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Optimization of vibratory welding process parameters using response surface methodology†

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Abstract

The current investigation was carried out to study the effect of vibratory welding technique on mechanical properties of 6 mm thick butt welded mild steel plates. A new concept of vibratory welding technique has been designed and developed which is capable to transfer vibrations, having resonance frequency of 300 Hz, into the molten weld pool before it solidifies during the Shielded metal arc welding (SMAW) process. The important process parameters of vibratory welding technique namely welding current, welding speed and frequency of the vibrations induced in molten weld pool were optimized using Taguchi's analysis and Response surface methodology (RSM). The effect of process parameters on tensile strength and hardness were evaluated using optimization techniques. Applying RSM, the effect of vibratory welding parameters on tensile strength and hardness were obtained through two separate regression equations. Results showed that, the most influencing factor for the desired tensile strength and hardness is frequency at its resonance value, i.e. 300 Hz. The micro-hardness and microstructures of the vibratory welded joints were studied in detail and compared with those of conventional SMAW joints. Comparatively, uniform and fine grain structure has been found in vibratory welded joints.

Keywords: ANOVA; Hardness property; RSM; SMAW; Taguchi analysis; Vibratory welding technique

1. Introduction

The grain structure of welded joints has a massive influence on its mechanical properties. The coarse grains in the weld structures, reduces the strength and impact resistance of the weld structures. Therefore to improve the mechanical properties of weld joints, vibration welding techniques have been used. The application of vibration technique during welding can refines the grain structures and comparatively more fine structures can be formed, which tends to enhancement in toughness and strength of the weld joints [1]. Vibratory welding technique is a mechanism which significantly changes the microstructures of the welds, causes enhancement in the mechanical properties of the welded structures. The imposed vibration accelerates the temperature gradient of the weld joints and speed up the temperature distribution. Further, the applied vibrations detached the growing dendrites that cause the formation of new nucleation sites which increases the growth in number of grains. It has been reported that application of external vibrating energies lead to grain refining both on macro as well as on micro scale, especially on the solidification structure of the weld pool [2-4]. Besides, vibration also helps to release of dissolved gases and the resulting weld beads greatly exhibit reduced porosity. Moreover, vibration leads to less investment and shorter manufacturing period [5, 6]. The vibratory welding technique has also been used to solve the problem of distortion and residual stress [7]. During vibratory welding some extra stresses transfers into the weld-zone and reduces the residual stress and improves the strength of weld structure. The technique to reduce the residual stress is often called Vibration stress relief (VSR) [8]. The VSR can control the residual stress and improve the solidification behavior of the weld pool [9, 10]. Welding process is a heterogeneous process, where the filler metal mixed with the base metal. An unmixed zone formed near the fusion boundary at which base metal solidifies during welding without mechanical mixing between the base metal and filler metal [11]. Since melting range of the base metal differs from filler metal causes unmixed zone forms at the fusion line of the weld structure. Several investigations have indicated that, the unmixed zone is the location at which corrosion occurs. The application of vibration techniques reduce or eliminate the unmixed zone in dissimilar welds [12, 13].

The mechanical properties of welded joints are primarily determined by the process of solidification, microstructure of

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weld zone affects its resultant properties. According to Hall-Petch theory, the mechanical property of the metal is directly affected by its grain structure. The strength of weld joints, prepared under the vibratory conditions, improved since the microstructure is refined. Grain refinement has the tendency to reduce the hot cracking [14]. Previous works reported that the tensile properties of the welded structure have been improved by inducing vibrations during welding operation [15-17]. The method of improving the strength of the weld structure without the need for heat treatments is interesting since it reduces the time consumption and production cost [18, 19]. Recently, Amini and Amiri [20] investigated the effect of ultrasonic vibrations on friction stir welding. The ultrasonic vibrations were employed in the perpendicular direction of the tool. The result shows that an ultrasonic vibration increases the strength of the welded joint.

Over the years, various vibratory welding techniques were developed by the researchers to improve the microstrucral and mechanical properties of weld structure. A brief literature of vibratory welding techniques is mentioned in Table 1 and showing the various mechanisms adopted by the researchers to perform the vibratory welding technique. External fields including ultrasonic vibrations, electro-magnetic fields, ultrasound and vibratory table has been used by the researches to improve the microstructures and mechanical properties of weld metal, even decrease or avoid some welding defects. Vibratory method is relatively simple but practically useful way to carry out during welding.

