An Experimental Investigation on Comparison of the Similar and Dissimilar Resistance Spot Welding of St12 and Galvanized Steel using Design of Experiments

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Abstract: In the present research, similar and dissimilar resistance spot welding (RSW) process of St12 and galvanized steel sheets with thickness of 0.9 mm was investigated. The experiments were carried out based on the statistical design of experiments (DOE) approach to investigate the effect of RSW parameters on the welding quality, achieving the mathematical regression equations and predicting the new results. Welding time and electrode force were considered as the input process variables while the tensile-shear strength of the joints was considered as the process response. By comparing three RSW types, galvanized steel has the highest tensile-shear strength. Statistical analysis shows that tensile-shear strength is increased with increasing electrode force and welding time. Good agreement between the verification tests and the optimization results revealed that the statistical modelling would be appropriate for RSW process. Welding time (T) = 5 s and electrode force (P) = 925 N, welding time (T) = 5 s and electrode force (P) = 1100 N and welding time (T) = 3 s and electrode force (P) = 925 N were obtained as the optimum settings for similar RSW of St12, dissimilar RSW of St12 to galvanized steel and similar RSW of galvanized steel, respectively.

Keywords: Design of experiments, Dissimilar welding, Optimization, Resistance spot welding, Tensile-Shear strength

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1 INTRODUCTION

Resistance spot welding (RSW) is a joining technology extensively used in manufacturing industries to join sheet metals. RSW is a thermo-electric process in which a strong electric current through the electrodes is applied and the heat generated due to the electrical resistance of the sheet metals results in a weld nugget [1]. Pressure exerted by electrodes lead to hold the work-pieces together. Therefore, a localized weld was produced to join sheet metals. Very short process time, no consumables such as filler materials, operator safety because of low voltage, clean and environmentally friendly, ease of automation, requiring relatively low levels of operator skill and a reliable electro-mechanical joint are some of advantages of RSW [2]. Choosing the process input variables is the main challenge for the manufacturer to obtain high quality joints. Carrying the experiments out based on the trial and error method conventionally is time consuming and causes a lot of errors. Design of experiments (DOE) usages has grown rapidly in many different applications in the last two decades [3, 4]. The advantages of response surface methodology (RSM) as one of the design of experiments approach are: considering all parameters variation and interaction effects, proper reduction in the number of experiments and developing regression mathematical functions to achieve a logical relation between input and output parameters [5].

Jidong Kang et al. [6] studied the effect of adhesive on dissimilar resistance spot welding of Aural2 to AA5754 and fatigue property was analyzed. X-ray computed tomography during interrupted fatigue testing of the spot welds was conducted. Full factorial design of experiments was applied for resistance spot welding of 2 mm CRCA sheet. They considered weld current and time as input variables [7]. Researchers optimized parameters of RSW that effect on tensile-shear strength by using design of experiments methods [7]– [11]. Mittal and Dwivedi [12] conducted the resistance spot welding in order to study the effects of process parameters on various characteristics of weld joints based on the Box-Behnken design and RSM. Weld strength was analyzed through experimental tests. Process parameter optimization was performed and the results compared with simulated results obtained by SYSweld software. Microstructural study and tensile-shear strength of dissimilar resistance spot welding of DP600 and DC54D steels were investigated by Yuan et al. [13]. Effect of surface lubrication on weldability of hot dip galvanized steel sheets were studied by Spitz et al. [14]. Dissimilar welding of different materials to galvanized steel were investigated recently [15]- [17]. Joining of AZ31 magnesium alloy and electro-galvanized DP600 steel were reported via resistance spot welding with a hot-dip galvanized Q235 steel interlayer [15]. Hamidinejad et al. [18] investigated the effects of process parameters (i.e. welding time, electrode force, and holding time) on the quality of the joints in resistance spot welding of galvanized steel sheets. They proposed an artificial neural network (ANN) in order to develop an accurate relationship between the process parameters and tensile-shears strength of the welds. Resistance spot weldability of Fe–31Mn–3Al–3Si twinning induced plasticity (TWIP) steel was investigated by razmpoosh et al. [19]. The microstructural evolution was studied to assess the effects of experimental conditions on spot welded (RSW) joints. Nowadays, despite the development of modern joining methods, conventional resistance spot welding is still the main joining technique in automotive structures. The unique status of RSW process is related to the respective technical and economic benefits as high potentiality for automation and procedure simplicity, low process cost and time and consequently high productivity [20]– [22]. The parametric characterization of the weld nugget of 304L stainless steel with 1.5 mm thickness was studied in various welding parameters such as the weld time and welding current [23]. The effects of resistance spot welding process parameters on the strength of eutectoid steel (AISI 1075) sheet was investigated by using response surface methodology [24]. They mathematically modelled the variation of tensile-shear strength depending on process parameters by using the regression analysis.

