ENERGY CONSUMPTION IN AC AND MFDC RESISTANCE SPOT WELDING

Wei Li
University of Washington

Eugene Feng
Welding Technology Corporation

Daniel Cerjanec and Gerald A. Grzadzinski
DaimlerChrysler Corporation

Abstract

This paper presents a comparative study of alternating current (AC) and direct current (DC) resistance spot welding (RSW) processes. Two identical weld guns were used, one with a single-phase AC and the other with a median-frequency DC (MFDC) weld control. The welders were instrumented such that the energy consumptions at both the primary and secondary side of the transformer could be calculated. A nugget growth experiment was conducted to compare the weld size and the energy consumption in the AC and MFDC welding processes. It has been found that given the same welding current, the weld sizes achieved in the AC and DC processes are different and the difference is more prominent when the welding current is low. When the welding current is high and close to the expulsion limit, the weld sizes are similar in the AC and DC processes. In general, it takes 10% more total energy to make a same size weld in the AC process than it does in the DC process. The differences in the AC and DC welding processes are explained with a finite-element simulation model. The energy efficiencies of the AC and DC welding processes are also discussed.

Introduction

DC RSW has been used for many years. It is generally considered advantageous over AC welding because it uses lower current, has wider weld lobes, and introduces less electrode wear.[1] However, the applications of DC RSW are generally limited to aluminum welding and aerospace sheet metal joining processes. The automotive industry is still predominantly using single-phase AC welding for their body-in-white assemblies. There are concerns for using DC welding in the automotive industry. These concerns include equipment cost and reliability.[2] In addition, the benefit of energy consumption of DC welds is not clear. Although it has been found that less current is needed in the DC welding process to make a weld, diode drops on the primary side of the high- or mid-frequency DC transformer are thought to waste a substantial amount of energy and would make the DC welding less economical compared to AC welding. The technology of DC welding power supplies, commonly referred to as inverters, have matured in recent years. The reliability of the equipment has been greatly improved and the price will continuously go down as more DC weld controls are used. Therefore, there is a keen interest in the total energy consumption of the DC welding processes.

Being relatively new to the auto industry, the MFDC welding process has not received much study on the characteristics related to the DC power source. DC welding has been used for aluminum welding, seam welding, and certain aerospace applications where high power requirements often require the use of three-phase rectified welding current.[1,3,4] It has been reported that as much as 20% less current is needed to produce a weld with DC than with AC current. However, this difference depends on the materials and welding parameters used.(1) In an electrode wear study of zinc-coated steels, it has been found that the electrodes wore unevenly, with the negative electrode erodes more rapidly, when welding with DC current.(5)

The purpose of this study is to examine the difference of the DC RSW process as compared to the AC process. Two identical weld guns were used for the comparison, one with an MFDC power supply and the other with a single-phase AC power supply. The machines were instrumented such that both the primary and secondary voltage and current were recorded using a computerized data-acquisition system. Energy consumption comparison was conducted based on a nugget growth study, where the welding force and time were fixed and the current was increased in steps to give incremental nugget sizes. The nugget growth study was performed for both DC and AC power supplies. The energy consumptions were compared when the nuggets of the same size were achieved.

This paper will present the experimental setup and the instrumentation of the DC and AC welders in the following section. The nugget growth study will be described and the results discussed. The nugget size and energy consumption at both the primary and secondary sides of the transformer for DC and AC welding processes will be compared. Conclusions and future work will also be given.

Experimental Setup

An overview of the experimental setup is shown in Figure 1. The experiment was conducted on two identical servo-motor-controlled C-guns. One of the welding guns was connected to an MFDC weld control and transformer, the other to a single-phase AC weld control and transformer. The moving arm of the weld guns was shared between the DC and AC setups. The throat area of the C-guns was approximately 50 in.^{2}, which is relatively small among typical guns used in the automotive industry. A computer data-acquisition system was used to collect both the primary and secondary voltage and current signals. These real-time signals were used to calculate the energy consumption on both the primary and secondary side of the transformer.

