ARCHIVE OF MECHANICAL ENGINEERING

Volume 67 2020 Number 2

DOI: 10.24425/ame.2020.131690

Key words: spot welding parameters, tensile-shear force, Taguchi method, optimization, design of experiment

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Prediction of the optimum tensile – shear strength through the experimental results of similar and dissimilar spot welding joints

Resistance spot welding is the most significant joining technique utilized in various industries, like automotive, boilers, vessels, etc., that are commonly subjected to variable tensile-shear forces due to the unsuitable use of the input spot welding variables, which mainly cause the welded joints failure during the service life of the welded assembly. So, in order to avoid such failures, the welding quality of some materials like aluminum must be improved taking into consideration the performance and weight saving of the welded structure. Thus, the need for optimizing the used welding parameters becomes essential for predicting a good welded joint. Accordingly, this study aims at investigating the influence of the spot welding variables, including the squeeze time, welding time, and current on the tensile-shear force of the similar and dissimilar lap joints for aluminum and steel sheets. It was concluded that the use of Taguchi design can improve the welded joints strength through designing the experiments according to the used levels of the input parameters in order to obtain their optimal values that give the optimum tensile-shear force as the response. As a consequence of the present work, the optimal spot welding parameters were successfully obtained.

1. Introduction

Spot welding is the most significantly process utilized for joining various sheet metal structures in industry, such as automotive structures, domestic applications, building structures, enclosures and aircraft components. The main characteristics of the spot welding technique involve the high operating speeds and its convenience for the automation and the inclusion in the high production assembly lines simulta-

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neously with other synthesis operations. Also, such technique can be implemented at the high production rates and low costs by employing less skill workers as well as controlling the employed current, welding time, and electrode force [1].

N. Mookam studied the optimization of welding parameters via Taguchi approach for dissimilar welded joints (stainless steel to high strength steel) using a filler material. The used parameters in this investigation included the current, electrode pressure, and time. It was noticed that the current possesses the major influence on the welded joint than others, and the joints manifested a good strength when using filler metal [2]. J. Valera used the welding intensity and time as input parameters and applied Taguchi method to determine the optimum circumstances for a dissimilar steel joint. The welding current elucidated a slightly higher influence on the tensile strength values in comparison with the welding time [3]. T.R. Mahmood et al. predicted the optimum tensile-shear force of three similar steel joints through a mathematical model. The welding parameters employed were current, welding time, and electrode force. The results evinced that increasing the current and welding time enhanced the strength of the welded joint. But, this strength was then decreased with the increasing of electrode force that increased the contact area between the sample and the electrodes. Consequently, the nugget size was minimized by such effect [4], this behavior was found similar to that obtained by S.K. Hussein et al., who welded the mild steel with aluminum [5]. Ying Lu et al. conducted a spot welded dissimilar joint (steel to aluminum) utilizing a new welding technique called the ultrasonic and resistance spot welding. Initially, thin aluminum inserts were used to join the steel sheets through applying the ultrasonic spot welding technique. Then, the thin aluminum insert was placed inside the steel sheet that was welded to an aluminum sheet using a conventional resistance spot welding. It was observed that the tensile-shear force and the fracture energy of the newly used method were improved with increasing the current when compared with the conventional spot welding process [6]. A. Subrammanian et al. implemented Taguchi approach to optimize the spot welding parameters of stainless steel. It was found that the best parameter that improved the tensile strength was the welding current with a minimum indentation, pursued by welding time and then electrode force [7]. B. Vijaya Sankar et al. predicted the optimum welding parameters of the dissimilar mild steel and the stainless steel joints by factorial design. The regression model was developed from the results of the tensile-shear force and hardness employing the response surface methodology technique. It was noted that the welding current and welding time had a more significant influence upon the measured outputs [8]. Pradeep M. et al. joined the dissimilar thicknesses of steel by spot welding process, the optimum process parameters (current and time) were obtained from the Taguchi analysis based on the shear test results. It was inferred that the welding time was the main factor in this process in comparison with the welding current [9]. Mohammad J. Zedan et al. invented a new technique to join the steel with aluminum by spot welding process that comprises a hole, which was drilled in the aluminum side under the electrode area to provide a path for inserting the molten metal through this hole. On the other hand, the external pressure between the used alloys, which formed a thin layer that prevented the welding process, was produced owing to the spread of the molten metal between the dissimilar alloys. The enhancement of welding outputs, like the electrode force, welding current and welding time improved the tensile strength and the nugget size [10].

