

An analysis to optimize the process parameters of friction stir welded low alloy steel plates

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Abstract

The friction stir welding (FSW) of steel is a challenging task. Experiments are conducted here, with a tool having a conical pin of 0.4mm clearance. The process parameters are optimized by using the Taguchi technique based on Taguchi's L_9 orthogonal array. Experiments have been conducted based on three process parameters, namely, the tool rotational speed, tool tilt angle and travel speed. Tensile strength has been predicted for the Optimum welding parameters and their percentage of contribution in producing a better joint is calculated, by applying the effect of the signal-to-noise ratio and analysis of variance. Based on the study, the tool tilt angle is found to be the most significant variable over the other process parameters, and it enhances the quality of the weld on steel rather by the tool axis which is perpendicular to the work plate. The optimum tensile strength predicted through the ANOVA is 472 MPa. Confirmation tests have been performed for the resulting optimum parameter and the average tensile strength was found to be 474 MPa. A metallurgical analysis for the optimum parameter was performed on the specimens and typically two distinct Heat affected zones (HAZ) were observed with variation in the micro structure.

Keywords: Low alloy steel, Taguchi, Tensile strength, conical pin, tool tilt angle

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1. Introduction

The need for joining materials having higher hardness property and tensile strength has arisen with the present advancement in science and technology. Friction stir welding (FSW) is a recent addition to the welding process and it is a solid state joining technique (Patil et al., 2010; Muthukumaran et al., 2006); it was performed on Al and its alloys is now carried out on copper, magnesium and different material combinations. Different tool pin profiles have been used to weld aluminum alloys (Elangovan et al., 2007; Palanivel et al., 2012), and it has been found that the tapered pin gave defective welds when compared to other profiles. When FSW of steels is performed by straight pin profiles, pin failure takes place before the complete insertion, and moreover, the weld joint could not be formed due to rapid tool wear. The tapered pin has been reported to give better joint strength because of the easy penetration of the pin inside the steel plate with reduced pin failures (Lakshminarayanan et al., 2010 & 2012). The amount of friction heat produced for a better weld depends mainly on the process parameters, such as the tool rotational speed, plunge depth, plunge force, tool tilt angle and travel speed (Hussain et al., 2010; Lakshminarayanan et al., 2008). Apart from the highest influencing process parameters, such as the rotating speed of the tool and traverse speed in FSW, the tool tilt angle is an added process parameter which could give better results in the FSW of steel (Choi et al., 2011; Ghosh et al., 2011). Tensile strength is the powerful mechanical property to optimize the process parameter of the weld to achieve a better joint (Balaji et al., 2011; Bozkurt, 2012).

The most efficient and simple way of designing an experiment can be achieved by the Taguchi method (Kumar et al., 2012; Wang et al., 2012) which helps to find out the most significant process parameter among the parameter combinations, by using the analysis of variance (ANOVA) and signal-to-noise ratio (S/N) (Vijian et al., 2007). The effect of the process parameters by welding with a shorter conical pin on the strength properties has been studied with the influence of the process parameters and

their combinations to produce a defect free weld. L_9 orthogonal array of the Taguchi design method has been used, because it is easy to use and solve complex problems more efficiently. The Calculation of the S/N ratio and mean response, by the ANOVA gives the most influential process parameter, while the mean effects of the plot for the S/N ratio and mean response predicts the optimum process parameter. Thus, the present optimization serves two main objectives; the first objective is to estimate the contribution of the individual process parameters, and to determine the optimum combination of the process parameters for better possible strength. The second objective is to analyze the hardness, and the micro and macro structure for the optimum parameter.

2. Material and its method

2.1 Material

The present investigation uses a low alloy steel plate of IS: 3039 grade II, and finds its application as structural steel for ship building and bridge decking. The work piece dimension is 100mm length, 50mm breadth and 3mm thickness, and it is prepared for a butt weld as shown in Fig.1 (a). The chemical composition of this base metal is presented in Table 1. The tool used for the FSW process is a tungsten alloy, with a concave shoulder 25 mm in diameter and the pin is tapered, and cylindrical in shape as shown in Fig.1 (b). A Short pin of length 2.6 mm is tapered with a diameter of 12mm near the shoulder and 4mm at its tip.

