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ANALYSIS AND OPTIMIZATION OF MECHANICAL PROPERTIES OF MARTENSITIC STAINLESS STEEL (SS410) WELDED JOINTS USING RESISTANCE SPOT WEDLING

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Abstract**: The Primary goal of this study is to examine the mechanical properties & optimize the parameters for resistance spot welding (RSW) of martensitic stainless steel (SS410) welded joints by conducting few mechanical tests like tensile test, Hardness test& Nugget Diameter determination. The Taguchi Method was utilized for the designing of experiments. The trials were performed by using L9 Orthogonal Array with 3 different parameters & levels; process parameters are "Electrode force, welding current & welding time". The mode of failure will also be investigated by the analysis of the fractured samples. After all these tests & examinations, by using MINITAB 19 program; the combination of the optimum welding parameters have been decided by the Analysis of Single-to-Noise (S/N) ratio; Analysis of Variance (ANOVA) is used to indicate the contribution & significance of parameters affecting the output; Regression Analysis was conducted to obtain the regression model & contour plots were also obtained from the analysis w/c are used to show the relationship b/w the parameters & the output.

Keywords: Martensitic stainless steel (SS410), Resistance spot welding (RSW), Tensile and Hardness Test, Taguchi Analysis, Optimization

I. Introduction

"In the transportation industry & the automotive industry in particular, (RSW) has for decades been the primary joining technique. The technique's affordability, high (dependability, time effectiveness, availability and high capacity) with respect to robotic automation, contrasted to many different joining techniques, makes it optimal for transportation & automation industry. A typical modern automobile comprises about 3500 – 5500 welds made by (RSW), whereas another joining techniques, for example, Arc & laser welding or mechanical fastenings is utilized in a considerably more restricted extent. The huge scale of RSW in manufacturing makes the strategy's outcomes exceptionally significant for product properties which include most important properties, for example, vehicle safety, crashworthiness & fuel efficiency."[1]

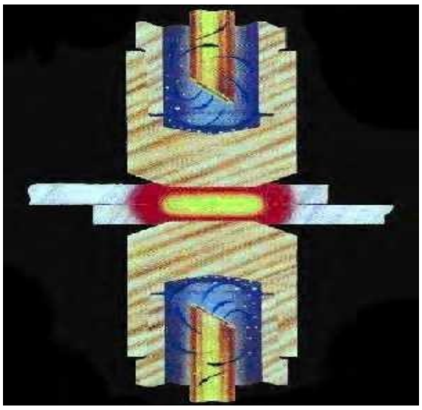


Fig. 1 RSW Principle

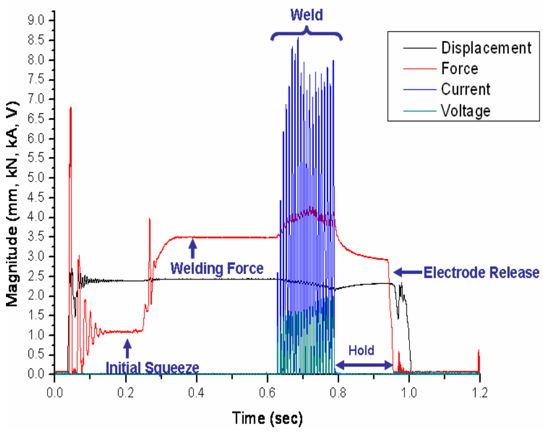


Fig. 2 Complete welding phenomena

In the process of RSW the sheet metals are joined by electric resistance heating & by the use of force with no use of any filler metal. It is generally utilized for designing sheet metal assemblies, for example, cars, motor cycles, truck lodges, rail vehicles and some devices or appliances used at home.

At the time of RSW phenomenon two constantly cooled electrodes clamp down upon 2 work samples as appeared in (Fig. 1). Then Alternating current (AC) or (DC) is made to run through the electrodes at nominal voltage w/c brings in fusion at the faying surface of the work sample.

