Shunting Effect in Resistance Spot Welding Steels — Part 1: Experimental Study

Shunting in resistance spot welding is affected by the process variables involved and caution must be taken when welding with narrow weld spacing

BY B. WANG, M. LOU, Q. SHEN, Y. B. LI, AND H. ZHANG

ABSTRACT

Shunting in resistance spot welding is difficult to avoid, as multiple welds are commonly designed in a specific area for strength and other considerations. This experimental study investigates the effects of several variables on shunting, including material, surface condition, welding schedule, and other process parameters. The experimental results show that weld spacing and surface condition have the largest effects on shunting. The electrode force in general helps avoid shunting, with the exception that for a narrow weld spacing it actually promotes shunting by reducing the electrical resistance in the shunting path. It was found that shunted welds may have larger/darker indentation marks than the shunt welds, although they are smaller in weld size. In general, it was found that the variables are tightly coupled and their interaction is complex, making it difficult to single out the influence of individual factors in shunting.

Introduction

In industrial applications of resistance spot welding, there are usually several welds arranged next to each other in the same region of a part. This is usually by design for structural and handling purposes, and may also result from weld repair work. Therefore, a premade neighboring weld(s) often exists when making a new weld. The existing welds may divert the electric current intended for the new weld, a phenomenon called shunting. As the applied electric current is shared by the weld to be made (the shunted weld) and the existing weld (the shunt weld), the heat generated in the shunted weld may not be sufficient for it to grow to the designated size. Although the shunting effect is well recognized by the resistance welding community, it has been discussed only in a few publications such as the work by Howe (Ref. 1), the book by Zhang and Senkara (Ref. 2), and *ASM Handbook on Welding* (Ref. 3).

The shunting process can be visualized through a simple schematic as shown in Fig. 1. The proportions of the electric current through the shunting and welding paths are determined by the relative values of electric resistances along these paths. These resistances can be categorized as follows:

Shunting path: contact resistances at the electrode-sheet interfaces at both the top and bottom surfaces, and the bulk resistance along the shunting path through the shunt weld.

Welding path: contact resistances at the electrode-sheet interfaces at both the top and bottom surfaces, bulk resistances of the top and bottom sheets, and the contact resistance at the faying interface where the shunted weld is to be made.

The contact resistances at the electrode contact can be assumed identical for these two paths, and they can be lumped as R_c for simplicity. The electric circuit of the welding setup can be simplified as shown in Fig. 2. In this diagram the total applied electric current, I, is split into a welding current and a shunting current, I_W and I_S, respectively. These two currents, and therefore the amounts of heat, are determined by the relative values of the resistances along the shunting and welding paths. An estimate of these resistances is helpful for assessing the amount of electric current and, therefore, heat, diverted through the shunting path. However, the resistances along these two paths do not remain constant during welding. The rising temperature, as well as metallurgical changes, has a great effect on the resistance levels. In addition, the contact area at the faying interface along the welding path experiences a large change from an intimate contact of two sheets to a single piece of metal due to melting, at which point the contact resistance R_{cw} disappears. As the contact resistance dominates the total resistance in the welding path, the resistance ratio of the two paths is expected to change drastically during welding. However, considering the detailed actual processes in welding would make it impossible to analyze the shunting phenomenon. As a matter of fact, the relative resistances at the beginning of welding can be used to simplify the analysis, and it should produce a reasonable estimate of the shunting effect as the initial state of the electrical resistance is crucial in determining the electrical current distribution and the heat generation throughout the welding process. There are many factors influencing shunting or the distribution of electric current during resistance spot welding. They can be classified into the following three groups:

Electrical Factors

The electrical factors are as follows:

Bulk resistance. The bulk resistance is a function of temperature for a certain material with fixed chemical composition. Such a temperature dependence is significant, although it is not accurately known for most of the metals beyond their melting points. As the total resistance along the shunting path is proportional to the bulk resistance, a large weld spacing would result in a long shunting path and thus a small amount of shunting.

Contact resistance. Shunting is also affected by the contact resistance at the fay-

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KEYWORDS

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Shunting
Mild Steel
Dual-Phase Steel
Weld Spacing

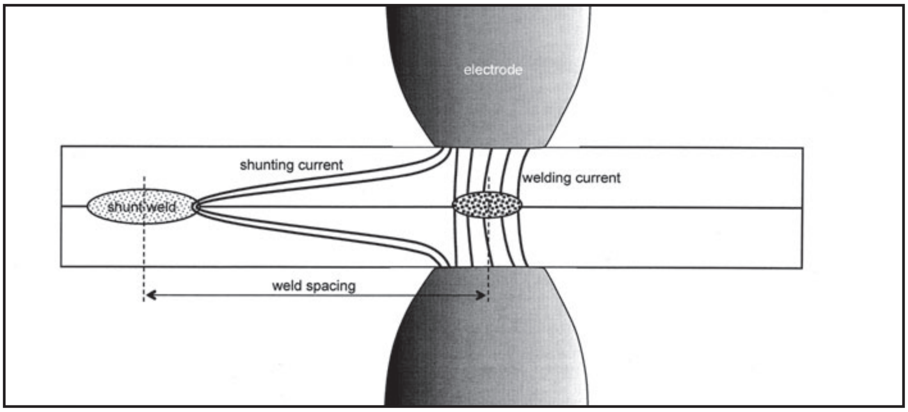

Fig. 1 — Schematic of shunting in welding (adapted from Fig. 2.6 of Zhang and Senkara, Ref. 2).

