



Numerical Study of Shunting Effect in Three-steel Sheets Resistance Spot Welding

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P A P E R I N F O

Paper history:

Received 29 September 2021

Received in revised form 14 November 2021

Accepted 02 December 2021

Keywords:

Resistance Spot Weld

Three-sheet Spot Welded Joint

Shunting

Electrical Current Density

Electrode Displacement

A B S T R A C T

The main purpose of the present research is to investigate the shunting phenomenon in a three-sheet RSW joint using finite element simulation. To this end, a three-sheet resistance spot welding joint was simulated as an electrical-thermal-mechanical coupling problem. To validate the presented simulation, the finite element results were compared with the experimental results, including nugget size and geometric shape in the resistance spot welding joint. Afterwards, the multi-spot welds of three-sheet low carbon steels with the same thicknesses were analyzed considering the sequential distance of 45 mm. Various techniques, including new spot-weld diameter measurement, electrical current density, electrical contact conductivity, and electrode displacement, were used to study shunting effects in the process of consecutive spot welds. The results obtained from different methods have greatly matched each other. Also, finite element results indicated that the assumption of neglecting the sheet deformation effect for low intervals between consecutive spot welds is acceptable. However, it is necessary to consider sheet deformation for distance intervals more than 45 mm.

doi: 10.5829/ije.2022.35.02b.17

1. INTRODUCTION

Weight reduction of the mechanical structures is one of the most important concerns of transportation industries including land, air, and rail transportation whose most elementary one is fuel consumption reduction. Therefore, the use of the Resistance Spot Welding (RSW) method in comparison with other connection methods has received more attention in the industry. For example, we can mention the widespread use of this welding method for connecting thin metal sheets in the automotive industry. In this regard, approximately 3000 to 5000 resistance spot welding joints are required to produce a passenger car [1-3]. In general, resistance spot welding is used to connect two metal sheets. However, it is necessary to use this process in some positions to connect three sheets in the construction of the car body.

One of the effective factors on the quality of successive spot weld and resulting in weld strength

is the electric current escape phenomenon, namely shunting. This phenomenon means the electric current pass through the previously created spot weld while creating a new one. The obvious effects of this phenomenon usually include generated heat reduction in the welding process and diameter reduction of the new spot weld. However, based on different standards with application of automotive engineering, the strength of spot-welded joint is directly related to the weld core diameter. In addition, impair diameter (IM) is one of the most important defects of RSW in the classification of strength defects due to the small diameter of the weld core. Accordingly, if the value of the weld core diameter is less than the value specified in the standard, this is IM defect, which is led to reduce the strength of the spot-welded joint. Therefore, the joint strength can be increased by preventing the shunting phenomenon. A schematic of the shunting phenomenon at a connection with more than one spot

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weld and diameter reduction of the welding core is shown in Figure 1 [4].

A few studies have been conducted to investigate shunting effects in the spot-welded joint as simulations, theoretical, and analytical models. Jafari Vardanjani et al. [4] have reviewed research about shunting phenomenon and its effect on RSW joint. Various parameters are effective on the intensity of shunting phenomenon, including number of previous spot welds, nugget size of previous spot welds, distance between spot welds, and so on which decrease the welding core diameter (new spot weld) and consequently decrease strength of the RSW joint. In addition, the parts of the sheet that are in contact with each other will be the electric current passage area where the presence of the oxide layer and the reduction of the electrode pressure have a significant effect on the intensity reduction of shunting phenomenon. Xing et al. [5] have studied the shunting effects in the resistance spot welding joint of medium carbon steel sheets based on the electrode displacement signals technique. In this research, the effect of the welding distance parameter was studied on the shunting phenomenon and its effect on welding core diameter in the new spot weld. Moreover, the minimum gap between multi-spot welds was reported about 20 mm. The most important achievement of the present work revealed that electrode displacement curves can be used as a proper tool to monitor the health status and quality control of RSW joint. In this regard, the electric current was set based on the electrode displacement curve at the previous spot-welded characteristics, like shunting effect, to create new spot weld. Figure 1 shows a schematic of the shunting phenomenon at a connection with more than one spot and diameter reduction of the welding core [4].

An analytical model has been presented for the shunting effect in the RSW joint of AA2219 aluminum alloy sheets with a thickness of 1 mm considering two consecutive spot welds [6]. Finally, the welding core diameter obtained from the presented analytical relationships by the finite element simulation results (validated with the experimental results [7]) was

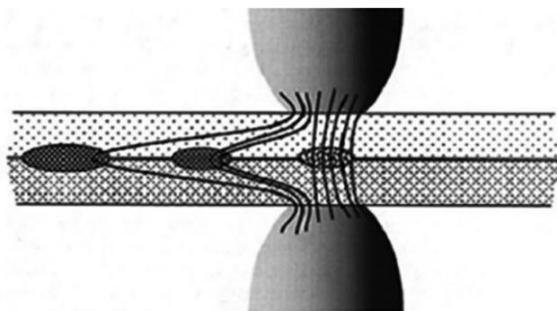


Figure 1. A schematic of the shunting phenomenon at a connection with more than one spot and diameter reduction of the welding core [4]

compared and the results were well matched. Moreover, the three-dimensional model has been presented as a thermal-electric coupling to simulate shunting phenomenon in the RSW joint [8]. In the current study, various experiments were performed in which the heat affected zone was considered as the study criterion to validate the proposed model.

