

Development of Mathematical Model for Resistance Spot Weld of dissimilar Metal Sheet using 'R' Programming

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Abstract

The growing demand for lightweight vehicle body structures often necessitates the use of dissimilar metals with varying thicknesses. Welding these dissimilar metals together poses a challenge due change in different type of properties. This paper aims to study the effect of welding parameters on the weld strength and quality. Spot-welding experiments were conducted using the Central Campsite Design Matrix for the combination of mild steel and 304L SS sheets of different thickness. The investigation was carried out to study the influence of weld current, weld time, and weld force on the strength of dissimilar metal welds. An empirical relation is developed using R-language to predicts weld strength. ANOVA was employed to identify the significantly affecting process parameters on weld strength. The optimum weld strength conditions for various sheet thicknesses was validated through confirmatory tests. The research finding provide valuable insights into understanding how the change in weld properties contribute in enhancing the weld joint quality.

Keywords: Dissimilar Metals, Resistance Spot Welding, Tensile Strength, R- Programming, ANOVA F-test.

1. Introduction

Resistance spot welding(RSW) process is shown in Fig.1is a highly efficient technique employed in mass production. It boasts the advantages of high speed and is well-suited for automation alongside other fabrication processes, requiring minimal adjustments to machine parameters for optimal weldability. RSW is a widely acknowledged method for joining sheet metals and attracting the attention from researchers focused on understanding its fundamental characteristics. Investigated and developed correlation on the influence of welding parameters weld strength analysing them statistically. The statistical tools like Factorial Design, 'R' Programming, Taguchi Method, and Response Surface Methodology have been employed to enhance prediction precision and facilitate the comparison of relevant process parameters [2, 3]. The quality of spot weld joints is evaluated through tensile shear strength tests, with welding parameters considered as factors for influencing weld joint quality.

A linear regression model was initially used, but non-linear behaviour was revealed through

residuals analysis [4]. Welding effort and welding time had minimal effects on mechanical properties

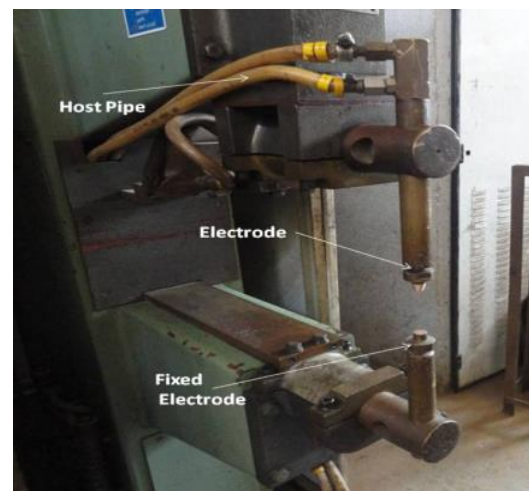


Figure 1 Resistance spot welding Machine

compared to welding current, which is crucial for achieving optimal mechanical strength in joined sheets [5]. The empirical relationship was developed using ANOVA and regression analysis to evaluate the results. Characterizing the micro hardness, weld nugget strength, microstructure, and parameter effects on responses was studied

thoroughly [6]. For aluminum spot welds, weld nugget diameter is a critical criterion for weld strength and fatigue life optimization [7]. The welding process are governed energy input, power, welding speed, beam diameter and angle, etc. The experimental and analytical approach revealed that the weld bead geometry and performance of the weld is significantly impacted by welding speed and power [8]. Experimentation on friction stir welding of similar aluminum alloy to study the impact of process variables [9-11]. Applied Taguchi Methodology to optimize residual stresses, finding feed rate had the maximum effect on longitudinal residual stress and also evaluated different types of residual stresses developed in dissimilar metal welds [12, 13]. A semantic framework for prediction of weldability of the materials is carried out using design of experiment techniques. The technique for planning, conducting, and analysing was done using common statistical techniques [14-17].

The above literature review indicates that the authors have previously conducted experiments statistical tools and DOE methods. This paper focuses on develop mathematical model that estimate the optimal response. Additionally, the investigation is carried out by writing the 'R' programming code for analysing the effect of process parameters on weld strength and also ANOVA is utilized to predict accuracy in this study.

2. Experimentation

The chemical composition of base metal 304 ASS and MS sheets (1.0 mm) are obtained by using SPRECTOMAX- optical emission spectrometer is provided in the Table 1.