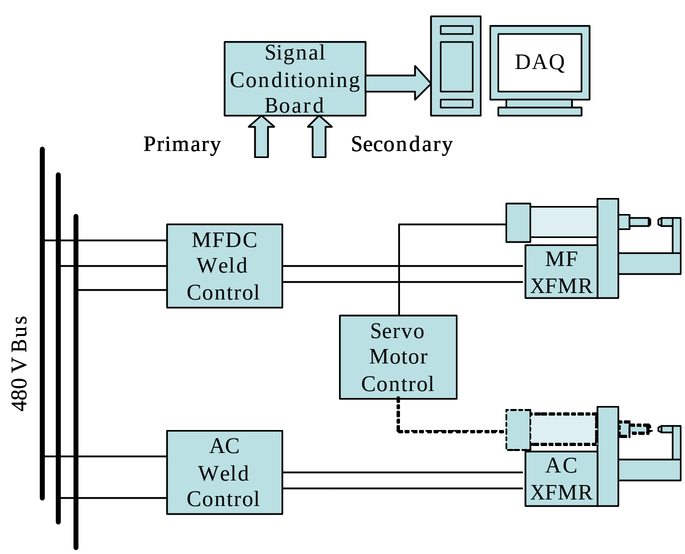


Figure 1. Overview of the Experimental Setup

The welding gun or the secondary side of the transformer was instrumented as shown in Figure 2. Similar instrumentation can be found in References 6 and 7. The tip voltage was measured using two electrical wires that were attached to the moving and fixed arm, respectively. These two wires, however, formed an inductance loop that would pick up the induced voltage from the welding current. The induced voltage is not the true voltage across the resistance load of the weld and therefore needs to be removed. A current coil was used to measure the intensity of the magnetic field (d*i*/d*t*), from which the welding current was found through integration. In this study, the inductance of the tip voltage loop is assumed to be a constant and that the voltage picked up by the tip wires is simply the signal from the current coil scaled by a factor. Therefore, the true tip voltage could be obtained by subtracting a scaled *di/dt* from the measured tip voltage. This was done by tuning a potentiometer on the signal conditioning board to match the phase of the secondary current and the tip voltage.

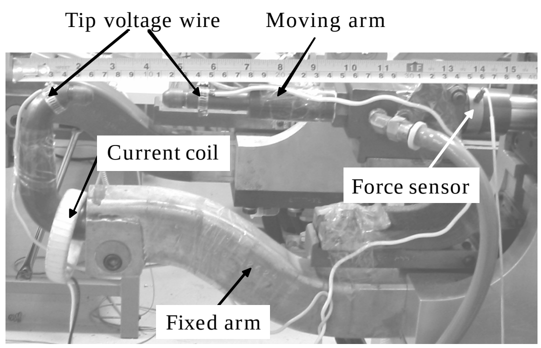


Figure 2. Instrumentation of the Secondary Side of the Transformer

The primary voltage and current were used to calculate the total energy consumption including the loss on the weld controls. Therefore, they were measured between the power bus and the weld controls, as shown in Figure 3. The electrical bus used in this study was a floating delta connection. The weld controls were connected to the power lines from the bus, three lines in the MFDC case and two lines in the single-phase AC case (see Figure 4). The line currents were measured using current transformers (i_1, i_2, and i_3). The voltages were measured between the lines (v_{AB}, v_{BC}, v_{CA}).