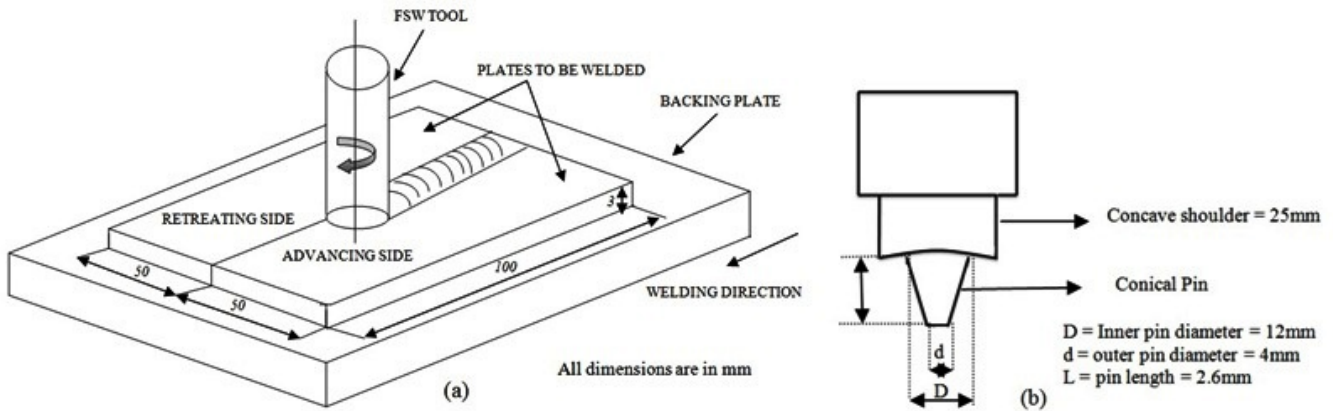


Figure.1. Schematic representation of (a) FSW process and (b) tool profile with dimension

Table.1 The chemical composition of base metal

C	Si	Mn	P	S	Cr	Mo	Al	Cu	Ti	V	Pb
0.204	0.129	1.10	0.040	0.017	0.309	0.0332	0.0940	0.0908	0.0063	0.0069	0.0014

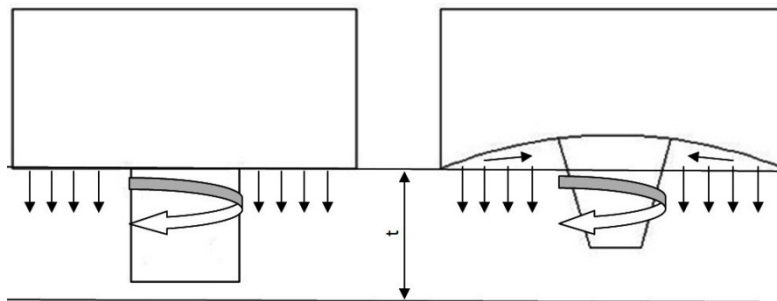


Figure.2 Schematic representation of (a) flat shoulder with cylindrical pin and (b) concave shoulder with tapered pin

The schematic representation shown in Fig.2 (a) is the normal tool with a flat shoulder and cylindrical pin, and though this tool profile finds its application in a variety of aluminum alloys, it is difficult in steel plates. However, a concave shoulder with a conical pin, as shown in the Fig.2 (b), is found to produce better joints in the welding of steel plates. When the cylindrical pin penetrates inside the steel plate, it is the initial step where the tool starts to wear, because of the wear at the edges of the pin as the work plate is of high strength material. The shoulder not only gives compaction, but favors additional stirring action. There is a gap between the plate surface and tool shoulder which creates some pressure over the material under plasticized flow to get more

mixing and compaction. The smooth penetration perhaps reduces the tool wear of the pin to some extent, and the concave shoulder produces high compaction to the plasticized material flow.

2.2 Taguchi Method

The Taguchi method is very effective, because it is simple to carry on the experimental design and its approach is very systematic to provide good quality and low cost in manufacturing (Demirci et al., 2011). The main aim of the Taguchi method is to analyze the statistical data, which has been given as an input function to produce an optimum result. The effect of the combination of the input functions as a result is produced by the S/N ratio and mean response (Wu et al., 2002). The strength of the weld is varied by the parameters such as the tool rotating speed, tool tilt angle, depth of tool penetration, dwell time and travel speed. Among these input parameters, rotating speed, tool tilt angle and travel speed are taken and the other parameters are maintained constant. The input parameters are entered in the array table with the output characteristics as the average tensile strength. The shorter conical pin with a concave shoulder should be optimized to have a better weld, with a suitable process parameter, and hence, the Taguchi technique is applied to a self analysis of the high strength material based on the tensile strength.

MINITAB Release 13 is the software that gives the statistical analysis of how to form a combination of input parameters and to find out the most significant combination (MINITAB™ 2008). Process parameters are control factors, and the factors which initiate variability in the process are the noise factors. In a Taguchi designed experiment, the noise factors are manipulated for the variability to occur, and from the results optimal control factors that make the process robust, can be identified. The Signal to Noise ratio (S/N) indicates the control factors settings that minimize the effects of the noise factors. The Taguchi experiments are carried out in a two step optimization process.

Step 1: use the S/N ratio to identify those control factors that reduce variability.

Step 2: identify the control factors that bring the mean to target and have little or no effect on the S/N ratio.

Usually, the calculation of the main effect of the S/N ratio and mean response is done by three categories of quality characteristics, as listed below.