In the present investigation, butt welded joints were prepared under the vibratory welding conditions. A new concept of vibratory setup has been designed and developed; a stirring rod is used to shake the molten weld pool of butt welded joints before the solidification takes place. Since the solidification rate of welding process is quick so it has been made possible to stir the molten metal before it becomes a complete solidifies mass. It has been done in the manner that the tip of vibrating rod is inserted into the molten weld pool and is made to keep contact with it while maintaining a constant speed along with the welding arc while welding process took place. So this case resembles the quasi-stationary state where the observer finds that at any instant of time across the entire weld length, the vibratory tip is submerged in the weld pool.

Further this study is focused on the Taguchi and RSM optimization of vibratory welding process parameters namely welding current, frequency and welding speed to achieve the most suited mechanical properties and microstructure.

2. Experimental procedures

2.1 Vibratory technique

The schematic block diagram of the present experimental setup is depicted in Figs. 1 and 2 [26]. The vibratory setup is assembled with following equipments: Eccentric rotation mass (ERM) motor, 3 mm diameter rod made up of thorium- zirconium –tungsten alloy which can be sustained at very high temperature, 9 volt rechargeable battery used as a power source for ERM, non conducting gripping handle and a regulator to control the range of frequency.

The ERM works on the principle of rotation of unbalanced mass. ERM generates the resonance frequency of 300 Hz and the amplitude is 0.5 mm in the transverse direction. This high frequency low amplitude vibrations transferred in to the molten weld through the thorium- zirconium –tungsten rod. The one side of the rod is dipped into the molten pool of the weld

Table 1. Vibratory welding techniques used by various authors.

S. No	Vibratory welding treatments	Frequency	Process	Reference
1	Vibratory table	80-400 Hz	SMAW	[2]
2	Vibratory table	54-59 rps	SAW	[3]
3	Electromagnetic	0-40 Hz	GTAW	[4]
4	Electromagnetic	50 Hz	Casting	[5]
5	Vibratory table	58 Hz	GTAW	[6]
6	Vibratory table	25 Hz	MIG	[7]
7	Vibratory table	2.5 Hz	MIG	[8]
8	VSR	-	-	[9]
9	Vibratory Table	54-59 rps	SAW	[10]
10	Ultrasonic	20 kHz	SMAW	[11]
11	Ultrasound	50 kHz	PAW	[12]
12	Electromagnetic	-	GTAW	[13]
13	Vibratory table	3000 Hz	GTAW	[14]
14	Vibratory table	-	SMAW	[15]
15	Wave guide	20 kHz	MIG	[16]
16	Vibratory table	150-350 Hz	TIG	[17]
18	Vibratory table	60.9 Hz	TIG	[18]
19	Vibratory table	15 kHz	TIG	[19]
17	Horn plus tool	429 Hz	FSW	[20]
20	*Vibrating rod*	*80-300 Hz*	*SMAW*	*PW**

Note: - SMAW: - Shielded metal arc welding; MIG: - Metal inert gas; GTAW: Gas tungsten arc welding, SAW: Submerged arc welding, TIG: Tungsten inert gas, PAW: Plasma arc welding, PW*: Present work.

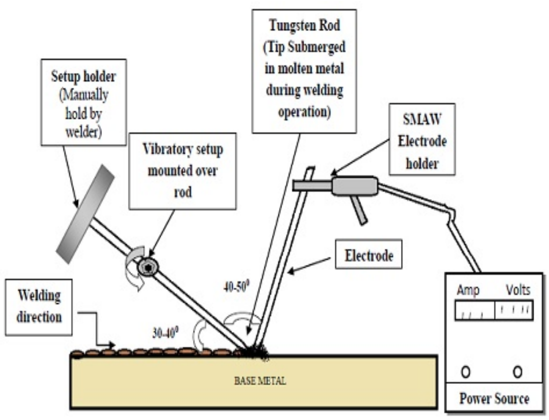

Fig. 1. Schematic block diagram of vibration setup.

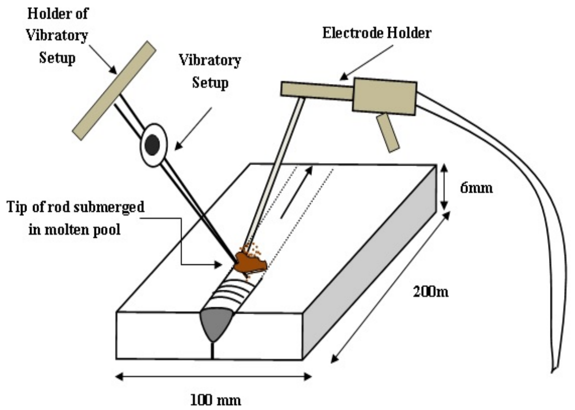

Fig. 2. Top view of vibratory setup.

zone during the Shielded metal arc welding (SMAW) process, that particular tip of the rod is tapered and casted with ceramic to make it to sustain at very high temperature. The other end of the rod is assembled with a non conducting holder, used to grip the vibratory setup during welding operation.