According to the aforementioned literature, it appears that few investigations have predicted the optimum tensile-shear force of the dissimilar spot welded joint, especially welding aluminum with steel despite the rapid failure of numerous spot welded structures due to the tensile-shear influence throughout their service life. Also, light materials are widely needed in the multi-material structures in order to reduce their weight in spite of the encountered problems in performing the spot welding process of dissimilar materials. In addition, few researchers have investigated the effect of squeeze time as a variable on the tensile-shear force of the spot welded joints. Therefore, this study is devoted to study the influence of the spot welding parameters (squeeze time, welding time and current) on the tensile-shear force of similar and dissimilar joints for the aluminum and steel sheets and to predict the optimal input welding parameters through carrying out the experimental runs designed by Taguchi method to obtain the optimum tensile-shear force.

2. Materials and experimental procedure

The materials used in this study were aluminum AA1200 and carbon steel 50HS, and their chemical compositions are depicted in Table 1. A sheet having 1 mm thickness from each material was cut into pieces with the required dimensions in order to weld each two of them to prepare the specimen for spot welding, as revealed in Fig. 1. Prior to welding, the surface of all specimens from both types of material were first ground by abrasive paper using acetone, then thoroughly cleaned, and finally spot welded to prepare the similar and dissimilar welded joints using a spot welding machine SIP type PPV50. A tensile test machine (Tinius Olsen) was used to carry out all the tensile-shear tests for the similar and dissimilar spot welded specimens, as displayed in Fig. 2. The procedure of experimental work was planned to be conducted in three groups according to the type of weld joint; firstly similar (Al + Al), secondly similar (steel + steel), and thirdly dissimilar (steel + Al). Nine specimens from each group were spot welded according to the

Table 1.

Chemical composition of the used materials

Elements	Si	Mg	Ti	Cu	Zn	Al
AA1200	0.95	0.048	0.05	0.05	0.1	Remain
Elements	C	Si	Mn	Cr	Mo	Fe
Steel 50HS	0.55	0.86	0.08	0.74	0.05	Remain

experimental design employed in the current work. During welding the aluminum with steel, it was needed to insert a 0.3 thick sheet of copper (AISI C10200) as a filler metal between the dissimilar materials of the specimen to be welded.

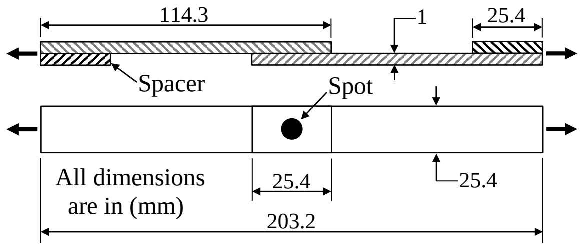

Fig. 1. The spot welded specimen

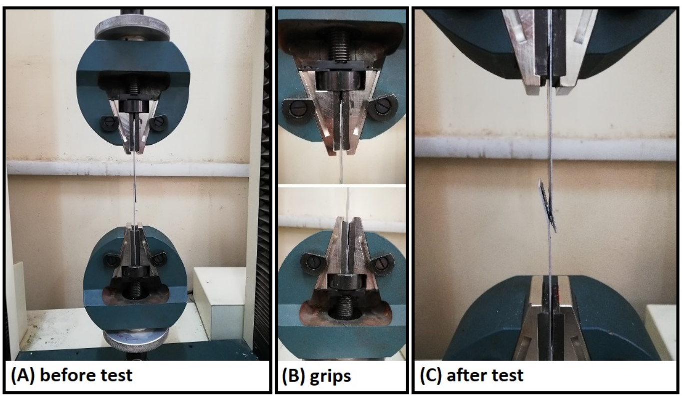

Fig. 2. The tensile-shear test of the spot welded specimen

3. Taguchi approach

Taguchi approach is a statistical procedure used to design an experiment of different fields and optimize the used input variables for obtaining optimal responses by using different programs like Minitab 16, which was implemented in the present study to minimize the number of trails and time. The input spot welding parameters employed in this software were squeeze time, welding time and current, while the holding time was kept constant, about 12.5 sec. The used levels for each input parameter applied in Minitab 16 for all groups are listed in Table 2; these levels were selected according to the researcher's previous experience and works.

