, and moving mass can affect welding results

BY H. TANG, W. HOU, S. J. HU, H.Y. ZHANG, Z. FENG, AND M. KIMCHI

ABSTRACT. Mechanical characteristics of resistance spot welding machines, such as stiffness, friction, and moving mass, have complex influences on the resistance welding process and weld quality. In this paper, these influences are systematically investigated through experiments. The mechanisms of the influences are explored by analyzing process signatures, such as welding force and electrode displacement, and other process characteristics, such as electrode alignment. A better understanding of the influences is achieved through this analysis. This study shows machine stiffness and friction affect welding processes and weld quality. It also confirms the moving mass does not significantly affect the process and quality of resistance spot welding.

Introduction

A resistance spot welding (RSW) machine consists of two distinct subsystems: electrical and mechanical. The characteristics of the mechanical subsystem, such as machine stiffness, friction, and mass, play important roles in the functionality and performance of a welding machine, and subsequently influence welding process and weld quality.

According to published literature, research on the influence of welding machines started in the 1970s. Early work focused on the differences in machine types. For example, Ganowski and Williams investigated the influence of machine type on electrode life for welding zinc-coated steels (Ref. 1). Kolder and Bosman studied the influence of equipment on the weld lobe diagrams of an HSLA steel at five sites (Ref. 2). Satoh and his coworkers concluded machine type was an important factor in weld performance based on their experiments on four types of welding machines (Refs. 3, 4).

More recently, researchers have addressed the effects of individual machine characteristics on various aspects of the welding process. Several studies were conducted on the influence of machine stiffness and electrode displacement. Hahn et al. (Ref. 5) found large displacement of electrodes resulted in defects of electrode contact and decrease of weld quality. Williams (Ref. 6) discovered an increase in throat depth and electrode stroke decreased electrode life. Similarly, Howe (Ref. 7) found electrode deflection significantly influenced electrode life. Dorn and Xu (Ref. 8) showed the stiffness of a lower arm had an effect on the oscillation and the mean value of electrode force when electrodes were in contact with the workpieces.

The influence of machine friction, or the friction between the moving parts and the stationary parts in contact within a welding machine, has also been studied. Satoh et al. (Ref. 3) found that friction had effects on nugget diameter and sheet separation. They also noticed that weld expansion occurred mainly in a direction perpendicular to the electrode axis if the friction effects were significant. Dorn and Xu (Refs. 8, 9) concluded an increase in friction reduces oscillation of electrode force during touching. They further found that the increase in friction reduced the tension-shear force and torsion moment of welds.

The moving mass of RSW machines was found less important to weld quality than stiffness and friction. Satoh et al. (Refs. 3, 4) did not find much influence from moving mass on weld nugget formation. They stated that the optimal weight of the moving part existed for electrode life in relation to the natural frequency of a RSW machine. Dorn and Xu (Ref. 9) observed that the moving mass affected vibration at low friction with a rigid lower arm. However, they did not detect any clear influence of the mass on weld quality. Theoretical attempts were made by Gould and his coworkers on the dynamic behavior of moving parts of a welding machine (Refs. 10, 11). In a recent study, Tang et al. (Ref. 12) performed a systematic investigation of the dependence of electrode force on machine mechanical characteristics, welding process parameters, and materials.

In summary, these researchers have made valuable contributions to the understanding of the effects of machine characteristics on welding. However, several issues remain to be resolved in this research area. First, the results of the previous studies were mainly descriptive and lacked convincing explanations. Due to the complexity of RSW, it is difficult to obtain explicit expressions of the influences only from comparisons. Second, weld quality was not emphasized in their studies, although improving weld quality has been one of the main concerns in both academic research and industrial practice. In addition, important mechanical characteristics of a resistance welding machine have not been systematically studied in previous works.

It is desirable yet challenging to obtain a scientific and systematic relationship between machine characteristics and weld quality. This research attempts to address

H. TANG is with Advance Manufacturing Engineering, DaimlerChrysler Corp., Detroit, Mich. W. HOU and S. J. HU are with the Dept. of Mechanical Engineering, University of Michigan, Ann Arbor, Mich. H. ZHANG is with the Dept. of Mechanical, Industrial and Manufacturing Engineering, University of Toledo, Toeldo, Ohio. Z. FENG is with Engineering Mechanics Corp. of Columbus, Columbus, Ohio. M. KIMCHI is with Edison Welding Institute, Columbus, Ohio.

KEY WORDS

Aluminum Alloys
Resistance Welding
Welding Machine Design

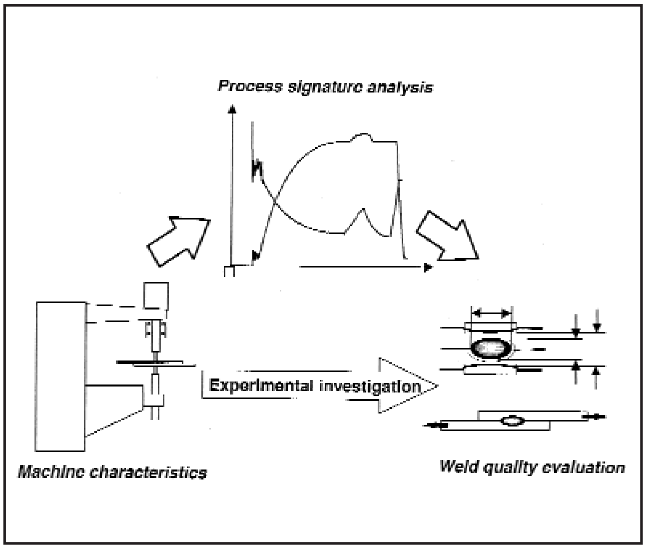

Fig. 1 — An approach to studying machine influence.

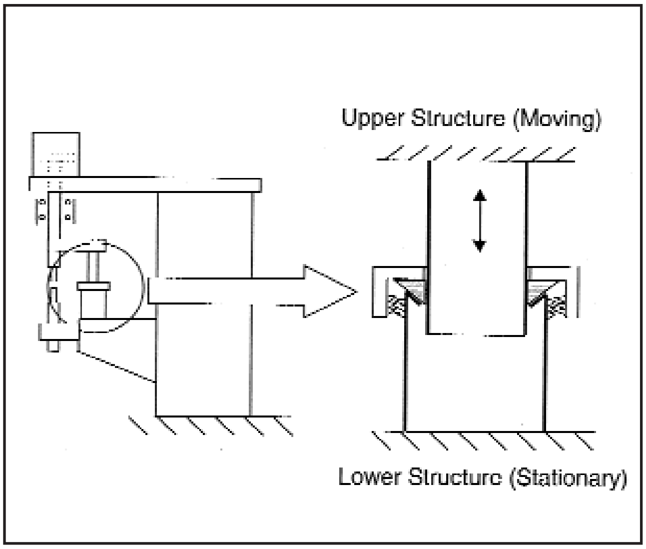

Fig. 2 — Modification of machine friction (Ref.12).

