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Investigation of the Effect of Some Factors on Resistance Spot Welding of DKP Steel Using Response Surface Method

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Abstract: Due to many advantages of Resistance Spot Welding (RSW) such as inexpensive, easy to automate, and high-quality joints capability, it is preferred and used mostly in automative industry. In the RSW process, metals are joined based on the contact resistance between the electrodes and metals. During the process, the cause of the welding nugget on the surface is the increase in temperature because of the electrical resistance of the materials and the melting formed. Many factors affect the success of the RSW process. In this research, we investigated the possibility of mild steel (DKP) sheets welding using the RSW method. There important factors, i.e., time, pressure, and current were tested. The results were evaluated by measuring the shear strength of DKP sheets having 1 mm thickness. To reduce the number of experiments, the experiments are designed and carried out according to the Box-Behnken experimental design. It is one of the most useful response surface methods (RSM). It was aimed to find the effects of investigated parameters and their possible interactions on tensile strength of DKP sheets joined by RSW process. Another important purpose was to generate a mathematical model which can be used to estimate tensile strength as a function of tested parameters. As a result, a second-order model which was important statistically was developed and it was capable of to estimate the dependent variable in very high accuracy.

Keywords: Resistance spot welding, DKP steel, Tensile strength, Response surface method, Box-behnken design

Introduction

Mild steels are widely used in various construction manufacturing in all areas of industry. Joining these materials, which can be in different forms, by welding techniques is a frequently used method, especially in the automotive sector. The temperature of the welding interface must be above or very close to the melting temperature for successful bonding. Although there are many different welding methods, we can collect them into two main groups as melting and solid-state welding methods. Resistance spot welding technique, which is a solid-state welding method, is used to join sheet-shaped materials.

Electric resistance spot welding is a method of welding with heat that occurs due to the resistance of the work pieces against the electric current passing through the work pieces held together under pressure between the electrodes. The contact surface of the parts to be welded is heated with low voltage and high current applied for a short time and transformed into a molten welding core. When the electric current is cut off, the molten metal quickly cools and solidifies. Meanwhile, the electrodes continue to hold the welded parts tightly and then retract

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and release the part. Welding process is usually completed in less than one second. (Yener, 1999; Baytemir, 2011).

The main resource variables affecting the welding quality are listed as follows; effect of the welding current, effect of the welding time, effect of electrode force, effect of electrode composition and shape on heating, material of workpiece, effect of surfaces of parts to be welded, effect of distance between welded points, contact conditions of electrode and workpiece (Hayat, 2005). Resistance spot welding is an easily controllable process, inexpensive equipment and a serially repeatable method. The welding process widely used in joining metal sheets such as iron, steel, aluminium alloys, magnesium alloys, titanium alloys, super alloys, and joining of different metals (Kahraman, 2007; Qiu et al., 2009; Han et al., 2010; Shirmohammadi et al., 2017; Bemani et al., 2020; Babua et al. 2012).

For the resistance spot welding, welding pressure, duration and current affect the welding quality depending on the sheet thickness. In this study, the effects of these three parameters on shear strength of resistance spot welded mild steels were determined using Box-Behnken experimental design.

Material and Method

In this study, we used sheets 1,0 mm in thickness and 20 mm x 40 mm in sizes (Figure 1). The diameter of spot size was 6 mm.

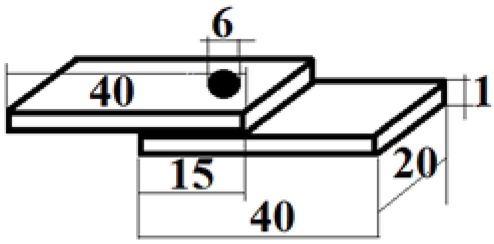

Figure 1. Dimensions in mm of the mild steels and welding diameter

The welding conditions were designed by Box-Behnken experimental method. The welding parameters used and their application values are:

Welding pressures: 500, 1000 and 1500 N
Welding currents: 2, 4 and 6 kA
Welding time: 20, 30 and 40 period

After welding, the strengths of the welds were determined using a universal tensile testing machine. An axial load was applied on room temperature with a chunk speed of 10 mm/min (Figure 2). The ultimate shear forces were reported as strength.