2.2 Materials and methods

Twenty seven pairs of specimen were SMAW- welded based on design of experiment of L_{27} OA by MINITAB-17. E-3106 electrode is used to prepare the butt welded joints of mild steel plates having dimension of 200×100×6 mm. The welding current was measured by using a regulator and welding speed is calculated by dividing the welding duration to the welding length (cm/min). Nine set of experiments were performed under the conventional condition which means no vibration has been imposed in to the molten weld pool during the welding operation. Rest experiments were conducted under the vibratory condition; the specimens were welded by imposing vibrations at 150 Hz and 300 Hz of frequency.

The Taguchi analysis is most efficient technique to aim the quality improvement of the experimentation. Signal to noise (S/N) ratio is use to determine the effect of each input factor on the response value. The mechanical property of the weld joint is generally expected as high as possible so the larger the better criteria have been chosen for S/N ratio. The equation to calculate the signal to noise ratio for the smaller is better is mentioned in Eq. (1) [21].

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

where n is the number of measurement i.e. number of repetitions of noise levels, y_i is the response of each welded specimen. The value of n is 27 for this investigation.

The significance of the model develop is tested by Analysis of variance (ANOVA). It is used to describe the relative importance of each input parameters. Further the response surface methodology has been used for mathematical modeling and analyzing the problems. The RSM makes a relationship between the input factors and the response values [22, 23].

2.3 Microstructure and mechanical testing

In order to study the effect of auxiliary vibrations induced in the weld zone and its consequentially affect on the corresponding solidification behavior, the microstructrual studies were conducted on different weld samples. For the microhardness test, the specimens were polished using emery papers of various grades that successfully removed corrosion, scratches and oxide layers from the surface of the specimens. The Vickers hardness test was performed on the polished surface of the welded specimen using a load of 500 gm and a dwell time of 20 sec. The hardness value was measured along the center line; each point was measured three times to inquire about its average value. The tensile specimens were prepared in accordance with ASTM E-08 standards. Tensile specimens were tested on a Universal testing machine, (Make: FIE, Capacity: 600 kN). The displacement rate was 0.5 mm/min. In order to ensure the accuracy of tensile strength data, three samples for each condition were tested.

3. Results and discussion

3.1 Design of experiments using Taguchi analysis

Taguchi's L_{27} Orthogonal array (OA) is chosen in the present design of experiments. The welding parameters and there levels are summarized in Table 2. Table 3 shows the 27 sets of coded experiments used to design the OA. Each parameter was divided into three levels: Higher, medium and lower level respectively. Welding current (I) is allotted in first column, frequency (f) in the second column and welding speed (S) in the third column respectively.

The response variable and the graph of S/N ratio for the hardness are mentioned in Table 4 and Fig. 3, respectively. The main effect plot and response table for S/N ratio for tensile strength of butt welded joint is given in Table 5 and Fig. 4. The observed results shows that, the hardness and the tensile strength increases with increasing the frequency levels, the highest UTS and hardness is found at the resonance frequency of 300 Hz. The optimal factors for hardness and tensile strength is found to be at a welding current of 60 Amp (level 1), welding speed of 20 cm/min (level 3) and welding frequency of 300 Hz (level 3). This is predicted by the above results and also it is well stated that, inducing vibration during welding operations enhanced the mechanical properties of the welded joints. Lu et al. [3] mentioned that the vibration disturbs the solidification behavior of the weld structures and large number of grains produced results in enhancement of the mechanical properties. Balasubramanian et al. [14] reported that the hardness at the weldment increases significantly with increasing in the frequency of vibration. Amini and Amini [18] found that with the application of ultrasonic vibrations

Table 2. Input parameters of vibratory welding and their levels.

Variables	Unit	Levels		
		1	2	3
Current	Amp	60	80	100
Frequency	Hz	0	150	300
Welding speed	cm/min	10	15	20

Table 3. L_{27} orthogonal array and experimental results.