Wang et al. [9] have conducted a laboratory study about the effect of the shunting phenomenon on the resistance spot welding joint in the first part of their research. In the present research, several effective factors were investigated, including sheet material, sheet surface conditions, welding program, and welding process parameters. Among all of them, the electrode force is the most effective parameter that can reduce the shunting effects when the distance between spot welds is limited. Three different materials, including medium carbon steel, DP590 steel, and DP780 steel, were used in the current research. Furthermore, different thicknesses (1, 1.2, 1.25, 1.5, and 2 mm) were considered to include the effect of sheet thickness on the shunting phenomenon. Test specimens were prepared by connecting two sheets with five resistance spot welds. Then, nugget diameter was measured from the cut section for each of the studied cases. Finally, statistical analysis showed that the gap between spot welds is the most important factor in the shunting phenomenon. Therefore, if this gap is large enough, shunting phenomenon will not occur. The results showed that high contact resistance created by very strong surface conditions or electrode force increases the shunting intensity. Moreover, there is a close relationship between sheet material (chemical composition), sheet thickness, and resistance spot welding strength with shunting phenomenon. In the second part of their research, they analyzed the electrical resistance during the welding process and identified the shunting path [10]. The minimum value of welding parameters and the gap between spot welds were extracted as can create a suitable nugget diameter based on the welding time, sheet thickness, and other influential parameters. Moreover, sensitivity analysis was performed for each of these parameters, and gap diagrams between spot welds were extracted in terms of these parameters.

In recent years, the characteristics of the shunting phenomenon have been investigated in the RSW joints made of aluminum alloys with non-uniform thicknesses [11,12]. To this end, ANSYS software was used to simulate the finite element of gap effects between spot welds. The results showed that gap increase between spot welds is not an effective method to prevent shunting phenomenon. The main reason for this case is the low strength of the bulk in the aluminum alloy. Therefore, increasing the electric current was proposed to compensate the effect of shunting phenomenon. Also, the current density parameter in the component was measured to study the electric current escape in the

connection. In addition, shunting phenomenon has been investigated in RSW joint using both simulation and laboratory methods [13]. In this study, the welding joint was considered for two sheets with the same thickness which was connected by two consecutive spot welds. Furthermore, the distance between spot welds was considered as a variable in the range of 2-8 times the diameter of the electrode head. The nugget diameter was measured at both spot welds and the percentage of size reduction was considered as a criterion for the occurrence of the shunting phenomenon. The results showed that if the distance between spot welds is at least 6 times the diameter of the electrode head, the shunting effects can be neglected. As reported, the nugget diameter is more sensitive to the shunting phenomenon than the welding core height.

Yu et al. [14] have proposed an adaptive RSW process intended to decrease the shunting effect, especially in the connection of high-strength steel sheets with applications in the automotive industry [15]. They used an exponential model to predict weld pitch in terms of dynamic resistance. Also, they considered the weld pitch as a function of nugget diameter and heat input. Then, they established a combined model of logic algorithm and regression method that has the ability to evaluate the input heat compensation with the aim of shunting reduction. Eventually, in practice, they tried to reduce the shunting effects by adjusting the welding time and keeping the constant ampere current.

In the present research, the connection of three sheets with different materials and the same thicknesses was simulated as an electrical-thermal-mechanical coupling problem in finite element software. Afterwards, to validate the presented finite element model, nugget diameter extracted from the simulation results was compared to the test results. Then, various techniques, including electric current density, contact electrical conductivity, and electrode displacement diagram were used to estimate the shunting phenomenon in the spot welds. Eventually, the obtained results from different methods were compared to each other which have a very good agreement. The following can be mentioned among the innovations of the present study in comparison with previous studies:

- Simulation of three-sheet RSW joint and its validation using experimental data by comparison technic;
- Investigation of shunting effects in three-sheet RSW joint;
- Considering different materials for sheets in the RSW joint;
- A comprehensive study of shunting phenomenon using various methods, including measurement of new welding core diameter, electric current density, contact electrical conductivity, and diagram of electrode head displacement.

2. LABORATORY STUDY

In the current research, two types of DC03A and DC04A steel sheets with the same thickness of 0.8 mm were used. Thus, both middle and bottom sheets are made of DC03A and the top sheet is made of DC04A. The chemical composition of these two steels based on the results of Quantometric test are reported in Table 1. Also, sheet samples were prepared and metallographic test was performed after mounting and polishing the surface to determine the initial phase and grain size of the raw material. The microstructure of the sheets is shown in Figure 2 which was obtained from the metallographic test after etching by 3% nital solution.

Microstructure observations showed that the initial phase of both sheets is completely ferrite. In addition, the grain size for both materials is equal to 7 based on the NFA04-102 standard.