Taguchi approach is a highly practical design utilized to estimate the main effects through few numbers of experiments, and such design is qualified to investigate the major influences when the variables have more than two levels [11].

Table 2.

The used levels of the spot welding parameters

Material	Parameters (unit)	Code	Level I	Level II	Level III
Al	Squeeze time (sec)	A	13.75	15	16.25
	Welding time (sec)	B	1	1.125	1.25
	Current (A)	C	60	64	68
Steel	Squeeze time (sec)	A	13.75	15	16.25
	Welding time (sec)	B	1	1.25	1.5
	Current (A)	C	50	60	70
Steel + Al	Squeeze time (sec)	A	13.75	15	16.25
	Welding time (sec)	B	0.375	0.5	0.625
	Current (A)	C	60	65	70

The analysis of variation in Taguchi procedure was accomplished through the calculation of Signal–to–Noise ratio (S/N). As stated earlier, the aim of this study is to obtain the maximum tensile–shear force at the optimal input spot welding parameters. Thus, the S/N ratio for each experiment of L9 of Taguchi method using Minitab 16 was calculated according to the "Larger is the better" approach, for three input parameters written in various codes (A, B and C) and nine experimental runs designed for each group, as manifested in Table 3. The S/N of "Larger is the better" was calculated by Minitab program applying the following equation [11]:

$$\frac{\mathrm{S}}{\mathrm{N}} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\left[\frac{1}{y_i^2}\right]\right], \tag{1}$$

where: S/N – the signal-to-noise ratio, y_i – the output characteristic, n – the number of trials.

Table 3.

Taguchi experimental design used in the present work

Run No.	Al			Steel			Steel + Al		
	A	B	C	A	B	C	A	B	C
1	13.75	1.000	60	13.75	1.00	50	13.75	0.375	60
2	13.75	1.125	64	13.75	1.25	60	13.75	0.500	65
3	13.75	1.250	68	13.75	1.50	70	13.75	0.625	70
4	15.00	1.000	64	15.00	1.00	60	15.00	0.375	65
5	15.00	1.125	68	15.00	1.25	70	15.00	0.500	70
6	15.00	1.250	60	15.00	1.50	50	15.00	0.625	60
7	16.25	1.000	68	16.25	1.00	70	16.25	0.375	70
8	16.25	1.125	60	16.25	1.25	50	16.25	0.500	60
9	16.25	1.250	64	16.25	1.50	60	16.25	0.625	65

4. Analysis of results and optimization

Table 4 presents the results of the tensile–shear force and the S/N ratio of all achieved spot welding experiments and elucidates that the maximum resulted force of (Al + Al), (Steel + Steel) and (Steel + Al) spot welded specimens are 1330 N, 7590 N and 1160 N, respectively.

Table 4.
Tensile–shear force results with S/N ratio of similar and dissimilar spot welded joints

Run	Al + Al		Steel + Steel		Steel + Al	
	Force (N)	S/N (db.)	Force (N)	S/N (db.)	Force (N)	S/N (db.)
1	987	59.886	6340	76.042	867	58.760
2	1040	60.341	7480	77.478	1160	61.289
3	1330	62.477	7450	77.443	848	58.568
4	1180	61.438	7510	77.513	10	20.000
5	910	59.181	7440	77.432	618	55.820
6	870	58.790	7101	77.026	315	49.966
7	802	58.084	7550	77.559	498	53.945
8	1210	61.656	6410	76.137	481	53.643
9	1280	62.144	7590	77.605	1010	60.086
Average	**1067.667**	**60.444**	**7207.889**	**77.137**	**645.222**	**52.453**

The influence of using the three parameters (squeeze time, welding time and current) on the tensile-shear force is evinced in terms of response graphs of S/N ratio and means for each type of welded joint. Fig.3 clarifies that the tensile-shear force for the similar (Al + Al) spot welded joint was reduced by increasing squeeze time and increased with the increase of welding time but raised as the current was increased until 64 A. These results are likely attributed to the fact that increasing the squeeze time reduced the size of nugget zone due to the pressure influence that resulted in less molten material existing between the two sheets to be welded, thus reducing the tensile-shear force of the joint. And, raising the welding time increased the quantity of the accumulated fused material at the joint interface which created a sufficient size of nugget zone, thereby giving a rise in the joint force. Also, increasing the welding current up to 60 A caused more fusion from both materials at the interface owing to the effect of more heat generation, thus resulting in an increase in the force of the welded joint, while the decrease of force after 60 A was owing to the detrimental influence of further induced heat generation.