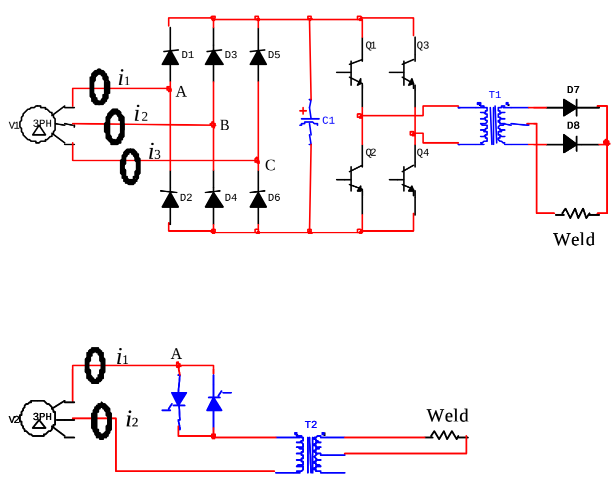


Figure 3. Schematics of (a) the MFDC Welder, and (b) the AC Welder

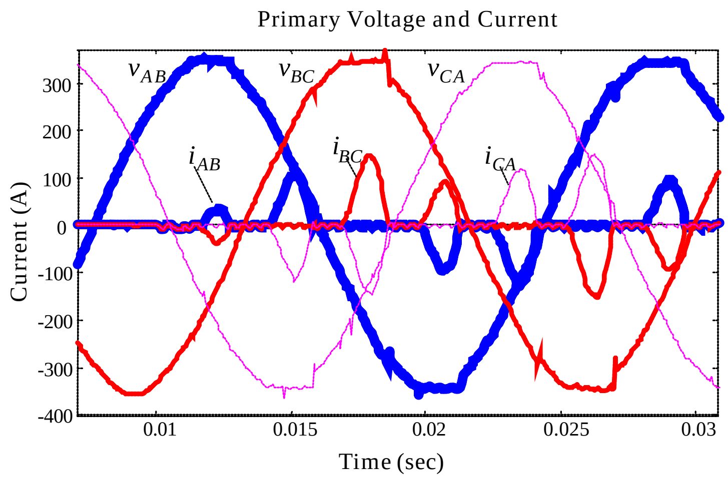


Figure 4. Primary-Phase Voltage and Line Current

A nugget growth study was conducted using both the AC and MFDC welding guns on 1.2-mm galvannealed low-carbon steel. Type-B cold-form electrodes were used. These electrodes had a 5.1-mm face diameter and were preconditioned by making welds at nominal conditions. Ten welds were made at each current setting from 9.5 to 12 kA with 0.5-kA increments. Among the ten welds, five of them were peeled and the button sizes measured. The weld size measurement followed a standard procedure where the maximum and minimum diameters of the button were measured and averaged.[8] The nugget growth study was first conducted for the AC welder. The moving arm of the weld gun was then moved to the MFDC weld gun. The electrode on the fixed arm was also moved. When the switch over was done, the electrode alignment was carefully examined and precondition welds were made to keep the mechanical conditions of the two setups as close as possible. The welding force was kept the same at 650 lb.

Energy Calculation

From the real time current and voltage signals, the energy consumption can be calculated as:

$$E = \int v \cdot i \cdot dt \tag{1}$$

This is true for both AC and DC and the primary and secondary energy. The collected voltage and current signals of the single-phase AC and the secondary side of the MFDC welding can be directly used. However, the primary signals of the MFDC welding need to be further processed before they can be used for energy calculation.

Because of the floating delta connection of the power source in the MFDC case, the currents measured are the line current, and the voltages are the phase voltages. In order to calculate the energy consumption, the phase currents need to be obtained. The phase and line currents of the floating delta connection can be expressed using the following equations:

$$i_1 = i_{AB} - i_{CA} \tag{2}$$

$$i_2 = i_{BC} - i_{AB} \quad (3)$$

$$i_3 = i_{CA} - i_{BC} \quad (4)$$

where i_{AB}, i_{BC}, and i_{CA} are phase currents corresponding to v_{AB}, v_{BC}, and v_{CA}, respectively. Simple algebraic manipulation of Eqs. (2)-(4) will not yield the phase currents. Closer examination of the primary voltage and current signals as shown in Figure 5 reveals that the phase currents are completely out of phase between each other, which means that the following conditions are satisfied:

$$i_{AB} \cdot i_{CA} = 0 \quad (5)$$

$$i_{BC} \cdot i_{AB} = 0 \quad (6)$$

$$i_{BC} \cdot i_{AB} = 0 \quad (7)$$

Multiplying any two of the Eqs. (2)-(3) and applying the conditions in Eqs. (5)-(7), the phase currents are obtained as:

$$|i_{AB}| = \sqrt{-i_1 \cdot i_2} \quad (8)$$

$$|i_{BC}| = \sqrt{-i_2 \cdot i_3} \quad (9)$$

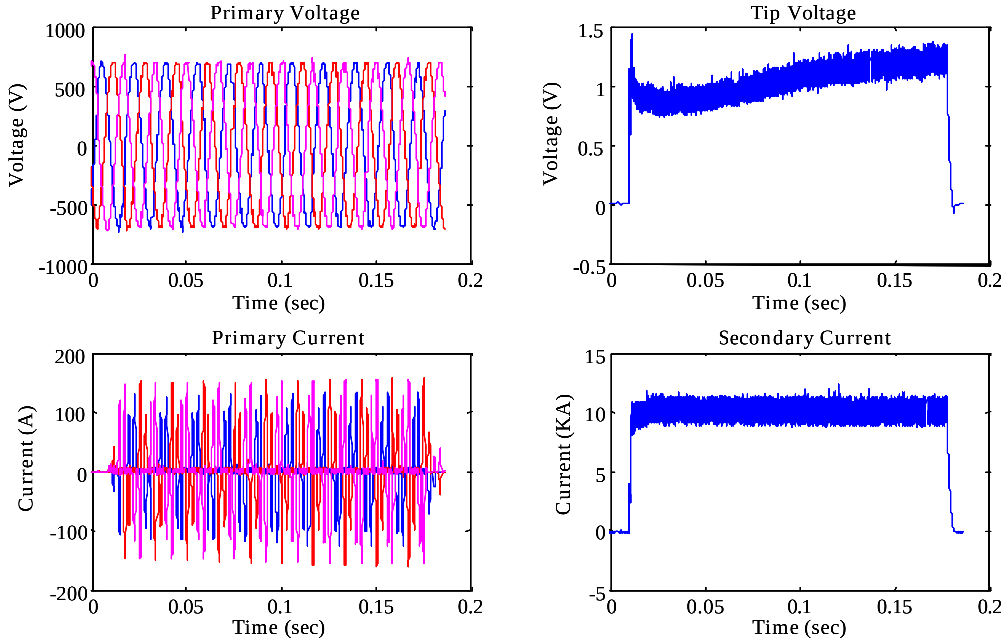
$$|i_{CA}| = \sqrt{-i_1 \cdot i_3} \quad (10)$$

Results and Discussion

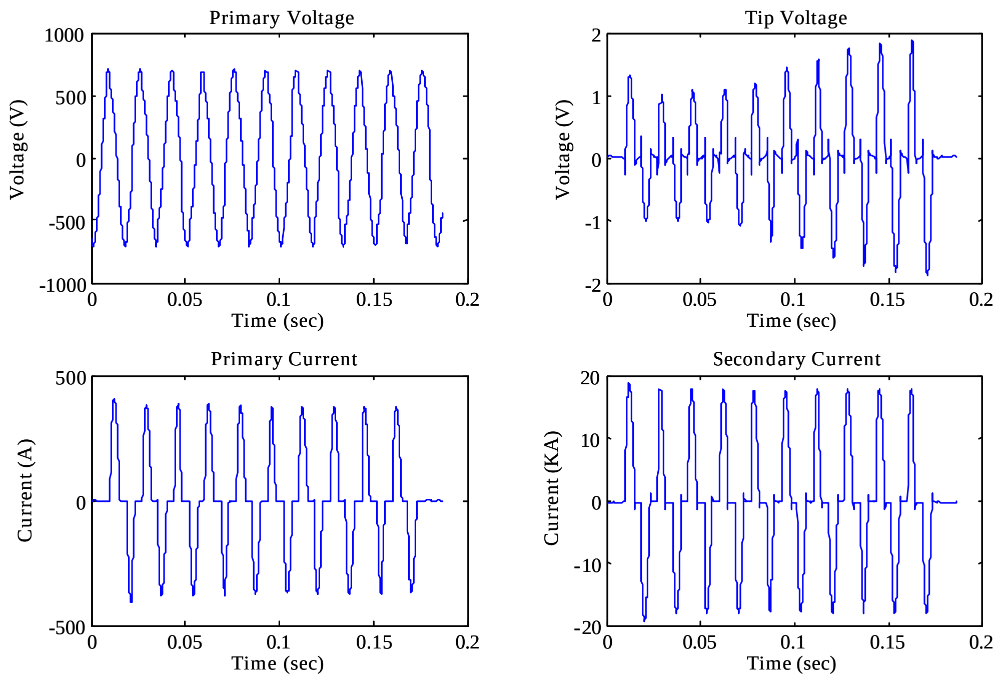
The data from the nugget growth study is summarized in Table 1. The standard deviations were calculated based on five samples. While most of the samples have small standard deviations, 10-kA AC welding has a large variation (2.5 mm). This is because among the five welds measured, two did not have a nugget. The energy consumption is calculated for both the primary and secondary side of the transformer according to the procedure described in the previous section.