(1) The Smaller the better:

The Smaller the better criterion is applied to the problems, when a minimization of the response is required for the output characteristics data; (i.e.) if the output result needs to be the minimum in value and the data are non-negative with a target value of zero. Here, in this optimization, maximum tensile strength is required and hence the smaller the better criterion is not applied.

$$\text{S/N ratio } (\eta) = -10 \log_{10} \left((1/n) \sum (y_{ij})^2 \right) \quad (1)$$

where n is the number of replications,
 y_{ij} is the observed response value.
 $i = 1, 2, 3, \dots, n; \quad j = 1, 2, 3, \dots, k$

(2) The Larger the better:

The Larger the better criterion is applied to the problems, when the maximization of the response is required for the output characteristics data. The data of the target value is positive. Here the optimized result needed is higher tensile strength, and hence this criterion is selected to find out the optimum process parameter, which can give better strength. The following formula is used to find the optimum result,

$$\text{S/N ratio } (\eta) = -10 \log_{10} \left((1/n) \sum (1/(y_{ij})^2) \right) \quad (2)$$

(The value of the response table for the mean and S/N ratio given by the MINITAB software is verified, using this equation manually. See appendix)

(3) The Nominal the best:

The Nominal the best criterion is applied to target the response, and base the S/N ratio on the mean and standard deviations. The data are non-negative with an absolute zero, in which the standard deviation is zero when the mean is zero.

$$\text{S/N ratio } (\eta) = -10 \log_{10} \left(\mu^2 / \sigma^2 \right) \quad (3)$$

where $\mu = (y_1 + y_2 + y_3 + \dots + y_n) / n$,
 $\sigma = ((y_i - \mu)^2 / (n-1))$

The Taguchi method has been implemented using MINITAB software, which includes the S/N ratio and ANOVA. Through ANOVA the contribution of the individual parameter in making better FSW welds can be identified. The response for the signal to noise ratio gives the most influencing parameter. Through the mean plots of the S/N ratio and mean response, the optimum parameter has been identified.

2.3 Experimental method

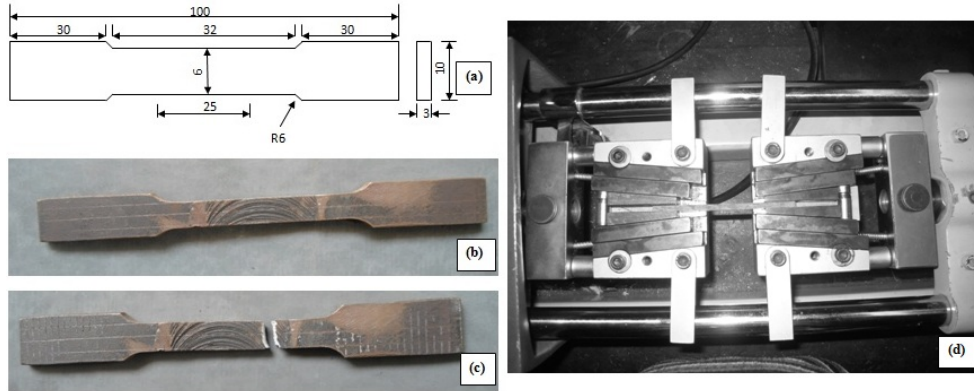
According to the L_9 orthogonal array, three experiments in each set of process parameters have been performed on IS: 3039 plates. The three factors used in this experiment are the rotating speed, tool tilt angle and travel speed. The factors and the levels of the process parameters are presented in Table.2 and these parameters are taken based on the trials to weld the FSW of steels. The experiment's notation is also included in the L_9 orthogonal array which results in an additional column, in order to represent the parameters, as presented in Table.3. The experiments are performed on a vertical milling machine which serves to perform the FSW operation. It is a well known factor that at higher rotating speed, FSW produces high heat input and these three levels were selected as low, medium and high speed among the highest speeds available in the machine. Only at low travel speeds, the weld could be achieved with a shorter pin and hence the three least travel speeds were taken. Beyond the tool tilt angle of 2° the pin pierces out the plasticized material for the thickness of 3mm plate, and hence 0° , 1° and 2° tool tilt angles were taken. The FSW butt joint weld being performed on steel needs careful experimentation, and hence the tool is plunged slowly into the work piece, till the tool shoulder comes in contact with the surface of the work piece. When the tool is inserted, the stirring action starts to occur, and only the pin penetrates deep into the work piece while the tool shoulder touches the top surface. Frictional heat occurs along with the stirring action. Twenty seconds dwell time is given before the start of each welding, and then the automatic feed is given. With reference to the ASTM standard E8 sub size dimension, the tensile specimens are prepared as shown in Fig.3 (a). The tensile tests for nine specimens are conducted and they yielded a variety of results. A sample tensile specimen, before and after the failure is shown in Fig.3 (b) & (c). The ultimate tensile strength of the specimen is tested with the Hounsfield tensometer machine, as shown in Fig.3 (d). The tensile failure has occurred in between the regions of HAZ and base metal. FSW joints of low alloy steel have been welded, and the average tensile strength of the three tensile specimens from the same sample was obtained and is presented in Table.4. It reveals that the FSW parameters do not lead to a significant variation, and hence, the ANOVA is used to find the optimum process parameter.