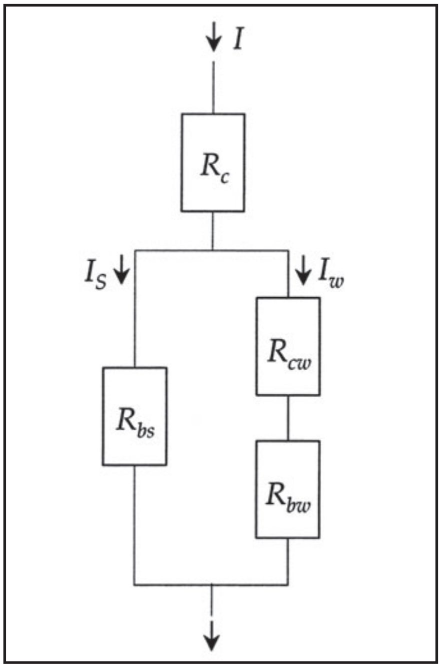

Fig. 2 — An electric circuit of the welding and shunting paths during resistance spot welding.

ing interface. A resistive surface may form due to surface contaminants such as oxides and greases. The contact resistance at the sheet faying interface plays a significant role in determining the proportions of the shunting and welding currents, especially at the beginning of welding. Its direct impact diminishes once melting starts and the contact area disappears. However, the influence of contact resistance exists beyond melting as it affects the heat generation in the sheet stack-up at the early stage of welding, which in turn dictates the resistivity distribution and, therefore, further heat generation as welding proceeds, even when the original contact area is completely replaced by the molten metal. It is necessary to consider this effect only in the welding path, not the shunting path as there is no contact area along this path. There are many variables affecting the contact resistance. For instance, zinc coating for corrosion protection significantly reduces, while other contaminants promote, contact resistance.

Welding time. Although it is not strictly electrical, welding time directly interacts with other electrical factors in welding. For instance, joule heating is proportional to the welding time. Extending the welding time may lessen the shunting effect by creating sufficient adhesion at the faying interface. It is also beneficial to homogenizing the variation in the distribution of electrical resistivity in the sheet stack-up.

Welding current. The electrical current used in welding is directly related to joule heating. Its effect in shunting is similar to that of the welding time. In general, a large welding current is preferred to reduce the shunting effect.

Metallurgical Factors

The metallurgical influence in shunting is reflected in the dependence of electrical resistivity on the chemical compositions and phase changes of the metals.

Material composition. As the ratio of electrical current is inversely proportional to the ratio of the resistances along the welding and shunting paths, increasing the bulk resistivity of the workpieces decreases the resistance ratio $(R_{cw} + R_{bw})/R_{bs}$ and, therefore, increases the proportion of welding current. That is, welding a metal with large bulk resistivity may require a small weld spacing to avoid the shunting effect. Therefore, a smaller weld spacing may be needed when welding steels than when welding aluminum alloys. Different metals exhibit different rates of increase in bulk resistivity with temperature. As seen from Fig. 2.2 of Zhang and Senkara (Ref. 2), aluminum and magnesium have significantly lower bulk resistivity than iron in their respective temperature ranges up to the melting point. The metallurgical properties of the coatings are also of importance, as they directly affect the contact resistivity. For instance, hot-dipped galvanized (HDG) steels possess lower contact resistance than galvannealed sheets and, therefore, may need smaller weld spacing because of a larger proportion of current passing through the welding path due to a lower $(R_{cw} + R_{bw})/R_{bs}$ ratio.

Phase change. A change in bulk resistivity is always associated with the phase transformation in the solid state, and there is always a jump in resistivity in metals when they melt, as seen in Fig. 2.2 of Zhang and Senkara (Ref. 2). However, the total resistance monitored during welding usually does not reveal such a sudden change in resistivity occurring at phase transformation, largely due to the competing changes in resistivity during heating (which increases the total resistance) and melting (which decreases the total resistance as it eliminates the contact resistance).

Table 1 — Materials Used in the Experiment

Material	Sheet Thickness (mm)	Coating	Yield Strength (MPa)
Mild Steel	1.0	Bare	205
Mild Steel	1.5	Bare	205
Mild Steel	2.0	Bare	205
DP590	1.2	HDG	590
DP780	1.25	HDG	780

Table 2 — Nominal Chemical Composition (wt-%) of the Test Materials

Material	Si	C	Mn	S	P	Cr	Mo	Al	V	Fe
Mild Steel	0.01	0.07	0.26	0.012	0.014	—	—	—	—	Bal.
DP590[(a)]	0.44	0.12	1.8	0.006	0.021	0.26	—	—	—	Bal.
DP780[(Ref. 5)]	0.23	0.1	2.33	—	—	0.03	0.02	0.04	0.06	Bal.

(a) The nominal chemical composition of DP590 is that for DP600 in Ref. 4.

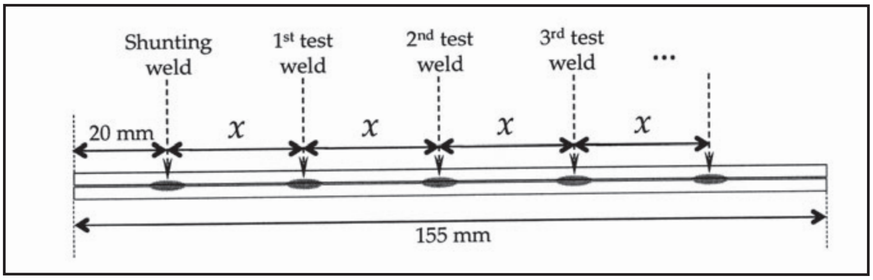

Fig. 3 — Welding sequence.

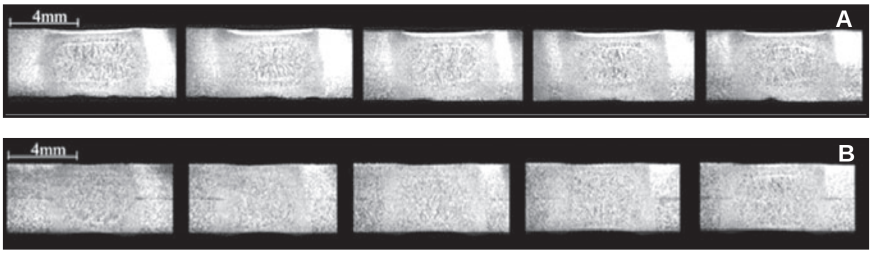

Fig. 4 — Cross-sectional views of the shunt and shunted welds made on a 2-mm bare mild steel, with 8-mm weld spacing. The parameters were welding current = 6 kA, welding time = 500 ms, and electrode force = 2.8 kN. A — #9 in Table 4 and 1.8 kN; B — #11 in Table 4.