Table 1. Results of the Nugget Growth Study

Welding	Weld Size (mm)				Primary Energy (Joule)				Secondary Energy (Joule)			
Current (KA)	AC	std	DC	std	AC	std	DC	std	AC	std	DC	std
9.5	0.0	0.00	4.0	0.49	4694	68	4659	62	1016	52	1666	71
10	2.7	2.50	4.5	0.23	5364	75	4982	42	1280	100	1721	36
10.5	5.0	0.23	5.2	0.21	5981	55	5498	89	1474	78	1975	90
11	6.0	0.27	6.4	0.21	6642	71	6149	89	1713	88	2328	88
11.5	6.4	0.31	6.2	0.17	7337	61	6440	68	1934	58	2327	69
12	Expulsion		Expulsion		7983	55	6924	68	2076	59	2504	71



(a) Typical signals for MFDC welding



(b) Typical signals for single-phase AC welding

Figure 5. Typical Welding Signals (RMS welding current is 10 kA.)

Weld Button Size

The weld button diameter is plotted against the welding current in Figure 6. It can be seen that, in general, less welding current is needed to make welds of the same size in the MFDC case. However, this difference is more prominent at low current end than it is at the high current end. At the low current end, there is no weld at 9.5 kA for the AC case. However, 4-mm-diameter welds on average have been achieved in the DC case. At the high current end, there is almost no difference between AC and DC welding. For example, 6.5-mm welds are made at 11.5 kA for both the AC and DC cases. At 12 kA, expulsions became heavy for both cases. Assuming this result is true for different weld times, conceptual weld lobes can be constructed as shown in Figure 7. The DC weld lobe can have a much lower low boundary than the AC one, which means that it takes much lower welding current to form a weld. On the expulsion side, however, the boundaries of the two weld lobes are almost the same. This indicates that DC welding has a wider weld lobe, which is generally preferred in the welding practice.

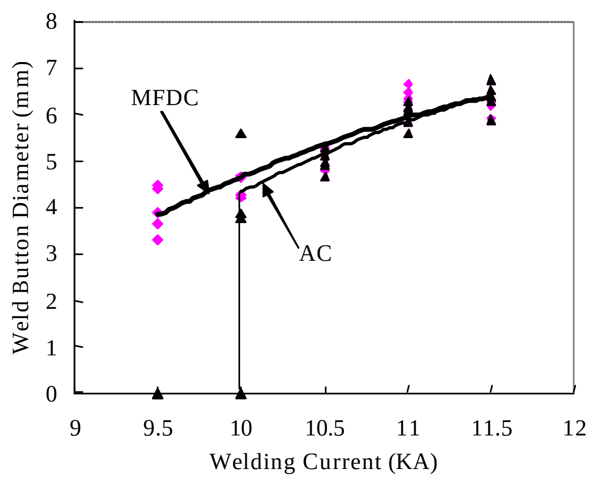


Figure 6. Nugget Growth Study for AC and MFDC

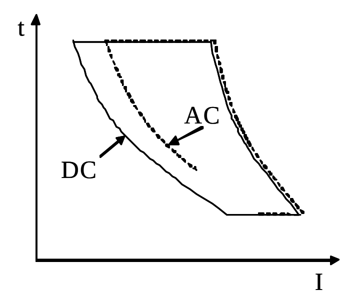


Figure 7. Weld Lobes of AC and DC Spot Welding

The differences of the AC and DC welding processes can be explained by dynamic resistance.

Figure 8 shows the dynamic resistances of AC and DC welding processes for welding currents at 9.5, 10.5, and 11.5 kA. When the welding current is 9.5 kA, there is a substantial difference between the dynamic resistances of AC and DC welds. As the welding current increases, the difference becomes smaller.

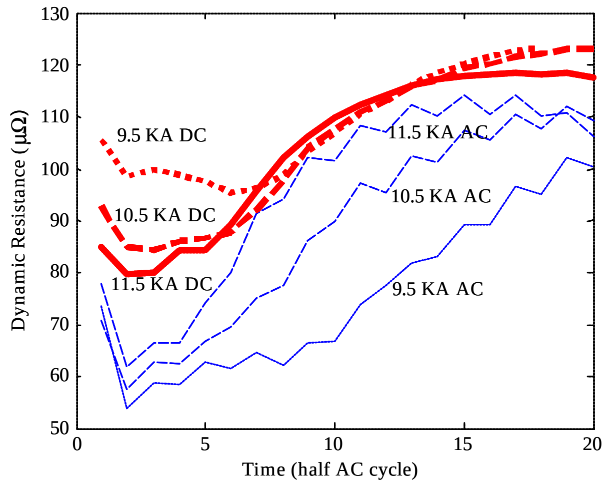


Figure 8. Dynamic Resistances of AC and DC Welding Processes with Different Welding Currents