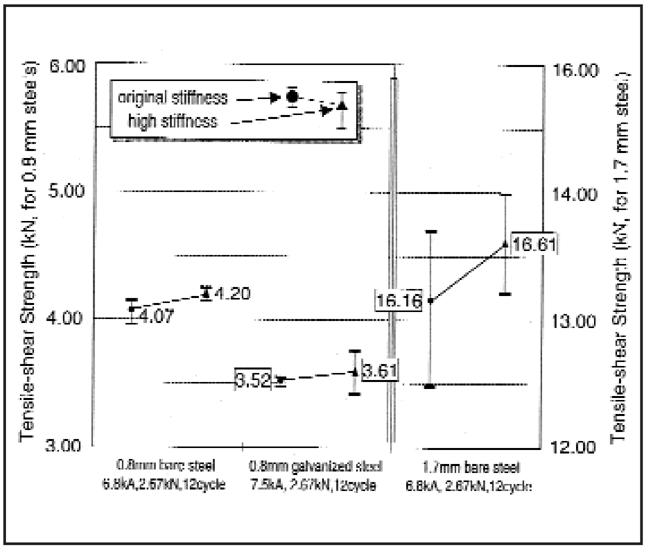

Fig. 3 — Influences of stiffness on weld strength (weld gun).

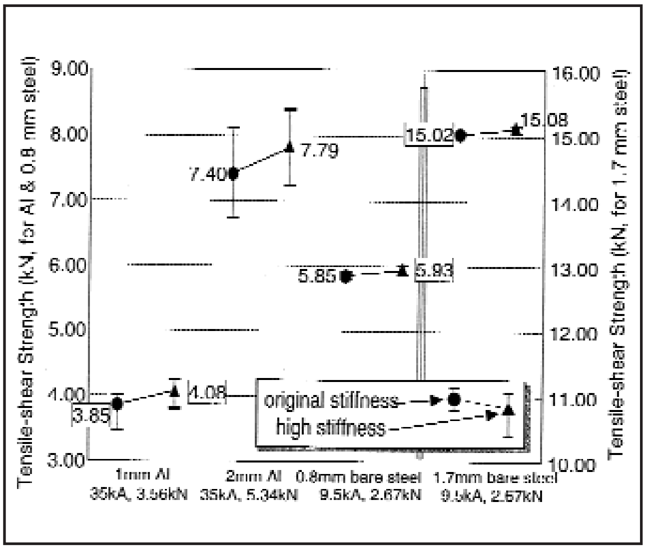

Fig. 4 — Influences of stiffness on weld strength (200-kVA pedestal machine).

some aspects of the relationship and also to understand how weld quality is affected. Both experimental and process signature analysis techniques were utilized in this study. Changes in machine mechanical characteristics are usually directly reflected by various process signatures recorded during welding. Therefore, the influence of machine characteristics on weld quality can be explained by analyzing the process signatures.

The electrode force was chosen as the primary process signature in this study. The influence of machine characteristics on weld quality may be largely explained through the analysis of the force characteristics because other process parameters, such as welding current and time, are not directly related to machine mechanical characteristics. Electrode displacement during welding is also important because it reflects the expansion, melting, growth, and solidification processes. Thus, both force and displacement were studied in this investigation of the relationship between RSW machines and weld quality. In the context of this work, weld quality refers to the geometric characters of a weld such as indentation, the appearance of expulsion, and the tensile-shear strength (peak load) of a weld.

The new approach attempted in this study combines experimental investigation (as performed by previous investigators) and process signature analysis — Fig. 1. Experimental investigations were systematically designed and conducted. Weld quality was emphasized in the study. Based on the experimental results and on analytical and numerical studies, the relationship between the individual characteristics and weld quality was explored through process signature analysis.

Experimental Investigation and Process Analysis

This experimental investigation was carried out on welding machines with modified mechanical characteristics. Such characteristics were then linked to weld quality, and the relationship was established through process signature analysis. The focus was placed on the signals during

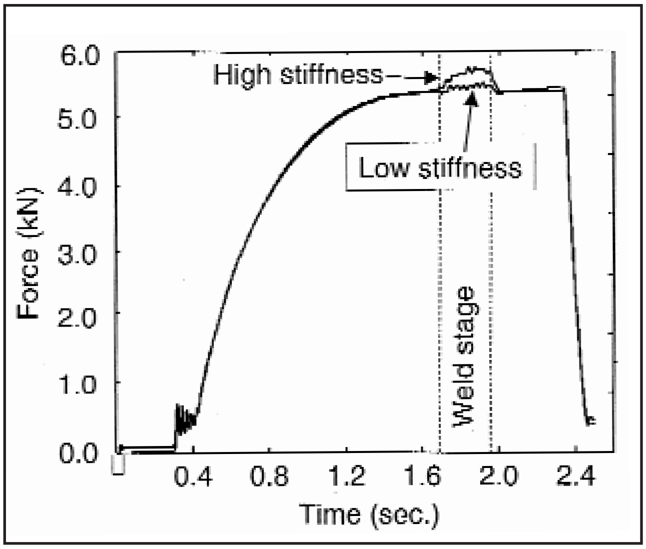

Fig. 5 — Force comparison under different machine stiffnesses (Ref. 12).

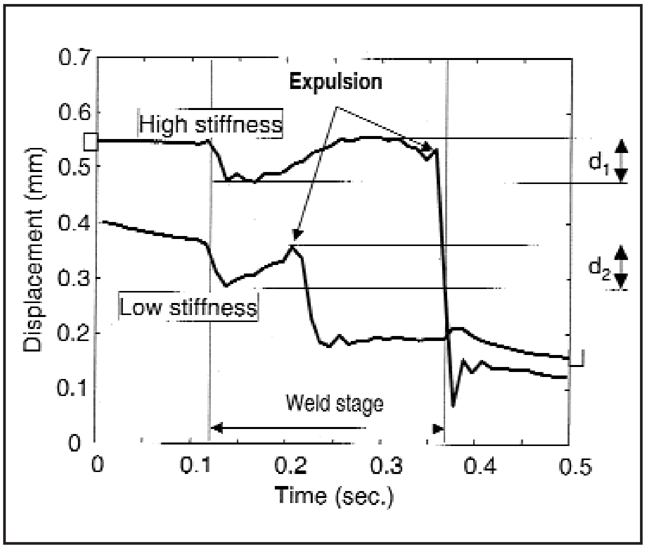

Fig. 6 — Displacement comparison under different machine stiffnesses.

