Shunting Effect in Resistance Spot Welding Steels — Part 2: Theoretical Analysis

Minimum weld spacing can be quantitatively predicted based on the process parameters and welding schedules

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ABSTRACT

Shunting is a phenomenon difficult to avoid in production welding, and it is of practical interest to quantitatively determine the minimum weld spacing. However, the large number of factors involved in shunting make it difficult to isolate their influence, let alone obtain a quantitative understanding of their effects. In this study, the shunting process was understood through an analysis of the electrical resistances along the welding and shunting paths. An analytical model was derived based on the equivalence of the joule heat generated in welding and that needed to create the weldment. The constants in the model were determined through experiments. Using the experimental results from a previous study, specific models were derived for several gauges of mild and dual-phase steels of various surface conditions. The models were then used to study the effects of process parameters on the minimum weld spacing needed to create certain sizes of shunted welds. The critical or minimum weld spacing was then plotted as a function of several variables. The effects of several process variables such as electrode force, welding time, shunt weld size, and sheet thickness on shunting were clearly demonstrated. Such relationships are crucial in understanding the effects of process variables on shunting, and can be used in quantitative determination of minimum weld spacing to avoid the adverse effect of shunting and put as many welds as possible onto a structure.

Introduction

Shunting in resistance spot welding is the diversion of the welding current from the weld to be made to a nearby existing weld (Ref. 1). If a significant proportion of welding current flows through the previously made weld, the heat generated may not be sufficient for making a weld of designated size. In general, shunting may have significant influence on weld quality when making more than one weld on a workpiece, which is common in sheet metal manufacture and repair. Quantitatively predicting the critical weld spacing to avoid significant reduction in weld size due to shunting has practical significance (Ref. 1). The distribution of welding current in shunting is illustrated in Fig. 1. The proportion of the diverted current is determined by the relative electrical resistance values in the shunting and welding paths. Therefore, determination and control of relative resistance in welding are of ultimate importance. Helped by the advances in numerical simulation techniques, efforts have been made to analyze the effect of shunting on weld nugget growth (Refs. 2–4), with some implication on the critical weld spacing. However, the highly variable and dynamic nature of electrical and thermal processes in welding makes it difficult to quantitatively understand the effect of shunting either by analytical analysis or numerical modeling. Because of a serious lack of material properties, especially as functions of temperature, a numerical modeling of the resistance spot welding process generally relies on idealized material behaviors and process setup. As a result, numerical predictions are more qualitative than quantitative, and empirical studies such as the ones by Howe (Ref. 5) and Wang et al. (Ref. 6) have been dominant in shunting study.

Fig. 1 — Schematic of shunting in resistance spot welding.

The limitations of empirical investigations are apparent. First of all, it is difficult to identify or isolate the influence of any individual variable as there are a large number of variables involved and extensive interactions exist among them in shunting. All of the welding parameters, i.e., welding current, time, and electrode force, and material properties such as bulk resistivity and surface conditions impact shunting to a more significant and complex extent than they do in making a single spot weld. In addition, other factors of a more random nature such as electrode wear, electrode alignment, and workpiece fitup may also affect the shunting process. Considering all these effects would make an experiment
matrix too complex to handle. As revealed in the work by Wang et al. (Ref. 6), many material and processing factors such as the electrode force affect shunting, and their effects also strongly depend on the values of other variables: increasing the electrode force reduces shunting when the weld spacing is large, while it actually promotes shunting when the weld spacing is small when welding thin sheets. The large number of variables and their complicated interactions also make it difficult to obtain an accurate account of the influence of an individual factor through experiments alone. On the other hand, theoretical analysis is difficult considering the number of variables involved and the limited knowledge on the material properties governing the physical processes during welding, especially their dependence on temperature, which makes shunting a very dynamic process. In this study, an analytical model was developed based on the understanding of the physical processes involved in shunting, and the numerical values of the coefficients in the model were derived from the experimental results obtained in a previous study (Ref. 6).