Almost every welding plan generally consists of 5 consecutive advances which appeared in (Fig.2) are; the initial squeeze where the electrodes clamp the metals, the phenomenon of force at w/c the welding happens, the phenomenon of current w/c brings in fusion, the holding time which allow molten metal solidification and the release of electrode.

The amount of heat produced throughout the (RSW) technique because of the bulk resistance & interface contact resistance is presented by the subsequent mathematical statement: ($\mathbf{Q^* = kI^2Rt}$)

Here **Q*** refers to heat content, **k** refers to calibration constant, **I** refers to welding current, **R** refers to total circuit resistance , & **t** refers to welding time. With the help of above statement it very well may be demonstrated that the time &current resistance both are important factors for the production of heat & for the nature of the welded part. Variables and Standards of RSW that influence the quality & nature of the welded part are:

(Electrode force holds time, squeeze time, welding current, weld cycles &diameter of electrode contact surface).

II. Methodology

This investigation presents the strategy of the methodology embraced to examine the spot welding conduct of Martensitic stainless steel (SS410) under various levels of electrode force, current and weld cycle. Most of the scientists explore the joining of comparative sheet metal those are welded with RSW. In numerous applications spot welds are designed b/w non-similar metals to observe the mechanical characteristics according to desired necessities. The goal of this examination is to decide the measures for choosing ideal state of RSW with comparable combination & to describe the attributes in like manner. Measuring the nugget diameter, hardness test & tensile test were going to be performed in this study. Failure mode of the welded metal part was additionally investigated.

A. Characteristics of Material

Martensitic Stainless Steel of Grade 410:

In this section the chemical composition and some applications of grade 410 (SS) were discussed.

Grade 410 (SS) are universally useful martensitic (SS) which contain 11.5% chromium and shows great corrosion resistance properties. The corrosion resistance of (SS) of grade (410) could be additionally upgraded by a progression of procedures, for example, polishing, solidifying, hardening etc., Quenching & then tempering can solidify (410) grade steels. 410 (SS) are commonly utilized for many functions including good strength, mild corrosion & heat resistance.

Martensitic (410) (SS) are designed utilizing strategies that require a reliable heat treatment process. (410) (SS) are very least resistant to corrosion when contrasted with austenitic grades.

B. Composition and Applications

TABLE I
{Composition range of grade (410) SS in (%)}[2]

Grade		C	Mn	Si	P	S	Cr	Ni
(410)	(Min.)	-	-	-	-	-	(11.5)	(0.75)
	(Max.)	(0.15)	(1)	(1)	(0.04)	(0.03)	(13.5)	

SS of Grade (410) discover many applications in different mechanical parts and components like gas turbines, bushings, mine ladder rungs, valves, shafts, petroleum fractionating structures, pumps, bolts, nuts and screws.

C. Size and dimensions of the Specimen

Martensitic Stainless Steel (SS410) strips of thickness (2.10 mm), width (31.10 mm), length (180 mm) and contact overlap of (45 mm) are utilized for the analysis. Stainless steels are one of the most welded materials with the (RSW) method. “The carbon present in the material may influence the properties of the material; after the welding the joint may turn out to be hard & fragile. As the thickness of material expand the welding current& Force needs to increment to deliver the joint of adequate strength”.[3]

Dimension& Configuration of the tensile test coupon (in mm) are shown in Fig. 3 & 4.

“The tested sample were cut according to rule indicated for this order of thickness in suggested practice for testing techniques for assessing the RSW conduct of automotive sheet steel materials (ANSI/AWS/SAE/D8.9-97)”[4]. Entire sheets were of a similar clump for their particular thickness.