However, notwithstanding the great efforts by various researchers, dissimilar RSW of St12 to galvanized steel is still not studied. The purpose of the present study is investigating the effect of resistance spot welding process parameters, electrode force (F) and welding time (T) on the tensile-shear strength of St12, galvanized steel and their dissimilar welded samples, through using RSM. The dissimilar joining of St12 to galvanized steel and comparison to similar welding are innovations of the present study over the previous researches. The statistical analysis is performed through the Minitab 17 software and regression equations are developed. Optimization of the RSW parameters is performed for achieving higher tensile-shear strength. In order to validate the results of optimization, three welding experiments are carried out at optimum settings and compared with the optimization results.

2 EXPERIMENTAL DESIGN AND METHODOLOGY

Response surface methodology, one of the optimizing techniques, is widely used in describing different processes and suggestion of optimum answers [25]. Response surface method is a set of statistical and mathematical edicts which are used for modelling and predicting results, affected by input parameters.

Response surface method explains relations between answers and input controllable parameters [26]. When all independent variable parameters during experiment are measurable and controllable, the response surface will be represented by [25]:

$$Y = f(x1, x2, x3, \ldots\ldots, xk) \quad (1)$$

Where, k is the number of independent variables. It is necessary to find a logical function to attribute the response to the independent variables. Thus, a second order polynomial function, as shown in equation 2, is usually used in response surface methodology [27].

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

In the above equation, β is constant, βi is linear coefficient, βii is coefficient of quadratic, βij is interaction coefficient and ε is the error of the parameters of regression.
Table 1 shows two input variables of the experiment, coded values and actual values of their levels. In the present study, in order to conduct the experiments, five-level RSM design with two parameters was applied (see Table 2). Figure 1 shows the schematic of the designed matrix. This plan includes four experiments as factorial points in cubic vertex, eight experiments as axial points and three experiments in the cubic center as center points experiments, which means a total of 15 experiments have been designed.

Table 1 Independent process parameters with design levels

Variable	Welding Time	Electrode Force
Notation	T	F
Unit	[S]	[N]
-2	1	400
-1	3	575
0	5	750
1	7	925
2	9	1100

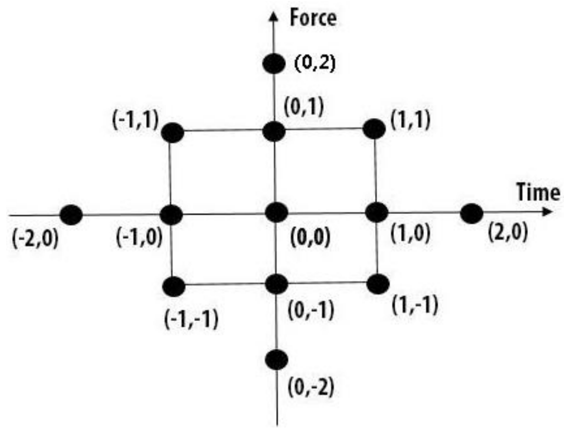

Fig. 1 Experimental space with the design levels (-2 to +2) for the two parameters varied, according to the design matrix in Tables 1 and 2

Table 2 Experimental layout and multi-performance result

Experiment No.	Time [s]	Force [N]	Shear Strength G-G [N]	Shear Strength St-G [N]	Shear Strength St-St [N]
1	-1	1	5125.7	2930.7	3924
2	1	0	4426.8	3028.8	3531.6
3	0	0	3531.6	3090.2	4316.4
4	0	1	4794.6	3764.6	4390
5	1	1	4512.6	3617.4	4230.6
6	1	-1	2673.2	1508.3	3188.3
7	-1	-1	2869.4	1422.5	3151.5
8	-1	0	4206	2759.1	3421.2
9	0	0	3126.9	2403.5	3985.3
10	0	-1	2648.7	2084.6	2820.4
11	0	0	3838.2	2697.8	3200.5
12	0	2	4696.5	4144.7	3752.3
13	0	-2	1250.8	1606.4	1532.8
14	-2	0	3372.2	3764.6	3200.5
15	2	0	3114.7	3372.2	3041.1

3 EXPERIMENTAL WORK

Stainless steel St12 and galvanized steel sheets with thickness of 0.9 mm were used as the material workpiece in this study. Chemical composition of the material is presented in Table 3, which has been reported by average of three X-ray fluorescence (XRF) measurements.

Table 3 Chemical composition of material workpiece (wt %)

Material	Mn	C	P	S	Si	Fe
ST12	0.50	0.10	0.035	0.035	-----	Ba.
Galvanized	-----	0.25	0.04	-----	0.04	Ba.

The specimens were cut by a hydraulic guillotine shearing machine in dimensions of 100 mm (length) × 25 mm (width) × 0.9 mm (thickness) in accordance with AWS D17.2/D17.2M:2007 as shown in Figure 2-a.