The analyses of the tensile-shear force results related to mean and S/N ratio response are given in Tables 5 and 6, respectively. Table 5 demonstrates that the welding time possesses a major impact on the tensile-shear force of (Al + Al) spot welded joint followed by current and squeeze time. The current has the main

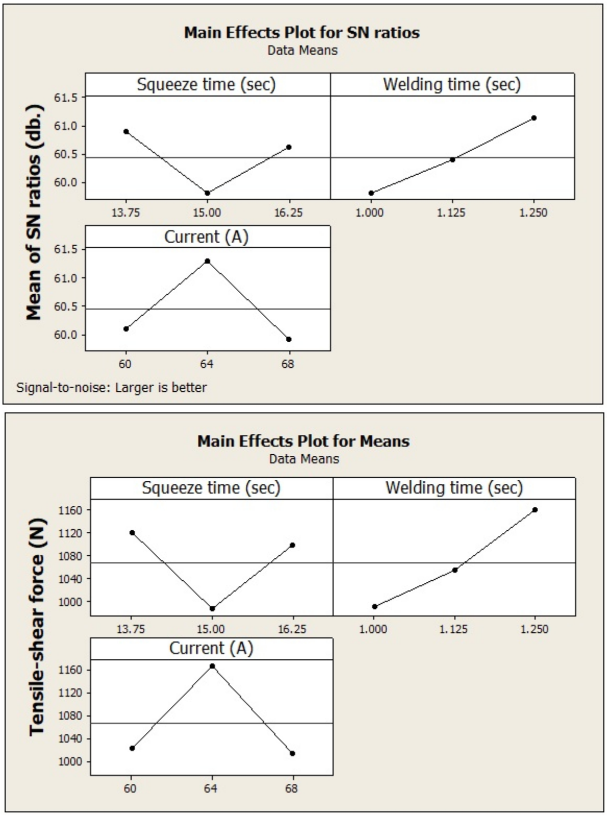

Fig. 3. The S/N ratio and means response plots of the (Al + Al) spot welded joint

influence on the tensile-shear force of (Steel + Steel) joint pursued by welding time and then squeeze time, whereas the squeeze time possesses a major impact on the tensile-shear force of (Steel + Al) joint followed by welding time and then current. Equation (2) explains how to compute the delta values listed in Table 5 as following:

$$\delta_{\mathrm{Al+Al}} = A_1 - A_2 = 1190 - 986.7 = 132.3\,, \tag{2}$$

Table 5.

Tensile-shear force response for mean

Level	Al + Al			Steel			Steel + Al		
	A	B	C	A	B	C	A	B	C
1	**1119.0**	989.7	1022.3	7090	7133	6617	**958.3**	458.3	554.3
2	986.7	1053.3	**1166.7**	**7350**	7110	**7527**	314.3	**753.0**	**726.7**
3	1097.3	**1160.0**	1014.0	7183	**7380**	7480	663.0	724.3	654.7
Delta	132.3	170.3	152.7	260	270	910	644.0	294.7	172.3
Rank	3	1	2	3	2	1	1	2	3

where: δ_{Al+Al} – the delta value of (Al + Al) for squeeze time, A_1 and A_2 – the highest and the lowest average responses, as listed in Table 5.

Minitab calculates the delta value for each parameter for the levels of that parameter. Then, it computes the rank, which is the order of the delta values from high to low. The parameter with the highest delta value is specified as rank 1, the parameter with the next highest delta value is specified as rank 2, and so on.

Fig. 4 views the influence of the three welding parameters used to spot weld the (Steel + Steel) joint on the tensile-shear force in terms of the response plots for S/N ratio and means. It is noticed that the tensile-shear force increases when the welding time is increased, and the highest values are recorded at the high level of squeeze time and current. This is also exhibited in Table 6, which illustrates the highest tensile-shear force response that appears in "bold and underline" values. This improvement in the tensile-shear force corresponding to the welding time may be ascribed to the increase of the weld nugget diameter regardless of the various welding variables [10, 15].