Table.2. Factors and the levels of the process parameter taken

Factors	Levels		
	1	2	3
A, Rotational speed, in rpm	900	1120	1400
B, Tool Tilt angle, in $^\circ$	0	1	2
C, Travel speed, in mm/min	8	15.75	20

Table.3. Experimental layout of L_9 Orthogonal array

S.I No	Experiment's notation	Friction Stir Welding Parameters level		
		A Rotating speed in rpm	B Tool Tilt Angle in degree	C Travel speed in mm/min
1	A1	1	1	1
2	A2	1	2	2
3	A3	1	3	3
4	B1	2	1	2
5	B2	2	2	3
6	B3	2	3	1
7	C1	3	1	3
8	C2	3	2	1
9	C3	3	3	2



All dimensions are in mm

Figure.3. (a) ASTM E8 sub size specimen; Tensile specimen (b) before failure (c) after failure (d) Tested with Hounsfield tensometer

Table.4 The input parameter of orthogonal array and the output characteristics

Experimental number	Input Parameters			Output characteristic Average Tensile strength (MPa)
	Rotational Speed (rpm)	Tool Tilt Angle (°)	Travel speed (mm/min)	
A1	900	0	8	448
A2	900	1	15.75	459
A3	900	2	20	446
B1	1120	0	15.75	445
B2	1120	1	20	457
B3	1120	2	8	462
C1	1400	0	20	438
C2	1400	1	8	469
C3	1400	2	15.75	449

3. Results and Discussion

3.1 Mean and Signal to Noise ratio

The Mean and signal to noise ratio are the two effects which influence the response of the factors. The influencing level of each selected welding parameter can be identified. The tensile strength of the FSW weld is taken as the output characteristic. The response table for the S/N ratio shows that the tool tilt angle ranks first in the contribution of good joint strength, while travel speed and rotation speed take the second and third ranks. The same trend has been observed in the response table of the mean which is presented in Tables 5 and 6 respectively. The responses for the plot of the S/N ratio and Mean are shown in Fig.4. The tensile strength is estimated to be the maximum at 1120 rpm rotation speed, 1° tool tilt angle and 8 mm/min travel feed; which is optimal from the plots obtained.

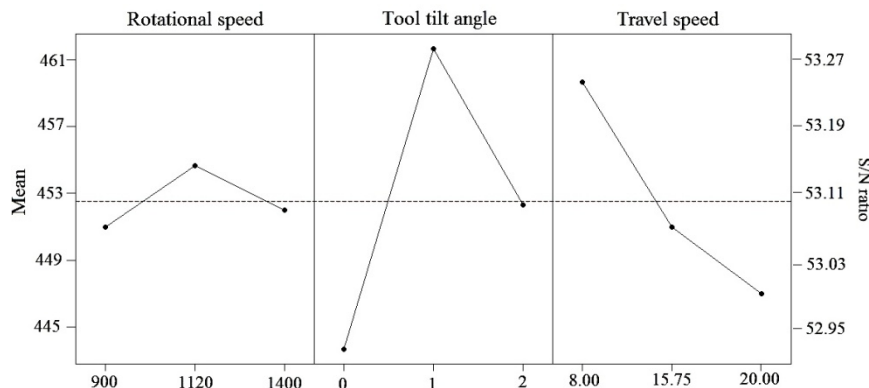


Figure.4. Main effect plot for S/N ratio and mean

Table.5. Response Table for Signal to Noise Ratio

Level	Rotating speed	Tool Tilt angle	Travel speed
1	53.0828	52.9407	53.2473
2	53.1528	53.2860	53.0828
3	53.0993	53.1082	53.0048
Delta	0.0700	0.3453	0.2425
Rank	3	1	2

Table.6. Response Table for Mean

Level	Rotating speed	Tool Tilt angle	Travel speed
1	451.000	443.667	459.667
2	454.667	461.667	451.000
3	452.000	452.333	447.000
Delta	3.667	18.000	12.667
Rank	3	1	2

3.2 Analysis of Variance

ANOVA is done on MINITAB software. The main aim of the analysis is to estimate the percentage of the individual contribution of the welding parameter on the tensile strength of the weld, and also give accurately the combination of the process parameters. Individual optimal values for the process parameters and their specified performance characteristics can be obtained. The relative importance of the welding parameters is presented in Table 7. The analysis of variance for tensile result shows that the tool tilt angle is the most influential parameter with a percentage of 63.46%, followed by the travel feed of 32.83% and rotation speed of 2.81%.

The optimum parameter obtained can be due to the two following possibilities; either the combination of the process parameters as prescribed may be present in the experimental combination, or may not be present in the combination. The optimum parameter for higher tensile strength obtained by the Taguchi method is presented in Table.8. With the tool tilt angle the material is pushed and stirred along the path of travel direction, but without the tool tilt angle only the normal stirring action takes place. Inclination of tool thus helps to provide a good plastic deformation at the weld zone, and better material flow can be achieved. The combination of the process parameters of 1120 rpm tool rotation speed, 1° tool tilt angle and 8 mm/min travel speed has been predicted to give the ultimate tensile strength of 472MPa.

Table.7. Analysis of Variance (ANOVA)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage of contribution
Rotating speed	2	21.56	21.56	10.78	3.13	0.242	2.81
Tool tilt angle	2	486.22	486.22	243.11	70.58	0.014	63.46
Travel feed	2	251.56	251.56	125.78	36.52	0.027	32.83
Error	2	6.89	6.89	3.44			0.9
Total	8	766.22					

Note: DF- Degrees of Freedom, Seq SS – Sequential Sum of Squares, Adj SS – Adjusted Sum of Squares, Adj MS – Adjusted Mean Square, F test of hypothesis, P value of hypothesis.