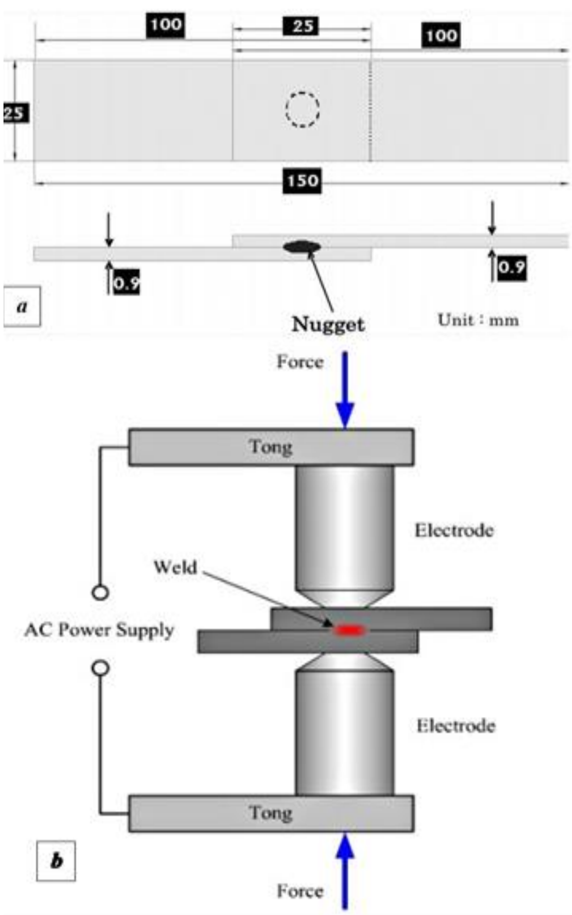

Fig. 2 The shape of specimens and the schematic diagram of the process: (a): specimens used in the RSW in accordance with AWS D17.2/D17.2M:2007 and (b): a schematic diagram of resistance spot welding process

The RSW was performed using resistance spot welder machine made by Crop Company. Copper electrode with the diameter of 8mm was used in the RSW process while the electrode was ground. The diameter of the electrode was measured and checked for each welding before conducting the operation test because of the wear in electrode. Schematic diagram of the RSW process is illustrated in Figure 2-b. Surfaces of the samples were cleaned with the acetone before RSW. The welding time (T) and the electrode force (F) were chosen as the process parameters while the voltage and current was fixed at 15 V and 70 A, respectively. Two aligned electrodes close upon the overlapped sheets (by 25 mm, see Figure 2-b) to hold them in position to produce spot welds at the center.

Experiments were conducted in accordance with DOE design matrix presented in Table 2 in a random order to avoid the effect of any error in the experiment. This same matrix design was used for three types of resistance spot welding (i.e St12 to St12, galvanized to galvanized and galvanized to St12 dissimilar joining). Resistance spot welded specimens are shown in Figure 3 according to Table 2 setting.

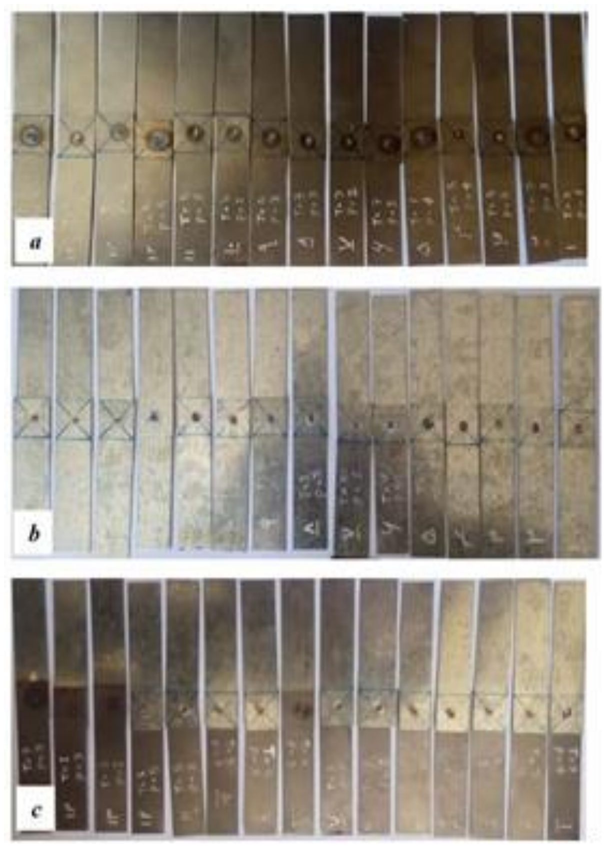

Fig. 3 Resistance spot welded specimens according to table 2 experiments: (a): ST12 – ST12 and (b): galvanized-galvanized c) ST12 – galvanized

For testing the mechanical properties of the joints, the tensile shear test was conducted using SANTAM universal testing machine (STM-250 model). Tensile shear test was performed at room temperature and the cross-head speed was 1 mm.min−1. Figure 4, shows the resistance spot welded specimen during the experimental tensile tests.