Table 1 — Influence of Stiffness on Expulsion Limits

Material	Current (kA) – Low Stiffness	Current (kA) – High Stiffness	Increase in Expulsion Current (kA)
0.8-mm Bare	7.0	8.0	1.0
0.8-mm Galvanized	8.3	8.7	0.4
1.7-mm Bare	6.9	7.1	0.2

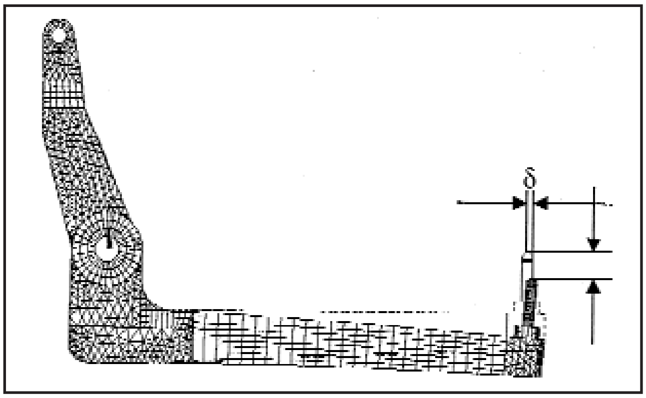

Fig. 7 — Deflection of machine structure.

welding, i.e., during the application of electric current. In addition, the hold stage was analyzed because it influences the solidification of liquid nuggets.

The majority of experiments were carried out on a 75-kVA pedestal welding machine. Some experiments were performed using a 42-kVA C-type gun and a 200-kVA pedestal welding machine. Truncated-cone electrodes were used in all experiments. Welding force, electric current, and thickness of metal sheets were chosen as experiment variables. To determine the welding current used in the experiments, weld lobe tests under various conditions were conducted first. The current profile when welding expulsion happened was recorded. The welding currents used for all following designed experiments were selected near the expulsion limits, or the minimum currents at which expulsion is observed. In order to ensure the reliability of experiments, five welds were made under each condition.

In the experiments, the process signals were recorded for subsequent analyses. The force was measured by a strain gauge-based load cell, while a linear variable differential transducer was used to measure the displacement. The current was also recorded in order to capture the exact welding stage duration.

Several measures were selected as criteria for evaluating weld quality. The tensile-shear strength was used as the primary index of quality. Weld indentation was also measured. Each of five specimens was measured three times for the indentation. Furthermore, metallurgical examinations were conducted on selected specimens. Materials used in the experiments are steel and aluminum sheets commonly used in automotive applications, and their specifications are listed in the individual sections.

The mechanical characteristics of the welding machines, i.e., machine stiffness, friction, and moving mass, were modified. In order to ensure the consistency of testing conditions, only one characteristic was modified at a time for specific experiments. Two levels of these individual characteristics were used in comparative experiments. The modifications of welding machines are briefly described in the following sections. Refer to an earlier paper (Ref. 12) for detailed descriptions.

Stiffness

The stiffness of welding machines reflects their ability to resist the deflection under loading. Since the upper structures of the welding machines used in this study are much stiffer than the lower structures, only the stiffness of the lower structures was considered and altered. The stiffness was modified in two ways. Reducing stiffness was realized by adding springs between the lower electrode and its support structure for the pedestal welding machines, while increasing stiffness was achieved by adding a supporting leg from the floor to the lower arm for the C-type gun. Therefore, two levels of stiffness were achieved on each machine: 4.3 kN/mm and 13.0 kN/mm for the gun; 8.8 kN/mm and 52.5 kN/mm for the 75-kVA pedestal welding machine.

Friction

Friction exits between two contact surfaces only when there is a relative movement or a moving tendency. For both the pedestal welding machines and the C-type gun used in this study, only the upper structure is movable during welding. A special device offering adjustable additional friction (Fig. 2) was designed and mounted on the pedestal welding machines in order to vary the friction force. In the experiments, two different friction situations were considered: the original setup and one with an additional 0.36-kN (80-lb) friction.

Moving Mass

Because some parts of the upper structures of the welding machines move during welding, a 20-kg weight was added on the movable parts to change their mass. Two levels of moving mass of the upper structures were considered for the pedestal welding machines: the original weight (about 40 kg) and the original weight plus additional weight.

Influence of Machine Stiffness

The investigation was conducted on both gun-type and pedestal-type welding machines. Three types of DS (drawing steel) steel specimens were used: 0.8-mm bare, 1.7-mm bare, and 0.8-mm galvanized. The welding time was 12 cycles for most experiments, and the welding current and force are listed in Figs. 3 and 4. Error bars are used in these and other figures to show the ranges of experimentally observed values, and solid dots and numerical values indicate the averages of the data. Expulsion, which has been proved undesirable (Ref. 14), and tensile-shear peak load (Ref. 15) are discussed in the following.

Expulsion

Tests were conducted first for the influence of machine stiffness on the expulsion limits and then for the selection of appropriate currents for subsequent experiments. In the tests, welding current was increased gradually while the force and time were unchanged. The experiment results show the expulsion limit rises with stiffness, as shown in Table 1. Because higher expulsion limits allow higher welding cur-

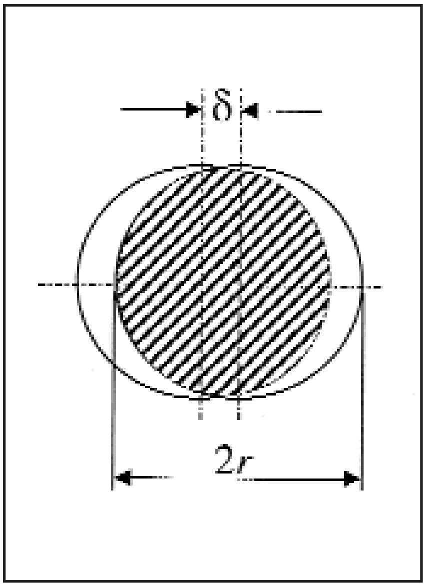

Fig. 8 — Geometric model for axial misalignment and contact area.

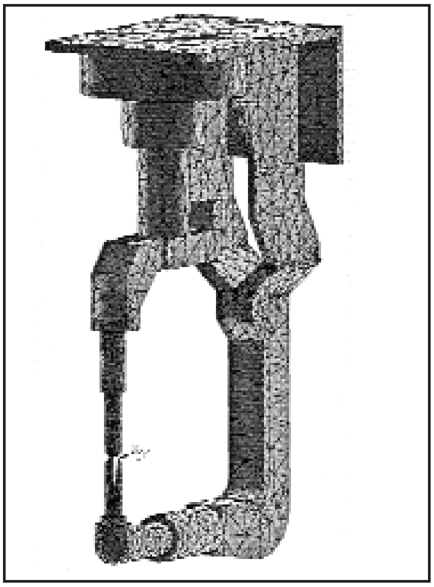

Fig. 9 — FEA model of weld gun body.

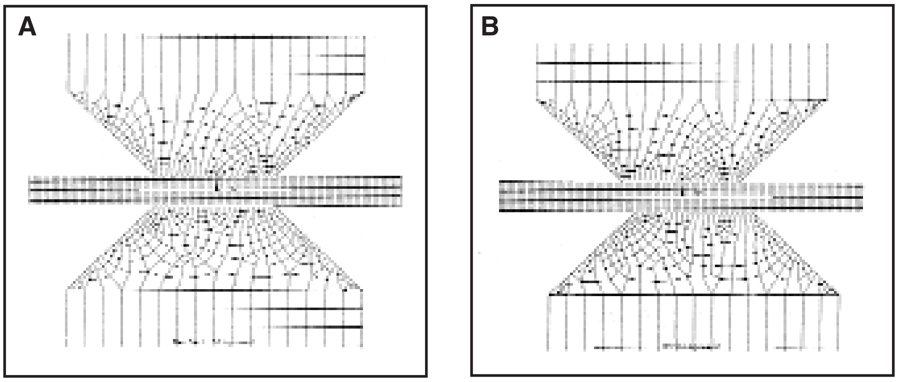

Fig. 10 — FEA models for pressure analysis. A — Perfect alignment; B — misalignment.