Table 3 — Welding Schedules and Weld Spacings

Material	Current (kA)	Time (ms)	Force (kN)	Weld Spacing (mm)
1.0-mm Mild Steel	6.0	200	1.8, 2.8	8.0, 15.0, 25.0
1.5-mm Mild Steel	6.0	400, 500	1.8, 2.8	8.0, 15.0, 25.0
2.0-mm Mild Steel	6.0	500	1.8, 2.8	8.0
1.2-mm DP590	8.0	500	3.5, 5.0	8.0, 15.0, 25.0
1.25-mm DP780	8.0	500	3.0, 3.5, 4.3, 5.0	8.0, 15.0, 25.0

Mechanical Factors

In addition to the electrical and metallurgical effects in shunting, an often overlooked effect comes from the mechanical aspect of welding.

Electrode force. It directly affects the contact resistance at the faying interface along the welding path. A large electrode force creates a contact area with small electrical resistance and is, therefore, beneficial to reducing the shunting effect.

Yield strength. The effect of electrode force is directly influenced by the resistance of the sheet metals to deformation. As plastic deformation of the metals is necessary for creating the electric contact at the sheet faying interface, the yield strength of the sheets should be considered a factor in shunting study.

Workpiece geometry. Other influential mechanical factors include sheet fit-up, electrode geometry (dimensions and shape), and electrode alignment (axial and angular misalignments). Sheet dimensions, such as thickness, also directly affect the mechanical resistance to plastic deformation under an electrode force. In general, any geometric conditions that are beneficial to creating a close contact at the faying interface reduce the required weld spacing. Therefore, thick sheets require large weld spacing as they are difficult to deform in order to create intimate contact when an electrode force is exerted. The effect of sheet thickness in shunting is also reflected in the relative lengths of the shunting and welding paths for electric current.

Because of the large number of variables, their intensive interactions, and their (often unknown) temperature-dependent properties, it is not viable to quantify their effects on shunting. Experimental studies are common in such investigations. In the work by Howe (Ref. 1), several types of steels of various gauges and surface (coating) conditions were studied in order to understand the shunting effect in these materials. As the weld spacing used in the tests was fairly large, larger than those specified by the recommendations of the International Institute of Welding (Ref. 4), the conclusion was that weld spacing was not a significant factor. Caution must be taken in practical welding as the experiments in Ref. 1 were not designed to determine the minimum weld spacing.

This investigation explored, in steel welding, the influence on shunting by a number of variables, including material (composition and strength), gauge, surface condition (coating, use of resistive insert), as well as welding parameters, most of them were not included in the previous studies. An experimental matrix was designed in which several values were selected for each of the variables. Their effects were then discussed based on the experimental observations, and a statistical analysis was conducted to test the significance of the combinations of the variables.

Experimental Procedure

Based on the material availability, three types of mild steels (MS) and two dual-phase (DP) steels were selected in this study. They are as listed in Table 1, and the nominal chemical compositions of these commercial sheet metals are listed in Table 2.

Several surface conditions were created to understand the effect of contact resistance. Bare steel surface, zinc-coated [hot-dipped galvanized (HDG)] surface, and a plastic film insertion in combination with either bare or coated surfaces were created to represent the normal surface conditions and extremely low and high resistive surface conditions. The plastic insertion used was a 0.05-mm-thick PVC (polyvinyl chloride) film. As it has a melting temperature range of 160° ~ 180°C, a large portion of the plastic film at the faying interface disappears through melting and vaporization at the beginning of welding. As the purpose was to explore the effect of contact resistance on shunting, plastic films were only used when making the shunted welds, not the shunt welds.

The sheet materials were cut into 30- × 155-mm coupons, and welds were made according to Fig. 3, with preselected weld spacing. Two toggle clamps, one on each side of the electrodes, were used to hold a sheet stack-up during welding. Two, three, or four (shunted or test) welds, depending on the weld spacing, were made using the same schedule as the first (shunt) weld on each specimen with fixed spacing. The welding schedules were selected to make ideal-sized shunt welds for the respective sheets, based on experience and trials.

The shunting effect was assessed by comparing the sizes of the shunt weld and the shunted ones on the same coupon. Peeling a weld coupon to measure the weld size was considered first for convenience. However, it was proven impractical as the weld spacing selected in this study was generally much smaller than that in a normal welding setting in order to obtain a significant shunting effect. A much more tedious approach had to be adopted. The welds were evaluated by longitudinal sectioning of the weld

Table 4 — Welding Process Parameters, Measured Widths of the Shunt and Shunted Welds, Difference between the First Shunted and the Shunt Welds (%), and Statistical T-Test Results