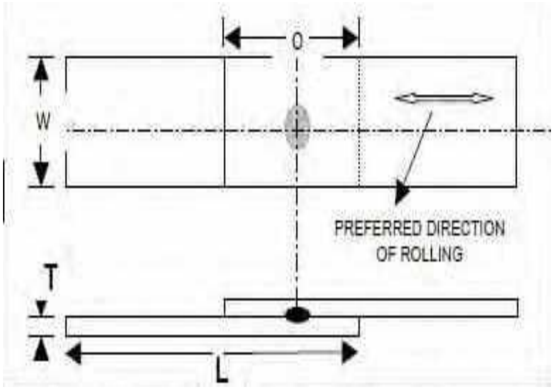


Fig. 3 “Dimensions of tensile test sample as stated by ANI/.AWS./.SAE/D.8,9,97”[4]

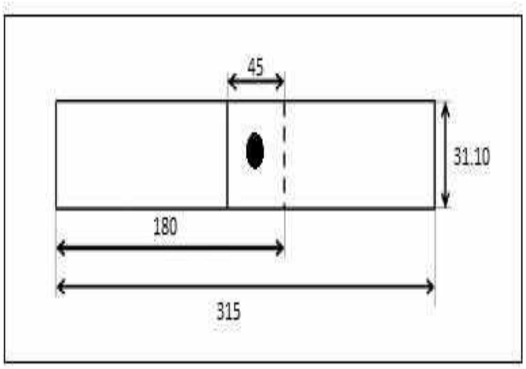


Fig. 4 Configuration & Dimensions of specimen (mm)

D. Preparation of specimen for welding parameter optimization

The Taguchi Method was utilized for the designing of experiments. The trials were performed by using L9 Orthogonal Array with 3 parameters & 3 levels. Heat, W2 (post heating), Hold time & Squeeze time were maintained constant throughout the testing. Electrode force, weld current, weld time, were increased step by step to get the best results. The process variables & varied levels are shown in the table II given beneath& table III shows experiment readings.

TABLE II

Process Variables & levels

Sign	**Process Parameters**	**Unit**	**Level 1**	**Level 2**	**Level 3**
A	Electrode Force	N	2000	2500	3000
B	Welding Current	KA	3	6	10
C	Welding Time	Cycle	10	20	30

TABLE III

Spot welding reading using L9 Orthogonal Array

Sample No.	Electrode Force (N)	Weld Current (KA)	Heat (KA)	Weld time (Cycles)*		Hold time (Cycles)*		Squeeze Time (SQ)	Electrode Diameter d(mm)
				W1	W2	H1	H2		
1	2000	3	10	10	8	13	10	2	7
2	2000	6	10	20	8	13	10	2	7
3	2000	10	10	30	8	13	10	2	7
4	2500	3	10	20	8	13	10	2	7
5	2500	6	10	30	8	13	10	2	7
6	2500	10	10	10	8	13	10	2	7
7	3000	3	10	30	8	13	10	2	7
8	3000	6	10	10	8	13	10	2	7
9	3000	10	10	20	8	13	10	2	7

*(cycle): 1 cycle is referred to 1/50 of a sec into a 50 Hz power backup.

By using all these parameters we have prepared 9 welded samples. In this Study 2 tests such as tensile test & hardness test were executed on each sample to record the best results & nugget diameter for each sample is also determined.

Fig. 5 Medium frequency direct current, (RSW) machine

Fig. 6 Welded Martensitic SS 410 Coupons

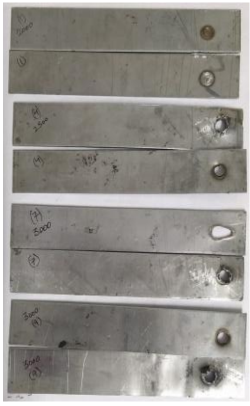


Fig. 7 Samples after Tensile Test

III. Results and Discussion

A. Experimental Results

Hardness of the welded area is one of numerous variables for the assessment of weldability. For RSW, on account of excessively fast cooling rate, weld nugget inclines towards hard martensitic stage, w/c is the reason for brittleness. Hardness was measured across the weld nugget. The Tensile test was executed by utilizing a Universal testing Machine (UTM). Specimens were set up as indicated by ANSI/AWS standards. Extreme Supervision was applied for maintaining coplanar alignment during the mechanical testing. The readings of nugget diameter, tensile test, hardness test and the failure mode are given in the table IV given below. Here (IF) refers to Interfacial Failure & (NPF) is Nugget Pullout Failure.