Table 1 Chemical Composition

Material	C %	Si %	Mn %	P %	Cr %	S %	N %	Ni %
304 ASS	0.077	0.055	2.00	0.045	18.00	0.030	0.010	8.00
MS	0.008	0.020	0.014	0.009	0.006	0.007	-	0.0032

A well designed experiment can substantially reduce the number of experiments to fit a quadratic surface and optimize the parameters. The complete design consists of 18 experiments; eight experiments (corner points) represent 2³. These points are located at the cube's vertices, and

experiments are also repeated 4 times at the center point to estimate pure error. The CCD provide quality predictions over entire design space by considering the parameters settings outside the range of the process parameters. The possibility of conducting experiments using CCD is recognized before start of the experiment. The factor spacing is reduced to ensure ± alpha value for each coded factor is given in Table 2. The Six additional experiments are included in this design to add the effect of axial star points in terms α values. The analysis of this data is performed by creating several blocks.

Table 2 Experimental factors and their levels for CCD

Factors	Levels of coded variables				
	- α	Low	Medium	High	+ α
	-1.682	-1	0	+1	+1.682
Welding Current (kA)	3.477	6.000	7.500	9.000	11.523
Weld time (Cycle)	6.59	15.00	20.00	25.00	33.41
Electrode Force (kN)	0.477	3.000	4.500	6.000	8.253

The tensile property is helpful for predicting the behaviour of a material under different loading conditions. The strength of material is measured in terms of deformation and stresses that material can withstand. The test specimen shown in Figure 2 is cut using water jet machining from as per ASTM E8 standard. The weld specimens tested for Ultimate Tensile Strength (UTS) using FIE make, UTN-40, 400 kN Capacity machine. The weld center line is placed perpendicular to the axis of loading during testing on UTS. The Table 3 shows the results of UTS and fracture position of the specimens. The specimens are cut and cleaned using NaOH and H2SO4 solution and prepared for microstructural examination.

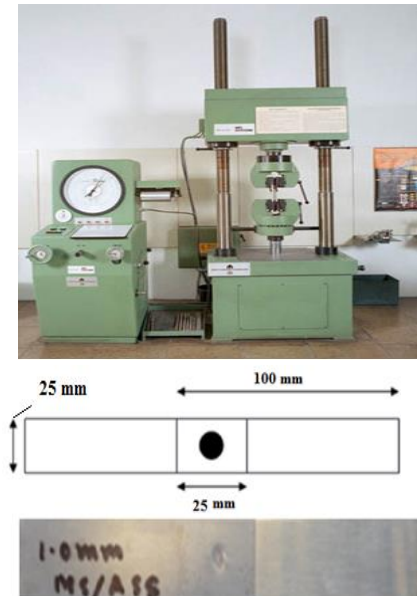


Figure 2 Universal Tensile Strength (UTS) Machine and Specimen

Table 3: Weld Strength results as per CCD

Sr. No.	Welding Input Parameters			Response
	Current (kA)	Time (Cy)	Force (kN)	
1	6.000	15.00	3.000	5.12
2	9.000	15.00	3.000	4.87
3	6.000	25.00	3.000	5.09
4	9.000	25.00	3.000	4.84
5	6.000	15.00	6.000	5.26
6	9.000	15.00	6.000	5.01
7	6.000	25.00	6.000	5.23
8	9.000	25.00	6.000	4.97
9	3.477	15.00	4.500	4.80
10	11.523	15.00	4.500	5.57
11	7.500	6.59	4.500	5.12
12	7.500	33.41	4.500	5.01
13	7.500	20.00	0.477	4.62
14	7.500	20.00	8.253	5.17
15	7.500	20.00	4.500	5.04
16	7.500	20.00	4.500	5.04
17	7.500	20.00	4.500	5.04
18	7.500	20.00	4.500	5.04
Average Weld Strength				5.04

3. Development of Mathematical Model

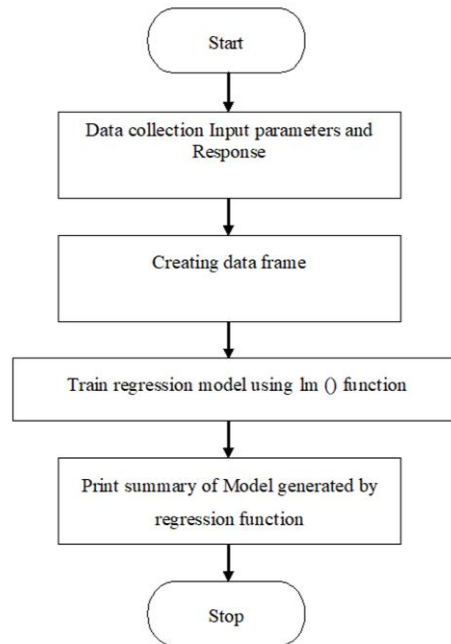


Figure 3 Flow chart Identify best fitted block

The procedure used for developing code using R-programming is shown in Figure 3 to estimate response based on input parameters. Power polynomial regression is applied for Block I, II and Total based on R2 and P-value, which decides the best block fitted and also gives the mathematical model in the form of power polynomial equation is developed using tensile strength results of various thick sheets.