#	Material	Thickness (mm)	Current (kA)	Time (ms)	Force (kN)	Spacing (mm)	Surface Condition	Shunt Weld (mm)	Shunted Weld_1 (mm)	Shunted Weld_2 (mm)	Shunted Weld_3 (mm)	Shunted Weld_4 (mm)	Change (%)	Standard Deviation (mm)	t_Value	p_Value
1	MS	1.5	6	400	2.8	8	bare	4.4	4.0	4.1	4.1	4.2	9.1	0.0812	-7.348	0.00266
2	MS	1.5	6	400	2.8	8	plastic	4.2	3.6	3.7	4.0	3.9	14.3	0.1826	-4.382	0.01123
3	MS	1.5	6	400	1.8	8	plastic	4.0	3.6	3.7	3.7	3.8	10.0	0.0816	-7.348	0.00266
4	MS	1.5	6	400	1.8	8	bare	4.1	3.8	3.5	3.7	3.7	7.3	0.1258	-6.755	0.00358
5	MS	1.0	6	200	2.8	8	bare	4.4	4.0	4.1	4.2	4.2	9.1	0.0957	-5.745	0.00530
6	MS	1.0	6	200	2.8	8	plastic	4.3	3.7	3.6	3.8	3.9	14.0	0.1291	-8.521	0.00211
7	MS	1.0	6	200	1.8	8	bare	4.5	4.0	4.2	4.1	4.3	11.1	0.1291	-5.422	0.00632
8	MS	1.0	6	200	1.8	8	plastic	4.2	2.8	2.7	2.7	2.6	33.3	0.0816	-36.742	0
9	MS	2.0	6	500	2.8	8	bare	5.0	4.5	4.6	4.6	4.8	10.0	0.1258	-5.960	0.00481
10	MS	2.0	6	500	2.8	8	plastic	4.6	4.3	4.2	4.4	4.4	6.5	0.0957	-5.745	0.00530
11	MS	2.0	6	500	1.8	8	bare	4.9	4.6	4.7	4.9	4.8	6.1	0.1291	-2.324	0.02096
12	MS	2.0	6	500	1.8	8	plastic	4.8	4.5	4.7	4.7	4.8	6.3	0.1258	-1.987	0.07561
13	DP780	1.25	8	500	4.3	8	HDG	6.5	6.2	6.3	6.4	6.4	4.6	0.0957	-3.656	0.01790
14	DP780	1.25	8	500	3	8	HDG	6.7	6.5	6.5	6.7	6.7	3.0	0.1155	-1.732	0.09342
15	DP780	1.25	8	500	3.5	8	HDG	6.6	6.4	6.5	6.5	6.6	3.0	0.0816	-2.449	0.04709
16	DP780	1.25	8	500	3.5	8	HDG + plastic	6.5	6.2	6.3	6.2	6.4	4.6	0.0957	-4.700	0.00921
17	DP780	1.25	8	500	5	8	HDG	6.3	5.8	6.1	6.2	6.1	7.9	0.1732	-2.887	0.03390
18	DP780	1.25	8	500	5	8	HDG + plastic	6.1	6.0	6.0	6.1	6.1	1.6	0.0577	-1.732	0.09342
19	DP590	1.2	8	500	5	8	HDG	5.8	5.7	5.7	5.7	5.7	1.7	0	-3.077	0.02817
20	DP590	1.2	8	500	5	8	HDG + plastic	5.9	5.8	5.8	5.9	5.9	1.7	0.0577	-1.732	0.09342
21	DP590	1.2	8	500	3.5	8	HDG	6.6	6.4	6.4	6.5	6.5	3.0	0.0577	-5.196	0.00703
22	DP590	1.2	8	500	3.5	8	HDG + plastic	6.3	6.1	6.1	6.2	6.3	3.2	0.0957	-2.611	0.04221
23	DP590	1.2	8	500	5	15	HDG	5.6	4.7	5.1	5.2		16.1	0.2646	-3.928	0.03178
24	DP590	1.2	8	500	5	15	HDG + plastic	5.8	5.4	5.5	5.5		6.9	0.0577	-10.0	0.00495
25	DP590	1.2	8	500	3.5	15	HDG	6.0	5.3	5.5	5.4		11.7	0.1	-10.392	0.00472
26	DP590	1.2	8	500	3.5	15	HDG + plastic	6.2	5.6	5.7	5.9		9.7	0.1528	-5.291	0.01721
27	DP780	1.25	8	500	3.5	15	HDG	6.3	5.7	5.8	5.8		9.5	0.0577	-16.0	0.00228
28	DP780	1.25	8	500	3.5	15	HDG + plastic	5.6	5.4	5.4	6.5		3.6	0.6351	0.455	0.65047
29	DP780	1.25	8	500	5	15	HDG	5.6	5.2	5.4	5.5		7.1	0.1528	-2.646	0.06358
30	DP780	1.25	8	500	5	15	HDG + plastic	5.8	5.4	5.5	5.5		6.9	0.0577	-10.0	0.00495
31	MS	1.0	6	200	2.8	15	bare	4.2	3.7	3.6	3.8		11.9	0.1	-8.660	0.00671
32	MS	1.0	6	200	2.8	15	plastic	4.3	3.4	3.8	3.7		20.9	0.2082	-5.547	0.01560
33	MS	1.0	6	200	1.8	15	bare	4.7	4.5	4.5	4.5		4.3	0	-2.887	0.05203
34	MS	1.0	6	200	1.8	15	plastic	4.5	4.0	4.1	4.0		11.1	0.0577	-14.0	0.00255
35	MS	1.5	6	400	1.8	15	bare	5.5	5.0	5.0	5.1		9.1	0.0577	-14.0	0.00255
36	MS	1.5	6	400	1.8	15	plastic	5.3	4.7	4.6	4.8		11.3	0.1	-10.392	0.00472
37	MS	1.5	6	400	2.8	15	bare	5.2	4.7	4.8	4.9		9.6	0.1	-6.928	0.01014
38	MS	1.5	6	400	2.8	15	plastic	5.1	4.7	4.8	4.7		7.8	0.0577	-11.0	0.00435
39	MS	1.5	6	500	2.8	15	bare	4.9	4.7	4.6	4.8		4.1	0.1	-3.464	0.04016
40	MS	1.5	6	500	2.8	15	plastic	5.0	4.4	4.6	4.7		12.0	0.1528	-4.914	0.01959
41	MS	1.5	6	500	1.8	15	bare	5.2	4.9	4.9	5.0		5.8	0.0577	-8.0	0.00766
42	MS	1.5	6	500	1.8	15	plastic	5.3	5.0	5.1	5.1		5.7	0.0577	-7.0	0.00992
43	DP590	1.2	8	500	5	25	HDG	6.1	5.7	6.0			6.6	0.2121	-1.667	0.17524
44	DP590	1.2	8	500	5	25	HDG + plastic	5.5	5.4	5.4			1.8	0	-1.010	0.34363
45	DP590	1.2	8	500	3.5	25	HDG	6.5	6.3	6.4			3.1	0.0707	-3.000	0.04855
46	DP590	1.2	8	500	3.5	25	HDG + plastic	6.3	6.1	6.3			3.2	0.1414	-1.000	0.34206
47	DP780	1.25	8	500	3.5	25	HDG	6.5	6.2	6.4			4.6	0.1414	-2.000	0.14834
48	DP780	1.25	8	500	3.5	25	HDG + plastic	6.0	6.0	6.0			0.0	0		1.00000
49	DP780	1.25	8	500	5	25	HDG	6.5	6.1	6.2			6.2	0.0707	-7.000	0.04732
50	DP780	1.25	8	500	5	25	HDG + plastic	6.5	6.0	6.3			7.7	0.2121	-2.333	0.13339
51	MS	1.0	6	200	2.8	25	bare	5.2	4.8	5.1			7.7	0.2121	-1.667	0.17524
52	MS	1.0	6	200	2.8	25	plastic	4.7	4.4	4.6			6.4	0.1414	-2.000	0.14834
53	MS	1.0	6	200	1.8	25	bare	5.0	4.6	4.9			8.0	0.2121	-1.667	0.17524
54	MS	1.0	6	200	1.8	25	plastic	4.5	4.1	4.3			8.9	0.1414	-3.000	0.04855
55	MS	1.5	6	400	1.8	25	bare	6.0	5.5	5.9			8.3	0.2828	-1.500	0.18944
56	MS	1.5	6	400	1.8	25	plastic	5.4	5.0	5.3			7.4	0.2121	-1.667	0.17524
57	MS	1.5	6	400	2.8	25	bare	5.6	5.2	5.4			7.1	0.1414	-3.000	0.04855
58	MS	1.5	6	400	2.8	25	plastic	5.1	4.7	5.0			7.8	0.2121	-1.667	0.17524
59	MS	1.5	6	500	2.8	25	bare	5.3	4.7	5.2			11.3	0.3536	-1.400	0.19796
60	MS	1.5	6	500	2.8	25	plastic	5.5	4.5	5.2			18.2	0.4950	-1.857	0.10289
61	MS	1.5	6	500	1.8	25	bare	5.3	5.0	4.7			5.7	0.2121	-3.000	0.04855
62	MS	1.5	6	500	1.8	25	plastic	5.5	4.3	3.0			21.8	0.9192	-2.846	0.11039