Ex. No.	Coded value			Actual value			Hardness (VHN)	Tensile strength (MPa)
	I	f	S	I	f	S		
1	1	1	1	60	0	10	250	556
2	1	1	1	60	0	10	251	553
3	1	1	1	60	0	10	250	558
4	1	2	2	60	150	15	278	578
5	1	2	2	60	150	15	271	570
6	1	2	2	60	150	15	273	573
7	1	3	3	60	300	20	299	598
8	1	3	3	60	300	20	292	592
9	1	3	3	60	300	20	295	594
10	2	1	2	80	0	15	251	550
11	2	1	2	80	0	15	250	559
12	2	1	2	80	0	15	255	557
13	2	2	3	80	150	20	274	574
14	2	2	3	80	150	20	277	577
15	2	2	3	80	150	20	269	570
16	2	3	1	80	300	10	290	589
17	2	3	1	80	300	10	296	596
18	2	3	1	80	300	10	293	593
19	3	1	3	100	0	20	255	558
20	3	1	3	100	0	20	254	554
21	3	1	3	100	0	20	251	551
22	3	2	1	100	150	10	269	568
23	3	2	1	100	150	10	275	573
24	3	2	1	100	150	10	273	571
25	3	3	2	100	300	15	289	589
26	3	3	2	100	300	15	292	592
27	3	3	2	100	300	15	294	596

Table 4. Response table for S/N ratio (Hardness).

Level	Current (I)	Frequency (f)	Speed (S)
1	**48.72**	48.03	48.68
2	48.70	48.73	48.69
3	48.69	**49.35**	**48.74**
Delta	0.03	1.31	0.06
Rank	3	1	2

Bold values indicate the levels of significant parameters.

Table 5. Response table for S/N ratio (Tensile strength).

Level	Current (I)	Frequency (f)	Speed (S)
1	**53.52**	53.14	53.49
2	53.49	53.49	53.48
3	53.48	**53.86**	**53.51**
Delta	0.04	0.72	0.03
Rank	2	1	3

Bold values indicate the levels of significant parameters.

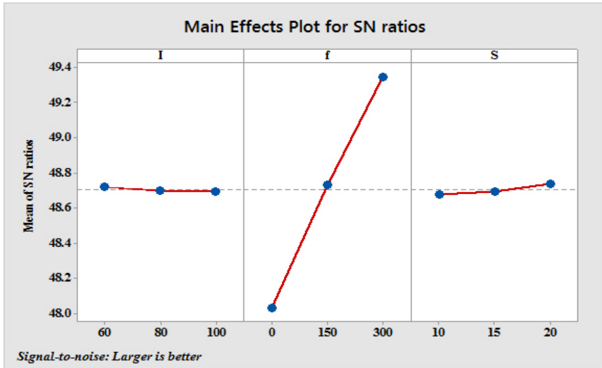

Fig. 3. Main effect plot of S/N ratio of hardness values.

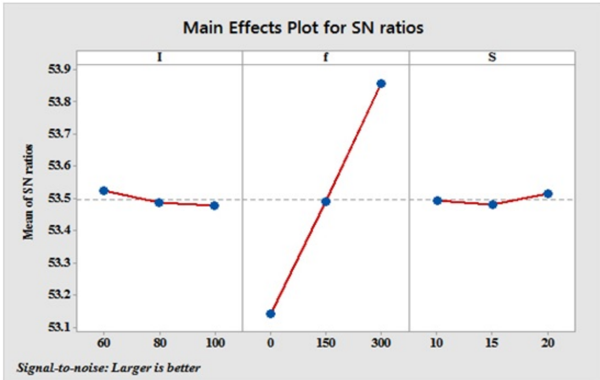

Fig. 4. Main effect plot of S/N ratio of tensile strength (UTS).

the tensile strength and hardness is increased under the certain range of conditions. Thus the fine grain structure has been found due to application of vibrations which would be the possible reason for the improvement in mechanical properties of vibratory welded joints.

Further, to analyze the most significant process parameter for the experimental results of hardness (H) and tensile strength (UTS) the Analysis of variance (ANOVA) technique was applied. The ANOVA analysis was accomplished at a significance α value of 0.05 i.e. 95 % of confidence value. ANOVA is used to study the influence of each input parameters on the response value. ANOVA states that total sum of squares of the deviation are equal to the sum of square of standard deviation caused by each input factor [21]. Table 6 shows the ANOVA table for hardness and the tensile strength. P- Values recognize the most significant values, affiliated with

Table 6. Analysis of variance for tensile strength and hardness.