The output obtained from of R-Programming for **Block-I is given as**

Block1. Lm = ws1.0block_1~ wc1.0block_1+ wt1.0block_1+wf1.0block_1, data = d1.0block_1

1	2	3	4	5	6	7	8	9
-	0.0	-	0.0	0.0	0.0	-	-	-
0.	14	0.	14	93	72	0.	0.	0.
05	5	02	4	9	3	03	02	02
1		2				5	8	8

Coefficients

Parameter s	Estimate	Standard Error	t-Value	Pressure
Intercepts	5.689919	0.141545	40.199	0.000007
Wc1,0block_1	-0.093009	0.009952	-9.346	0.000236
Wt1,0block	-	0.0039	-	0.1523

k_1	0.0066 95	68	1.68 7	44
Wf1,Obloc k_1	0.0466 67	0.0213 36	2.18 7	0.0803 75

The residual standard error of 0.06401 with 5 degrees of freedom, Multiple R² value is 0.95, Adjusted R² is 0.92 and F-statistic is 31.66 on 3 and 5 DF the p-value is equal to 0.00112. After calculating ANOVA table and p-value of Block- I is found most significant and may be stated as,

$$Y = 5.6899 - 0.093009X_1 - 0.006695X_2 - 0.046667X_3$$

Where Y is response X1 is the weld current, X2 is the weld time and X3 is the weld force or electrode force respectively.

The output obtained from of R-Programming for **Block-II is given as**

block 2. Lm = ws1.0block_2 ~ wc1.0block_2 + wt1.0block_2 + wf1.0block_2, data = d1.0block_2).

1	2	3	4	5	6	7	8	9
-	-	0.0	0.	0.0	0.0	-	0.	-
0.	0.	15	0	93	03	0.	28	0.
00	01	2	1	9	4	27	0	00
7	2					7		6

Coefficients:

Parameter	Estimate	Standard Error	t-Value	Pressure
Intercepts	5.5768 62	0.5117 03	10.8 99	0.0001 13
Wc1,Obloc k_2	- 0,0850 0	0.0588 85	- 1.44 3	0.2084 81
Wt1,Obloc k_2	- 0.0030 48	0.0112 58	- 0.27 1	0.7974 29
Wf1,Obloc k_2	0.0372 74	0.0301	1.24 1	0.2695 64

The results of standard residual error of 0.1767 with 5 degrees of freedom, Multiple R² value is 0.8211, Adjusted R² is 0.7382 and F-statistic is 1.213 on 3 and 5 DF the p-value is equal to 0.3957. Rounding of the numbers up to 3 decimal places the equation becomes;

$$Y = 5.689 - 0.093X_1 + 0.0066X_2 - 0.0466X_3$$

The output obtained from of R-Programming for Total Block is given as

Total Block.Lm = ws1.0_total_block ~ wc1.0_total_block + wt1.0_total_block + wf1.0_total_block, data = d1.0_total_block

The output obtained from of R-Programming for Total block, lm is as follows

Min	IQ	Median	3Q	Max
-	-	-	-	0.125
0.176	0.0117	0.0023	0.0301	9
2	7	5	9	

Coefficients:

Parameters	Estimate	Std, Error	t-value	Pr
Intercepts	5.569 267	0.110 715	50.3 03	1.0x10 ⁻⁶
Wc1.0_total_block_2	- 0,091 434	0.010 419	- 8.77 6	0.0004 59
Wt1. 0_total_block_2	- 0.005 913	0.003 071	- 1.92 5	0.0747
Wf1. 0_total_block_2	0.061 928	0.010 65	5.81 5	0.0000 449

Therefore, the Block value are more correlate with response here R Multiple R² value is 0.95, Adjusted R² is 0.92 and F-statistic is 31.66 on 3 and 5 DF the p-value is equal to 0.00112.

$$WS = 5.5639I^{-0.92}T^{0.0059}F^{-0.061}$$

4. Results and Discussion

The results obtained from the mathematical models analysis for the main effect plots for the strength, optimality and using Pareto charts is explained. The detailed discussions about the interaction of the parameters with responses are explained using surface plots.