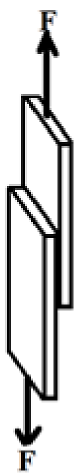

Figure 2. Determination of shear forces by universal tensile testing machine

Box-Behnken Design (BBD) of Experiments

In this research, Box-Behnken Design (BBD) which is one most important nonlinear model of Response Surface Methodology (RSM) was applied to reduce the number of experiments and to determine the main effects, interaction effects of the tested parameters (pressure, time and current) on the shear strength of resistance spot welded mild steels. The BBD also enables a quadratic model to estimate dependent variable(s) as a function of independent variables and optimize the desired input and output process parameters (Myers, et al., 2016).

In this study, we applied a BBD with 3 parameters and 3 levels to optimize 3 process parameters (pressure, time and current) in determining shear strength of resistance spot welded mild steel. Table 1 shows the coded and real levels of independent parameters. In this design, required number of experiments is 15 when repeated experiments at the middle levels of variables are 3 (Myers et al., 2016). Trial version of Design Expert 7.0 software was used for the Box-Behnken design of experiments and analyzing the results of experiments.

Table 1. Parameters tested and their levels

Independent parameters	Symbol	Code levels		
		-1	0	1
Pressure (N)	A	500	1000	1500
Time(period)	B	20	30	40
Current (kA)	C	2	4	6

Table 2 gives the 15 randomized experiments' levels of BBD in coded unites. Here, the codes -1, 0 and 1 are high, medium and low levels of the parameters respectively.

Table 2. The BBD of experiments and their coded levels

Experiment no	(A) Pressure (N)	(B) Time(Period)	(C) Current (kA)
1	-1	-1	0
2	1	-1	0
3	-1	1	0
4	1	1	0
5	-1	0	-1
6	1	0	-1
7	-1	0	1
8	1	0	1
9	0	-1	-1
10	0	1	-1
11	0	-1	1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

While analysing the 3 parameters and 3 levels BBD, a quadratic mathematical model which involves main, interaction and second order terms are obtained. General form of quadratic model for 3 parameters design to estimate the response is as following:

$$Y = b_0 + b_1A + b_2B + b_3C + b_{12}AB + b_{13}AC + b_{23}BC + b_{11}A^2 + b_{22}B^2 + b_{33}C^2 \quad \text{.............................(1)}$$

Results and Discussion

Analysis of Box-Behnken Design of Experiments

The shear force values obtained from the experiments that was designed according to the 3 parameters 3 levels BBD are given in Table 3. Using the trial version of Design Expert 7.0 software, these results were analysed. After evaluating the BBD, a second order mathematical model (Equation 2) where the shear force is estimated as a function of pressure, time and current variables was obtained. Equation in terms of coded factors is as following:

Shear force (N) = $5338.33+86.37A+359.37B+1990.25C+71.25AB+24.50AC+148.50BC+553.71A^2-683.29B^2-1181.04C^2$

The determination coefficient (R^2) of Equation 2 is 0.9703. This means that 97,03% of the total variation in estimating the shear force of resistant spot welded mild steels by using tested 3 variables can be explained by Equation 2, the remaining variance can be explained by the experimental errors.

Signaficance importance of the model terms of Equation 2 and adequacy of model was evalutaed by ANOVA (Analysis of Variance) and the results are given in Table 4. The model has a F value of 18.14 and p value of 0,0026, i.e., the model suggested is staticically significant at % 95 significance level (p<0,05). Therefore, this model is statistically adequate for estimating shear force of resistance welded mild steels. Lack of fit of the model is insignificant (p=0,0549>0,05) which is desired for a good model. The statistically important terms at 95% significance level are current and time. The linear (C) and second order effects of current (C^2) abd time (B^2) variables have more important effect on shear pressure than the other variables. Linear term of time (B) and second order term of pressure (A^2) are statistically important term at 90% significance level. The order of importance is $C>C^2>B^2>A^2>B$. Interaction terms (AB, AC and BC) are all insignificant.

Table 3. The BBD result of shear strength for resistance welded mild steels

Runs	(A) Pressure (N)	(B) Time(Period)	(C) Current (kA)	Shear force (N)
1	500	20	4	5000
2	1500	20	4	5050
3	500	40	4	5225
4	1500	40	4	5560
5	500	30	2	3016
6	1500	30	2	3120
7	500	30	6	6253
8	1500	30	6	6455
9	1000	20	2	750
10	1000	40	2	1523
11	1000	20	6	5128
12	1000	40	6	6495
13	1000	30	4	5492
14	1000	30	4	5336
15	1000	30	4	5187

Table 4. Analysis of Variance (ANOVA) table of response surface quadratic model (Eq. 2)