Fig. 5 present the effect of the three welding parameters used in (Steel + Al) spot welded joint on the tensile-shear force in terms of the response plots of

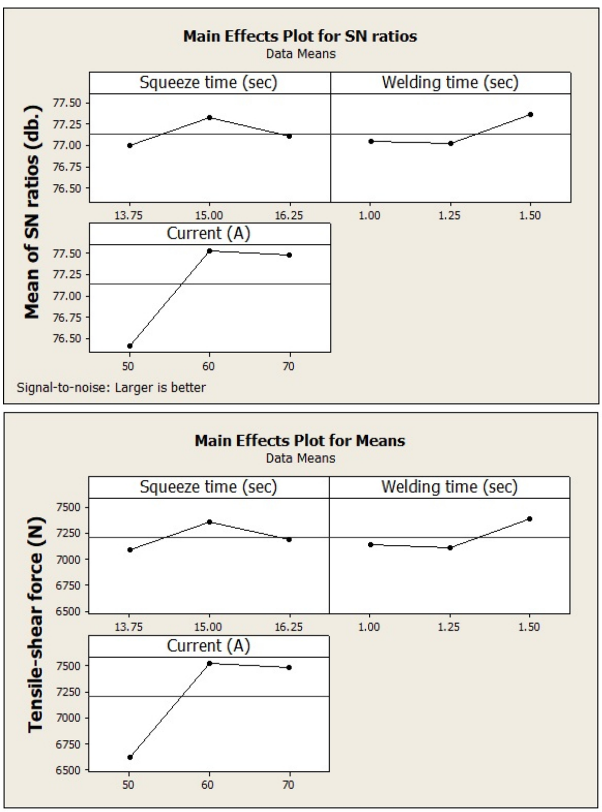

Fig. 4. The S/N ratio and means response plots for (Steel +Steel) spot welded joint

Table 6.

Tensile-shear force response for S/N ratio

Level	Al			Steel			Steel + Al		
	A	B	C	A	B	C	A	B	C
1	**60.84**	59.80	60.11	76.99	77.04	76.40	**59.54**	44.23	54.12
2	59.80	60.39	**61.31**	**77.32**	77.02	**77.53**	41.93	**56.92**	47.13
3	60.63	**61.07**	59.85	77.10	**77.36**	77.48	55.89	56.21	**56.11**
Delta	1.03	1.27	1.46	0.34	0.34	1.13	17.61	12.68	8.99
Rank	3	2	1	3	2	1	1	2	3

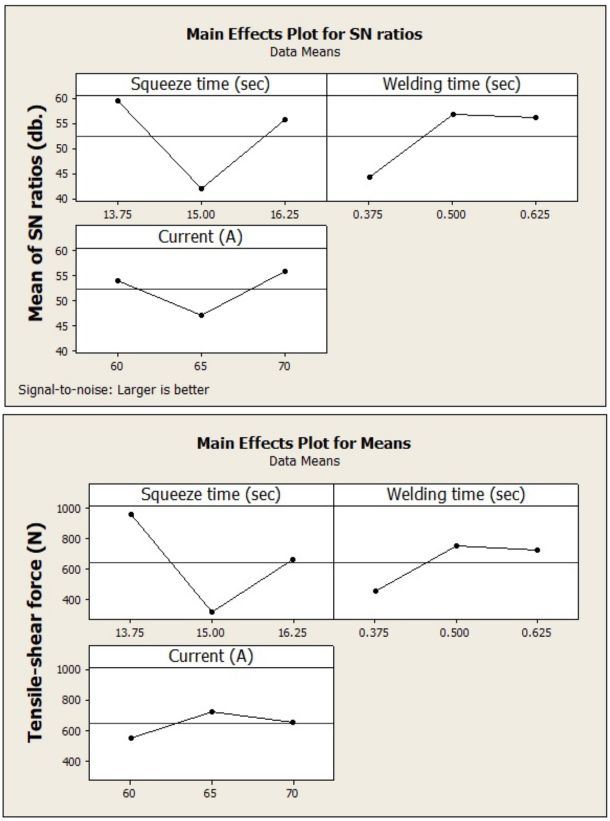

Fig. 5. The S/N ratio and means response plots for (Steel + Al) spot welded joint