TABLE IV

EXPERIMENTAL READINGS

Sample No.	Electrode Force (N)	Weld Current (KA)	Weld Time (Cycles) (W1)	Nugget Diameter (mm)	Weld Nugget Hardness (HRB) (Fusion zone)	Base Metal Hardness (HRB)	Tensile Strength/ Load (kN)	Visual Inspection Results	Failure Mode
1	2000	3	10	6.24	66	80	14.0	Good Quality Weld	IF
2	2000	6	20	6.25	66	80	14.2	Good Quality Weld	IF
3	2000	10	30	6.28	67	80	14.5	Good Quality Weld	NPF
4	2500	3	20	6.27	67	80	14.8	Unsymmetrical	NPF
5	2500	6	30	6.29	68	80	14.9	Unsymmetrical	NPF
6	2500	10	10	6.30	68	80	15.5	Excessive Penetration	NPF
7	3000	3	30	6.29	69	80	15.0	Unsymmetrical	NPF
8	3000	6	10	6.30	68	80	15.5	Unsymmetrical	NPF
9	3000	10	20	6.31	69	80	15.9	Excessive Penetration	NPF

From the above readings it can be determined that when the Electrode force, welding current & time increments consistently the hardness, diameter & tensile strength of the weld nugget also increases.

B. Parameter Optimization

1) Signal-to-Noise Ratios and Means:

TABLE V

S/N Ratio and Means

Exp. No.	electrode Force (N)	weld current (KA)	Weld Time Cycles (W1)	Tensile Strength/ Load (kN)	Nugget Diameter (mm)	S/N Ratios		Means	
						Tensile Strength	Nugget Diameter	Tensile Strength	Nugget Diameter
1	2000	3	10	14.0	6.24	22.9226	15.9037	14.0	6.24
2	2000	6	20	14.2	6.25	23.0458	15.9176	14.2	6.25
3	2000	10	30	14.5	6.28	23.2274	15.9592	14.5	6.28
4	2500	3	20	14.8	6.27	23.4052	15.9454	14.8	6.27
5	2500	6	30	14.9	6.29	23.4637	15.9730	14.9	6.29
6	2500	10	10	15.5	6.30	23.8066	15.9868	15.5	6.30
7	3000	3	30	15.0	6.29	23.5218	15.9730	15.0	6.29
8	3000	6	10	15.5	6.30	23.8066	15.9868	15.5	6.30
9	3000	10	20	15.9	6.31	24.0279	16.0006	15.9	6.31

Table V shows the S/N Ratios and means those were calculated based on the nugget diameter & tensile strength results by using Larger is better Equation with the help of mini tab 19 software.

Taguchi Analysis: Tensile Strength (kN) vs "Electrode Force, Welding Current & Welding Time (Cycles)":

Table VI Response for S/N Ratios

Level	Electrode Force (N)	Welding Current (KA)	Welding Time (Cycles)
1	23.07	23.28	23.51
2	23.56	23.44	23.49
3	23.79	23.69	23.40
Delta	0.72	0.40	0.11
Rank	1	2	3

Table VII Response for Means

Level	Electrode Force (N)	Welding Current (KA)	Welding Time (Cycles)
1	14.23	14.60	15.00
2	15.07	14.87	14.97
3	15.47	15.30	14.80
Delta	1.23	0.70	0.20
Rank	1	2	3

Fig. 8

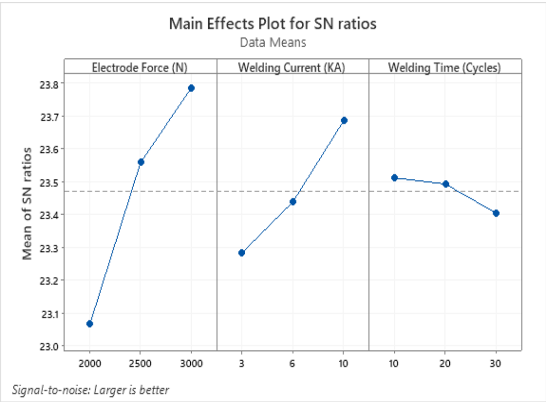


Fig. 9

Response tables and main effect plots clearly shows that Electrode force is the most significant parameter that regulates the weld strength. Optimal Control Parameters for tensile strength are 3000 (N) Electrode force, 10 KA weld current & 10 weld time (cycles).