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	Significance
Model	$4.111x10^7$	9	$4.568x10^6$	18.14	0.0026	significant
A-Pressure (N)	59685.12	1	59685.12	0.24	0.6469	insignificant
B-Time(Period)	$1.033x10^6$	1	$1.033x10^6$	4.10	0.0986	*
C-Current (kA)	$3.169x10^7$	1	$3.169x10^7$	125.88	< 0.0001	**
AB	20306.25	1	20306.25	0.081	0.7878	insignificant
AC	2401.00	1	2401.00	9.538E-003	0.9260	insignificant
BC	88209.00	1	88209.00	0.35	0.5796	insignificant
A^2	$1.132x10^6$	1	$1.132x10^6$	4.50	0.0874	*
B^2	$1.724x10^6$	1	$1.724x10^6$	6.85	0.0473	**
C^2	$5.150x10^6$	1	$5.150x10^6$	20.46	0.0063	**
Residual	$1.259x10^6$	5	$2.517x10^5$			
Lack of Fit	$1.212x10^6$	3	$4.041x10^5$	17.37	0.0549	insignificant
Pure Error	46520.67	2	23260.33			
Cor Total	$4.237x10^7$	14				

*: Significant at 90% confidence level, **: Significant at 95% confidence level

Figure 3 shows that disribution of the residuals (difference between the actual and predicted shear force) fits very well to normal distribution (left handside plot). Right handside plot in Figure 3 depicts the actıal versus predicted shear force by the model. As seen clearly, there is an excellent accordance and the points are very near to 1:1 line. Figure 3 confims the adequacy of the second order model which formulated in Equation 2.

Main Effects of Parameters

Figure 4, gives the main effects of tested parameters of pressure, time and current on shear force of resistance welded mild steels. In each plot, other varibles kept at their middle levels. While keeping the pressure and current at middle values, shear force increaese with increasing time uptu 30 period, then decreases slightly. It is evidence that time has a quadratic effect. The shear force of resistance welded mild steels almost remains unchanged with increasing pressure. It decreases very slightly up to 1000 N, then increases very slowly. The shear force is most affected from the increase of current parameter. Keeping the time and pressure in middle values of 30 period and 1000 N respectively, shear force increases very quickly and reach the maximum at 6 kA current value.

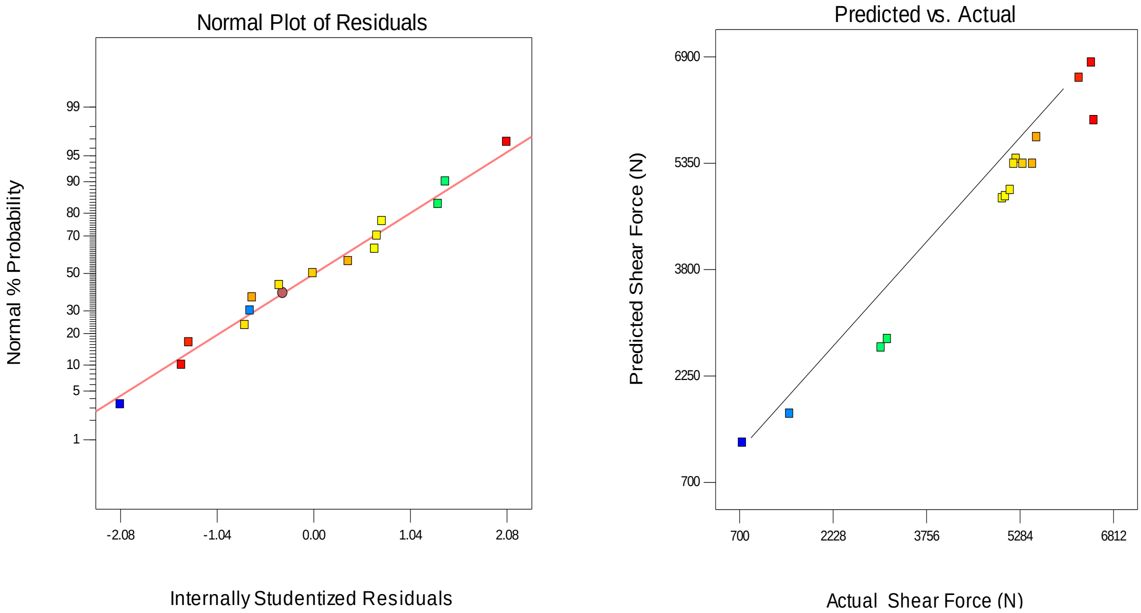

Figure 3. Normal distribution plot of model residuals and actual versus predicted shear force plot