Source	DOF	Adj SS	Adj MS	F-value	P-value
(a) Analysis of variance for tensile strength (UTS)					
I	1	2.03	2.03	0.20	0.660
f	1	3379.02	3379.02	331.84	0.000
S	1	0.13	0.13	0.01	0.912
I*f	1	7.63	7.63	0.75	0.397
I*S	1	20.64	20.64	2.03	0.170
f*S	1	7.14	7.14	0.70	0.412
Error	20	203.33	10.18		
Lack of fit	2	2.32	1.16	0.10	0.902
Pure error	18	201.33	11.19		
Total	26	7102.67			
R- sq = 97.13		R-sq(adj) = 96.27			
(b) Analysis of variance for hardness (H)					
I	1	3.50	3.50	0.44	0.514
f	1	3291.56	3291.56	414.32	0.000
S	1	1.56	1.56	0.20	0.663
I*f	1	3.50	3.50	0.44	0.514
I*S	1	0.39	0.39	0.05	0.827
f*S	1	0.39	0.39	0.05	0.827
Error	20	158.89	7.94		
Lack of fit	2	1.56	0.78	0.09	0.915
Pure error	18	157.33	8.74		
Total	26	7838.67			
R-sq = 97.97		R-sq(adj) = 97.36			

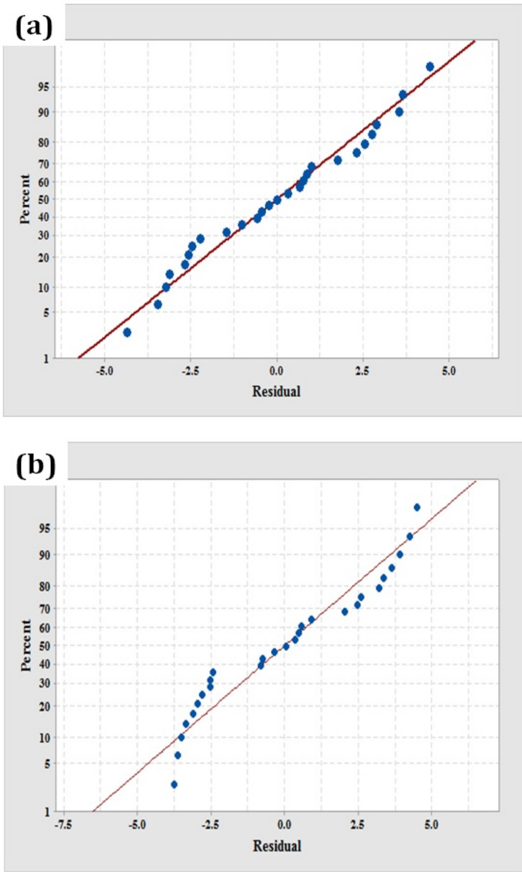

Fig. 5. Normal probability plot of residuals for (a) hardness; (b) tensile strength.

the F-test for each source of process parameters [22]. The significance of the process parameters to the response value will be acceptable when the P- value is less than 0.05. Table 6 reported that frequency (f) is the only process parameter whose P-value is less than 0.05 and having the highest F value. Thus the ANOVA test reveals that frequency is the only significant parameter which affects the mechanical property of the welded joints. No considerable effect is noticed on the tensile strength and the hardness of the welded joint by changing the current and welding speed.

R^2 (Coefficient of determination) is used to check the goodness of the model; it determines how close the predicted values with the experimental values [23, 24]. The values of R^2 are mentioned in Table 6, for the tensile strength (Table 6(a)) R-sq = 97.13 and R- sq (adj) = 96.27, and for hardness (Table 6(b)) R-sq = 97.97 and R- sq (adj) = 97.36. These values indicate the goodness of designed model at states that designed model is valid for the further investigation.

Fig. 5 shows the normal probability plot of the residuals for hardness and tensile strength. These plots are used to check the assumptions of ANOVA for a particular model by investigating the distribution of the population of data. The graph was plotted between residuals (difference between observed and the fitted response values) versus frequency percent [25, 26]. If the plot follows the straight line then the residual is significant. Figs. 5(a) and (b) depict that the residual plots for hardness and tensile strength are almost follow the straight line so the design of the model is valid.

3.2 Response surface analysis

Response surface methodology (RSM) is used for the regression analysis of the designed model. RSM is a collection of mathematical models which are useful for justifying the engineering problems. This methodology makes a co-relationship between input factors and obtained responses.