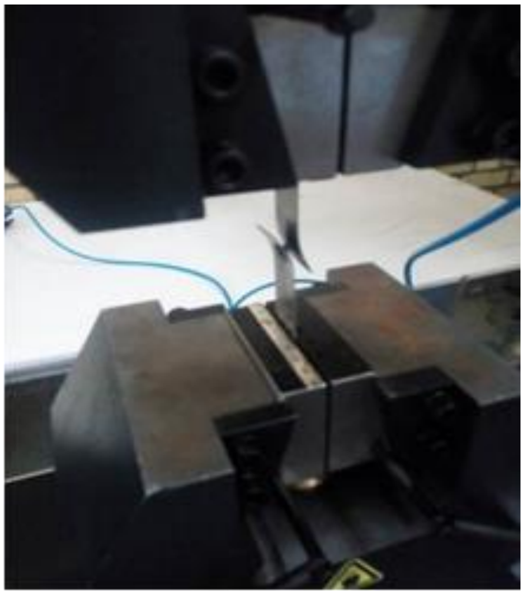

Fig. 4 Resistance spot welded specimen during the experimental tensile tests

4 RESULTS AND DISCUSSION

Resistance spot welding process was conducted to joint St12, galvanized steel and dissimilar joining of them based on RSM. The influence of electrode force (F) and welding time (T) on tensile-shear strength of the joint in RSW were studied. Analysis of variance (ANOVA) was employed using Minitab statistical software in order to investigate significant effective parameters on resistance spot welding and interpretation of the results. In these analyses, a full quadratic polynomial function was used.

4.1. Similar resistance spot welding of St12

According to variance Analysis of resistance spot welding of St12-St12, Table 4, electrode force (F) is linear effective parameter. The quadratic term of electrode force (F2) and welding time (T2) have a significant effect. Moreover, interaction effect of parameters has insignificant effects on each other. The regression equation obtained is evaluated as significant and Lack-of-Fit as insignificant. In the best analysis, regression is to be significant and Lack-of-Fit insignificant. Therefore, according to the analysis, the final regression in terms of coded parameter values yields in equation (3).

$$\text{Tensile-shear strength of RSW St12-St12} = 3871 + 9.6\,T + 558.8\,P - 175.1\,(T)^2 - 280.1\,(P)^2 \quad (3)$$

Table 4 Revised analysis of RSW tensile-shear strength of St12-St12

Source	Df	Adj.ss	Adj.ms	F-value	P-value
Model	4	6204302	15511075	13.25	0.001
Linear	2	4373129	2186565	18.68	0.000
Time	1	1302	1302	0.01	0.918
Pressure	1	4371828	4371828	37.35	0.000
Square	2	1831172	915586	7.82	0.009
T ×T	1	663588	663588	5.67	0.039
P × P	1	1697279	1697279	14.5	0.003
Error	10	117045	117045	-	-
Lack-of-fit	8	513527	64191	0.2	0.963
Pure error	2	656924	328462	-	-
Total	14	7374753			

Figure 5 illustrates response surfaces of the tensile shear strength in terms of input parameters. As it is observed in Figure 5-a and b, it is evident that with increasing the welding time and the electrode force, the tensile shear strength is increased. Increasing the welding time causes to generated heat in the welding area and also penetration depth is increased. Thus, the strength of spot welded joints is increased. Pursuant to Joule law: Q = RI2t where, Q (J) is generated heat, R (Ω) is resistance of the workpiece, I (A) is welding current and t (s) is welding time. With increasing welding time, the tensile -shear strength of welding specimens is severely increased.

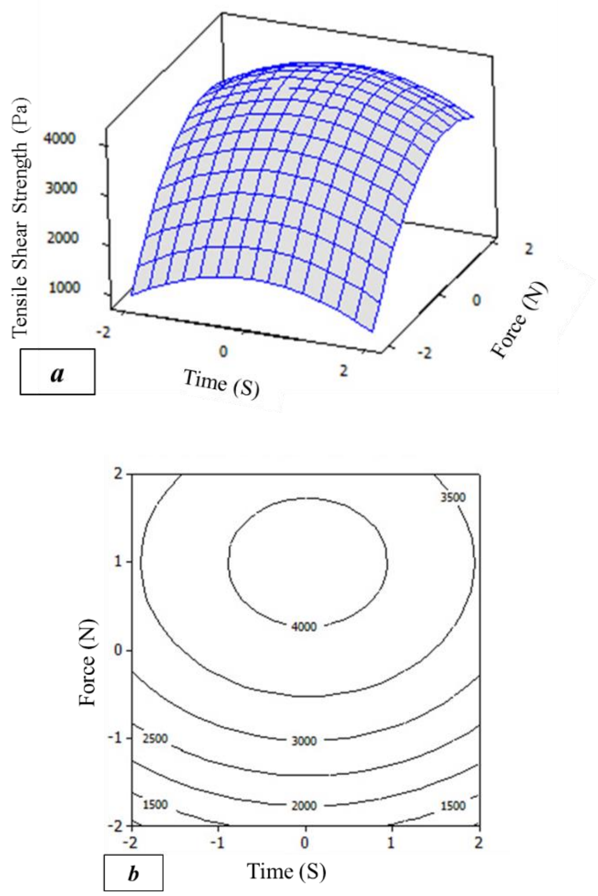

Fig. 5 (a): Response surface of tensile shear strength of St12-St12 joints in terms of the input parameters and (b): contour plot in terms of the input parameters

Figure 6 shows the main effect plot parameters for the tensile-shear.