4.1 Scatter plot of Actual Vs Predict weld strength

weld strength values obtained from Experimentation and R Programming Model are plotted in scatter diagram as shown in figure 4, It is observed that there is an average deviation of 0.02 kN between actual and predicted results are more accurate as compare to actual, as R² value of is 95.63%.

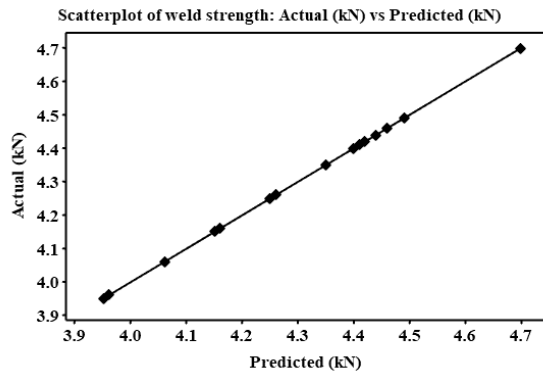


Figure 4 Actual vs Predicted weld strength

4.2 Main effect plot for the weld strength

The main effects plot of weld strength illustrated in Figure 5 represents the primary impacts of each parameter on thickness. The main effect plot highlights the substantial influence of weld current in comparison to other parameters. Specifically, an escalation in current supply correlates with an increase in weld strength. Additionally, the effect of weld time on strength is observed to be moderate, with strength initially rising with an increase in weld time up to a certain threshold, beyond which it begins to decrease in weld force a decline in weld strength.

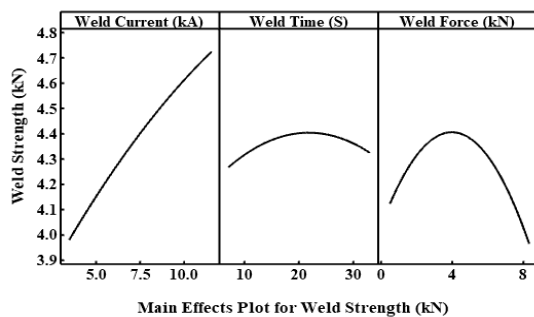


Figure 5 Main effect plot for the weld strength

4.3 Normal Probability plots for tensile shear strength

The plots obtained from ANOVA results indicate the significance of the regression, encompassing various types of fits and interaction within the developed model. The developed mathematical models are validated through residual plots, as depicted in Figure 6, showcasing normal probability plots for the strength of the sheet. These plots reveal that the residuals align with a straight line, signifying a normal distribution of errors. The coefficient of determination, R^2 , is employed to gauge the proximity between predicted and

experimental values. The statistical model developed for strength demonstrates the greater than 95% of R^2 value.

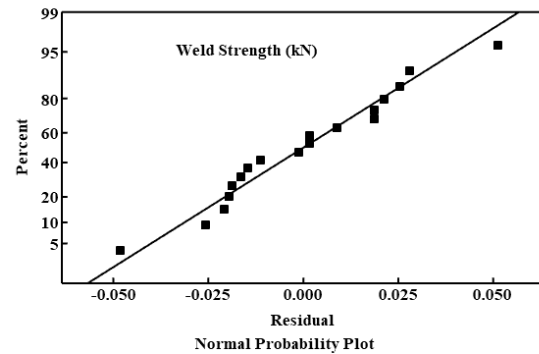


Figure 6 Normal Probability Plot

4.4 Pareto Analysis

Figure 7 presents a Pareto chart display the absolute values of standardized effects arranged from largest to the smallest. These standardized effects, represented by t-statistics, serve as tests for the null hypothesis. The chart includes a reference line to delineate statistically significant effects. Notably, bars in the Pareto chart that intersect the reference line are deemed statistically significant. The factor A and the interaction of CC and AB factor distinctly cross the reference line at 2.78 indicates the statistical significance at 0.05 level. The Pareto chart conclusively identifies that factors A, CC, and AB exert a notable influence on the response.