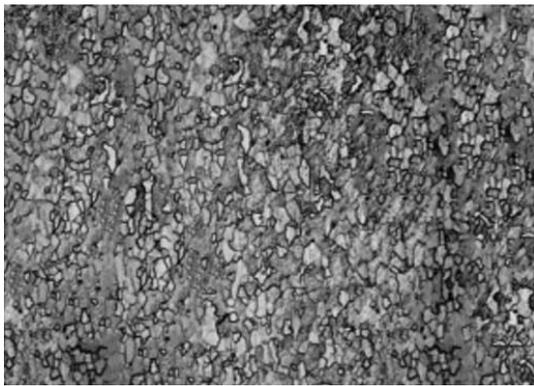
Next, standard electrode (F0-16-20-8) was used to fabricate test samples of three-sheet spot-welded joint. The electrode is made of copper alloy with 1.1% alumina. The geometric dimensions of the sheets and the location of the spot weld at the three-sheet joint are demonstrated in Figure 3. Also, the welding process parameters are presented in Table 2. Furthermore, an electric current was applied alternately with a frequency of 50 Hz [16, 17].

The laboratory sample was cut transversely from the middle of the spot weld after its preparation and metallographic observations including measurement of the nugget diameter and the Heat Affected Zone (HAZ) were performed (Figure 4).

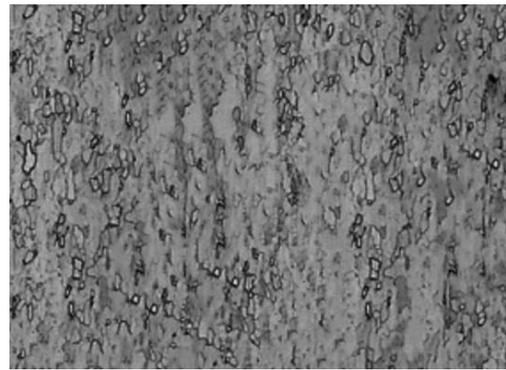
From this figure, the two diameters created between the top and middle sheets and the bottom and middle sheets are 5.63 and 5.47 mm, respectively. Moreover, the length of the HAZ in the upper part ($L = 7.04$ mm) is different from the lower part ($L = 6.48$ mm) of the three-sheet RSW joint.

TABLE 1. Chemical composition of DC03A and DC04A steels based on the Quantometric test results

Steel grades	DC03A	DC04A
Fe	Base	Base
Al	0.0284	0.03
C	0.0377	0.034
Mn	0.2036	0.24
P	0.013	0.009
S	0.0047	0.011
Si	0.0036	0
Cr	0	0.03
Cu	0	0.01
Ni	0	0.02



(a)



(b)

Figure 2. Metallographic images of raw materials with 100x magnification: a) DC03A steel and b) DC04A steel

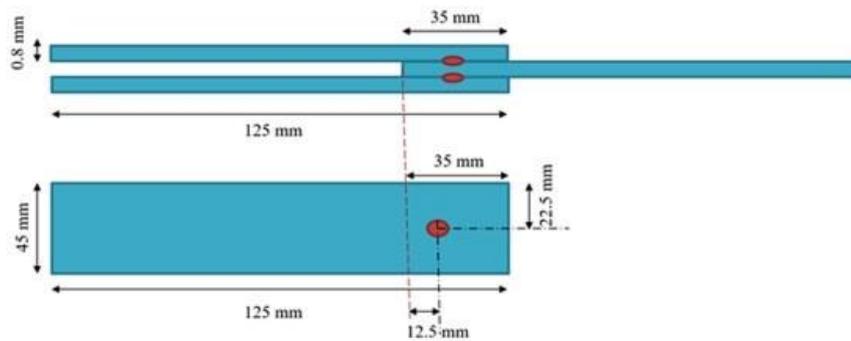


Figure 3. Geometric dimensions of three-sheet spot-welded joint [16]

TABLE 2. Resistance spot welding process parameters [16, 17]

Parameter	Unit	Value
Force	N	365
Welding current	KA	11.5
Squeeze time	Cycle	25
Up slope	Cycle	3
Welding time	Cycle	12
Hold time	Cycle	9

3. FINITE ELEMENT SIMULATION

To extract the mechanical, electrical, and thermal properties of the raw materials, JMatPro software version 7 was used. To this end, percentage of chemical composition (Quantometric test results), the initial phase of the sheets, and its grain size (metallographic test results and microstructural studies) were used as input in the software. Afterwards, three-dimensional simulation of the RSW process as an electrical-thermal-mechanical coupling analysis was performed using Simufact Welding software (Edition 6). In other words, for the first time, a hybrid finite element-experiment method was used to simulate this type of welding process. Figure 5 represents the algorithm used to simulate the RSW process with higher accuracy than other models presented in the past. Also, the geometry and conditions of the spot welding process were applied following the experimental procedure.