Taguchi Analysis: Nugget Diameter (mm) vs "Electrode Force, Welding Current & Welding Time (Cycles)":

Table VIII Response for S/N Ratios

Level	Electrode Force (N)	Welding Current (KA)	Welding Time (Cycles)
1	15.93	15.94	15.96
2	15.97	15.96	15.95
3	15.99	15.98	15.97
Delta	0.06	0.04	0.01
Rank	1	2	3

Table IX Response for Means

Level	Electrode Force (N)	Welding Current (KA)	Welding Time (Cycles)
1	6.257	6.267	6.280
2	6.287	6.280	6.277
3	6.300	6.297	6.287
Delta	0.043	0.030	0.010
Rank	1	2	3

Fig. 10

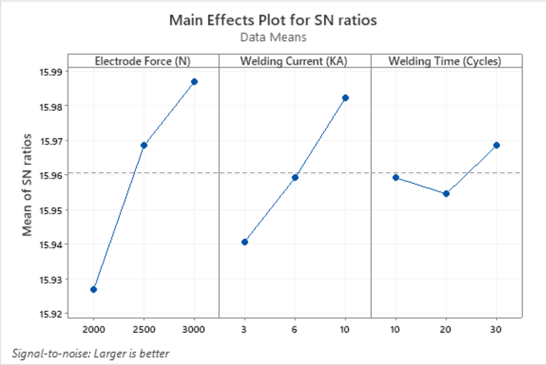
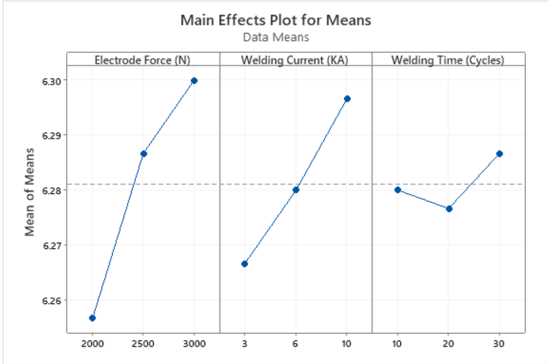


Fig. 11



Response tables and main effect plots clearly shows that Electrode force is the most significant parameter that regulates the welded nugget size. Optimal Control Parameters for Nugget Diameter are 3000 (N) Electrode force, 10 KA weld current & 30 weld time (cycles).

2) *Analysis of Variance (ANOVA): "*The major goal of ANOVA is to examine the design parameters & to indicate which parameters are significantly affecting the output. In the analysis, the sum of squares and variance are calculated. F-test value at 95 % confidence level is used to decide the significant factors affecting the process and percentage contribution is calculated. Larger F-value indicates that the variation of the process parameter makes a big change on the performance."[5]

General Linear Model: Tensile Strength (kN) vs "Electrode Force, Welding Current & Welding Time":

TABLE X

Factor Information

Factor	Type	Levels	Values
Electrode Force (N)	Fixed	3	2000, 2500, 3000
Welding Current (KA)	Fixed	3	3, 6, 10
Welding Time (cycles)	Fixed	3	10, 20, 30

TABLE XI

ANOVA Results for Tensile Strength

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	Remarks
Electrode Force (N)	2	2.37556	73.34%	2.37556	1.18778	1069.00	0.001	Most Significant
Welding Current (KA)	2	0.74889	23.44%	0.74889	0.37444	337.00	0.003	Significant
Welding Time (cycles)	2	0.06889	2.16%	0.06889	0.03444	31.00	0.031	Least Significant
Error	2	0.00222	0.07%	0.00222	0.00111			
Total	8	3.19556	100.00%					

General Linear Model: Nugget Diameter (mm) vs "Electrode Force, Welding Current & Welding Time":