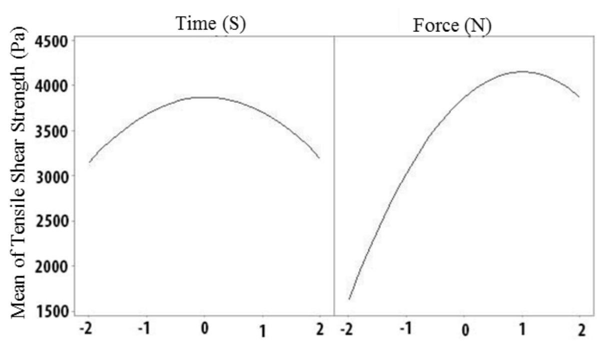

Fig. 6 Main effect plot for the tensile-shear strength of St12-St12 joints

Strength is predicted from the mathematical model. The results show some persuasive trends of process parameters that have effect on the tensile-shear strength which is explained in the previous paragraph. As it is obvious in Figure 5 and is depicted in Figure 6, increasing welding time and electrode force more than enough, has a reverse effect on joint strength.

The residual plot for tensile-shear strength of St12-St12 joints is displayed in Figure 7. As it is shown in the normal probability diagram, the response tensile-shear strength, in comparison to others around the diagonal line, is scattered and shows a normal distribution. Therefore, the final extracted regression model is a suitable model for prediction and investigation the effects of parameters in proportion to other responses. Thus, the result of mathematical equation is a desirable model to predict and investigate the effect of F and T using the experiment parameter. An F-test is any statistical test in which the test statistic has an F-distribution under the null hypothesis. A t-test is any statistical hypothesis test in which the test statistic follows a Student's t-distribution if the null hypothesis is supported.

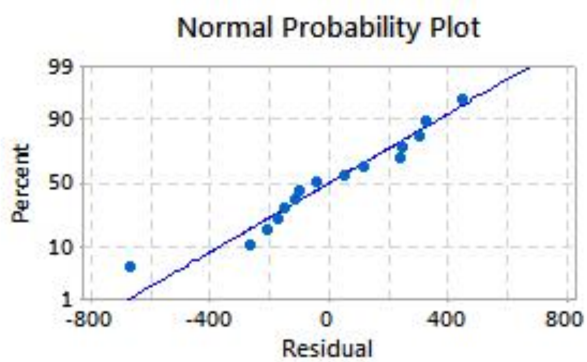

Fig. 7 The normal probability plot for tensile-shear strength of St12-St12 joints

4.2. Dissimilar resistance spot welding of St12 to galvanized steel

Table 5 shows analysis of variance for the tensile-shear strength of dissimilar St12-Ga resistance spot welding. As shown in Table 5, the main effective parameter is electrode force (F) and welding time (T) is not significant. Among quadratic terms, only the quadratic term of welding time (T2) has a significant effect and no interaction effect of parameters was identified as the significant term. As Table 5 indicates, Lack-of-Fit was determined as insignificant and it shows that a suitable analysis has been performed. According to performed analyses of variance (ANOVA) presented in Table 5, equation 4 represents the regression equation for the tensile-shear strength of dissimilar St12-Ga resistance spot welding considering significant parameters based on coded values.

Tensile-shear strength of RSW St12-Ga = 2647+ 18 T + 741 F + 177.7 T^2 (4)

Table 5 Revised analysis of RSW tensile-shear strength of St12-St12

Source	Df	Adj.ss	Adj.ms	F-value	P-value
Model	3	8479391	2826464	15.48	0.000
Linear	2	7691718	3845859	21.07	0.000
Time	1	4732	4732	0.03	0.875
Pressure	1	7686986	7686986	42.11	0.00
Square	1	787673	767873	4.31	0.062
T × T	1	787673	787673	4.31	0.062
Error	11	2008194	182563	–	–
Lack-of-fit	9	1770812	196757	1.66	0.432
Pure error	2	237382	118691	–	–
Total	14	10487586	–	–	–