Mesh sensitivity analysis was performed to obtain the optimal finite element model (independence of the response from the number of elements) and to reduce computational costs. Thus, the element size of 1 mm and two times refinement around the spot weld position were considered. Eventually, the final FE model consisting of

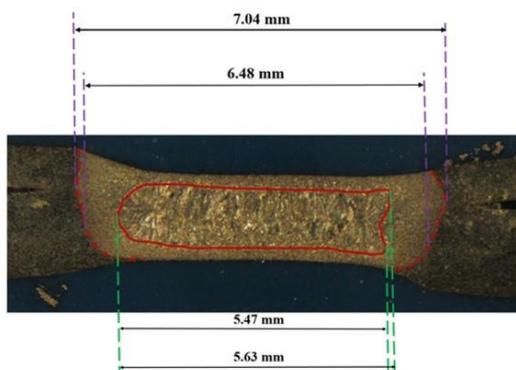


Figure 4. Measurement of nugget diameter and HAZ, experimentally [17]

33750 elements along with the position of the electrodes on both sides of the sample is demonstrated in Figure 6. In addition, more details on finite element simulation of RSW process in the three-sheet joint can be found in a previous paper published by the authors [17].

Nugget diameter between the top and middle sheets (5.903 mm) and between the bottom and middle sheets (5.896 mm) was obtained as shown in Figure 7. Also, the

results of finite element simulation were 4.8% and 7.9% different from the experimental data, respectively.

The sequential spot welding process was simulated to investigate the shunting effects after validating the finite element model. One of the most important innovation of the presented FEM in comparison with previous studies is to consider the deformation of the sheets during the creation of previous spot welds and

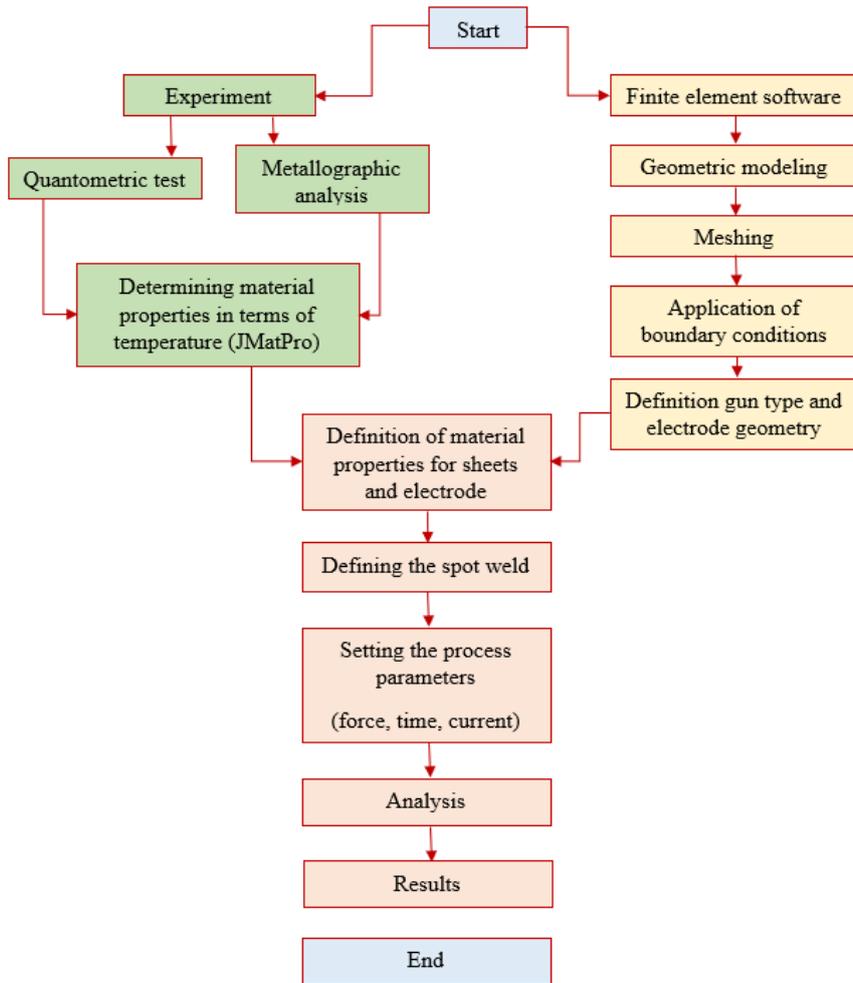


Figure 5. A hybrid finite element-experiment algorithm used to simulate RSW process with higher accuracy than available models

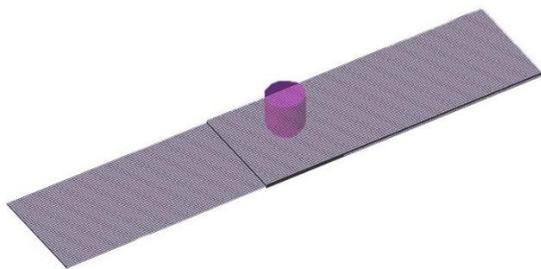


Figure 6. The 3D-FE model of RSW with 33750 elements

studying its effect on shunting phenomenon, for the first time. Also, the interval between two consecutive spot welds was considered 45 mm. This distance reduces the effect of electric current escape from previous spot welds as much as possible. Hence, the shunting effect becomes more noticeable for the deformation of the sheets. The welding sequence in a three-sheet connection with three spot welds is demonstrated in Figure 8. In addition, the conditions of welding process were considered completely in agreement with the previous case.