The cause of these differences in the resistance values has been suggested due to the lack of high current peaks in the DC welding process.(1) High current peaks would tend to break down the contact interfaces more rapidly and result in lower resistance. In addition, the mechanical vibration generated due to the alternating current polarity would tend to enhance the breakdown of the contact surface. In order to confirm this suggestion, a finite-element simulation model is developed to study the contact resistance effects in the AC and DC processes. To simplify the model, only thermal-electrical effects are considered. A constant current load is applied for the DC welding process. The true AC waveform measured in the process is used for the AC welding simulation. All other conditions including material properties are kept the same except the contact resistances.

The contact resistance for DC welding used in the simulation is based on the measurement data published in Reference 9. The data was measured statically using a DC power supply and micro-ohmmeter. To account for the peak current and mechanical "pounding" effects of the AC welding process, a contact resistance curve with faster breakdown is used in the AC welding simulation. The contact resistances used in the simulations are shown in Figure 9.

The results of the simulation with the 9.5-kA welding current are shown in

Figure 10. The highest temperature achieved in the DC process was 2325 K; whereas, it was 1733 K in the AC process. The melting temperature of low-carbon steel is 1808 K. Therefore, it is easy to see that there is a fairly large molten zone in the DC welding process that will become a weld nugget after it cools down, where there is no melting occurring in the AC welding process.

The simulated nugget sizes in both AC and DC processes are shown in Figure 11 along with the penetration of the welds. The 1808 K melting temperature is used to determine the profile of the nuggets. The nugget size and penetration are determined as shown in the figure. The differences between the AC and DC welds shown in the figure agree with what have been observed in. The DC process can achieve a weld with a smaller welding current. The nugget size difference is more prominent when the welding current is low.

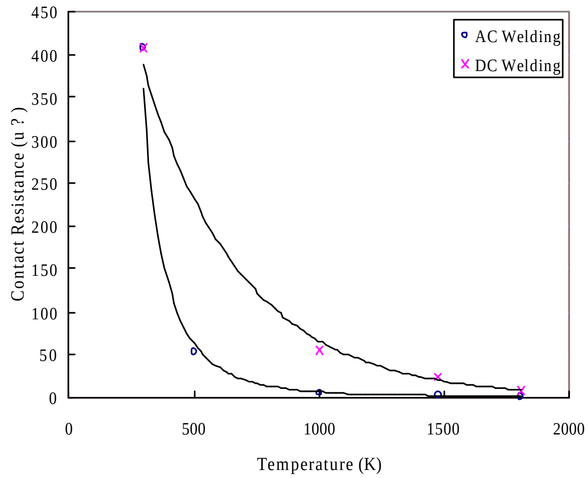
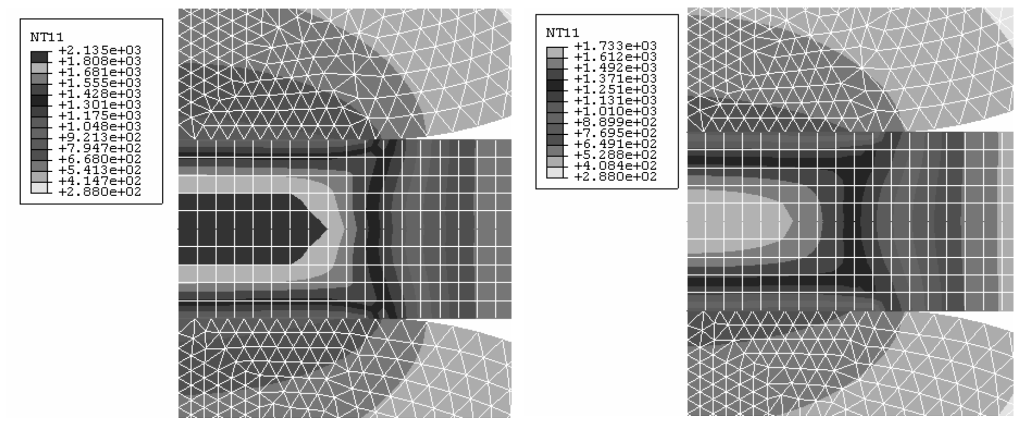
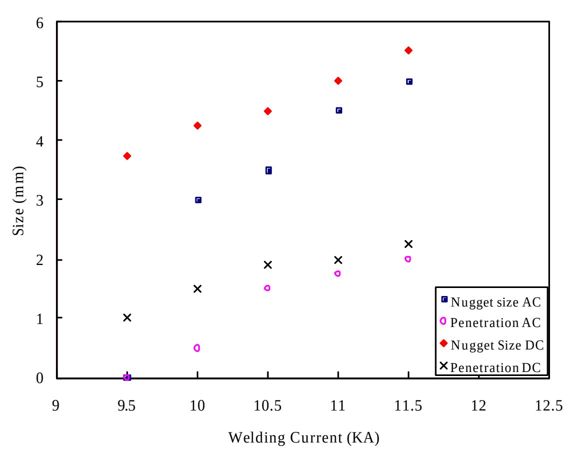