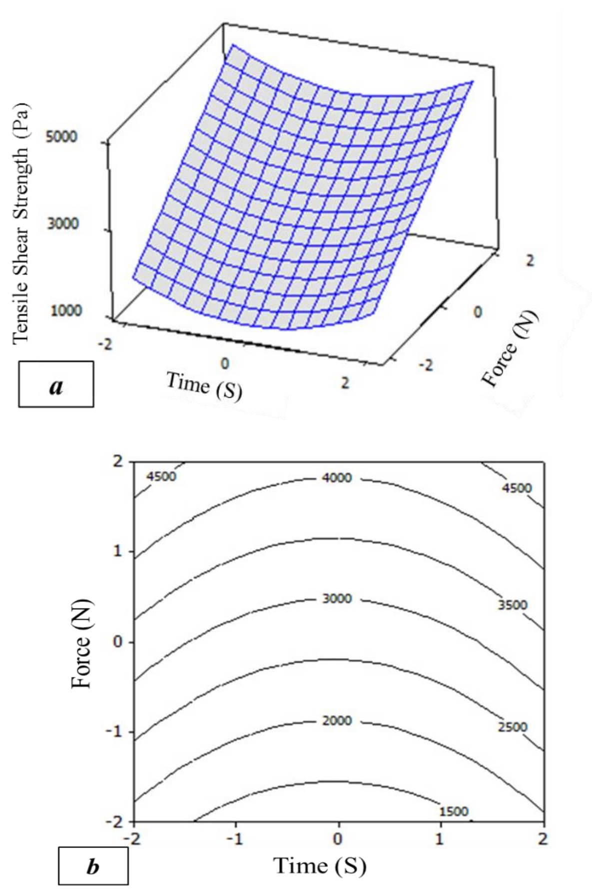

Fig. 8 (a): Response surface of tensile shear strength of dissimilar welding in terms of the input parameters and (b): contour plot in terms of the input parameters

Figures 8 and 9 display the response surface and the main effect plots of input variables versus tensile-shear strength of dissimilar St12-Ga joints, respectively. In both Figures, it is evident that the response has a linear relation with electrode force. Increasing the electrode force leads to increase in the tensile-shear strength. The parabolic curvature of the main effect plot of the welding time shows different manner of this parameter on the response due to different melting points and physical properties of two materials. Different thermal properties cause different melting time; for example, when Galvanized steel is melted St12 does not melt at that condition (melting point of St12 and galvanized steel are around 1400 °C degree and 400 °C, respectively). Because of this manner, welding time is not a significant term in the statistical analysis of dissimilar welding.

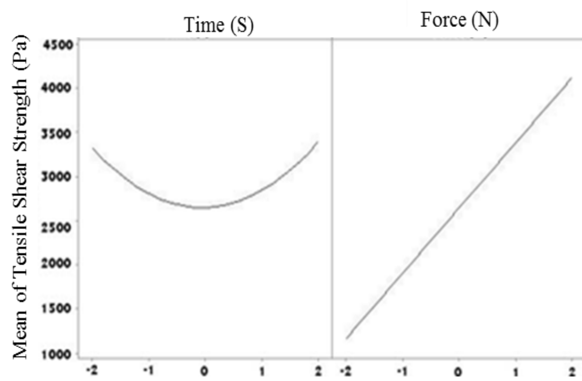

Fig. 9 Main effect plot for the tensile-shear strength of dissimilar joints

4.3 Similar resistance spot welding of galvanized steel

According to the results of analysis of variance on the tensile-shear strength of resistance spot welding of Ga-Ga, electrode force parameter is effective (see Table 6). Quadratic effect of the electrode force (F2) is significant and no interaction effect of the parameters are identified as significant terms. From the statistical analysis of the Minitab software, the following regression formula for the tensile-shear strength of resistance spot welding of Ga-Ga as a function of the varied process parameters was developed:

Tensile-shear strength of RSW Ga-Ga = 3768 – 79 T + 938 F -166.9 F^2 (5)

Table 6 Revised analysis of RSW tensile-shear strength of Ga-Ga

Source	Df	Adj.ss	Adj.ms	F-value	P-value
Model	3	13101405	4367135	22.59	0.000
Linear	2	12406672	6203336	32.09	0.000
Time	1	86979	86979	0.45	0.516
Pressure	1	12319692	12319692	63.74	0.000
Square	1	694734	694734	3.59	0.085
P × P	1	694734	694734	3.59	0.085
Error	11	2126153	193287	-	-
Lack-of-fit	9	1871576	207953	1.63	0.437
Pure error	2	254578	127289	-	-
Total	14	15227558	-	-	-