coupon, and metallurgical examination was conducted to obtain the dimensions and other characteristics of welds. Fixed weld spacing was used in welding for convenience. The welding schedules and weld spacing for welding the sheets shown in Table 1 are listed in Table 3.

Truncated flat-face Cu-Cr-Zr electrodes with a 5-mm tip diameter were used for welding the steels. The electrodes were conditioned by making 50 welds before being used in the experiments.

Results and Discussion

The welded coupons were sectioned and specimens prepared following standard metallographic examination procedures. The weld width was measured on the sectioned specimens using an optical microscope. The measurements are listed in Table 4, and the effects of various variables are discussed in the following sections.

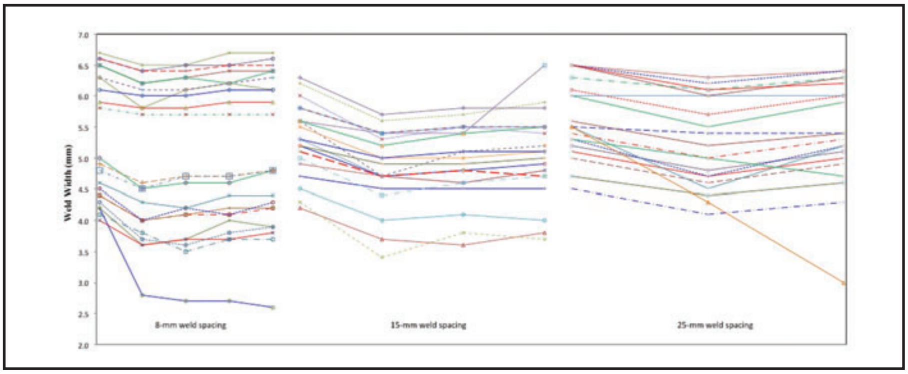

Fig. 5 — Weld widths on the coupons in the order of welding sequence. In the group on the left are the specimens with four shunted welds and 8-mm spacing; the center group has three shunted welds with 15-mm spacing; and the one on the right has two shunted welds with 25-mm spacing.

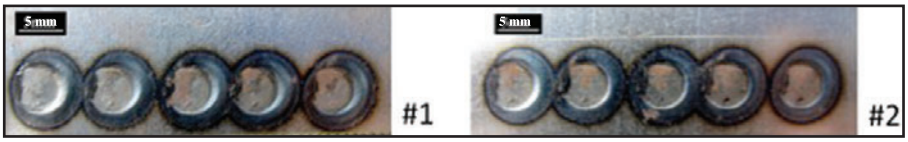

Fig. 6 — Typical welded specimens of 1.5-mm bare m ild steel sheets with 8-mm weld spacing. A — Welds made with the original bare surfaces (weld specimen #1 in Table 4); B — those made using a plastic film as insert (weld specimen #2 in Table 4). The welding sequence is from left to right.

Effect of Shunting on Weld Geometry, Microstructure, and HAZ

In addition to the weld size, the metallographic cross-sectional views also revealed other useful information. Figure 4A shows a shunt weld with four subsequently made shunted welds. The shunting effect is apparent, as there is a clear difference in heat input, reflected by the weld size, between the shunt and shunted welds; and the coarser grains in the shunt weld than in the shunted ones are the result of more concentrated heating when making the shunt weld. In addition to the smaller size of the shunted welds than of the shunt weld, the differences in weld height, weld shape, and shape of the heat-affected zone (HAZ) are also visible from the figure. The first shunted weld (the second weld in the sequence) is smaller than the shunt weld, and its shape is more oval than that of the shunt weld, which is more rectangular. The four shunted welds have similar shapes, and the weld size slightly increases along the welding sequence away from the shunt weld. Another difference is the shape of the HAZ. Those of the shunted welds have corners extending to the edges of the contact areas between the electrode and sheets, indicating concentrated heating at these locations. Therefore, the shunted welds may experience a different heating from the shunt weld, resulting in asymmetrical HAZ due to shunting.

Effect of Electrode Force in Shunting

The electrode force is responsible for creating sufficent electric contact at the faying interface. Part of it is consumed to deform the separated sheets and close the gap, and the rest is used to create an area of electric contact. Sheet separation or distortion may result from fabrication or from welding the shunt weld. The first shunt weld generates the largest sheet separation because of the undiverted heating, and subsequent shunted welds create gradually reduced separation as the welding current is diverted due to shunting. The effect of electrode force is evident in Fig. 4. The coupons in Fig. 4A, B were created under identical conditions except the electrode force, which was 2.8 and 1.8 kN for the specimens in Fig. 4A, B, respectively. The first (shunt) weld in Fig. 4B has a different size and shape from its counterpart in Fig. 4A, possibly due to the smaller contact area at the faying interface created by the smaller electrode force used when making this weld. The shunted welds are drastically different from the shunt weld and from each other in the sequence. The first shunted one is significantly smaller than the shunt weld, apparently due to the fact that a large portion of the applied electric current was diverted from the welding path to the shunting path, and resulted from the large contact resistance at the faying interface created under a small electrode force. The subsequent shunted welds in the sequence get larger, away from the shunt weld, due to the smaller amount of the diverted electric current from their respective shunt welds, the immediate welds prior to the welds being made. It is interesting to see that the 4th shunted weld (the 5th in the sequence) is actually slightly smaller than the 3rd shunted weld (the 4th in the sequence), possibly due to a sufficiently large shunting effect from its shunt weld (4th in the sequence), which grew to a certain size larger than its shunt welds. The level of electrode force, 1.8 kN, appears insufficient in deforming the separation of 2-mm steel sheets created by the shunt weld. Under the same electrode force, the shunting effect may become smaller when welding more compliant sheets. For instance, there is a 5.8% drop in the size of the first shunted weld when welding 1.5-mm bare steels (Specimen #41 in Table 4), while the drop is 6.1% when welding 2.0-mm bare steels (Specimen #11 in Table 4).