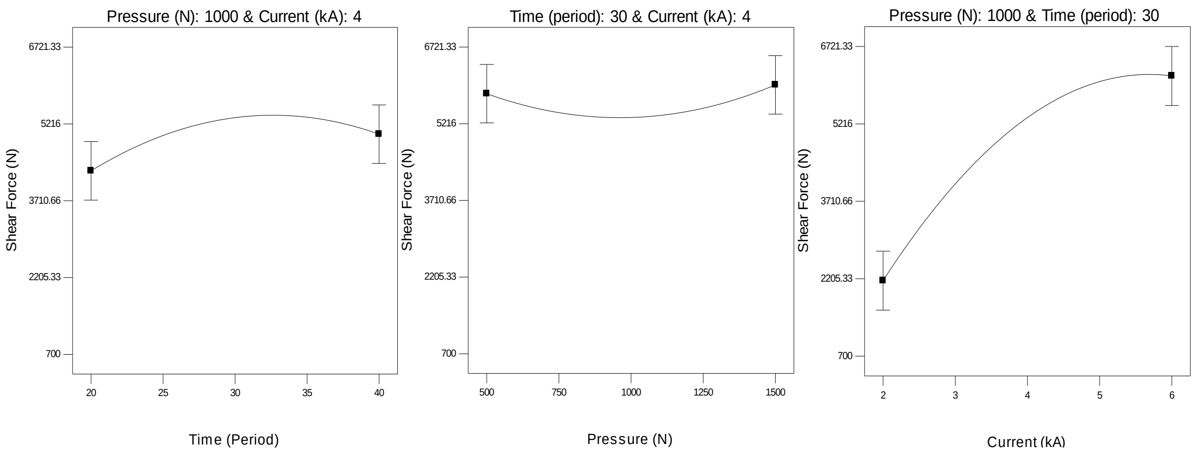

Figure 4. Main effects of tested parameters on the sheer force of resistance welded mild steels (all the other parameters is kept at their middle values)

Interaction Effects of Parameters On Resistance Welded Mild Steel

Figure 5, 6 and 7 shows the relationships between shear force and 3 parameters tested. In these plots, two parameters are within their studied ranges while the third parameter at its middle level.

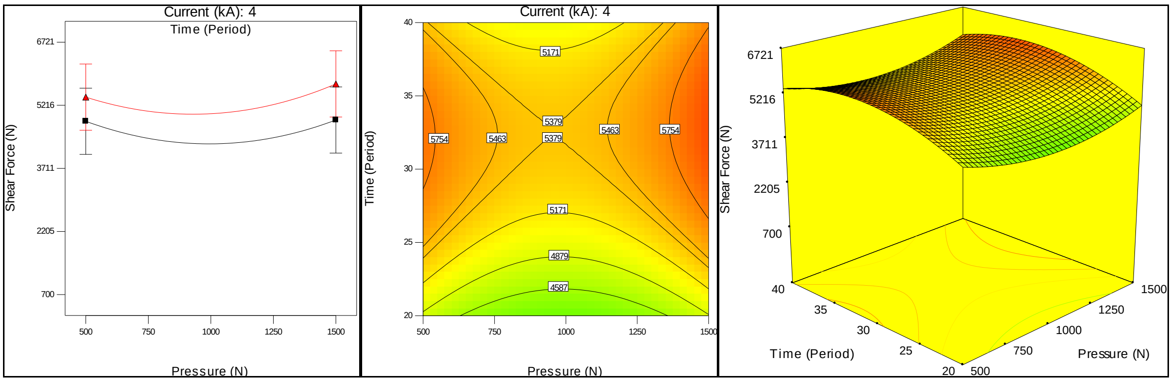

Figure 5. Effect of time and pressure on tensile strength: Interaction plot (left), contour plot (middle) and 3D surface plot (right).(Current: 4 kA; ■: 20 period; ▲: 40 period)

Figure 5 depicts interaction, contour and 3D response surface plots between time and pressure at the middle level of current (4 kA). The is no intersection between plots in interaction plot (left plot). There is intersection between the curves in intersection plot (left), since they are parallel and near to each other. This character confirms there is interaction between time and pressure as in determined in ANOVA results in Table 4. When the time increases from 20 to 40 period at current 4 kA, shear force increases slightly and it remains almost constant with increasing pressure.

The plots in Figure 6 indicates that current has an important factor on shear force and there is no any interaction between current and pressure factors. Shear force increases with increasing current and increasing pressure at tle lower and higher level of current has almost no effect on the shear force of resistance welded mild steels.