**Modeling of the Shunting Process**

As resistance spot welding is basically a joule heating process, an understanding of shunting can be achieved through an analysis of the electrical resistances involved in the process. A common welding mode in industrial applications, constant current welding mode was assumed in the model development. For simplicity only the nearest neighboring weld was considered, and the influence of all other welds was assumed negligible. The electrical process of shunting is readily represented by flowing electric current through a simple electric circuit, identical to that in Fig. 2 in Ref. 6, consisting of several resistors based on the effects of various portions of the sheet stack-up on heat generation and electric current flow, which can be derived from the schematic in Fig. 1. First, the contact resistance at the electrode-sheet interface could be significant in affecting the welding process. However, it can be assumed identical for the weld being made (the shunted weld) and its shunt weld and, therefore, its effect can be ignored for simplicity and it can be excluded in the study of the shunting effect. As a result, the number of resistances needed to be considered in developing the shunting model is reduced, and they can be classified according to their contributions to welding and shunting, along their respective paths.

The electrical resistance to the shunting current $I_0$, in the path through the previously made weld (shunt weld) can be assumed to be dominated by bulk resistance, and approximated as

$$R_{sh} \approx \frac{\rho_{bulk} 2L}{A_0}$$

where $L^2 = D^2 + r^2$, and the dimensions are illustrated in Fig. 1. $D$ is the horizontal projection of the shunting current path $L$. Its value can be assumed as

$${\text{Spacing}} - \alpha d_0 - \beta d_f$$

where **Spacing** is the distance between the centers of the shunt and shunted welds (marked as “Weld Spacing” in Fig. 1). $\alpha$ and $\beta$ are constants used to specify the ends of the shunting path between the shunt weld and the indentation impression mark. These two constants would assume a value of 0.5 if the shunting current flew directly from the edge of the indentation mark to the edge of the shunt weld, which is the shortest path as can be seen in Fig. 1. The metallography in Fig. 2 of welds made on a 2.0-mm mild steel sheet with 8-mm weld spacing from an experimental study of shunting (Ref. 6) shows they should be slightly smaller than 0.5. From the figure it can be seen that the outlines of the heat-affected zones (HAZ) of the shunted welds are asymmetric, indicating uneven heating during welding. The HAZ of a shunted weld has upper and lower left corners extending to the electrode contact surfaces, which are different from those on the right side, indicating possible concentrated electric current passing through these areas. Similar phenomenon has been observed in other shunting welds in experiments (Ref. 6). Consider the upper left corner of the HAZ in the first shunted weld (the second in the sequence) in Fig. 2. As the darkened area near the electrode surface is located inside the edge of the indentation mark, it is reasonable to assume that the shunting current path starts from this place, not the indentation edge. For the same reason the center of the shunting path is assumed passing through a point inside the shunt weld, not on its edge. Considering the possible shunting path revealed by this figure, the vertical projection of the shunting path should also be slightly smaller than $2\alpha$ as exhibited in Fig. 1. Because of this, $\gamma$ instead of $t$, where $\gamma$ is smaller than unity should be used for calculating $L$, i.e.,

$$L^2 = (\text{Spacing} - \alpha d_0 - \beta d_f)^2 + (\gamma t)^2$$

The average cross-sectional area of the shunting path, $A_0$, can be assumed to be proportional to the average of the projected areas of the shunt weld and the electrode indentation onto the shunting path, i.e.,

$$A_0 \approx \frac{1}{2} \left[ \frac{1}{4} \pi d_0^2 + \frac{1}{4} \pi d_f^2 \right] \sin \theta = \frac{1}{8} \pi \left( d_0^2 + d_f^2 \right) \sin \theta$$

where $\theta$ is as shown in Fig. 1. As $\sin \theta \approx t/L$, the bulk resistance of the shunting path is

$$R_{sh} \approx \rho_{bulk} \frac{L^2}{\left( d_0^2 + d_f^2 \right)^\frac{1}{2}} = \rho_{bulk} \frac{\left( \text{Spacing} - \alpha d_0 - \beta d_f \right)^2}{\left( d_0^2 + d_f^2 \right)^\frac{1}{2}}$$