TABLE XII

ANOVA Results for Nugget Diameter

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	Remarks
Electrode Force (N)	2	0.002956	65.84%	0.002956	0.001478	133.00	0.007	Most Significant
Welding Current (KA)	2	0.001356	30.20%	0.001356	0.000678	61.00	0.016	Significant
Welding Time (cycles)	2	0.000156	3.47%	0.000156	0.000078	7.00	0.125	Least Significant
Error	2	0.000022	0.50%	0.000022	0.000011			
Total	8	0.004489	100.00%					

"According to ANOVA, the most significant parameters with respect to tensile strength & nugget diameter are electrode force (most), welding current & welding time (least) in respective order. Percentage contribution indicates the relative power of a factor to reduce variation. For a factor with high percent contribution, a small variation will have a great influence on the performance."[6][7][8]

3) *Regression Analysis:* This analysis was conducted to obtain the regression model for nugget diameter & tensile strength. This analysis was used to generate a model to describe the relationship b/w the parameters & the output, this also helps us in predicting the best suited observations. The Equations & prediction tables for nugget diameter & tensile strength are given below:

"Tensile Strength = 11.403 + 0.001233 Electrode Force (N) + 0.1005 Welding Current (KA) – 0.01000 Welding Time (cycles)"

TABLE XIII

Prediction for tensile strength

Exp. No.	Electrode Force (N)	Weld Current (KA)	Weld Time (Cycles) (W1)	Tensile Strength/ Load (kN)	Fit	SE Fit	95% CI		95% PI	
1	2000	3	10	14.0	14.07	0.1129	13.78	14.36	13.59	14.54
2	2000	6	20	14.2	14.27	0.0773	14.07	14.47	13.84	14.69
3	2000	10	30	14.5	14.57	0.1158	14.27	14.87	14.09	15.05
4	2500	3	20	14.8	14.58	0.0748	14.39	14.77	14.16	15.01
5	2500	6	30	14.9	14.78	0.0773	14.58	14.98	14.36	15.21
6	2500	10	10	15.5	15.39	0.0992	15.13	15.64	14.93	15.84
7	3000	3	30	15.0	15.10	0.1129	14.81	15.39	14.62	15.57
8	3000	6	10	15.5	15.60	0.0977	15.35	15.85	15.15	16.05
9	3000	10	20	15.9	15.90	0.0992	15.62	16.16	15.45	16.36

"Nugget Diameter = 6.1390 + 0.000043 Electrode Force (N) + 0.004279 Welding Current (KA) + 0.000333Welding Time (cycles)"

TABLE XIV

Prediction for Nugget Diameter

Exp. No.	Electrode Force (N)	Weld Current (KA)	Weld Time (Cycles) (W1)	Nugget Diameter (mm)	Fit	SE Fit	95% CI		95% PI	
1	2000	3	10	6.24	6.241	0.0054	6.227	6.255	6.218	6.264
2	2000	6	20	6.25	6.258	0.0037	6.248	6.267	6.237	6.278
3	2000	10	30	6.28	6.278	0.0056	6.264	6.292	6.255	6.301
4	2500	3	20	6.27	6.266	0.0036	6.257	6.276	6.246	6.287
5	2500	6	30	6.29	6.283	0.0037	6.273	6.292	6.262	6.303
6	2500	10	10	6.30	6.293	0.0047	6.281	6.305	6.271	6.315
7	3000	3	30	6.29	6.291	0.0054	6.277	6.305	6.268	6.314
8	3000	6	10	6.30	6.298	0.0047	6.285	6.310	6.276	6.319
9	3000	10	20	6.31	6.318	0.0047	6.306	6.310	6.296	6.340

Here: PI: Prediction Interval, CI : Confidence Interval, SE Fit : Standard Error, Fit : Fitted Values

Based on regression analysis the comparison b/w the experimental values & the prediction values for nugget diameter & tensile strength are shown in the above tables (XIII&XIV). It can be clearly seen in the tables that the values for 95% confidence interval & 95% prediction interval are slightly lower than the experiment/actual readings.

However the Fit mean values for all predictor values are almost equal for both nugget diameter & Tensile strength, the standard error (SE) is negligible. It clearly shows that the developed regression model is adequate & successfully validates the experiment results.