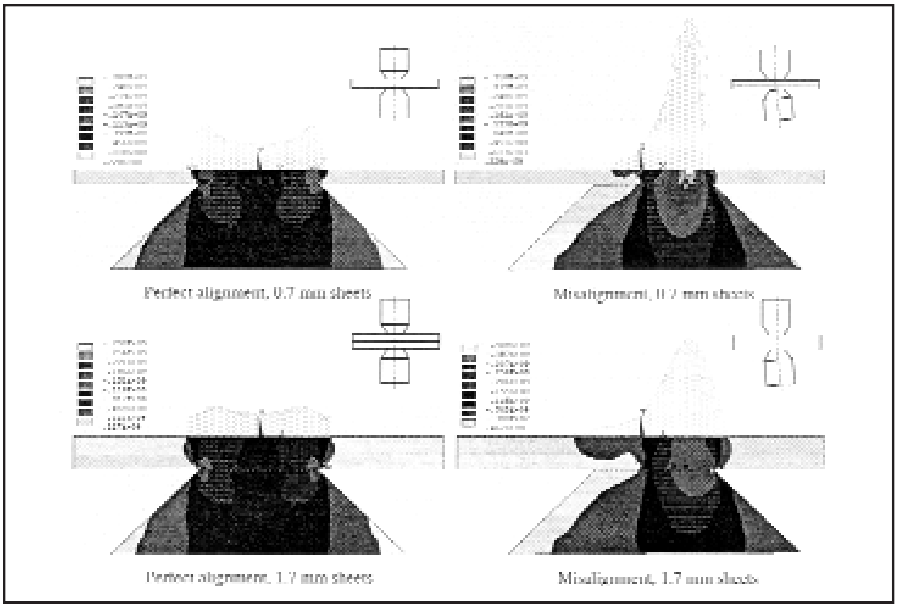

Fig. 11 — Comparison of pressure distributions.

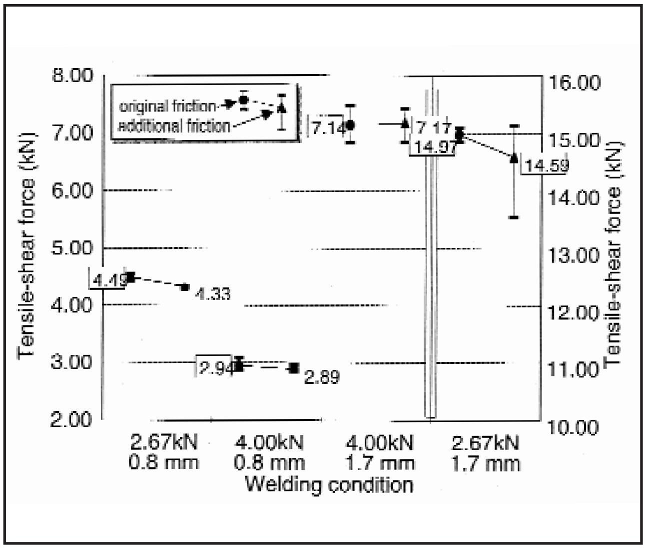

Fig. 12 — Influence of friction on weld strength (steel).

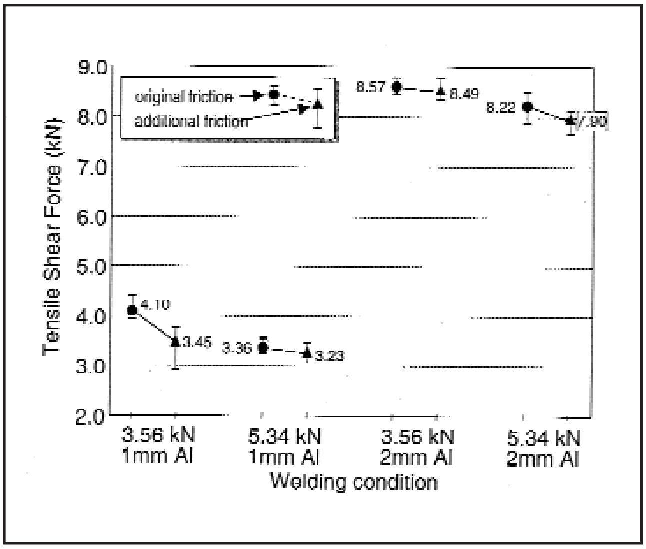

Fig. 13 — Influence of friction on weld strength (aluminum).

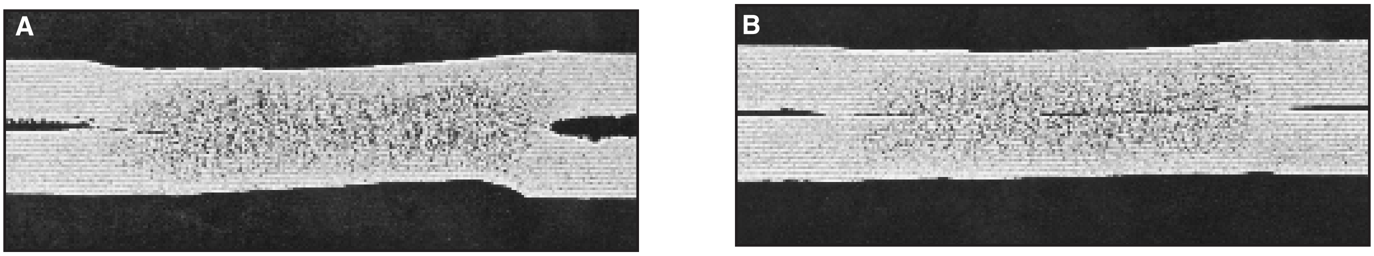

Fig. 14 —Weld cross sections with different friction (0.8-mm steel). A — Without additional friction; B — with additiional friction.

rents, potentially larger welds can be made without expulsion.

Peak Load

A comparative experiment was conducted under identical conditions with various machine stiffnesses. As shown in Fig. 3, weld quality is improved in terms of tensile-shear strength (peak load) with machine stiffness. However, the improvement is not significant because only about a 3% difference exists and the data ranges overlap.

Similar experiments were performed using the 200-kVA pedestal welding machine. In these experiments, both steel and aluminum specimens were used: 0.8-mm and 1.7-mm bare steel, and 1-mm and 2-mm aluminum alloy (AA5754). The experiment results show the stiffness is slightly beneficial to weld quality in terms of tensile-shear strength — Fig. 4. However, the experiment data did not show the influence of machine stiffness on weld indentation. The experiment results of both gun-type and pedestal-type machines are consistent.