S/N ratio and means. It is evinced that the tensile-shear force decreases when the squeeze time is increased, while it is enhanced with the increasing of welding time and current. Generally, the improvement in the results corresponding to the welding current and time is attributed to the heat generation during the welding process [14], which increases the nugget diameter that can be larger than before [15]. Due to the expulsion during the welding, the tensile-shear force does not grow with the extra increase in current, because both the heat and metal loss obtained from the weld reduce the tensile-shear force [16]. If the nugget diameter becomes the largest during welding, it cannot increase, and the additional fused metal is separated out from the spot area [3].

The "Larger is the better" values of the tensile-shear force related to squeeze time, welding time and current are listed as the optimum conditions of input variables for the optimum force in Table 7 for all groups. The mean optimum values of the tensile-shear force can be predicated and computed from the higher values in Table 5 [11, 12] as following:

$$F_{\text{opt}} = \left(\sum R\right) - 2\bar{X}, \tag{3}$$

where: F_{opt} – the optimum predicated force, R – the highest mean response of each parameter, as given in Table 5, $\bar{X}$ – the average mean, as computed in Table 4.

Table 7.
Optimum conditions and prediction results

Materials	Optimum condition	Prediction mean result	Prediction of S/N
Al	A1, B3, C2 13.75 sec, 1.25 sec, 64 A	1.4 kN	62.3 dB
Steel	A2, B3, C2 15 sec, 1.5 sec, 60 A	7.8 kN	77.9 dB
Steel + Al	A1, B2, C3 13.75 sec, 0.5 sec, 70 A	1.1 kN	68.0 dB

Similarly, the optimum S/N values can be predicated for all groups from the higher values in Table 6 as following:

$$\frac{S}{N}_{\text{opt}} = \left(\sum S\right) - 2\bar{Y}, \tag{4}$$

where: $\frac{S}{N}_{\text{opt}}$ – the optimum predicated S/N ratio, S – the highest S/N ratio response of each parameter, as listed in Table 6, $\bar{Y}$ – the average mean, as calculated in Table 4.

For instant, the optimum predicated force and the optimum predicated signal to noise ratio of aluminum are:

$$F_{\text{opt}} = 1119.0 + 1160.0 + 1166.7 - (2 * 1067.667) = 1.4\ \text{kN},$$

$$\frac{S}{N}_{\text{opt}} = 60.84 + 61.07 + 61.31 - (2 * 60.444) = 62.3\ \text{dB}.$$

The results associated to the correlation coefficients are tabulated in Table 8. The positive value refers to the enhancement of the outputs with the increase of input variables, but the negative value indicates that the outputs will be decreased

Table 8.

The outputs correlation coefficients

Tensile-shear force with:	Squeeze time	Welding time	Current
Al + Al	−0.049	0.388	−0.019
Steel + Steel	0.082	0.217	0.758
Steel + Al	−0.353	0.318	0.120

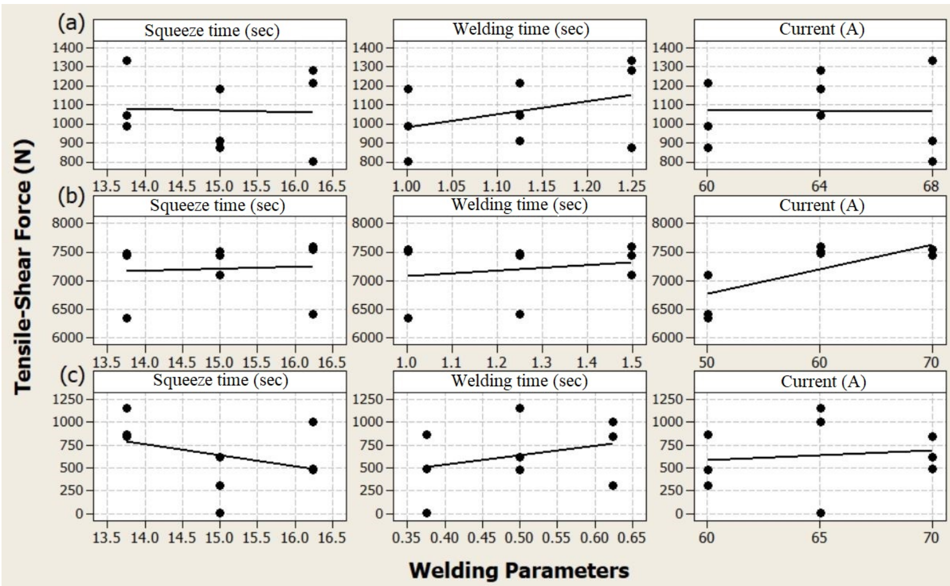

Fig. 6. Linear regression of output results for (a): (Al + Al), (b): (Steel + Steel), and (c): (Steel + Al) spot welded joints