The influence of other possible factors on $R_{sh}$ can be assumed unchanged during shunting, and lumped into a constant $C_{sh}$ for quantifying the bulk resistance of the shunting path.
The cross-sectional area of the welding path can be approximated by the average of the contact area at the faying interface (or the projected area of the shunted weld), and that at the electrode-sheet interface

\[ A_{W} = \frac{1}{2} \left( \frac{\pi d_{2}^{2}}{4} + \frac{\pi d_{1}^{2}}{4} \right) \]  

And \( R_{W} \) can be written as the following, with a constant \( C_{W} \) for the effect of all other fixed variables

\[ R_{W} = C_{W} \rho_{E} t \left( \frac{d_{1}^{2} + d_{2}^{2}}{l} \right) \]  

The contact resistance at the faying interface in the welding path can be assumed to stem from a cylinder of a mixture, hereafter called “contact cylinder,” of the bulk metal and the substances/contaminants on the surfaces. This cylinder has a height of \( l_{1} \), and cross-sectional area of \( A_{W} \), which is a function of the applied electrode force. The contact resistance is affected by the electrode force squeezing the weld stack-up, and such effect is reflected by the deformation of this contact cylinder, approximated as \( \alpha_{W} \). A base metal with a high yield stress, \( \alpha_{y} \), resists the deformation and reduction of electrical resistance; a large electrode force generates a large applied stress at the faying interface, \( \alpha_{y} \), and reduces contact resistance. Therefore, the contact resistance at the faying interface, \( R_{W} \), based on the aforementioned discussion, can be assumed

\[ R_{W} = \left( C_{W} \rho_{E} l_{1} \right) \frac{\alpha_{y}}{l_{1}} \neq \eta \]  

The dependence of the shunted weld on the shunt weld size, welding time, current, and electrode force, in addition to the sheet thickness and strength, can be derived by considering the equivalence of heat needed for making the shunted weldment and the heat generated through joule heating along the welding path. The shunted weldment can be divided into two parts, and different amounts of heat are needed to create them. One is the weld nugget. It can be approximated by an ellipsoid with a volume

\[ V = \frac{4}{3} \pi \left( \frac{d}{2} \right)^{3} \left( \frac{\pi d}{2} \right) \]  

where \( \lambda \) is a constant, representing the ratio of the height of the ellipsoid nugget to its diameter. On the other hand, the joule heat is also consumed to generate the HAZ, the volume of which can be approximated by the difference between a cylinder of size

\[ V = \frac{1}{2} \pi d^{2} l \]
and that of the nugget. Therefore, the total heat needed for the shunted weldment is approximately

\[
\frac{1}{3} \pi \alpha d^3 + \frac{1}{2} \pi \beta d^2 - \frac{1}{3} \pi \lambda d^3 = \frac{c_s}{n} d^3 + c_s^2 \beta d^2
\]

In the above expression, the coefficients on the left-hand side represent the unit heats needed for making the nugget and the HAZ, and they can be lumped up as on the right-hand side for convenience.

The heat needed comes from resistance heating, and using Equation 5 the joule heat can be expressed as

\[
I^2_w (R_{bw} + R_{cw}) \tau_w = I^2 \left( R_{bw} \right) \left( R_{bw} + R_{cw} \right) \tau_w
\]

Here \( \tau_w \) is the welding time and \( I \) is the total welding current used when making the shunted weld. Equating the joule heat to that needed for making the weld produces the relationship between the shunted weld size and the welding parameters, material properties, and premade shunt weld size:

\[
c_s \frac{1}{3} \pi \alpha d^3 + c_s^2 \beta d^2 = I^2 \tau_w
\]

The constants in the equation were determined through curve fitting using experimental observations in a previous study (Ref. 6) for each of the four types of surface conditions and as many combinations of variables as possible. They are clearly material dependent, and the surface condition plays an important role in affecting the values of these constants. It should be noted that although the model shown in the equation is generic, a fitted model developed for a specific material system should be limited to that material in the ranges of the relevant material properties.