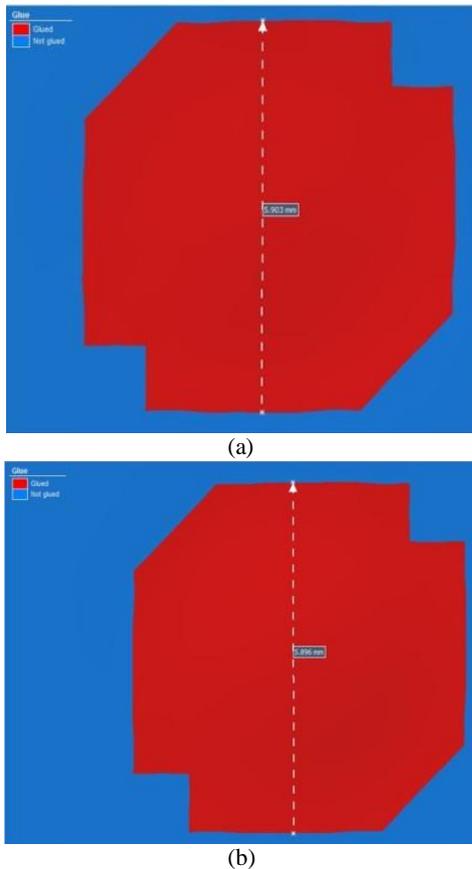


Figure 7. Geometry and size of welding core: a) between the top and middle sheets and b) between middle and bottom sheets

4. RESULTS AND DISCUSSION

In the present research, various techniques, including measuring nugget diameter, electrical current density, contact electrical conductivity, and electrode displacement diagram, were used to study the shunting effects in the process of successive spot welding. Therefore, the results obtained using each method are reviewed as follows:

4. 1. Measuring the Nugget Diameter of New Spot Weld

One of the most elementary methods to identify shunting phenomenon in the process of successive spot welding is to measure and compare the nugget diameter of new spot welds with the original one. Therefore, the nugget diameter between the top and middle sheets and the nugget diameter between the middle and bottom sheets in all three consecutive spot welds were extracted as given in Table 3.

From Table 3, the nugget diameter of the second spot weld has decreased compared to the first spot weld. Therefore, it is inferred that the second spot weld was impressed by the shunting phenomenon. However, the

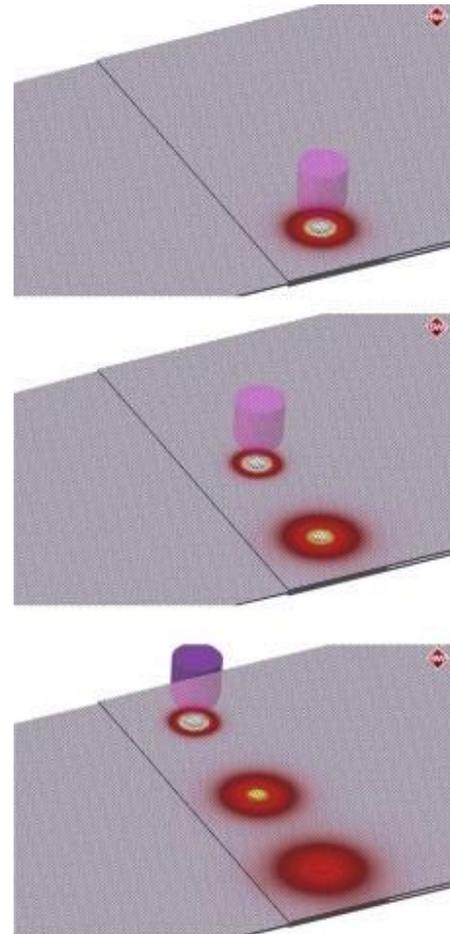


Figure 8. The sequence of welding in a three-sheet connection with three spot welds

TABLE 3. Nugget diameter between different sheets in the process of successive spot welds

Number of consecutive spot welds	Nugget diameter	
	Between top and middle sheet (mm)	Between bottom and middle sheet (mm)
1	5.84	5.73
2	5.74	5.70
3	5.83	5.78

nugget diameter of the third spot weld has increased in comparison with the previous spot weld. Moreover, the nugget diameter of the third spot weld was obtained around the target diameter in the first spot weld. As a results, the third spot weld is not in the path of the electric current escape. Later, the main reason for this occurrence is analyzed in more detail using other techniques.

4. 2. Studying the Electric Current Density The electric current density equals the ratio of electric current

to the area of the passed surface through it. This parameter was extracted by software capabilities at the same times of the welding process in three different modes including one, two, and three spot welds via distance from the center of spot welds in four positive and negative paths of X and Y axes (Figure 9). The blue and red lines indicate the positive and negative directions of the coordinate axes, respectively.

Also, the center of the coordinate axis for each spot weld is located in its center. The positive direction of the X axis is to the right and the end of the top and bottom sheets and the negative direction is to the left and the end of the middle sheet. Moreover, the positive direction of the Y axis is considered for each spot weld towards the next spot weld and its negative direction is considered towards the previous spot weld. Furthermore, zero-

interval means reporting the electric current density in the center of the spot weld.