Figure 9. Contact Resistances for AC and DC Process Simulation



(a) DC (b) AC

Figure 10. Simulation Results for 9.5-kA Welding Current



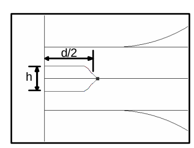


Figure 11. Simulated Nugget Sizes in AC and DC Processes

The differences in the simulation results are caused by the difference in the contact resistance models used. When the same contact resistance model was used, the differences in nugget size and penetration could not be found. This confirms that the contact resistance behavior is the cause of the differences between the AC and DC welding processes. In the DC welding process, there is little or no mechanical pounding effect to help break down the contact resistance. Contact resistance breakdown relies on the heat generated in the first few milliseconds of the welding cycle. When the current is low, the heat generated is also low and thus the contact resistance remains high in the beginning of the welding cycle. Therefore, compared to the AC welding process with the same current, more heat is generated. This initial heat in turn causes the bulk resistivity increases rapidly, drawing more energy into the weld. This joint effect causes the DC process to form a nugget early at lower current. When the welding current is high, a lot of heat will be generated in the beginning of the welding process. This high initial heat helps break down the contact resistance quickly. Therefore, the difference between the AC and DC processes becomes smaller.

Energy Consumption

To compare the energy consumption of AC and DC welding processes, both the primary and secondary energy are plotted in Figure 12. It can be seen that the energy difference on the primary side increases with the welding current. At low currents the energy from the primary side is almost the same. On the other hand, the secondary energy, which is the energy went into the welds, is lower in the AC process. Figure 12 indicates that in order to provide the same welding current, more energy needs to be drawn from the power bus in the AC process than it does in the DC process. With the same welding current, more energy goes into the metal in the DC process than it does in the AC process.

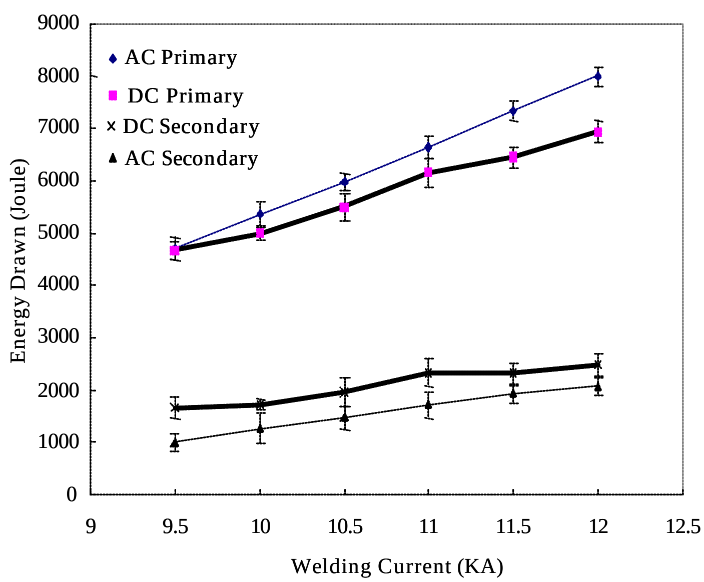


Figure 12. Energy Consumption at Different Current Settings

The energy consumption difference can be explained by the energy breakdowns in the welding process. In general, the total primary energy (E_1) in the spot welding process can be decomposed into two parts: the energy used to heat the metal (the secondary energy, E_2) and the energy lost in the welding machine (E_o). The secondary energy E_2 can further be broken down to the energy used to form the nugget (E_n) and the energy lost in the metal (Eo'). The energy loss in the welding machine comes from the transformer loss and the diode voltage drops. In addition, AC welding generates high magnetic field and cause the machine to vibration. This kinetic energy is also lost in the welding process.