Using the experimental results linear + interaction model was established for the hardness and tensile strength with 95 % of confidence level. As the tensile strength (UTS) and hardness (H) are the function of welding current (I), Frequency (f) and welding speed (S), so it can be mathematically expressed as:

$$H = f(I,\ f,\ S) \quad (2)$$
$$UTS = f(I,\ f,\ S)\,. \quad (3)$$

The linear plus interaction regression equation that represents the response surface 'Y' is:

$$y = C_0 + \sum C_i x_i + \sum C_{ij} x_{ij} \quad (4)$$

$$\mathrm{H} = C_0 + C_1(I) + C_2(f) + C_3(S) + C_{12}(I \times f) + C_{13}(I \times S) + C_{23}(f \times S) \,. \quad (5)$$

Similarly for UTS:

$$\mathrm{UTS} = C_0 + C_1(I) + C_2(f) + C_3(S) + C_{12}(I \times f) + C_{13}(I \times S) + C_{23}(f \times S) \quad (6)$$

where

C_0 = Average response.

C_{ij} = Coefficient of the interaction effect of the parameters.

Using the Response surface methodology (RSM), regression equation for hardness and tensile strength are presented in Eqs. (7) and (8).

$$\mathrm{H} = 244.8 + 0.067I + 0.169f + 0.42S - 0.000333(I \times f) + 0.0033(I \times S) + 0.00044(f \times S) \,. \quad (7)$$

For, R^2 = 97.97 and R^2 (adj) = 96.41

$$\mathrm{UTS} = 582.4 - 0.316I + 0.1489f - 2.25S - 0.000492(I \times f) + 0.0243(I \times S) + 0.0019(f \times S) \,. \quad (8)$$

For, R^2 = 97.13 and R^2 (adj) = 96.27.

The linear model determines the effect of each individual factor over the response value where as the interdependency of each factor can also be visualized by interaction of the process parameters through Response surface methodology (RSM). The Eqs. (7) and (8) can predict the response value for the particular set of experiment.

Figs. 6 and 7 show the interaction plot of process parameters (current, welding speed and frequency) and their effects on the response values (hardness and tensile strength). These plots are 3D plots explains the behavior of response values at various conditions of process parameters As shown in Fig. 6, the maximum hardness is demonstrated at the top point of the plot. Similarly the maximum value of tensile strength is found at the peak value of surface plot (Fig. 7). The response surface plots shows variation in hardness and tensile strength when each vibratory welding parameter moves from there reference point.

3.3 Response surface optimization: A confirmation test

A response surface optimization technique has been used to determine the welding parameters for the best response value means at highest hardness and UTS values. Figs. 8 and 9 show the results obtained from the response surface optimization technique for maximum hardness and maximum tensile values respectively. The optimal vibratory welding parameters for maximum hardness value were found to be at current (I) of 60 Amp, Frequency (f) 300 Hz and Speed (S) at 20 cm/min and for maximum UTS value the optimal values are at I = 60 Amp, f = 300 Hz, S = 10 cm/min. The calculated value of hardness and tensile strength are 295.44 and 597.04 MPa, respectively

Table 7. Validation test results.

	Optimum parameters			Actual	Predicted	% error
	I	f	S			
H	60	300	20	296.77	295.44	-0.5 %
UTS	60	300	10	590.30	597.04	1.1 %

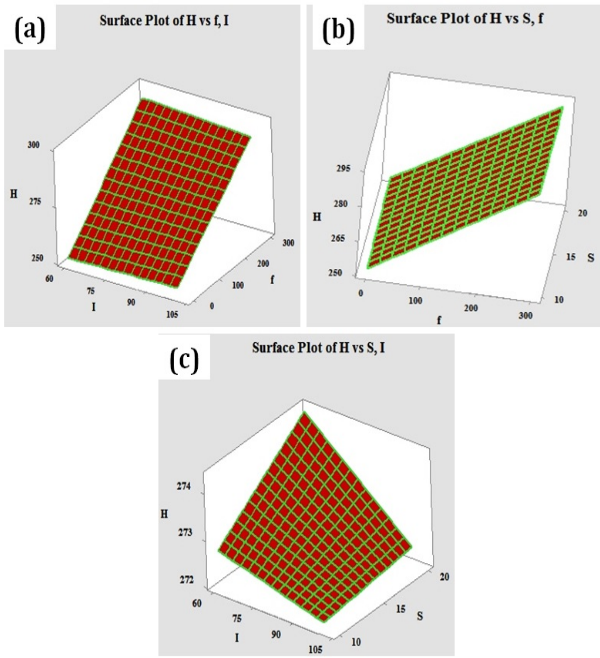

Fig. 6. Surface plot for hardness.