To illustrate the procedure of determining the constants and the use of the model in understanding shunting, the experimental observations in a previous study (Ref. 6) were used to obtain the explicit models for the material systems studied. The experiments include two types of materials: mild steel (MS) and dual-phase steel (DP) of several gauges. Several types of surface conditions were used, including bare steel surface, zinc-coated or hot-dipped galvanized (HDG) surface, plastic insertion of a thin polyvinyl chloride (PVC) film, and their combinations. The prevalence of the contact resistance was determined through experiments with sufficient replications and as many combinations of variables as possible. They are clearly material dependent, and the surface condition plays an important role in affecting the values of these constants. It should be noted that although the model shown in the equation is generic, a fitted model developed for a specific material system should be limited to that material in the ranges of the relevant material properties.

The constants in Equation 7, \( c_1, c_2, c_3, c_4, c_5, c_6, c_7, \) and \( c_8 \), can be determined through experiments with sufficient replications and as many combinations of variables as possible. They are clearly material dependent, and the surface condition plays an important role in affecting the values of these constants. It should be noted that although the model shown in the equation is generic, a fitted model developed for a specific material system should be limited to that material in the ranges of the relevant material properties.

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The constants in the equation were determined through curve fitting using Mathematica8™ (Ref. 9) for each of the four types of surface conditions. A fixed size of electrode indentation, \( d_e \), taken...
as 5.0 mm from the experiments, was used in the curve fitting. In curve fitting, the physical meaning of the constants should not be sacrificed for the closeness of numerical fitting. For instance, a negative $c_7$ produces a better numerical fitting than a positive one. However, it makes no physical sense according to the analysis in the previous sections on the cantilever beam as demonstrated in Fig. 3. In the present study, certain conditions were imposed on such coefficients in order to preserve their physical meaning. The constants determined for the four types of surface conditions are listed in Table 1.

The values of the constants in the table vary in drastic ranges. The main reason is that the units of the variables in Equation 7 were not made consistent, for the convenience of practical welding. For instance, the unit of sheet thickness in the equation is millimeter while that of the yield strength of material is MPa. This can be observed by comparing the coefficients $c_3$ and $c_6$, while the former is for the dimensions, with a large value, and the latter corresponds to pressure with a much smaller value.

The accuracy of the models in Table 1 was verified by comparing the two sides of Equation 7. Very small differences between the values of the two sides were obtained for all the sets of experimental observations and, therefore, the models were considered valid. The fitted models shown in Table 1 can be used to study the influence of various parameters. As weld spacing is the most important parameter in weld design, it was expressed in this study as a function of other variables. The weld spacing needed to obtain a shunted weld of certain size was expressed as a percentage of the shunt weld size, in order to meet the requirements of weld quality, mainly in terms of weld size, in practice.

**Effect of Sheet Thickness**

Figure 4 shows the required weld spacing to achieve a certain sized shunted weld goes up with sheet thickness. As expected, a large weld spacing is necessary in order to have a shunted weld of size close to that of the shunt weld. For 0.5-mm bare mild steels, an increment of little more than 1 mm is needed when the shunted weld size goes from 70 to 85%, and then 100% of that of the shunt weld, as seen in Fig. 4A. Such an increment is more than 3 mm for the 3-mm sheets. A greater increase in weld spacing is necessary when a plastic film was inserted in the faying interface. The plastic insertion clearly raises the contact resistance and, therefore, the electrical resistance along the welding path, amplifying the shunting effect. However, this effect is thickness dependent. For thin sheets, a larger weld space is necessary for the bare steels than for those with a plastic insert, and the latter overtake the former when the sheet thickness goes beyond the range of 1.5–1.7 mm. In general, shunting is more sensitive to sheet thickness when the plastic insert is used, implying that the contact resistance along the welding path plays a decisive role in shunting. A sizeable difference exists between these two types of interfaces for thick sheets as well. For instance, the 3-mm sheet with plastic insert needs a weld spacing of 45 mm, 12 mm larger than that without the plastic insert.