Effect of Shunting on Weld Size

The shunting effect on weld size along the welding sequence is summarized in Fig. 5. The shunt and shunted welds on the same weld coupons are plotted in three groups according to the weld spacing, regardless of the material and welding parameters. In each of the three groups, with weld spacing of 8, 15, and 25 mm, the dual-phase steels take the upper portion in the figure because more heat was used when making these welds, resulting in larger welds than the mild steels. There is a direct correspondence between the lines in Fig. 5 and the specimens in Table 4. All three groups of specimens show a size drop in the first shunted welds compared with their respective shunt welds. After the initial drop, subsequent shunted welds tend to recover from the shunting effect with an increase in size. The concave downward trend is observed in most cases in these groups. The second shunted welds are generally larger than the first shunted ones, and the upward trend is of different magnitudes depending mainly on the weld spacing, in addition to other variables. On each of the weld coupons with 8-mm spacing, the shunted welds continue to grow in size in the welding sequence. The growth rate is slower when the spacing is increased to 15 mm, and similar trend is observed on the coupons with 25-mm spacing. The increase in the shunted weld size is the result of an increase in the resistance in the shunting path from the preceding shunt welds and an increase in the contact area for the welds being made.

There are a few anomalies in Fig. 5. For instance, a linear drop in weld size is observed in one of the specimens with 25 mm weld spacing (Specimen #62 in Table 4), as a result of significant shunting effect when welding 1.5-mm sheets with a small electrode force of 1.8 kN and plastic film insert at the interface.

In Table 4, the welds with an 8-mm spacing are smaller on the MS coupons than those on the DP steels, as less heat in

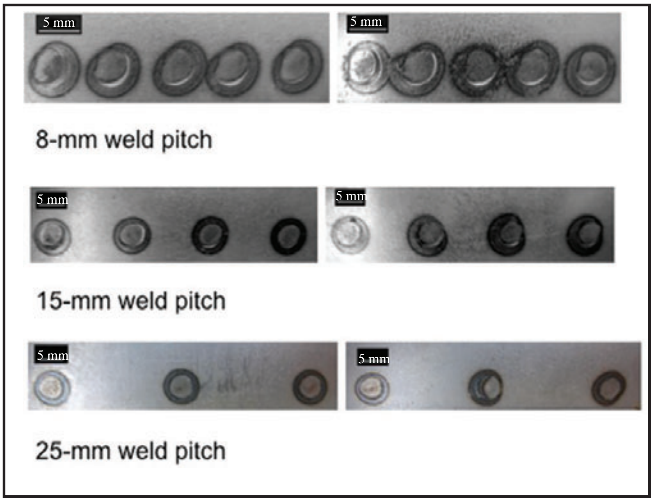

Fig. 7 — Welded coupons of 1.0-mm bare mild steel sheets, without (left) and with (right) the plastic insert of 8-, 15-, and 25-mm weld spacing.

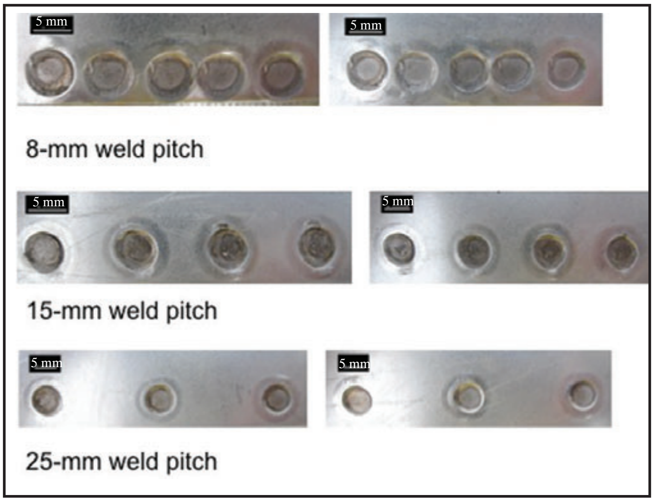

Fig. 8 — Welded coupons of 1.2-mm HDG steel sheets, without (left) and with (right) the plastic insert of 8-, 15-, and 25-mm weld spacing.

welding was put into the mild steels than into the DP steels, which require higher welding current and longer welding time to compensate for the zinc coating. In general, welding HDG DP steels requires higher electric current, longer welding time, and larger electrode force as shown in Table 3. Table 4 also shows that a larger drop in weld size from the shunt weld to the shunted ones occurs when a layer of plastic film was inserted into the faying interface on which the shunted welds were made, compared with welding the same materials under identical conditions without a plastic insertion.

Effect of Shunting on Weld Appearance

Table 4 shows a significant reduction in size in the shunted welds, compared to the shunt weld, in almost all the specimens made using all the three weld spacings. The shunt and shunted welds on the same weld coupon can also be distinguished by their appearance. Figure 6 shows a series of welds made on 1.5-mm bare mild steel sheets with a very tight spacing: 8 mm from center to center. As a result, the impressions of the neighboring welds overlap. By observing only the indentation marks of the welds on the coupons in the figure, one may conclude that the first weld (the shunt weld) has the smallest weld nugget as its impression mark is smaller than those of the shunted ones. This was proven untrue as the metallographic examination of these specimens reveals the opposite. The weld widths for the specimens in Fig. 6, as listed in Table 4, have a reduction of more than 10% from the shunt weld to the first shunted one, in both cases with the original bare surface and the plastic insert. Such an observation, i.e., the welds having large impression marks but smaller sizes has been obtained in other specimens as well. Therefore, it is important to recognize that in the case of multiple welding, it may be misleading to judge the weld quality by visual inspection of the weld indentation alone. The welds in Fig. 6 have slightly skewed indentation marks, resulting from angular misalignment of the electrode tips.