DC welders have a diode drop in the secondary circuit because of the rectifier. This diode drop should generate more resistive heat on the machine than the AC case. However, the energy loss because of the vibration in the AC process increases with the welding current. This loss seems more significant than the resistive one in the DC process.

As has been seen previously, the same welding current does not produce welds of the same size in the AC and DC processes. In RSW, weld button size is generally used as a quality indicator. Therefore, the energy consumption is plotted against the weld size in Figure 13. It is seen that the total energy needed to make a same size weld in the AC process is consistently higher than that in the DC process. On average, 10% percent more energy is needed in the AC process to produce welds of the same sizes as the DC process. Comparing the primary and secondary energy, it can be found that the energy efficiency of AC welding is about 26%, which means only 26% of the total energy is used to heat the metal and over 75% of the total electrical energy is wasted on the welding machine itself. In the DC welding process, the energy efficiency is about 37%, and 63% of the electrical energy is wasted on the machine.

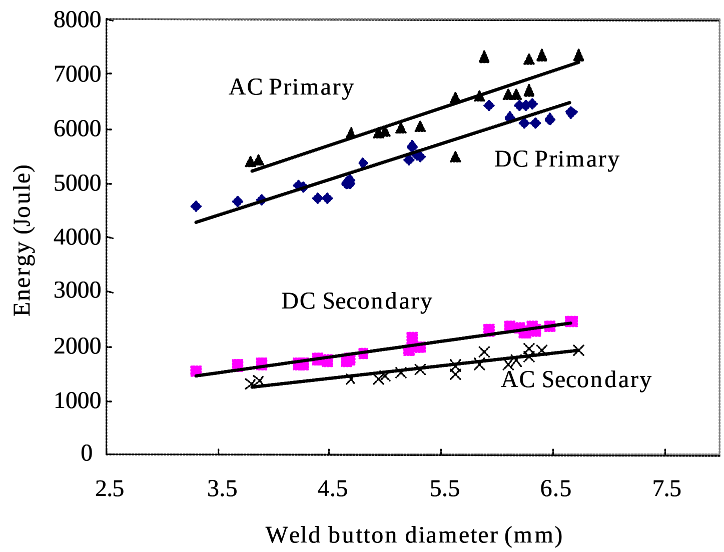


Figure 13. Energy Consumption of Different Weld Sizes

Consider the secondary energy. It is found that on average 28% more energy is needed for the DC process than it is for the AC process to make a same size weld. For nuggets of the same size the energy required to melt the metal in the AC and DC process should be the same, i.e., $E_{nact} = E_{nd}$. Therefore, it can be seen that more heat is dissipated into the metal and ambient environment in the DC welding process. This extra heat might be generated at the electrode-to-sheet interfaces and taken away by the cooling water.

Conclusions

The following conclusions can be drawn from this study:

(1) The weld sizes achieved in the AC and DC processes are different and the difference is more prominent when the welding current is low. When the welding current is high and close to the expulsion limit, the weld sizes are similar in the AC and DC processes.
(2) The total energy needed to make a same size weld in the AC process is consistently higher than that in the DC process. In general, DC process saves 10% of the total energy.
(3) The cause of the differences between the AC and DC welding processes is the behavior of the contact resistance. Contact resistance breaks down differently because of the heat patterns and the mechanical pounding effects in the AC welding process.
(4) In general, the DC welding machine is more efficient. The energy efficiency of the AC welding is about 26%, which means 74% of the total electrical energy is wasted on the welding machine itself. In the DC welding process, the energy efficiency is about 37%, and 63% of the electrical energy is lost on the machine.
(5) More heat is dissipated into the metal and the environment in the DC welding process. Therefore, the secondary energy in the DC process is 28% higher than that in the AC process.

Acknowledgements

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