In summary, machine stiffness slightly improves weld quality in terms of weld strength under the same conditions and significantly raises welding expulsion limits. Further analysis was made on the influence of the machine stiffness on two aspects of the welding process: the characteristics of the welding force and electrode displacement, and electrode alignment.

Electrode Force

In welding steels using the pedestal welding machine, electrode force increases immediately after electrical current is applied — Fig. 5 (Ref. 12). The maximum increase of electrode force is about 5–10% of its preset value. The increase is due to thermal expansion of the weldment and the constraint imposed by machine stiffness. When a machine is stiff, the constraint is strong and results in a large force. The increased electrode force imposes a forging force on the nugget, which is beneficial to preventing welding expulsion.

Electrode Displacement

Electrode displacement may be the best indicator of nugget initiation and growth, and other characteristics (such as expulsion, etc.) during welding. Although the amount of electrode movement during welding varies according to the stiffness of the welding machine, similar displacement characteristics have been observed when welding with different machine stiffness, as shown in Fig. 6 where relative displacement between the upper and lower electrodes was plotted. It takes a similar amount of expansion (i.e., $d_1 \approx d_2$) for nuggets to grow, but with the stiffer machine it takes longer for expulsion to happen. This is because a stiffer machine provides a larger constraint or force, which delays expulsion according to Ref. 13. In the case of Fig. 6, welding time was set at 16 cycles and expulsion occurred at the fifth cycle (0.083 s) in the weld stage when the machine stiffness was low. However, expulsion happened almost at the end of welding when stiffness was high. If welding time had been set at 10 cycles, the expulsion would have not occurred under the higher stiffness, but still could have occurred under the lower stiffness. The amount of relative displacement of the electrodes of the stiffer welding machine is larger when expulsion happens, as shown in Fig. 6, as the machine asserts more squeezing force on the softened weld.

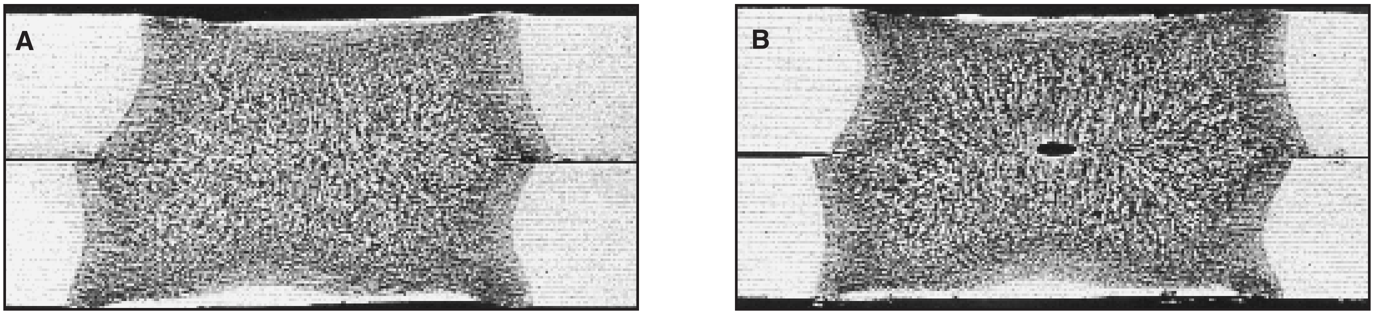

Fig. 15 — Weld cross sections with different friction (1.7-mm steel). A — Without additional friction; B — with additional friction.

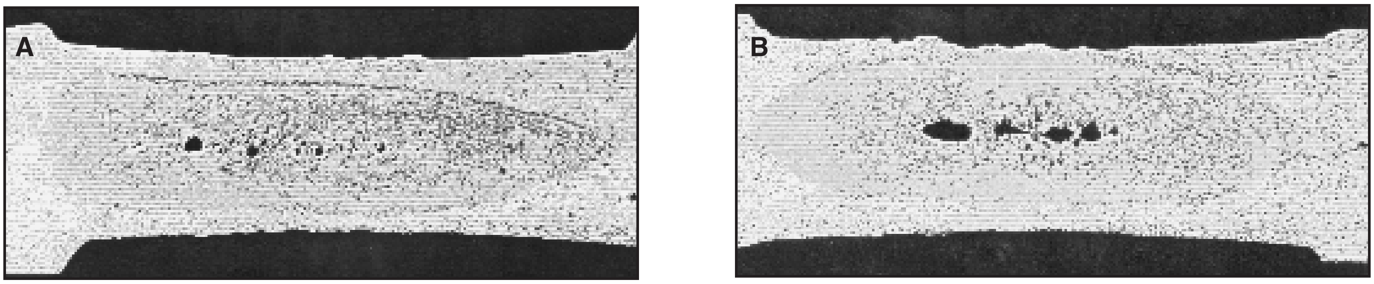

Fig. 16 — Weld cross sections with different friction (2-mm aluminum). A — Without additional friction; B — with additional friction.

Table 2 — Pressure on Faying Surface under Different Electrode Alignments

	Maximum	At Center
Perfect Alignment (0.8-mm sheets)	131 MPa	73.7 MPa
Misalignment (0.8-mm sheets)	299 MPa	38.5 MPa
Perfect Alignment (1.7-mm sheets)	106 MPa	78.4 MPa
Misalignment (1.7-mm sheets)	195 MPa	45.3 MPa

Electrode Alignment

Ideally, electrodes should be aligned during the RSW process because a misalignment induces unfavorable features to the process and weld quality. Misalignments, either axial or angular, may cause irregularly shaped welds and reduce weld size because misalignments result in asymmetrical distribution of force and current. A misalignment can result from machine deflection under an applied force, as shown by a finite element model (Fig. 7), even if the electrodes appear aligned under no loading or very low loading. Such misalignment is often ignored in practice. In this section, analytical and numerical (finite element modeling) analyses are conducted to provide a quantitative understanding of the reduction in contact area that affects the welding current density, and the effect on the pressure distribution due to deflection-induced misalignment.

Axial misalignment reduces the (overlapped) contact area between the sheets, as shown in Fig. 8. The actual contact area (C_r), in percentage of electrode face area, can be approximated by Equation 1. It can be seen from the equation that the reduction in contact area is strongly correlated with the axial misalignment.

$$C_r = \frac{2r^2 \arccos\left(\frac{\delta}{2r}\right) - 2\delta\sqrt{r^2 - \left(\frac{\delta}{2}\right)^2}}{\pi r^2} \quad (1)$$

where r is the radius of electrode face; δ is the axial misalignment.

A misalignment due to structural deflection can be quantified when the geometry and mechanical properties of a welding machine are known through theoretical or numerical analyses. Finite element analysis (FEA) is a convenient tool for evaluating the deflection and corresponding misalignment.