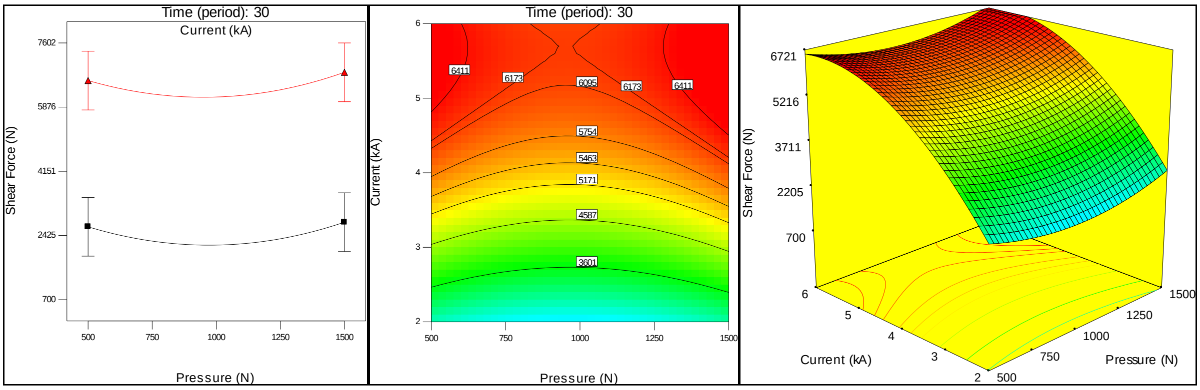

Figure 6. Effect of current and pressure on tensile strength: Interaction plot (left), contour plot (middle) and 3D surface plot (right). (Time: 30 period; ■: 2 kA; ▲: 6 kA)

Figure 7 shows that higher shear force can be obtained at higher current values and higher time. Even the interaction between time and current was found statistically unimportant, theirr relationship is more effective than the other factor interactions.

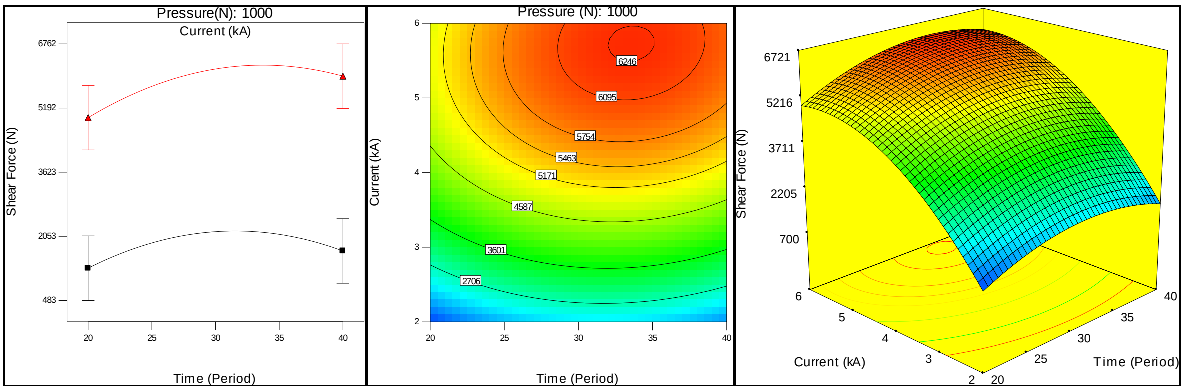

Figure 7. Effect of current and time on tensile strength: Interaction plot (left), contour plot (middle) and 3D surface plot (right). (Pressure: 1000 N; ■: 2 kA; ▲: 6 kA)

Conclusion

The Box-Behnken Design (BBD) was applied successfully in order to determine the effects of pressure, current and welding time on the shear force of resistance welded mild steels. According to BBD results, the welding pressure seems to have a negligible effect on shear force. However, its quadratic effect was found significant at 90% confidence level and the quadratic effects the other parameters were significant at 5% significance level. The current parameter was the most important parameter on shear force and it has both linear and quadratic effect at %5 significance level. All interaction effects between parameters were determined insignificant, i.e., their individual effects were more dominant.

A second order mathematical model, which is statistically important and has R^2 of 97,03 determination coefficient, was developed to predict the shear for of resistance spot welded mild steel as a function time, current and pressure. This model is valid within the limits of parameters tested and can be used conveniently to detect shear force in untested parameter conditions.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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