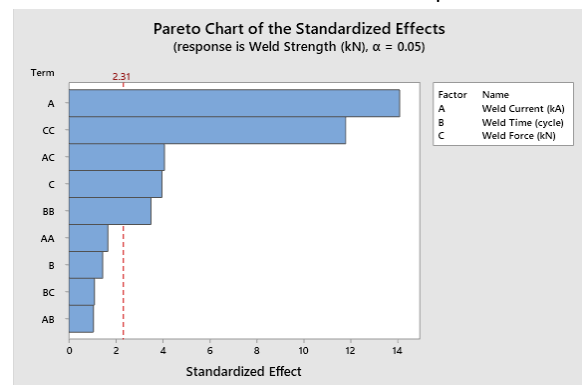


Figure 7 Pareto analysis plots for tensile-shear strength

4.5 Response Optimization of weld Strength

The main effects of different process parameters on the weld strength of 1.0 mm thick sheet are predicted from the mathematical model are given in Figure 8. The effect of current on weld strength given in Figure 8 for the spot welds increases with increasing the weld current and a maximum weld strength of 4.95 kN is obtained at current (11.53

kA). This is due to increase in weld current results in heat generation in the weld reason which ultimately lead to increase in depth of penetration.

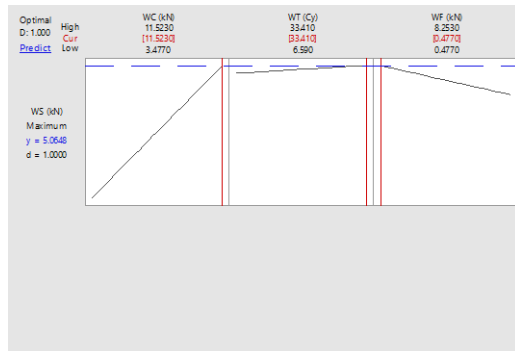


Figure 8 Response Optimization

The effect of weld time on weld strength is shown in Figure 7, it reveals that the spot weld strength increases with increasing the time. The maximum weld strength of 4.95 kN is obtained at 32.05 cycles of weld time. The reason for obtaining higher strength is directly increased with increasing the welding time (Joules law). Effects of electrode forces on weld strength decreased with an increase in the weld force and the maximum joint strength of 4.95 kN is obtained at electrode force of 6.13 kN, then it decreases. This is due to increase in electrode force lead to increase in the heat energy which results in decrease of electrical resistance of the weld nugget.

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4.6 Contour plots of Models

The contour plots provide the information about the interaction of input and response parameters, that are of great interest and assist the quality engineer to find the optimal process parameters. Figure 9 shows the counter plots of weld current verses weld time that the low weld current (10 kA), gives low weld strength (4.0 kN) at lower weld time (12 cycle). As optimal values of weld current (11.53 kA) and weld time (20 cycle) get maximum weld strength (4.6 kN). As current produced heat, due to

heat temperature goes on increasing thus gives the effect on weld size and weld strength, as per Joule law increasing weld current the weld strength increase. In addition, the weld current is more sensitive to changes in weld strength than weld time.

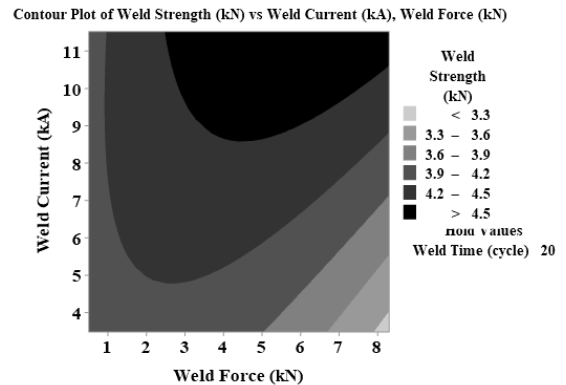


Figure 9 Contour plots of weld strength

The contour plots shown in Figure 10 depicts the weld strength obtained for the variation of current from 4.0 kA to 12.0 kA and the electrode force from 1.0 kN to 8.0 kN. The higher strength is obtained at the higher current and lower force at a constant weld time (20 cycles). It is also revealed that the maximum weld strength is 4.5 kN obtained when weld current is 9 kA to 11.53 kA at weld force is 2.5 kN to 8 kN. Increase in the current and electrode force, the lesser welding heat caused by the increase in weld force compensated by the larger current. The contour plot concludes that weld mode at specific combination of process parameters leads to achieve a specific weld strength characteristic. The contour plots provide the guidance for the production, for setting the appropriate process parameters to obtain desired weld strength based on production demands.