with the increase of input variables. Minitab 16 program was used to calculate the correlation coefficients. A linear regression model was estimated by Minitab 16, as illustrated in Fig. 6.

The relation model between a separate factor and an output response by fitting the linear equations allows recognizing the data [13]. The tensile-shear force equations for (aluminum to aluminum), (steel to steel), and (steel to aluminum) spot welded joints according to the linear regression can be predicated as follows:

$$F_{TS} = a + (b \times W), \qquad (5)$$

where: F_{TS} – the tensile-shear force, a and b – constants, which are obtained by Minitab, and are listed in Table 9, W – welding variable value.

It is noticed that the tensile-shear force of (Al + Al) joints reduces as the current and squeeze time are increased, while it increases as the welding time is increased, but the tensile-shear force of (Steel + Steel) joints increases with the increasing of squeeze time, welding time and current. Also, the tensile-shear

Table 9.

Constant values of linear regression equation (5)

	Aluminum		Steel		Steel to Aluminum	
	a	*b*	*a*	*b*	*a*	*b*
Squeeze time	1198	−8.67	6648	37.3	2417	−118.1
Welding time	301.2	681.3	6590	494	113.2	1064
Welding current	1134	−1.04	4619	43.15	−7	10.03

force of (Steel + Al) joints decreases with the increasing of squeeze time, but it increases with the increasing of welding time and current. In general, the tensile-tensile-shear force is improved by the increase of welding time and current which may be ascribed to the increase of the nugget diameter during welding process [3, 6, 7, 10, 14, 15]. The longer welding time led to dismissing the fused metal besides the increase of the indentation depth which influenced the tensile-shear force [15].

5. Conclusions

This research clarifies the methodology for investigating the influence of the spot welding parameters on the tensile-shear force for similar and dissimilar spot welded joints of aluminum and steel materials. The "Larger is the better" approach was applied in Taguchi approach using Minitab 16 software to design the experiments and analyze the results. This methodology was designed to predict which input variables give the optimum responses.

According to the results obtained in the present work, the following conclusions can be drawn:

1. The optimum results can be achieved by a parametric optimization method, which provides a short period of time with a lower cost.
2. The dissimilar welded joints (steel to aluminum) are not effective without using a copper thin sheet between the dissimilar materials to be welded.
3. Analysis of the experimental results through the signal to noise ratio and means responses exhibited that the significant influence on the tensile-shear force for the similar material joint is the current. While, the squeeze time possesses a major impact pursued by welding time and then current for the dissimilar material joint.
4. Tensile-shear force enhanced as the welding time was increased for the all welded joints. But, the other parameters exhibited a different behavior, and the linear regression of the output results demonstrated this behavior. For the dissimilar joints, it is preferred to apply a lower squeezing time with a higher welding time and current.
5. Tensile-shear force increased with the rise of current for the similar (steel to steel) and dissimilar (steel to aluminum) spot welded joints, whereas it

had the best result at 64 A for the similar (aluminum to aluminum) spot welded joints.

6. The optimum spot welding parameters are 13.75 sec, 1.25 sec, 64 A, 15 sec, 1.5 sec, 60 A and 13.75 sec, 0.5 sec, 70 A for similar (aluminum to aluminum), (steel to steel) and dissimilar (steel to aluminum) spot welded joints, respectively which give the optimum tensile-shear force.

It should be mentioned here that the current research can improve the spot welding process for similar and dissimilar welded joints through predicting the optimum input welding parameters for the optimal responses in order to avoid the encountered problems in the spot welding procedures of different structures as well as to reduce many expensive welding trials.

Manuscript received by Editorial Board, February 04, 2020;
final version, April 27, 2020.

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