Table.8. Optimized result obtained from ANOVA - Minitab

	Rotational speed in (rpm)	Tool Tilt Angle in(°)	Travel Speed in (mm/min)	Ultimate Tensile strength in (MPa)
Taguchi method	1120	1	8	472

3.3 Experimental result

The estimated joint strength obtained from the optimization study is verified by conducting experiments, using the optimal combination of the process parameters (tool rotation speed 1120 rpm, 1° tool tilt angle and 8 mm/min traverse speed). Three experiments are conducted with the optimum combination, and the average joint strength of the weld obtained with this process parameters is found to be 474 MPa and this value is close to the predicted value. The ultimate tensile strength of the base material is 442MPa, and hence the optimized weld has given better ultimate tensile strength. The tool design with a conical pin and concave shoulder can give a better weld, with reduced pin length, which helps in reduction of the tool material for mass welding.

When the process parameters are observed individually as per the contribution, each parameter shows a different characteristic behavior. If the rotating speed increases, then the rate of heat generation also increases in the stir zone. Then, the optimized value should be higher speed, but here it has resulted in a moderate speed, which indicates that sufficient heat alone is required for

plasticized material flow. The tool tilt angle favors the material movement towards the travel direction and also the mixing of the plasticized material flow in the weld zone. The material movement along the travel direction plays an important role in the bond formation. The tool edges are represented by ‘a’ and ‘b’ in Fig.5, which shows the schematic diagram of the tool tilt angle influence on the work plate. Normally, when the tool is perpendicular to the work plate horizontal axis, the edges ‘a’ and ‘b’ are at a uniform level. When the tool is tilted 1° towards the feed direction, the edge ‘a’ touches the work plate and ‘b’ slightly penetrates the plate. If the tool tilt angle is further increased to 2° the tool lifts up at ‘a’ and ‘b’ penetrates deeply into the work plate, making a defective weld. Apparently, the tool tilt angle with 1° gave a defect free weld and better strength to the weld.

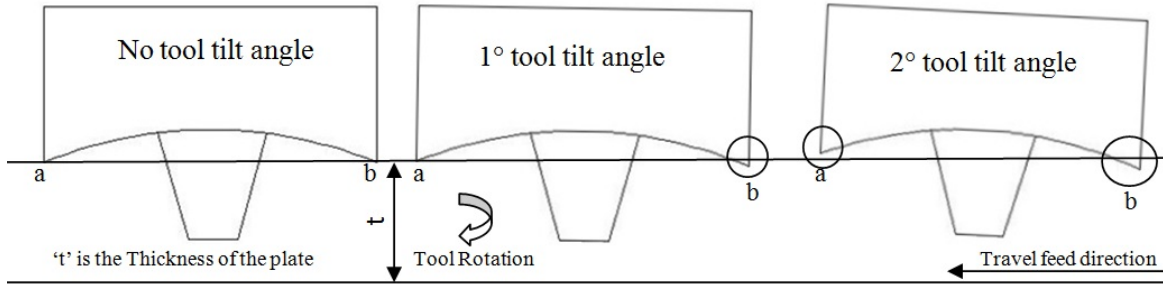
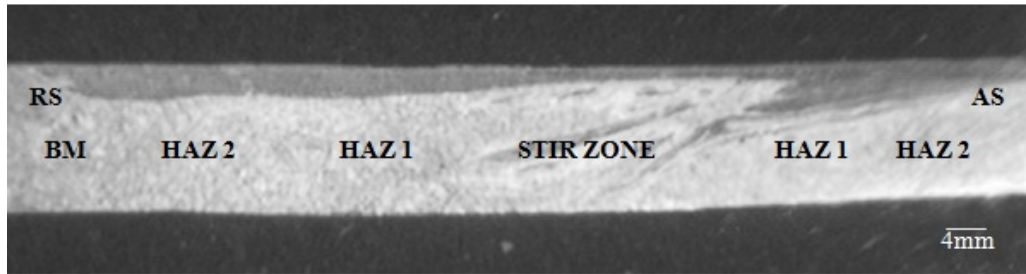


Figure.5. Schematic representation of tool tilt angle .



Note: RS – Retreating Side, AS – Advancing side

Figure.6. Transverse cross-section of a typical low alloy steel butt welded plate exhibiting various regions.