4) *Contour Plots:* Contour plots were also obtained from the analysis. They are used to show the relationship b/w the parameters & the output means w/c parameter contributed the most & the least to the output. Figures given below show the contour plots for nugget diameter, hardness & tensile strength vs electrode force & welding current. The Red shades show the area where the output value is lowest while the purple shades show the area where the output value is highest. When the parameter values increases, the size of weld nugget, Tensile strength & hardness also increases. These plots also prove the validity of the optimized parameter settings for nugget diameter & tensile strength and they also proves that electrode force & welding current are the most significant parameters for the output.

Fig.12

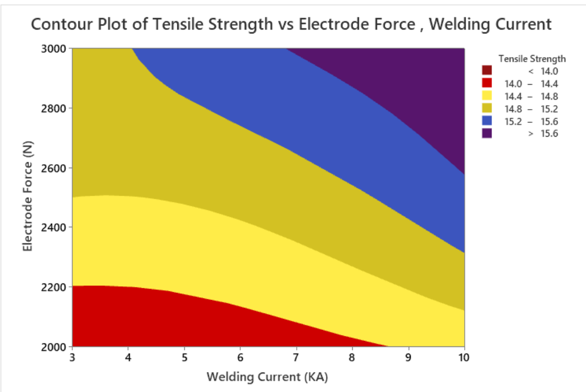


Fig. 13

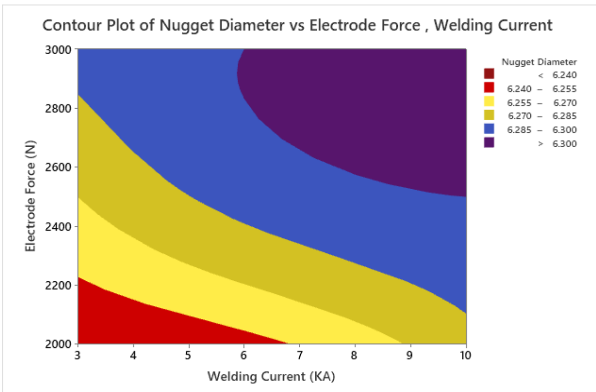
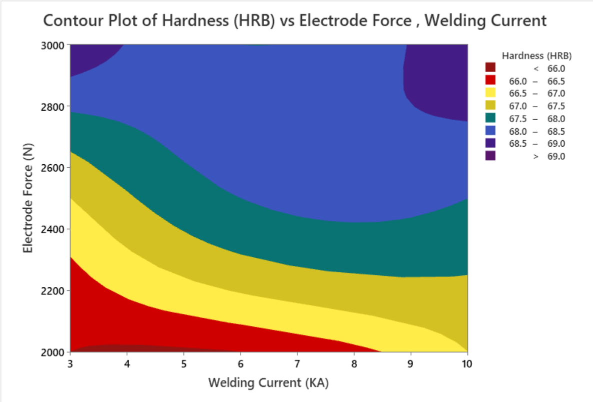


Fig. 14



IV. Conclusion

So after conducting all the Destructive tests and analysis the accompanying end and conclusion can be drawn:

- The two similar metal strips of Martensitic SS (410) can be spot weld to each other which results into a perfect weld joint likewise with a sensibly decent quality and good strength.
- With the help of this investigation it can be concluded that when the Electrode force, welding current & time increments consistently the hardness, diameter & tensile strength of the weld nugget also increases.
- Tensile load readings likewise relies upon the nugget diameter, greater the value, greater will be the Strength of the Welded nugget. The max nugget dia. recorded at 3000 (N) Electrode force, 20 weld time (cycle) & 10 (kA) weld current is 6.31 mm.
- Maximum hardness of 69 HRB is seen at 3000 (N) Electrode force, 20 weld cycles & 10 KA current whereas minimum hardness of 66 HRB is seen at 2000 (N) Electrode force, 10 cycles & 3 KA current. It is recorded that hardness of the (FZ) is lesser than that of the base metal, SS410 welded coupon shows manageably decreased hardness in weld zone. Decreased hardness should prompt better mechanical properties by strengthening weld nuggets.
- Maximum tensile strength of 15.9 kN is recorded at 3000 (N) electrode force, 20 weld time (cycle) & 10 (KA) weld current with nugget dia. approximately of 6.31 mm.
- Fractured and Cracked examples reveal the modes of failure of the welded coupon. First failure mode is (PFM), in this mode the welded nugget breaks out from the weld sample & deserts a roundabout impression of the failure upon the surface of the metal piece. The second failure mode which is the (IFM), where the welded sample disengaged from one another at the spot welded joints. No “Tearing of the metal failure” is found is the experiment.
- Optimal Control Parameters for tensile strength are 3000 (N) Electrode force, 10 KA weld current & 10 weld time (cycles) & Optimal Control Parameters for Nugget Diameter are 3000 (N) Electrode force, 10 KA weld current & 30 weld time (cycles).
- This analysis shows that Electrode force is the most significant parameter for both nugget diameter & tensile strength &contributed the most for the output (results) whereas welding time is the least significant parameter. The order of parameters that influence the most to the output according to ANOVA was Electrode Force > Welding Current > Welding time.
- The Predicted values for both tensile strength & nugget diameter were in agreement with the experiment values. The values for 95% confidence interval & 95% prediction interval are slightly lower than the experimental readings. However the Fit mean values for all predictor values are almost equal for both nugget diameter & Tensile strength, the standard error (SE) is negligible. It clearly shows that the developed regression model is adequate & successfully validates the experiment results.

V. Recommendations

Some recommendations for future examinations are given below:

- In this examination we utilize most extreme 10 kA weld current however for process improvement we can utilize additionally weld current.
- Samples can also be examined after Fatigue testing.
- Corrosion investigation of the welded specimen can also be conducted to view the impact of heat contribution on the erosion properties of weldments.
- We recommend higher weld cycle for better process advancement for further studies.
- Some different parameters like Electrode tip Diameter, Squeeze time & Hold time can also be added to the investigation.

REFERENCES

[1] H. Z. a. J. Senkara, "Resistance welding: fundamentals and applications, Boca Raton: FL:CRC Press, 2006.

[2] "AZO MATERIALS (AZOM)," [Online]. Available: http://www.azom.com/amp/article.aspx?ArticleID=970. [Accessed 12 September 2020].

[3] S. A. a. N. S. V.J Badheka, ""Mode of Failure of Resistance Spot Welded Martensitic Stainless Steel"," in *International Welding Congress*, Chennai, 2008.

[4] ""Recommended Practices for Evaluating the Resistance spot welding behaviour of Automotive sheet steel materials"," *AMERICAN WELDING SOCIETY.,* 2002.

[5] M. R. R. a. D. K. Inamdar, "Application of Taguchi method for resistance spot welding of stainless stell-304 grade," *International journal of science and research (IJSR),* vol. 3, no. 6, pp. 2721-2726, 2014.

[6] U. Esme, ""Application of Taguchi Method for the Optimization of resistance spot welding process"," *The Arabian Journal for Science and Engineering,* vol. 34, no. Number 2B, pp. 519-528, 2009.

[7] [Online]. Available: http:www.millerwelds.com/pdf/Resistance.pdf. [Accessed 12 September 2020].

[8] A. A. a. C. Nachimani, ""Analysis of spot weld growth on mild and stainless steel"," *Welding Journal,* vol. 90, pp. 143-147, August, 2011.

[9] K. Nizamettin, ""The Influence of welding parameters on the joints of strength of resistance spot welded material and design"," *Material and Design,* vol. 28, pp. 421-427, 2007.

[10] M. Pouranvari, ""Prediction Of Failure mode in AISI 304 Resistance spot welds"," *Association of Metallurgical Engineers of Serbia, UDC: 621.791.763,* pp. 23-29, 2011.

[11] Y. Chao, ""Failure mode of Resistance Spot Welds: Interfacial versus Pullout"," *Science Technol, Weld Joining ,* vol. 8, pp. 133-137, 2003.