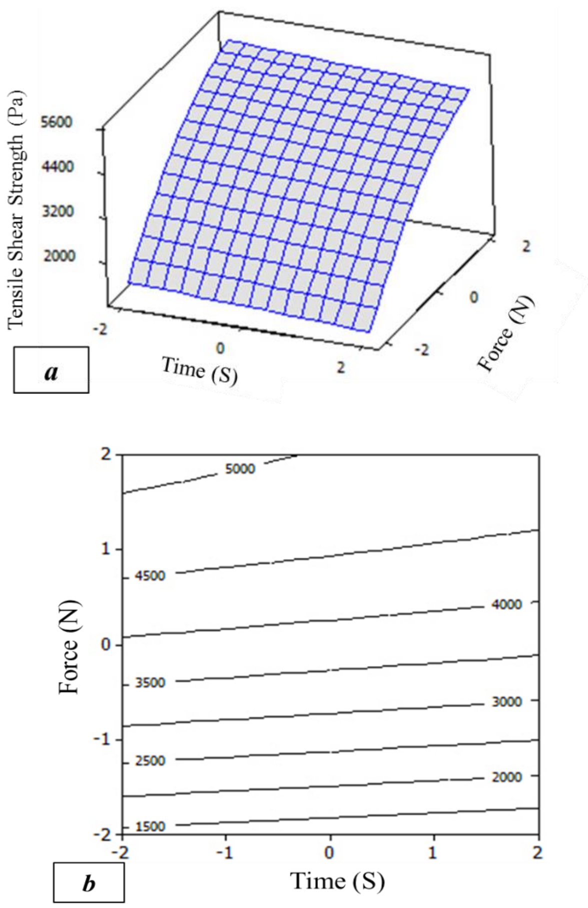

Fig. 10 (a): Response surface of tensile shear strength of Ga-Ga welding in terms of the input parameters and (b): contour plot in terms of the input parameters

Response surface and the main effect plots of input variables versus tensile-shear strength of Galvanized joints are depicted in Figures 10 and 11, respectively. It could be understood that electrode force has a direct influence on response while welding time does not have a significant effect. The tensile-shear strength increases by increasing the electrode force. Comparing galvanized steel joints with St12 joints (see Table 2), higher tensile-shear strength occurs in galvanized joint in the same setting. Lower melting point of galvanized steel is a reason for this difference. Considering the effect of welding time on 3 types of joint (see Figures 5, 8 and 10), it effects on tensile-shear strength in 3 different modes; concave downward, concave upward and a negative slope line, respectively. Thus in galvanized steel, increasing welding time has a reverse effect on tensile-shear strength.

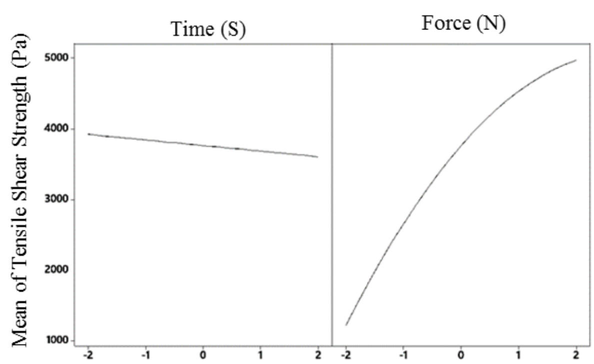

Fig. 11 Main effect plot for the tensile-shear strength of Ga-Ga joints

5 OPTIMIZATION

Statistical analysis of obtained data from experimental tests was performed. Regression equations explain logical relations between input variables and responses. The response optimizer option within the DOE module of Minitab 17 software package has been used to optimize input parametric combinations resulting in the most desirable compromise between different responses using desirability function [28], [29]. Maximum tensile-shear strength is the criteria for the optimization. Figure

12 shows the visual representation of the optimization results of three optimization processes. Each cell in Figure 12 presents how the response varies as a function of the input process parameters while the other parameters are kept fixed. Also, the vertical lines inside the cells show current optimal parametric settings whereas the spotted horizontal lines denote the current response values.
The most important part is the optimal parameter settings required to realize the process criteria, located in the middle row between the high and low row, symbolized by “cur” and expressed in coded procedure. Verification experiments were performed at the obtained optimal input parametric setting to compare the actual tensile-shear strength with that as optimal responses obtained from optimization. Table 7 presents the optimization results along with experimentally obtained responses and their percentage relative verification errors. In Figure 13, three calculated load-distance diagrams in the tensile test for three types of resistance spot welding in optimum conditions are shown. Figure 13-a, b and c depict the tensile diagram for St12-St12, Ga-Ga and dissimilar welding of St12-Ga, respectively.

6 CONCLUSIONS

In the present study, tensile-shear strength of the similar and dissimilar resistance spot welding of St12 and galvanized steel was investigated. The obtained data from the experimental tests were analysed by DOE. Regarding the performed experiments and statistical analyses, the following conclusions can be drawn:

1- Developed curvature of the response surface (3D plots) designates appropriate use of Response Surface Methodology. In addition, it shows that the parameters of the process have been selected properly and optimized configuration of the concerned parameters has existed.

2- The results show that welding time displays more effects on tensile-shear strength in RSW. Because with increasing the welding time, generated heat in the welding area and also penetration depth are increased. Therefore, the strength of spot welded joints is increased.

3- Similar RSW of galvanized steel has the highest strength in comparison with St12 and dissimilar galvanized steel to St12. Dissimilar RSW of St12 to galvanized has the lowest tensile shear-strength.

4- By performing an optimization process using desire ability approach, the following settings can be described as the optimum settings; RSW of St12 process: welding time (T) = 5 s and electrode force (P) = 925 N, dissimilar RSW of St12 to galvanized steel: welding time (T) = 5 s and electrode force (P) = 1100 N and RSW of galvanized steel: welding time (T) = 3 s and electrode force (P) = 925 N.