Similar to that observed in the MS, the weld spacing goes up with sheet thickness for both zinc-coated and zinc-coated + plastic insert when welding DP steels — Fig. 4B. The effect of plastic insert in HDG DP steels is not as significant as in the MS. This could be the result of a nullified influence of the zinc coating by the plastic film.

**Effect of Welding Time**

In Fig. 5, the shunt weld size was fixed at 4.8 mm for a 1.5-mm MS. It shows that increasing welding time is an effective means of minimizing the effect of shunting as it puts more heat into a weld and reduces the weld spacing needed. When welding time is short, the time to melt the interface takes a significant proportion of the entire welding time. The electric current diverted by the shunt weld results in a large percentage of heat loss, and a large weld spacing is necessary in order to avoid shunting. With a long welding time, however, it takes a small fraction of the total time for the contact resistance to disappear when the interface melts, and more current and heat are distributed to the shunted weld as a result. This effect is more profound when the plastic insert is used at the faying interface. The diversion of electric current from the welding path into the shunting path is magnified by the plastic in-
Effect of Electrode Force

Comparing Fig. 6A with Fig. 5, it can be seen that the influence of electrode force on weld spacing is similar to that of welding time. A large electrode force reduces the contact resistance in the welding path, as can be seen from Equation 3. Therefore, a small weld spacing is allowed with large electrode forces. Figure 6 also shows the electrode force has a smaller effect when the plastic insert was used at the faying interface. This is related to the way the plastic-inserted interface evolves during welding. Under a large electrode force, a certain amount of (molten) plastic is “sealed” by the electrode force exerted at the faying interface, and this amount doesn’t change much with increasing electrode force. As a result, the contact resistance is largely determined by the “entrapped” polymer, and the electrode force, which is the dominant factor on steels without plastic insert, is less effective in creating an intimate contact between the two sheets. Therefore, with the existence of plastic film at the interface, the electrode force has a lesser effect compared with that of a bare interface.

It is interesting to see that in the DP steels, the dependence of weld spacing on electrode force shows similar trends in the HDG and HDG + plastic insert specimens. With a loose requirement of the shunted weld reaching 70% of the shunt weld in size, the plastic insert makes negligible difference. When making larger shunted welds, however, the difference in weld spacing between those of the original HDG and plastic-inserted HDG faying interfaces goes up, yet the difference is virtually a constant. Therefore, the influence of electrode force on weld spacing is similar with these two types of contact interfaces. This appears related to the zinc coating. The existence of pure zinc on the surface reduces the contact resistance, while inserting a plastic film at the faying interface does the opposite. Increasing the electrode force squeezes some of the molten zinc out of the contact area to its periphery. But this part of the zinc still contributes to conducting electric current along the welding path, as it accumulates along the periphery of the contact area, forming a ring of molten zinc. Therefore, increasing the electrode force has a smaller effect on the contact resistance, resulting in a smaller decrease in weld spacing as shown in Fig. 6B than observed in the uncoated mild steels in Fig. 6A. The increased joule heating, along with a corresponding decrease in weld spacing, results from a decrease in contact resistance and an increase in welding current when increasing the electrode force on the original zinc-coated interface. A similar process could occur in the plastic-inserted stack-up. The larger contact resistance with the plastic insert generates more heat compared to the one of original surfaces, and results in smaller weld spacing when making similar sized welds.

Effects of Other Factors

As several DP steels of different grades were used in the experiment, the yield strength can be regarded as a variable. The weld spacing requirements as functions of yield strength from 300 to 900 MPa are plotted in Fig. 7. Similar to the dependence of weld spacing on other variables in the HDG DP steels, the yield strength of the sheet material has a smooth effect on the weld spacing. Increasing the yield strength results in an increase in weld spacing at a fixed electrode force, as a sheet with a large yield strength is less compliant and a small intimate contact is produced at the faying interface. However, such an intimate contact has a smaller impact on the overall contact resistance in HDG steels, as the molten zinc can easily fill the root opening at the faying interface. A larger rise in weld spacing should be expected when welding bare steels.