A 3-D FEA model was created for a gun body using ANSYS 5.4 — Fig. 9. In the model, the gun body was modeled by tetrahedral solid elements; the interface between sheets and electrodes was modeled by nonlinear contact elements. Under an electrode force of 2.67 kN (600 lb), the electrodes misalign 0.75 mm axially and 0.28 deg in angle. The electrode face diameter was assumed 6.4 mm, and the contact area was reduced to 85% of the electrode face area according to Equation 1. Therefore, a welding schedule designed on perfect alignment conditions may not be adequate, and weld strength may be reduced due to misalignment.

Furthermore, a contact pressure analysis was conducted based on the above misalignment information, i.e., 0.75-mm axial and 0.28-deg angular misalignment using a 2-D FEA model for the electrodes and workpieces — Fig. 10.

The pressure distribution on the faying surface under 2.67 kN (600 lb) of electrode force is shown in Fig. 11 and some data are listed in Table 2. The average pressure with perfect alignment on the faying face is 83.0 MPa. Under ideal alignment, high pressure always occurs around the electrode edge, which plays a role in containing the molten nugget and preventing possible welding expulsion. When the electrodes misalign, the pressure distributes asymmetrically. Obviously, this asymmetrical pressure distribution is unfavorable in terms of expulsion prevention

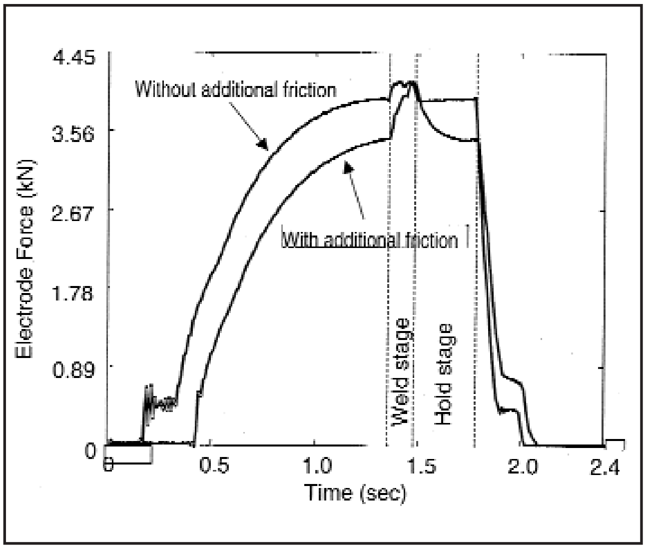

Fig. 17 — Comparison of electrode force with different friction.

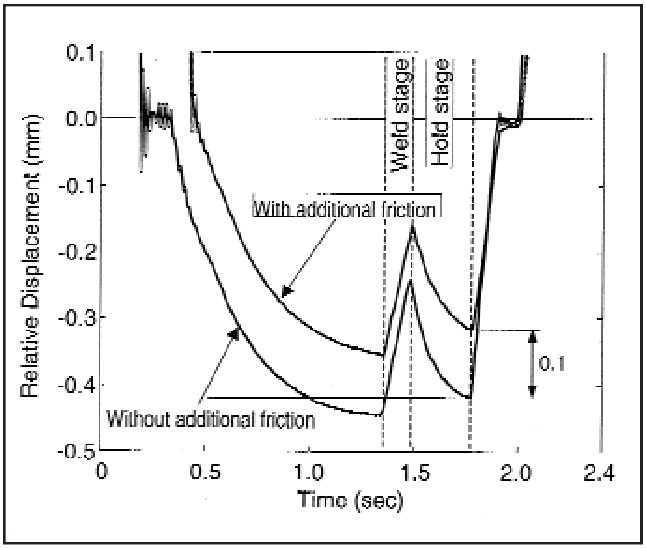

Fig. 18 — Comparison of electrode displacement with different friction.

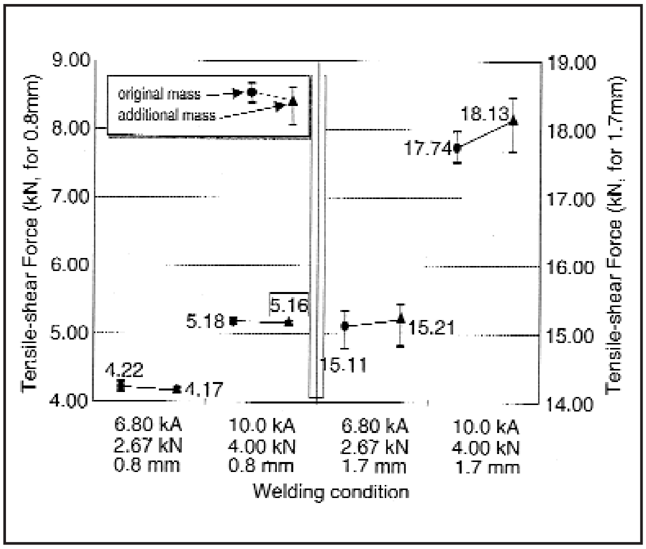

Fig. 19 — Influence of mass on weld strength (steel).

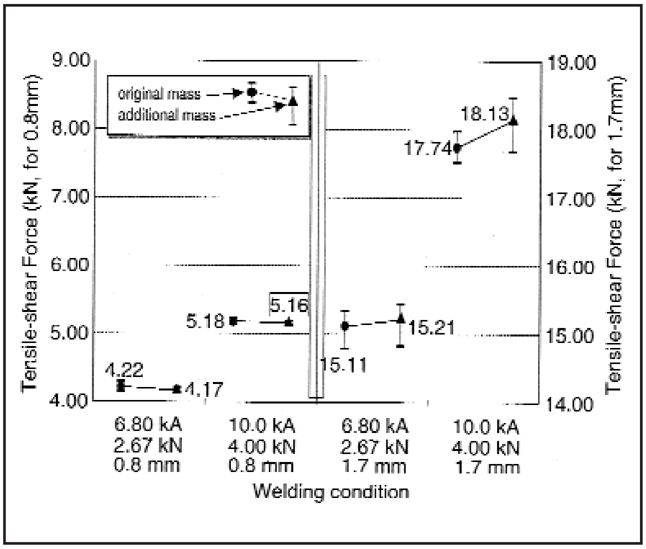

Fig. 20 — Influence of mass on weld strength (aluminum).

(Ref. 13) and electrode life. Therefore, expulsion happens easily when electrode misalignment exists.

In addition, the analysis results show sheet thickness is another factor on pressure distribution. Thicker sheets can reduce the asymmetrical pressure on the faying surface, which partially explains why machine stiffness has less influence on welding expulsion for welding thicker sheets.

Influence of Machine Friction on Weld Strength and Microstructure

In the experiments, welding specimens were 0.8- and 1.7-mm bare steel and 1- and 2-mm aluminum sheets. The welding time was 12 cycles. The current was 7.1 kA for steel and 35 kA for aluminum. The force was set at two levels: 2.67 kN (600 lb) and 4.00 kN (900 lb) for steel; 3.56 kN (800 lb) and 5.34 kN (1200 lb) for aluminum.