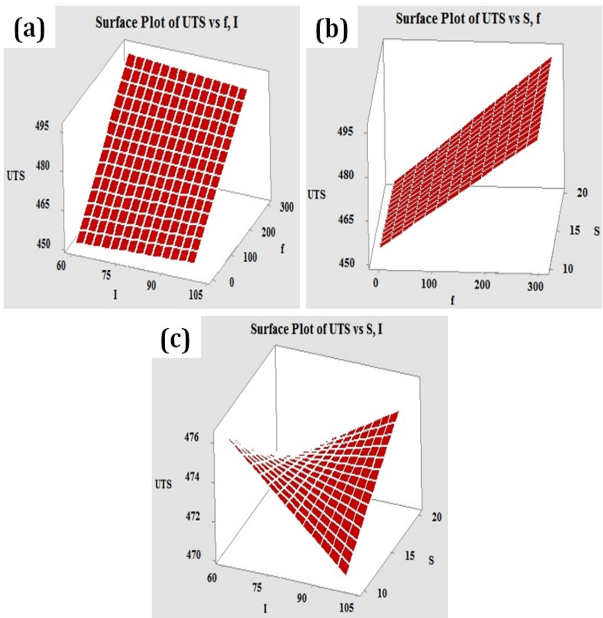

Fig. 7. Surface plot for tensile strength.

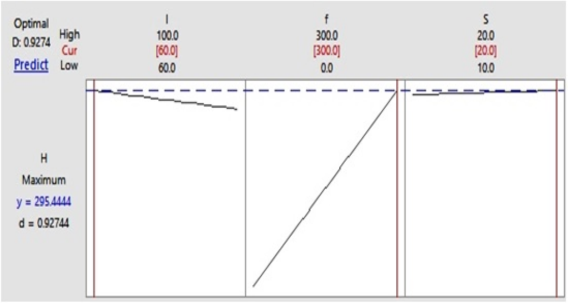

Fig. 8. Response optimization plot for hardness.

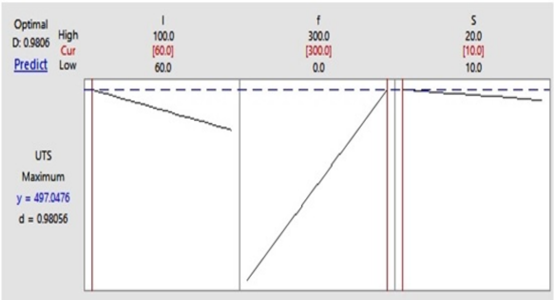

Fig. 9. Response optimization plot for tensile strength.

(refer Figs. 8 and 9). To validate the proposed models, experiments were conducted at its optimum values. The butt welded joints were prepared and its hardness and tensile strength were measured. The experimental result is the average of three measured results for responses. Table 7 shows the actual value, predicted value and percentage error of experiment. The new obtained hardness is 296.77 VHN, which is varying by approx. 0.5 % from the calculated value (295.44) and the UTS is 590.30 MPa makes a difference of 1.3 % from its calculated value (597.04 MPa). These values confirm that the proposed model is good enough to predict the response values of vibratory welded butt joints.

3.4 Analysis of microstructures

For a comparative study between vibratory welding and conventional welding (no involvement of vibration during welding) process, the experiments were conducted and their hardness property and microstructure behavior has been investigated. Two different welding experiments were performed, first one is under the vibratory condition at the optimal setting of welding parameter (Current = 60 Amp, frequency = 300 Hz and speed = 10 cm/min) and another experiment was conducted under the conventional condition i.e. vibratory setup has not being in used during welding operation (the welding parameters are: Current = 60 Amp, frequency = 0 and speed = 10 cm/min) to serve as a source for comparison. Fig. 10 shows the Micro-hardness values across different zones of the weld samples. The red line is showing the hardness value of the vibratory welded specimen where as black line is hardness value for conventionally.

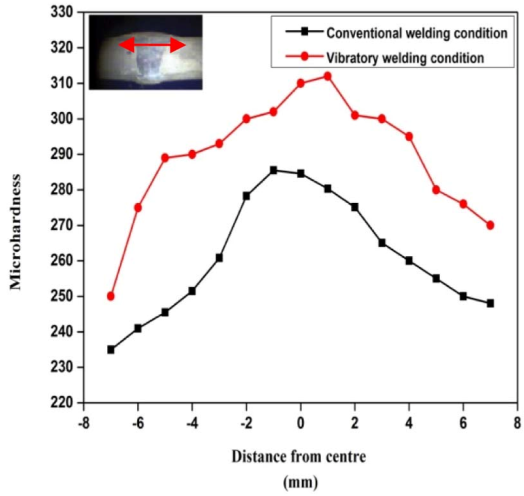

Fig. 10. Micro-hardness investigation of conventional and vibratory welded joints.