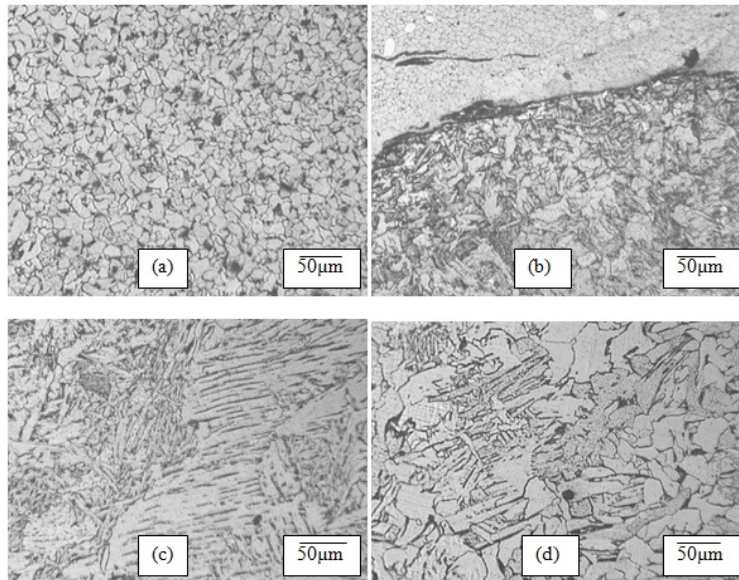
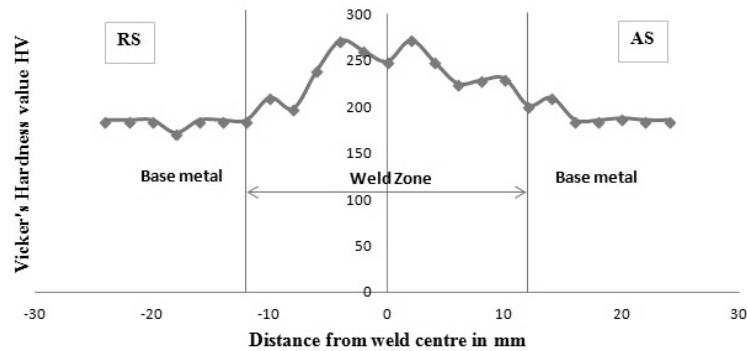


Figure.7. Micro structures at advancing side (a) Base metal having Polygonal Ferrite and Pearlite. (b) Upper surface of the stir zone near HAZ Zone 1 region. (c) HAZ Zone 1 having Coarse Bainite with Grain Boundary allotriomorphic Ferrite. (d) HAZ Zone 2 having Grain Boundary Ferrite and Ferrite with aligned grains and nonaligned grains.

A typical macrostructure of the transverse cross- section at different regions of the Friction stir weld for the optimum process parameters of tool rotational speed of 1120rpm, 1° tool tilt angle and travel feed of 8mm/min is shown in the Fig.6. The left side of the weld centre corresponds to the retreating side while the right side corresponds to the advancing side. The macrostructure of the

weld cross section can be divided into three distinct regions, namely, the Stir Zone (SZ), Heat Affected Zone (HAZ), and the Base Metal (BM). Two different zones of HAZ can be observed, viz., HAZ 1 and HAZ 2 and all the zones are found to be defect free. The Grains in the TMAZ zone are elongated and pulled towards the retreating side direction due to the thermo mechanical action. The microstructural characterization is typically not observed in this case, and this may be due to the transformation of thermal cycles (Paventhana et al., 2011). The joint in various zones experiences different thermomechanical cycle, and hence, the microstructural changes are a complex phenomenon. HAZ 1 has coarse grains while HAZ 2 has fine grains. The difference in the grain sizes may be due to the change in nucleation and the growth rate. The base metal microstructure consists of Polygonal Ferrite matrix, in which Pearlite is distributed randomly throughout the structure as shown in Fig.7 (a); and the upper surface of the stir zone exhibits the structure of Equiaxed Ferrite grains, while the layer below the upper surface contains Ferrite carbide aggregates and polygonal ferrite as shown in Fig.7 (b). The recrystallization of grains produces equiaxed ferrites at equal intervals, since the amount of heat imposed on the grains may be uniform. Some polygonal ferrites are distributed at the intersection area of the base metal and the weldment. When the pin is inserted, the grains are severely twisted in the stir zone. The HAZ 1 has the distribution of Bainite with Grain Boundary allotriomorphic Ferrite as shown in Fig.7(c). The grains in the HAZ experience high strain due to the welding stresses and thermal expansion. This results in a coarse grain structure, which in turn, reduces the toughness in the HAZ region. The grain boundary under compaction and thermal stress tends to react, and produces a coarse bainite structure. HAZ 2 which has Grain Boundary Ferrite and Ferrite with nonaligned and aligned grain structures, is very complex as the area is closer to the base metal and HAZ 1 as shown in Fig.7(d).



Note: RS – Retreating Side, AS – Advancing side

Figure.8. Transverse cross section of weld micro hardness profile having the parameter 1120rpm, 1° and 8mm/min.

The distribution of the micro hardness is taken along the transverse section of a typical weld plate, along the weld zone with the base metal. A load of 500g is applied for testing the hardness with a dwell time of 30s. The micro hardness result confirms the presence of bainite and ferrite for higher hardness in the weld, which is obtained from the optimized process parameters. The micro hardness distribution for the optimum process parameter is shown in Fig.8. The base metal micro hardness varies between 150 -170 HV, while that of HAZ 1 and HAZ 2 varies between 205 HV - 272HV and 180HV- 210HV respectively. The upper surface of the stir zone consists of fully ferritic grains, below the layer by which ferrite carbide aggregates were formed as shown in Fig.7 (b). The nonlamellar dispersion of ferrite carbide aggregates is responsible for the bainite structure, and the finer grains of the grain boundary ferrite in HAZ 1, formed due to the thermal cycles is responsible for the highest hardness in the stir zone as shown in Fig.8. The fractograph in Fig.9 (a) and (b) shows the fractured tensile specimen of the base metal and FSW weld respectively. Dimple like patterns were observed in the fractured tensile specimen of the base metal, while the FSW welded specimen shows a river like pattern. It denotes that base metal failure is ductile in nature and the FSW weld brittle in nature.