Figures 12 and 13 show the comparisons of the joint strength, with data range bars, under different conditions. Based on the comparisons, it can be concluded that friction is unfavorable for both steel and aluminum welding. However, for some combinations of parameters, strength reduction is not statistically significant since the data ranges overlap. In general, the influence of friction varies with welding conditions.

In order to gain further understanding, the welded specimens were sectioned and examined through standard metallographic techniques. Typical cross sections are shown in Figs. 14–16. In the cross sections, it is easy to recognize there is incomplete fusion on the faying surface under higher friction condition.

For 0.8-mm steel (Fig. 14), incomplete fusion on the faying surface was observed when the machine had additional friction. This could be the reason for the reduction of weld strength. For 1.7-mm steel (Fig. 15), it is obvious the weld under greater friction has shrinkage porosity. A similar situation was observed in the weld of 2-mm aluminum — Fig. 16. However, the internal porosity may not affect the tensile-shear strength of the welds in some cases, as reported in Ref. 16 for aluminum welds.

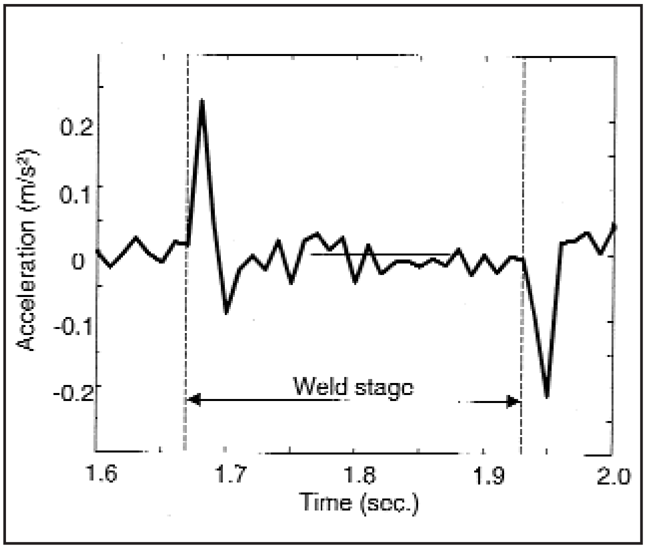

Fig. 21 — *Acceleration of nugget expansion in electrode axial direction.*

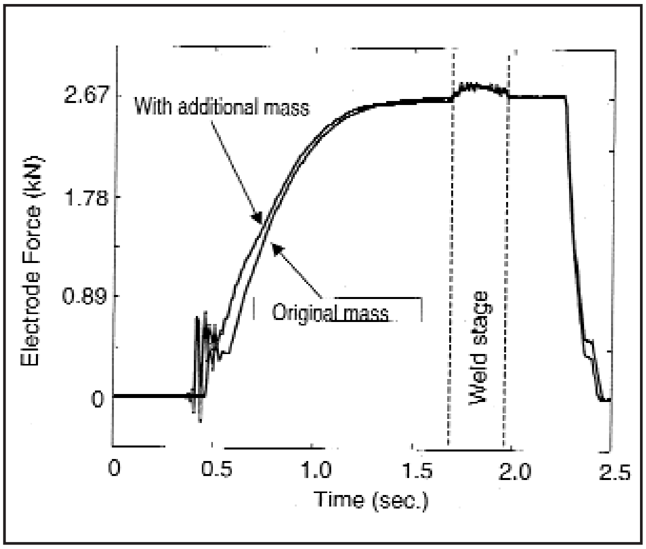

Fig. 22 — *Force comparison with different mass.*

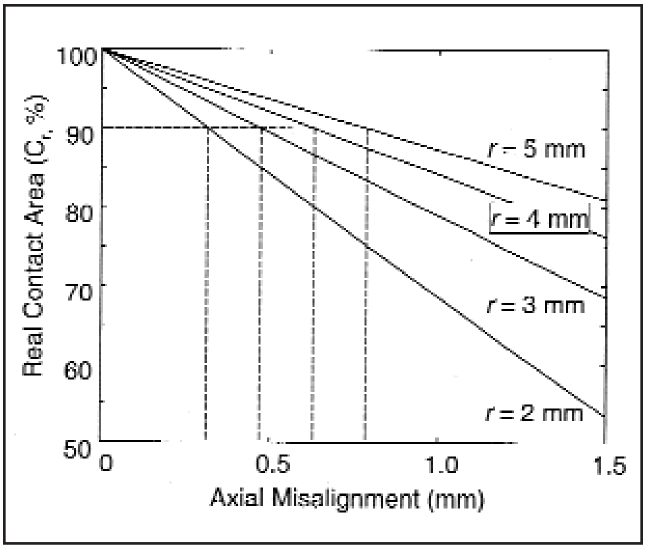

Fig. 23 — *Axial misalignments vs. contact areas.*

Therefore, machine friction adversely influences weld quality. Although the internal discontinuities may not always be harmful, premature failures may happen if incomplete fusion exists.

Effect on Electrode Force

The friction in RSW machines contributes significantly to total electrode force. Under the same preset value, the actual force with larger friction is smaller than that with smaller friction — Fig. 17. When large friction exists, electrode movement is sluggish and cannot promptly follow the contraction. Thus, it is most likely internal discontinuities, such as porosity, appear in the nugget. The desired situation should be that the electrodes move freely in the welding and holding stages.

Effect on Electrode Displacement

The displacement signal provides explicit information on weld indentation. An example of 2-mm aluminum welding under 3.56-kN force is shown in Fig. 18. The electrodes extrude less into the workpieces with larger friction. The difference in displacement was about 0.1 mm as electrodes were retracted. The initial impact of electrodes onto workpieces is also reduced by friction, which may be beneficial to electrode life.

In summary, machine friction influences welding process and weld quality. The friction always opposes electrode movement and makes it difficult for electrodes to follow nugget expansion during welding and contraction during cooling. The latter effect may help the creation of internal discontinuities in welds. With large machine friction, electrodes indent less into workpieces for aluminum welding.

Influence of Moving Mass on Weld Quality

Various experiments were conducted by altering the mass of the upper structure of the pedestal welding machines. The selected welding schedules were the same as used in the early part of the experiments of this work. Some results are shown in Figs. 19 and 20. The results, in terms of the tensile-shear strength of welds and welding expulsion limits, do not show any significant influence of machine moving mass for both steel and aluminum welding. Therefore, the effect of moving mass of a welding machine can be neglected in design.

The insignificance of the effect of the moving mass was expected because of the small amount of motion of electrodes during welding. The effect of mass, in the form of dynamic force, can be significant only when weld volume thermally expands with a large acceleration. The dynamic force can be obtained if moving mass and the acceleration of electrode movement are known. The force (F) can be calculated by $F=ma$ where m is the moving mass and a is acceleration, which can be approximated by the following differential equation:

$$a = \frac{x(t+1) - 2x(t) + x(t-1)}{(\Delta t)^2} \qquad (2)$$

where $x(t)$ is the measurement of electrode displacement during welding at the instant t; and Δt is the sampling interval.