It is clear that for the first spot weld, the changes in the electric current density in different directions, in the X directions are almost identical to each other and follow a specific procedure. The density of electric current slightly increases from the center of spot weld to the electrode surface separation area from the sheet surface. Afterward, its value decreases at a significant rate to the range of 4 mm from the center of the spot weld. Finally, the rate of the electric current density decreased to the interval of 6 mm from the center of the spot weld. This behavior is also seen in different Y directions. Also, this behavior is repeated for different Y directions for the second spot weld. Nonetheless, the difference between the two directions gradually increases in different X

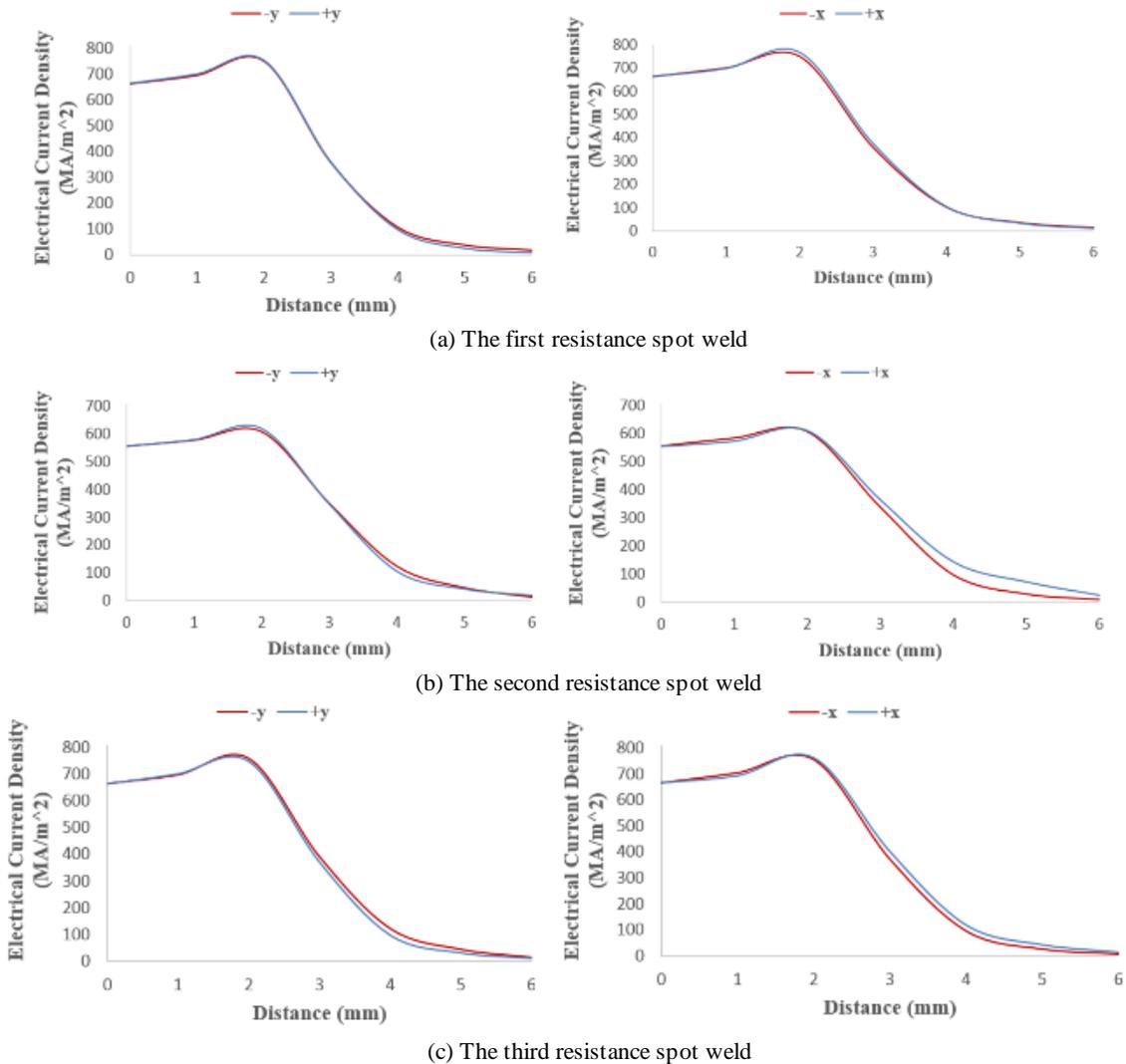


Figure 9. Variations of the electric current density in terms of distance from the center of the spot weld in the sequential spot welding process, including a) The first resistance spot weld, b) The second resistance spot weld, and c) The third resistance spot weld

directions in the second spot weld from a 2 mm interval onwards. This difference shows that the electric current in the second spot weld is more inclined to pass in the positive X direction. Furthermore, the maximum level of electric current density in the second spot weld is much lower than its level in the first spot weld which shows the effect of the shunting phenomenon in the RSW process of the second spot. Nonetheless, it is observed in the third part of Figure 9 that the maximum level of electric current density has increased and reached its value in the RSW process of the first spot. The obtained results using this method are in complete agreement with the reported results about measurement of nugget diameter. Next, another effective parameter such as contact electrical conductivity was studied to find the reason for the re-increase of the electric current density in the third spot weld.