In addition to the sizes of the impression marks, another difference in appearance can be observed in the distinct burning marks on the surfaces between the shunt and shunted welds, as seen in Fig. 6, with and without the plastic insert. The shunted welds have darker and larger burn marks than the shunt weld; even their sizes (widths) are smaller. As a matter of fact, this was observed on all the welded coupons, although some of them are not as obvious as others. Several representative welded coupons made on the mild steels with various spacings are shown in Fig. 7. With 8-mm spacing, the shunted welds have significantly wider and darker burn marks. The differences become less obvious as the weld spacing get larger to 15 mm and then 25 mm with original (bare) faying interfaces. The use of plastic inserts at the faying interfaces when making shunted welds appears to amplify the difference in burn marks. The appearance clearly distinguishes the shunt weld from the shunted ones even for those of 15- and 25-mm spacings when the shunted welds were made using plastic inserts. When welding zinc-coated steels, as shown in Fig. 8 for 1.2-mm DP590 steels, the welds appear to be very similar judging from the weld marks, even for the 8-mm spaced weld coupons.

The difference in weld marks between the shunt and shunted welds, when welding the uncoated mild steels, can be attributed to the role played by the contact resistance at the electrode-sheet interfaces. A rise in the contact resistance at the faying interface, R_{cw}, increases the shunting current I_S and reduces the welding current I_W, according to Fig. 2. It is reasonable to assume that the contact resistance at the electrode-sheet interface is identical when making the shunt weld and the shunted weld, as shown in Fig. 2 as R_c. Assume that the total resistance in the secondary loop, excluding R_c, is R_T when making a shunted weld, and R_T' when making the shunt weld. The existence of the shunting path lowers the resistance in the weld stack-up, i.e., $R_T' > R_T$. Therefore, the proportion of heating, in terms of heating rate, resulted from joule heating at the electrode-sheet interface to the entire secondary loop, is not the same when making the shunt weld and the shunted weld, i.e.,

$$\frac{I^2 R_C}{I^2\left(R_C + R_T'\right)} < \frac{I^2 R_C}{I^2\left(R_C + R_T\right)}$$

This means the heating at the electrode-sheet interface is faster, relative to the rest of the secondary loop, when making a shunted weld than when making a shunt weld. Therefore, the temperature at this interface rises faster relative to that at the faying interface than in making the shunt weld. As a result, the resistance at the electrode-sheet interface increases at a faster pace that in turn produces more heat at this interface than at the faying interface, compared with the heating when making the shunt weld. The larger amount of heat generated at the electrode-sheet interface in a shunted weld than in a shunt weld is responsible for the larger and/or darker burn marks on the shunted welds. There is little difference in the indentation marks between the shunt and shunted welds when welding coated DP steels, as seen in Fig. 8. This could be attributed to the fact that the molten zinc from the coating forms a conducting ring at the faying interface from the beginning of welding, which smooths out the difference between R_T' and R_T. The molten zinc at the electrode-sheet interface also results in low contact resistance, and less heat is generated at this location.

Effect of Weld Spacing on Shunting

Shunting is affected by many factors, and they interact with each in shunting. Therefore, the effect of one factor should be discussed with the consideration of other factors. Some of the influential factors are analyzed together in the following, considering the interactions among the factors. As shunting is almost always significant when welding with 8- or 15-mm spacing, the roles of process variables depend largely on the weld spacing. Therefore, the influence of various variables on shunting is discussed in the categories of weld spacing.

1. Mild steels with 8-mm weld spacing. This weld spacing represents an extreme of small weld spacing that may make the process parameters affect the welding and shunting processes in a different way from welding with larger weld spacing.

For the bare mild steels, the average changes in weld size depend on the sheet thickness. They are 10.1, 8.2, and 8.1% for steels of 1.0, 1.5, and 2.0 mm, respectively, in thickness. The effect of sheet thickness on shunting comes from two parts: the lengths of the shunting and welding paths, and the resistance to bending under an electrode force that affects the contact resistance at the faying interface. These factors interact with others such as weld spacing in affecting shunting.

With the plastic insertion when making the shunted welds, the drop in weld size is more dramatic. An average of 23.7, 12.15, and 6.4% for the 1.0-, 1.5-, and 2.0-mm sheets, respectively, was calculated using the data in Table 4. The electrode force also appears to be influential. A sharp increase in the shunting effect, from a 14% drop to a 33% drop in weld size is observed in the 1.0-mm sheets, which is a far larger change than welding without the plastic insert. Similar to welding bare MS steels, there is a decrease in shunting effect when increasing the electrode force on the 1.5- and 2.0-mm sheets with the plastic insert. Therefore, the shunting effect is, in general, inversely proportional to the sheet thickness, and the plastic insertion at the faying interface amplifies such an effect.

The increase in shunting with a rising electrode force on the 1.0-mm sheets, and a decrease when welding 1.5- and 2.0-mm sheets clearly indicate an interaction between the electrode force and sheet thickness. Increasing the electrode force would normally reduce the contact resistance at the faying interface along the welding path and therefore, reduces shunting. When welding 1.0-mm sheets, however, the sheets can be easily deformed and the gap at the faying interface between the welds closed, as thin sheets have less resistance to deformation, resulting in increased shunting.

The 8.0-mm weld spacing used in welding clearly dictates the role the electrode force plays in shunting. The 8.0-mm space between the shunt and shunted welds creates a distance less than 4.0 mm between the edges of the welds. The gap along such a small distance at the faying interface can be easily closed on the 1-mm stack-ups under an electrode force. A large electrode force is more effective than a small one in closing this gap in thin sheets, resulting in a low electrical resistance along the shunting path and a large shunting effect. Closing of such a gap is more difficult to achieve when the stiffness of the sheets, proportional to the sheet thickness, is large and, therefore, increasing the electrode force produces decreased shunting in 1.5- and 2.0-mm sheets.