For 1.7-mm steel, welding with 6.8-kA current and 2.67-kN (600-lb) force, as an example, the calculated acceleration of weld expansion is shown in Fig. 21. From the calculated results, the largest acceleration occurred during the first cycle in the weld stage, but was only 0.23 m/s^2. Afterward, the acceleration was nearly zero. If the moving mass is 40 kg, then maximum dynamic force is 9 N (2 lb). Its effect is very small compared with the applied electrode force.

In addition to its small magnitude, the dynamic force happens only at the very beginning of the weld stage; therefore, it has little effect on weld formation. The effect of moving mass on the force is negligible (Fig. 22), and the mass influence on weld quality is expected to be insignificant. However, the influence may be significant during the touching of electrodes; therefore, moving mass may influence electrode life.

Guidelines on Machine Design

As shown in previous sections, mechanical characteristics of welding machines have complex influence on weld quality. Based on the understanding obtained in this study, guidelines can be developed for designing welding machines to improve weld quality.

In general, high machine stiffness improves weld quality because it ensures good electrode alignment, provides large forging force, and raises expulsion limits. Therefore, high stiffness is recommended for the structure design of RSW machines. However, the appropriate level of stiffness should be determined because extremely high stiffness is neither achievable nor necessary. Based on the application-dependent relationship between machine stiffness and the electrode alignment due to structure deflection, a criterion can be established in terms of electrode misalignments rather than the abstract stiffness.

In order to ensure weld quality, a certain amount of contact area (overlap of electrode faces) should be maintained. If a certain percentage of contact is deemed necessary for achieving reasonable weld strength, then the axial misalignment should be limited accordingly. With different sizes of electrode faces, an acceptable misalignment can be obtained through Equation 1, or estimated from Fig. 23 where r is the radius of electrode face. For a specific welding machine, its structure can be designed to ensure a certain percentage of contact area. For instance, when a 90% contact is assumed, the allowable misalignment can be specified as 0.31, 0.47, 0.63, and 0.79 mm for electrode radius (r) of 2, 3, 4, and 5 mm, respectively.

Similarly, for some types of welding guns, such as long-arm scissors guns, angular misalignment should also be a concern in order to avoid strong pressure and current concentrations. According to the FEA analysis of this study, a 0.28-deg angular misalignment with 0.75-mm axial misalignment result in significant asymmetrical pressure distribution. Such a conclusion should be considered as a reference only because this calculation did not consider thermal-mechanical interaction occurring during welding. However, it indicates possible influence of machine stiffness on electrode alignment and possibly on weld quality. In practice, a certain amount of angular misalignment can be compensated by the fact that electrodes are usually slightly worn after a few welds, and by using dome-shaped electrodes. In general, establishing a tolerance of axial and angular misalignments for RSW machine design needs further FEA and experimental study.

As discussed in previous sections, machine friction is generally unfavorable to weld quality. Friction should be kept as small as possible for this reason. There are several practical ways to minimize friction. For instance, the moving parts of RWS machines should be supported by a roller guide, such as ball screws, rather than by a sliding mechanism. A specific mechanism may be designed so that the friction is applied only during the hold stage to increase forging force.

According to this study, moving mass of RSW machines has no significant effect on weld quality. Therefore, the mass or weight should be minimized to reduce the impact at touching for improved electrode life and to improve gun portability for energy and ergonomic considerations. Further research is needed to obtain optimal machine and process design.

Summary

In this paper, the influence of RSW machine mechanical characteristics on welding process and weld quality was systematically investigated. Both experimental and analytical studies were performed to understand such influences. In general, machine stiffness has a positive influence on expulsion prevention and weld quality. Specifically, high stiffness can reduce electrode misalignment, increase expulsion limits, and provide forging effect. Thus, high stiffness is recommended. Machine friction should be reduced whenever possible because of its negative effects on weld quality, especially on internal discontinuities. Machine moving mass shows no influence on weld quality.

In addition to experimental investigations, a systematic approach is developed based on analyzing process information. From such analyses, new understanding of the influences of the machine mechanical characteristics can be obtained, and guidelines for the design of RSW machines can be developed.

Acknowledgment

The authors are grateful for the support of the Advanced Technology Program (NIST/ATP) through the Intelligent Resistance Welding (IRW) Consortium.

References

1. Ganowski, F. J., and Williams, N. T. 1972. Advances in resistance spot and seam welding of zinc-coated steel strip. *Sheet Metal Industries* 49(11): 692–704.
2. Kolder, M.W., and Bosman, A.W. M. 1984. Influence of the welding equipment on the weldability lobe of an HSLA-steel. IIW Doc. No. III-796-84. Research and Development, Ijmuiden, The Netherlands.
3. Satoh, T., Katayama, J., and Nakano, T. 1988. Effect of mechanical properties of spot welding machine on spot weld quality. IIW Doc. no. III-912-88, pp. 118–122.
4. Satoh, T., Nakamura, T., and Matsuyama, K. I. 1989. Current status of research and development on resistance spot welding machines in Japan.
5. Hahn, O., Budde, L., and Hanitzsch, D. 1990. Investigations on the influence of the mechanical properties of spot welding tongs on the welding process. *Welding and Cutting,* No. 1, pp. 6–8.
6. Williams, N.T., Chilvers, K., and Wood, K. 1992. The relationship between machine dynamics of pedestal spot welding machines and electrode life. IIW Doc. No. III-994-92. p. 27.
7. Howe, P. 1996. The effect of spot welding machine characteristics on electrode life behavior on two welders. *Proceedings of AWS Sheet Metal Welding Conference VII,* Detroit, Mich.
8. Dorn, L., and Xu, P. 1993. Influence of the mechanical properties of resistance welding machines on the quality of spot welding. *Welding and Cutting*, No. 1, pp. 12–16.
9. Dorn, L., and Xu, P. 1992. Relationship between static and dynamic machine properties in resistance sport welding. *Welding and Cutting,* no. 1, pp. 19–22.
10. Gould, J. E., and Dale, W. N. 1994. Theoretical analysis of weld head motion. *Sheet Metal Welding Conference VI,* Detroit, Mich.
11. Gould, J. E., Feng, Z., Chou, J., and Kimchi, M. 1999. Analytical models for the mechanical response of a resistance spot welding machine. *CRP Report SR9902.* Edison Welding Institute.
12. Tang, H., Hou, W., Hu, J. S., and Zhang, H. 2000. Force characteristics of resistance spot welding of steels. *Welding Journal* 79(7): 175-s to 183-s.
13. Senkara, J., Zhang, H., and Hu, J.S. 2002. Expulsion prediction in resistance spot welding. To be published by *Welding Journal*.
14. Zhang, H. 1999. Expulsion and its influence on weld quality. *Welding Journal* 78(11): 373-s to 380-s.
15. M. Zhou, M., Hu, S. J., and Zhang, H. 1999. Critical specimen sizes for tensile-shear testing of steel sheets. *Welding Journal* 78(9): 305-s to 313-s.
16. Thornton, P. H., Krause, A. R., and Davies, R. G. 1996. The aluminum spot weld. *Welding Journal* 75(3): 101-s to 108-s.