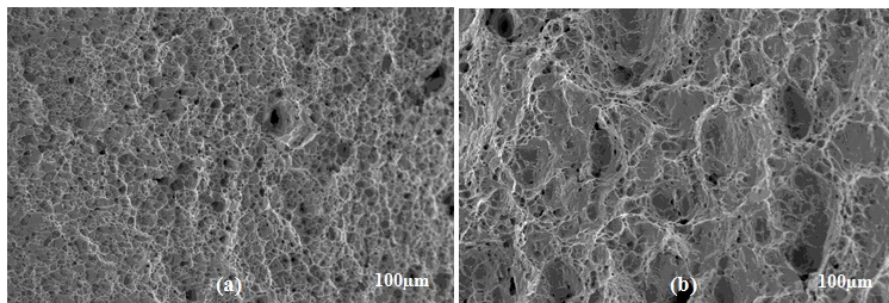


Figure.9. Fractograph of (a) base metal (b) welded sample

4. Conclusions

The Taguchi method has been used to optimize the welding parameters of friction stir welding to weld a 3mm plate of IS:3039. The conclusions drawn from the present study are listed below :

1. The Analysis of Variance for the tensile result concludes that the tool tilt angle is the most significant parameter with a percentage of 63.46%, followed by the travel feed of 32.83% and rotation speed of 2.81%.
2. The optimum combination of parameters obtained from the main effect plot for the S/N ratio and mean is 1120rpm rotational speed, 1° tool tilt angle and 8mm/min traverse speed, and the tensile strength has been predicted as 472 MPa. The confirmation test performed with the optimum process parameter is found to have an average tensile strength of 474 MPa, and hence, the optimization is useful.
3. The macro and micro structural analysis shows that two distinct regions of HAZ are present and their hardness values are in the range of 205HV- 272 HV and 180HV- 210HV respectively.
4. The tool tilt angle of 1° is favorable to weld low alloy steels with good mechanical and metallurgical properties.
5. A conical shorter pin gave better strength of weld at a lower travel speed, and the pin length indirectly helps in the reduction of tool wear, by lesser usage of the tool material.

Appendix

Calculation:

Rotational speed:

$$\text{Level 1: Rotational speed} = (A1+A2+A3)/3 = (448+459+446)/3 = 451 \text{ (Minimum)}$$

$$\text{Level 2: Rotational speed} = (B1+B2+B3)/3 = (445+457+462)/3 = 454.6666 \text{ (Maximum)}$$

$$\text{Level 3: Rotational speed} = (C1+C2+C3)/3 = (438+469+449)/3 = 452$$

$$\text{Delta} = \text{Maximum value} - \text{Minimum value} = 454.6666 - 451 = 3.6666$$

Tool tilt angle:

Level 1

$$\text{Tool tilt angle} = (A1+B1+C1)/3 = (448+445+438)/3 = 443.6666 \text{ (Minimum)}$$

$$\text{Level 2: Tool tilt angle} = (A2+B2+C2)/3 = (459+457+469)/3 = 461.6666 \text{ (Maximum)}$$

$$\text{Level 3: Tool tilt angle} = (A3+B3+C3)/3 = (446+462+449)/3 = 452.3333$$

$$\text{Delta} = \text{Maximum value} - \text{Minimum value} = 461.6666 - 443.6666 = 18$$

Travel feed:

$$\text{Level 1: Travel feed} = (A1+B3+C2)/3 = (448+462+469) = 459.6666 \text{ (Maximum)}$$

$$\text{Level 2: Travel feed} = (A2+B1+C3) = (459+445+449)/3 = 451$$

$$\text{Level 3: Travel feed} = (A3+B2+C1) = 446+457+438 = 447 \text{ (Minimum)}$$

$$\text{Delta} = \text{Maximum value} - \text{Minimum value} = 459.6666 - 447 = 12.6666$$

Interaction value for S/N ratio:

Rotational speed:

Larger the better

$$\text{Level1: S/N ratio } (\eta) = -10 \log_{10} ((1/n) \sum (1/(y_{ij})^2)) = -10 \log_{10} ((1/1) \sum (1/(451)^2)) = 53.0835 \text{ (Minimum)}$$

(Refer the value of level 1 of rotational speed)

$$\text{Level 2: S/N ratio } (\eta) = -10 \log_{10} ((1/1) \sum (1/(454.6666)^2)) = 53.1538 \text{ (Maximum)}$$

$$\text{Level 3: S/N ratio } (\eta) = -10 \log_{10} ((1/1) \sum (1/(452)^2)) = 53.1027$$

$$\text{Delta} = \text{Maximum value} - \text{Minimum value} = 53.1538 - 53.0835 = 0.0703$$