2. 1.25-mm HDG DP780 steel sheets with 8.0-mm weld spacing. Without the plastic insert, the HDG surfaces appear to make the shunting effect more sensitive to the electrode force. When the electrode force is increased from 3.0 to 3.5 kN, 4.3 kN and then 5.0 kN, the decrease in weld size due to shunting is 3.0, 3.0, 4.6, and 7.9%, respectively. That is, a large electrode force produces more shunting. This is similar to what had happened in the MS as discussed previously, i.e., a large electrode force actually helps close the gap between the shunt and shunted welds and elevate the shunting effect when the weld spacing is small. The molten zinc at the faying interface easily fills the gap that reduces the electrical resistance along the shunting path.

3. 1.2-mm HDG DP590 steel sheets with 8-mm weld spacing. Increasing the electrode force slightly reduces shunting when welding DP590 sheets with both zinc-coated only and zinc-coated plus plastic insert surfaces. This is the result of an interaction among weld spacing, coating, and electrode force. The small weld spacing and the zinc coating together elevate the shunting effect, but the lower yield strength (compared to the DP780 steels) that makes deforming the sheets easier under an electrode force, produces less shunting under a large electrode force. The opposite effects of electrode force on shunting when welding with DP780 and DP590 steels could be attributed to the difference in yield strength and, therefore, the different easiness of collapsing the contact area and lowering the contact resistance at the faying interface.

4. Welding with 15-mm weld spacing. The effect of electrode force is not consistent as observed when welding the MS and DP steels, with or without the plastic insert. This could be because a 15-mm space approaches critical weld spacing for some of the sheets at which the shunting is not significant and, therefore, the influence of the process variables appears to be random.

5. When welding 1.0-mm MS sheets with a weld spacing of 25 mm, decreased shunting is observed with an increased electrode force for both bare and plastic film-inserted faying interfaces, as the electrode force is responsible for reducing the contact resistance along the welding path. With 25-mm spacing, the gap between the welds is not easily closed, which is different from what was observed in welding with 8- and 15-mm weld spacings. A similar observation is made on 1.5-mm MS sheets. When welding 1.2-mm DP590 and 1.25-mm DP780 sheets with a 25-mm weld spacing, increasing the electrode force produces an inconsistent effect in HDG and HDG + plastic insert surfaces. More experiments are needed to draw conclusions in such cases.

Statistical Analysis of Various Influential Factors

An analysis was performed to determine if, under various combinations of material and process parameters, the shunting effect is truly significant. A standard statistical procedure was employed to test the statistical significance of the differences between the shunt and shunted welds. An appropriate testing statistic in this case is a *t*-value (Ref. 5), as the standard deviations of the weld size populations are unknown. It can be calculated using the following formula

$$t = \frac{\bar{d} - d_0}{s / \sqrt{n}}$$

where d_0 is the width of the shunt weld, $\bar{d}$ is the mean value of the n shunted weld widths, and s is the standard deviation of these welds. The *t*-values were compared with the critical values of the *t*-distribution, and corresponding *p*-values were also calculated. They are as listed in Table 4. For the specimens made using 8-mm weld spacing, 18 out of 22 of them have a *p*-value below, and most of them far below, 0.05; the remaining 4 of them have *p*-values between 0.07 and 0.09. Therefore, it is reasonable to conclude that 8-

mm weld spacing results in significant shunting for the materials tested. When the weld spacing is increased to 15 mm, the p-values for 18 out of 20 specimens are far below 0.05, and for the rest, one is 0.06 and another is apparently an outlier with a p-value of 0.65. Therefore, the shunting effect is significant when the weld spacing is 15 mm. When the weld spacing is further increased to 25 mm, only 5 out of 20 specimens have p-values just below 0.05. The p-values of the others are apparently high, meaning that the shunted welds are statistically not different from their shunt welds. This analysis indicates that the critical weld spacing for these materials lies between 15 and 25 mm.

The t-testing results in Table 4 demonstrate that the influence of the shunt welds on the subsequent shunted welds depends on the size of weld spacing. Using identical welding schedules, the shunted welds made on a weld coupon are significantly smaller than their shunt weld when welding with narrow weld spacing. Such a drop in weld size from the shunt weld to the (especially the first) shunted ones diminishes when the weld spacing is sufficiently large. Considering the percent decrease in weld size from the shunt weld to the first shunted weld, shown in column 14 of Table 4, the effects of various process parameters can be estimated. Among the variables involved, the surface condition appears to play a major role in shunting. As a matter of fact, it overshadowed the influence of all other factors. When an ANOVA (analysis of variance, Ref. 5) was conducted, all factors, except the surface condition, appeared to be insignificant. This clearly is not true, and it is the result of the overwhelming significance of the surface condition, as the plastic insert used in the experiments and the pure zinc -coated surfaces represent two extremes of excessively high and low contact resistances at the faying interface. ANOVA appears to be inadequate in this situation to analyze the influence of other factors.

The results obtained in this experimental investigation prove that shunting in resistance welding is a complex process, with multiple influencing factors and strong interactions among these factors.

Conclusions

In this experimental study, the effects of various factors such as material, surface condition, welding schedule, and other process variables were investigated on several typical MS and DP steel sheets. The findings on shunting in resistance spot welding can be summarized as follows:

1. Weld spacing is the most influential factor in shunting, and increasing weld spacing is the most efficient means of avoiding shunting;

2. As it determines the proportion of shunting current, the contact resistance has a significant effect on shunting. In general, large contact resistance, created by highly resistive surface conditions or low electrode forces promotes shunting;

3. The chemistry, thickness, and mechanical strength of the workpiece material play an important role in shunting. There is a strong interaction between these material parameters and other process variables;

4. Shunting is clearly affected by welding parameters. The electric current and welding time were selected mainly for making sizable welds in this study, not for understanding their effects. Therefore, it is inappropriate to draw conclusions on these two parameters, although the experimental results have shown their influence on shunting. On the other hand, shunting is clearly a function of electrode force, often under the influence of other process parameters;

5. Although generally smaller in size, shunted welds may have larger/darker electrode impressions than their respective shunt welds. This should be recognized in visual inspection of weld quality.

This study shows that shunting is affected by almost all of the process parameters involved in resistance spot welding. Because of the difficulties in systematically/simultaneously studying many factors, shunting experiments are often designed to understand the influence of only a few parameters, with others fixed. Caution must be taken when drawing conclusions from such experiments, the experimental conditions must be clearly stated, and the limitation of applications well understood.

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