The horizontal projected length and, therefore, that of the shunting path decrease when the shunt weld size increases as seen in Fig. 1. The actual shunting path and, therefore, the shunting effect change along with the shunt weld even with fixed weld spacing. Figure 8 shows the dependence of weld spacing on the shunt weld size in order to achieve a certain sized shunted weld. As expected, weld spacing increases with the shunt weld size, and for the same sized shunt weld a larger shunted weld requires a larger weld spacing.

The combined effect of the electrode force and welding time on weld spacing can be presented using a contour plot as shown.
in Fig. 9. For this bare steel, both the electrode force and welding time reduce the weld spacing needed to produce a weld of the same size as the shunt weld. Increasing either electrode force or welding time individually can shorten the weld spacing from approximately 32 to 26 mm, and simultaneously raising these two welding parameters to 3.0 kN and 500 ms, respectively, may render an identical-sized weld to the shunted one with a weld spacing of only 21 mm.

When a plastic film was inserted into the faying interface when making the shunted weld, the effects of electrode force and welding time on the required weld spacing were different from those observed in welding bare steels. In Fig. 10, a long welding time reduces the weld spacing, which is similar to what was observed in Fig. 5, while the weld spacing is fairly insensitive to the electrode force. This observation is consistent with that in Fig. 6A, where increasing electrode force is no longer effective in reducing weld spacing when the electrode force reaches a certain level. The largest weld spacing appears at the corner of maximal electrode force and minimal welding time. The different roles the electrode force plays in welding bare and plastic insertion-filled faying interfaces are the result of the containment of the plastic film in the contact area by the electrode force, as discussed in the previous section on the effect of electrode force. As the plastic insertion represents an extreme of contaminated sheet surfaces that is normally encountered in practice, the trend, rather than the value, of the weld spacing shown in the figure is more important. Many of the surface contaminates such as grease, etc., may disappear under the intensive heating in resistance spot welding and, therefore, their influence on weld spacing is more suitably represented by Fig. 9 than Fig. 10.

Weld Spacing Requirements

In welding design, it is often necessary to determine the weld spacing as a function of sheet thickness. In Fig. 11, the weld spacing needed for different gauges of MS and zinc-coated DP steels is plotted, in order to create a shunted weld of the same size as the shunt weld. Note that different welding parameters are used for predicting the weld spacing in these two types of materials, based on the actual values obtained from the experiments. For the ease of use in welding practice step functions were created. It shows that the weld spacing required for welding the MS is larger than that for the DP steel, largely due to the difference in the surface resistance between the steels used in the experiments. The MS steel was uncoated in fabricated condition, while the DP steels were hot-dip coated with zinc. A faying interface covered by pure zinc has significantly lower electrical resistance than that of a bare steel. As a result, the current in the shunting path takes a smaller portion than in a bare steel stack-up. Therefore, the weld spacing required to avoid shunting in the coated steel is smaller than in the bare steel. This effect is offset slightly, though, by the yield strength of the DP steels, because a steel of higher yield strength usually requires a larger weld spacing as it takes more electrode force to create an intimate contact at the faying interface. For a fixed electrode force, a large weld spacing is required when the material is strong, as seen in Fig. 7.
shunting in resistance spot welding a specific material. The con-

Two. The size of the shunt weld directly affects shunting as it dic-

tates the shunting path;

3. Contact resistance plays a dominant role in shunting, and zinc-coated surfaces generally behave significantly different than bare steels;

4. The models also reveal the complex interactions among the process parameters in affecting shunting. For instance, the elec-

trode force and welding time interact with the surface contact re-

cistance in affecting shunting. Such an interaction is prevalent in shunting.

Through a carefully planned experiment, this analytical model can be used to describe the influence of process parameters on shunting in resistance spot welding a specific material. The conclu-
sions derived, however, are only applicable to the material sys-
tems in the range of experiment. Extrapolation is not recom-

mended, especially in the cases of large variation in contact re-


distance.

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