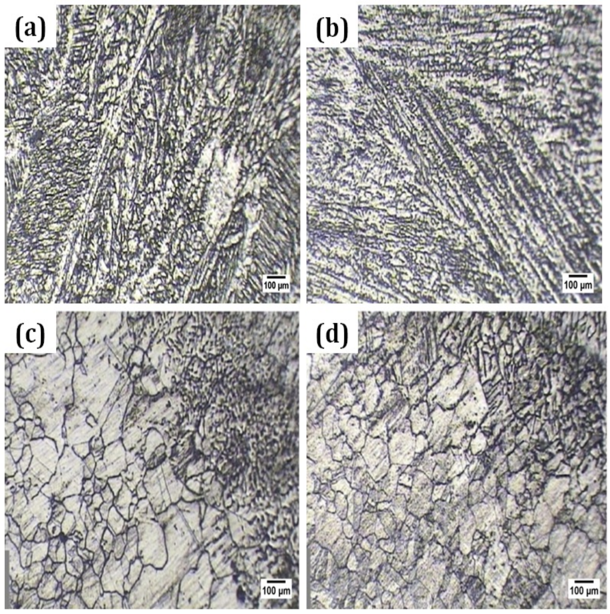

Fig. 11. Microstructures of (a) conventional welded joint; (b) vibratory welded joint; (c) HAZ of conventional welded joint; (d) HAZ of vibratory welded joint.

It has been clear from the hardness result, that external energy in the form of vibrations disturbed the solidification process of welded joints. So for the verification, it is necessary to study the microstructure of welded joints. As per microhardness investigation the specimens were further used for microstructure studies.

Figs. 11(a) and (b) show the microstructure of conventional welded joint and vibratory welded joint, respectively. Whereas Figs. 11(c) and (d) is showing the microstructure of Heat affected zone (HAZ) for conventional welded joints and vibratory welded joints, respectively. In vibratory welding technique, dendrites of the weld metal while solidifying experienced a hindered growth i.e. an opposing force generated due to auxiliary mechanical vibrations induced, did not allow these dendrites to grow to their fullest extent as these would have grown in the absence of any such disturbance. In this way the grain refinement has been increased and the number of grains increased accordingly the fine grains structure was found. While Fig. 11(a) shows dendrite microstructure having the large grain size in the conventional weld joints, whereas in the vibratory conditions, a uniform, fine grain structures has been formed (Fig. 11(b)). Fig. 11(c) depicts the large size of grains in HAZ of conventional welded joints were as a small grain size was found in HAZ of vibratory welded joints (Fig. 11(d)). When vibration is employed the cooling rate of the weld zone increased thus establishing relatively higher the thermal gradients across the HAZ and resulted in fine grain microstructure forms in HAZ [27]. Thus this uniform fine grain structure causes the high hardness value during vibration and thus the mechanical properties have been improved.

4. Conclusions

(1) Based upon the problem undertaken and experimental work carried out it has been found that, it is possible to enhance the mechanical properties of welded joints if mechanical vibrations are induced into the molten weld pool during the SMAW process. So the present experimentation provided an alternative method for grain refinement of weldments.

(2) An empirical relationship was developed to predict the mechanical property of vibratory and conventionally welded MS plates at 95 % confident level.

(3) The main effect plot shows, the hardness and tensile strength is principally affected by frequency. The mechanical property is improved with the increasing the frequency of vibration. The high hardness and tensile strength has been obtained at vibratory welding parameters of current 60 Amp (1^{st} level), speed 20 cm/min (3^{rd} level) and frequency at 300 Hz (3^{rd} level). It is evident from ANOVA results that, frequency is most influencing factor for changing the mechanical properties of welded joints.

(4) The regression equation has been developed by RSM and found to be a successful tool for the vibratory welding parameters and have significant influence on the responses. The model has been justified by various Design of experimental analysis.

(5) The comparative study between vibratory welded joints and conventionally welded joints demonstrate that hardness property of weld joint is highly influenced by inducing vibration; it has been found that hardness value is increased by approximately 35 VHN during the vibratory condition as compare to the conventional condition.

(6) The metallographic characterization shows a drastic change in microstructure due to the effect of vibration during welding operation. It revealed that due to auxiliary stirring of the weld pool using a vibratory tip, steeper thermal gradients are established that lead to a condition where grain coarsening is relatively less.

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