4. 3. Studying the Contact Electrical Conductivity

Since three sheets are in contact with each other in the range of 135×35 mm from the beginning of the welding process, there is always contact electrical conductivity in this range of sheets. The exerted force by the electrodes on the surface of the sheets during compression makes a range at the contact surface of the sheets which has a higher electrical conductivity than other non-pressurized contact surfaces. On the other hand, one of the effective parameters in increasing the contact electrical conductivity is the presence of microscopic roughness on the surface. Electric current passes difficulty through these roughness and small spaces between them. This roughness is compressed and fitted together better when force is applied to a part of a sheet. In addition, some of the small spaces between them are completely or partially filled which makes it easier for electricity to pass through this contact area. Increasing the contact electrical conductivity in one area means the electrical resistance reduction in that area than the other areas. Moreover, electric current tends to pass through an area with less electrical resistance. This makes a significant electric current pass from the upper sheet to the lower sheet through the pressure range which finally makes a spot weld at that location. Therefore, there was a shunting phenomenon in the first spot weld because of the contact of three sheets from the beginning of the welding process. The contact electrical conductivity in the place of the first spot weld after posing force and before applying an electric current is illustrated in Figure 10.

From this figure, a range with high contact electrical conductivity is made in the mentioned place to make the first spot weld caused applying force by the electrode. In addition, there are spot welds on the contact surface. Although their contact electrical conductivity does not reach the pressure range, their size is big to the extent that causes a significant amount of electrical current to escape

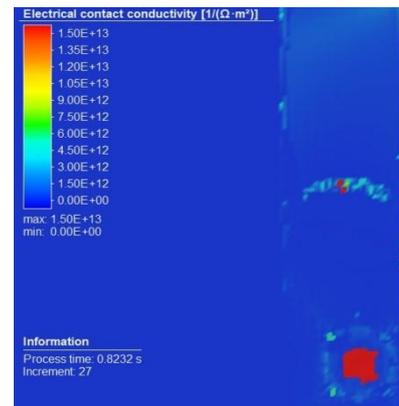


Figure 10. Contact electrical conductivity in the first spot weld

from those spot welds. One of these is nearly in the range of contact and the relative place of the second spot weld. In other words, by applying pressure by an electrode in the first spot welding place and sheets deformation, it is possible that the sheets will be pressured more than usual in a spot weld and higher contact electrical conductivity is made in those spot welds which are the main reason of increasing the contact electrical conductivity in the relative place of the second spot weld. Moreover, it was observed that contact electrical conductivity has increased in two both transverse ends of the sheets (the parts where the top edge of the sheet is in contact with the middle sheet and the edge of the middle sheet is in contact with the bottom sheet). Contact electrical conductivity actually increases regardless of the force applied in areas where the sharp edge of one sheet is in contact with another sheet. Therefore, the geometry and placement of the sheets relative to each other are effective on the shunting phenomenon.

From Figure 11, the amount of contact electrical conductivity at the transverse edge of the contact range decreases by increasing the number of previous spot welds. This makes the electric current in the Y direction more inclined to propagate than the X direction. In other words, the electric current becomes more concentrated in the Y direction. Consequently, shunting effects in the X direction will be less than in the Y direction for the third spot weld. One of the most important reasons for this event is the deformation parameter of the sheets and the weakening of the contact in the initial contact range.

4. 4. Investigating the Electrode Head Displacement During Spot Welding Process

One of the newest methods that were provided in recent years is using an electrode displacement diagram during the welding process to study the shunting phenomenon [3]. In this regard, shunting can be investigated using the comparison technique for three statistical characteristics,

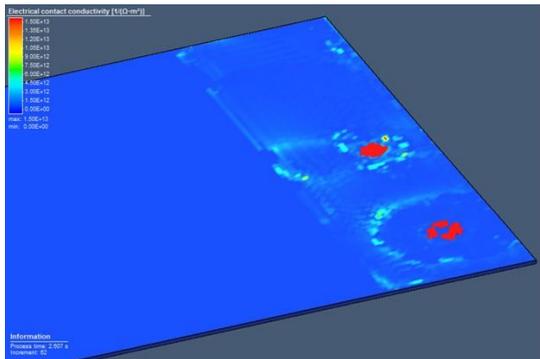


Figure 11. The effect of the current location on the contact electrical conductivity

including graph diagram, diagram slope to the maximum spot, and standard data scatter. The electrode head displacement diagram for three consecutive spot welds is illustrated in Figure 12.