Table 7 Optimum prediction results and experimental validation

Category		Input Parameters		Desirability	Response	
		T [s]	P [N]		Tensile-Shear strength [N]	
Similar RSW of St12	Coded value	0	1	0.91582	Experiment	4390
					Predicted	4149.4706
	Actual Value	5	925		Error %	5.79%
Dissimilar RSW of St12 to Ga	Coded value	0	2	1	Experiment	4144.7
					Predicted	4876.8502
	Actual Value	5	1100		Error %	-15.01%
Similar RSW of Ga	Coded value	-1	1	1	Experiment	5125.7
					Predicted	5134.4119
	Actual Value	3	925		Error %	-0.169%

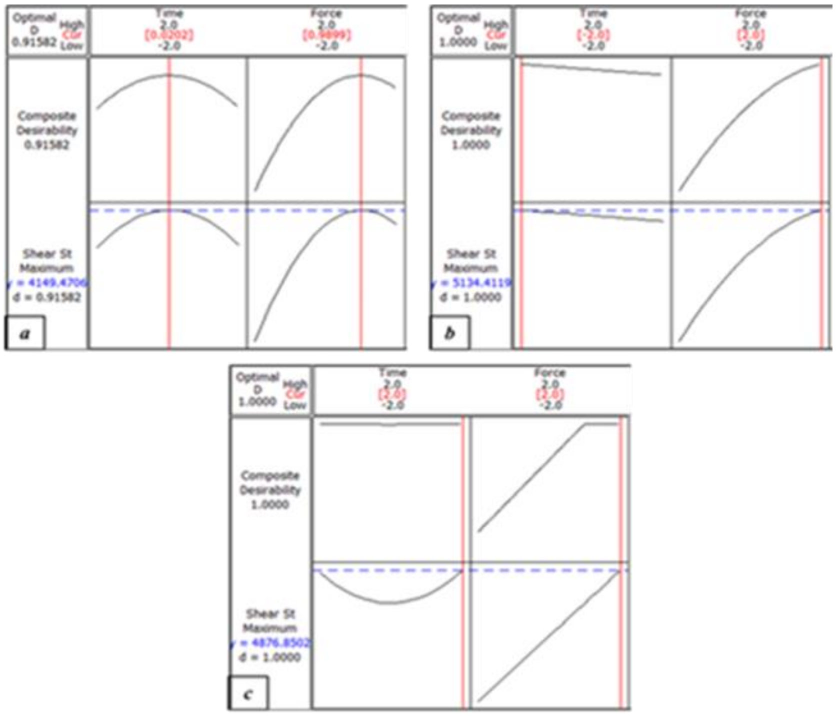

Fig. 12 Calculation of optimal parameters a) St12-St12 b) Ga-Ga c) St12-Ga

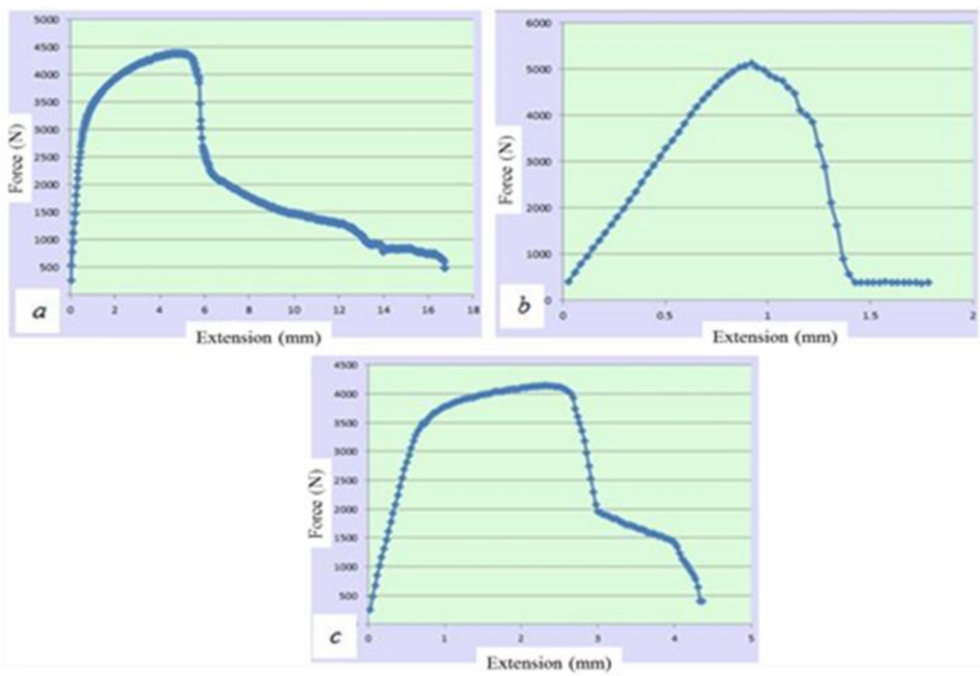

Fig. 13 Load-displacement diagrams for the resistance spot welded joints a) St12-St12 b) Ga-Ga c) St12-Ga

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