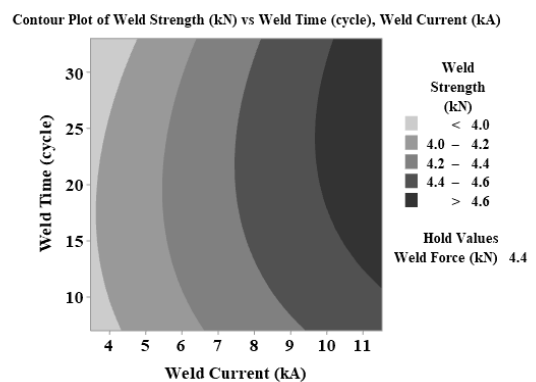


Figure 10 Contour plots of weld strength

The contour plots for weld strength obtained against weld time and weld force are given in Figure 11. The contour lines of the predicted values of the weld strength values rose from 3.9 kN to 4.4 kN for change in weld time from 18 cycles to 28 cycles and the electrode force changes from 3 kN to 4.5 kN. The effect of weld time exhibits positive effects on strength whereas, the weld force has a negative role on weld strength for the constant value of current (7.5 kA). The longer the weld time, more heat accumulates in the weld region, results in strength to grow more adequately. On other hand, a larger weld force generates bigger contact area, lesser contact resistance, and greater heat dissipation. Thus, the optimal welding process might be achieved under a relatively higher welding time accompanied with lower electrode force. As compared to the weld time and weld force at the constant weld current of 7.5 kA, weld time is more sensitive to the strength than weld force.

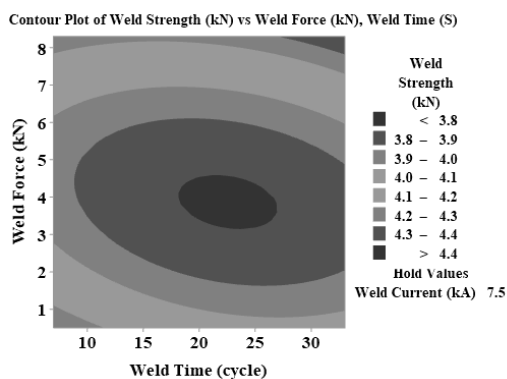


Figure 11 Contour plots of weld strength

4.7 Microhardness measurements

Figure 12 illustrates the Microhardness values obtained through automated Microhardness measuring machine on flanks of the weld nugget. The hardness value on ASS HAZ side is found to be lower than that on the MS side. Within the weld nugget region, the Microhardness readings indicate an increase, reaching 394 VHN. The Microhardness distribution across the weld nugget region appears consistent, but a higher hardness, specifically 15 VHN more, is discerned on the MS side. This disparity is attributed to greater melting in comparison to the ASS (304) plate, leading to a rapid cooling process.

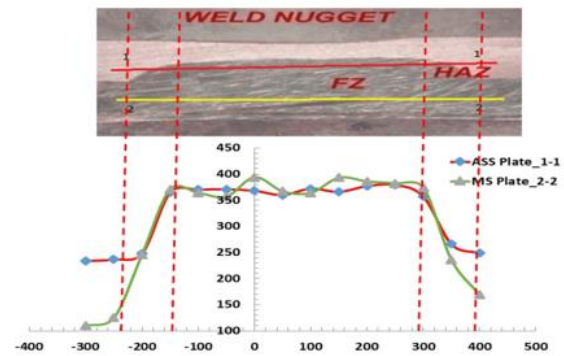


Figure 12 Weld hardness variation in weld nugget

5 Conclusion

The study using CCD reveals the feasibility dissimilar metal RSW of thin sheets of 1.0 mm, the mathematical model was formulated using the 'R' Programming language. The conclusions derived from this investigation are mentioned below:

- 1) The weld current is most affecting parameter on weld strength and nugget dimensions whereas clamping force affects least.
- 2) Central Composite Design with eighteen trials adopted to study the effect of current, time and force at two levels each using the experimental data collected. The mathematical model developed revealed that the weld strength with accuracy greater than 95% within the range of parameters of the process selected for welding thin sheets.
- 3) The tensile strength of ASS 304 and Mild steel are 5.10 kN and 4.10 kN in base metal. However, the weld strength of is found 5.57 kN thus the weld strength has increased by 9.21% above ASS 304, whereas 35.80% in mild steel sheet.
- 4) The weld joint prepared at optimal input process parameters (11.53 A weld current, 33.41 Sec Weld time and 0.477 kN) depicts the weld strength of 5.0648 kN, which was 26.62 % higher than Mild steel and 0.69 % less than Austenitic stainless steel.
- 5) The micro hardness towards MS side of the weld nugget is 4.09 % less as compared to ASS side.

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