In this figure, the blue dotted line displays the electrode head displacement during the RSW process at the first spot weld. Two vertical black lines show the beginning and end of the welding period. The time interval is related to the maintenance time after the second vertical line. The black horizontal line is drawn from the beginning of the welding interval. Furthermore, its surface difference with the end of the displacement figure of each spot welding shows the degree of penetration of the electrode at the end of the RSW process and before the start of the maintenance time. In this research, the figure of the first spot weld was used as a basis to detect the electric current escape. When the maximum spot welding diagrams of subsequent graphs is lower than the maximum spot welding diagram of the first spot weld, the shunting rate increases. This issue is true for the slope of reaching the maximum value and the standard scatter value of the chart data. Figure 12 clearly shows that the slope of reaching the maximum value is

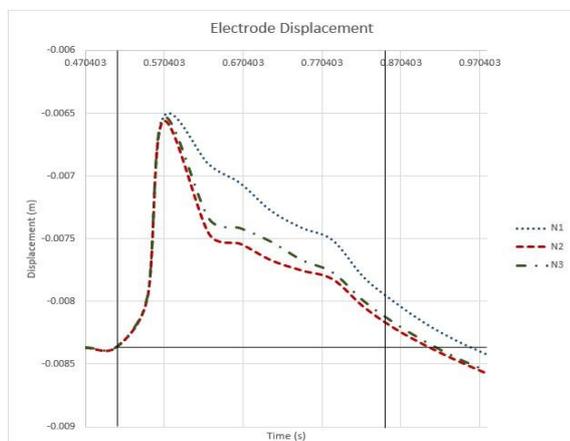


Figure 12. Electrode head displacement vs. time for three consecutive spot welds

the same for all three spot welds. However, the difference between the maximum value of the second and third spot welds is obvious with the first spot weld. This difference between the first and second spot welds is higher than the difference between the first and third spot welds. This matter shows that the effect of shunting phenomenon in the second spot weld is higher than the third spot weld which was analyzed in the previous part. It is clear by comparing the maximum first and second spot welds that there was a significant amount of electric current escape, and affect nugget diameter between the upper and middle sheets are tangible despite the great gap between their two centers. On the other hand, the tiny maximum difference between the first and third spot welds shows the intangibility of the electric current escape which has a slight effect on the nugget diameter between the upper and middle sheets which can be neglected.

5. CONCLUSION

In the present research, the shunting phenomenon in the successive RSW processes of three-sheets connection was studied. Various techniques were used to reach this goal, including nugget diameter measurement, investigating the electric current density, contact electrical conductivity, and displacement of electrode head during welding process. Findings of this research include:

- Providing a three-dimensional finite element model of RSW process as an electrical-thermal-mechanical coupling: the obtained results from simulation for nugget diameter between the top and middle sheets and between the middle and bottom sheets had a very good agreement with the experiment results.
- Considering the sheets deformation while previous spot welds and investigating its effect on the shunting phenomenon using finite element simulation.
- Investigating shunting phenomenon using various techniques: the obtained results are aligned with each other completely which shows the high precision of research.
- The most achievements of the present research show that the shunting phenomenon is neglected from the previous spot welds in a three-sheet connection based on a 45 mm interval. This matter is despite the published reports by considering the minimum 20 mm interval between the spot welds or the interval 6 times more than the electrode cross-section to reduce the effect of shunting phenomenon in two-sheet connection.
- The results reveal that the reduction of shunting effects for three consecutive spot welds is impressed by the deformation of the sheets which is less than or approximately equal to the electric current escape that occurs from previous spot welds. If the interval between

spot welds is less than the considered value in this research, the electric current escape will be higher than the previous spot welds. Therefore, the assumption of neglecting the deformation of the sheets in the simulation of RSW process will not significantly influence the results for more than one spot weld and short intervals. However, it is essential to consider the deformation of the sheets while investigating the electric current escape in more than one spot welding model with equal and higher than 45 mm intervals.

6. ACKNOWLEDGEMENTS

We sincerely appreciate Mr. Gholamreza Khanmohammadi, Seyed Mohammad Navidi, and Ramin Eslami who assisted us in this work.

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Persian Abstract

چکیده

هدف اصلی پژوهش حاضر بررسی پدیده فرار جریان الکتریکی در یک اتصال نقطه جوش مقاومتی سه ورقی با استفاده از شبیه‌سازی المان محدود است. برای دستیابی به این هدف، اتصال جوش نقطه ای مقاومتی سه ورق به عنوان یک مسئله کوپل الکتریکی-حرارتی- مکانیکی شبیه‌سازی شد. برای اعتبارسنجی شبیه‌سازی ارایه شده، نتایج اجزای محدود با نتایج تجربی، اعم از اندازه و شکل هندسی جوش در اتصال جوش نقطه ای مقاومتی مقایسه شد. پس از آن، فرآیند جوشکاری چند نقطه‌ای در اتصال فولادهای سه ورقی کم کربن با ضخامت‌های یکسان با در نظر گرفتن فاصله متوالی ۴۵ میلی‌متر مورد تجزیه و تحلیل قرار گرفت. تکنیک‌های مختلفی از جمله اندازه‌گیری قطر نقطه جوش جدید، چگالی جریان الکتریکی، هدایت تماس الکتریکی و جابجایی الکترون، برای مطالعه اثرات فرار جریان الکتریکی در فرآیند جوش نقطه‌ای متوالی مورد استفاده قرار گرفت. نتایج به دست آمده از روش‌های مختلف تا حد زیادی با یکدیگر مطابقت دارد. همچنین نتایج اجزای محدود نشان داد که فرض نادیده گرفتن اثر تغییر شکل ورق برای فواصل کم بین نقطه جوش‌های متوالی قابل قبول است. با این حال، لازم است تغییر شکل ورق برای فواصل متوالی بیش از ۴۵ میلی‌متر در نظر گرفته شود.