Tool Tilt Angle:

$$\text{Level1: S/N ratio } (\eta) = -10 \log_{10} ((1/1) \sum (1/(443.6666)^2)) = 52.9411 \text{ (Minimum)}$$

$$\text{Level 2: S/N ratio } (\eta) = -10 \log_{10} ((1/1) \sum (1/(461.6666)^2)) = 53.2865 \text{ (Maximum)}$$

$$\text{Level 3: S/N ratio } (\eta) = -10 \log_{10} ((1/1) \sum (1/(452.3333)^2)) = 53.1091$$

$$\text{Delta} = \text{Maximum value} - \text{Minimum value} = 53.2865 - 52.9411 = 0.3454$$

Travel Feed:

$$\text{Level 1: S/N ratio } (\eta) = -10 \log_{10} ((1/1) \sum (1/(459.6666)^2)) = 53.2488 \text{ (Maximum)}$$

$$\text{Level 2: S/N ratio } (\eta) = -10 \log_{10} ((1/1) \sum (1/(451)^2)) = 53.0835$$

$$\text{Level 3: S/N ratio } (\eta) = -10 \log_{10} ((1/1) \sum (1/(447)^2)) = 53.0061 \text{ (Minimum)}$$

$$\text{Delta} = \text{Maximum value} - \text{Minimum value} = 53.2488 - 53.0061 = 0.2427$$

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References

- Balaji G.K., Muthukumar S., Kumaran S.S., Pradeep A. 2012. Optimization of friction welding of tube to tube plate using an external tool with filler plate. *Journal of Materials Engineering and Performance*. Vol. 21, pp. 1199-1204.
- Bozkurt Y. 2012. The optimization of friction stir welding process parameters to achieve maximum tensile strength in polyethylene sheets. *Materials and Design*. Vol. 35, pp. 440-445.
- Choi D.-H., Lee C.-Y., Ahn B.-W., 2011. Hybrid friction stir welding of high-carbon steel. *Journal of Material Science and Technology*. Vol. 27, pp. 127-130.
- Demirci M.T., Samanci A., Tarakcioglu N., Asilturk I., 2011. Optimization of fatigue life parameters with Taguchi method. *6th International Advanced Technologies Symposium (IATS'11)*, 16-18 May, Elazığ, Turkey.
- Elangovan K., Balasubramanian V. 2007. Influences of pin profile and rotational speed of the tool on the formation of friction stir processing zone in AA2219 aluminium alloy. *Materials Science and Engineering A*. Vol. 459, pp. 7–18.
- Ghosh M., Kumar K., Mishra R.S. 2011. Friction stir lap welded advanced high strength steels: Microstructure and mechanical properties. *Materials Science and Engineering A*. Vol. 528, pp. 8111-8119.
- Hussain A.K., Quadri S.A.P. 2010. Evaluation of parameters of friction stir welding for aluminium AA6351 alloy. *International Journal of Engineering Science and Technology*, Vol. 2, pp. 5977-5984.
- Kumar C.V., Muthukumar S., Pradeep A., Kumaran S.S. 2011. Optimizational study of friction welding of steel tube to aluminium tube plate using an external tool process. *International journal of Mechanical and Materials Engineering*. Vol. 6, pp. 300-306.
- Muthukumar S. and Mukherjee S. K. 2006. Two modes of metal flow phenomenon in friction stir welding process. *Science and Technology of Welding and Joining*, Vol. 11, p. 337.
- Lakshminarayanan A. K., Balasubramanian V., Salahuddin M. 2010. Microstructure tensile and impact toughness properties of friction stir welded mild steel. *Journal of Iron and Steel Research International*, Vol. 17, pp. 68-74.
- Lakshminarayanan A.K., Balasubramanian V. 2012. Assessment of sensitization resistance of AISI 409M grade ferritic stainless steel joints using modified Strauss test. *Materials and Design*, Vol 39, pp. 175-185.
- Lakshminarayanan A. K., Balasubramanian V. 2008. Process parameters optimization for friction stir welding of RDE-40 aluminium alloy using Taguchi technique. *Transaction of Non ferrous Metals .Society of China*. Vol. 18, pp. 548-554.
- Paventhan R., Lakshminarayanan P. R., Balasubramanian V.. 2011. Prediction and optimization of friction welding parameters for joining aluminium alloy and stainless steel. *Trans. Nonferrous Met. Soc. China*. Vol. 21. pp. 1480-1485
- Palanivel R., Mathews P. K., Murugan N., Dinaharan I. 2012. Effect of tool rotational speed and pin profile on microstructure and tensile strength of dissimilar friction stir welded AA5083-H111 and AA6351-T6 aluminum alloys. *Materials and Design*. Vol. 40, pp. 7–16.
- Patil H. S., Soman S. N. 2010. Experimental study on the effect of welding speed and tool pin profiles on AA6082-O aluminium friction stir welded butt joints. *International Journal of Engineering, Science and Technology*. Vol.2, No. 5, pp. 268-275.
- Vijian P., Arunachalam V. P. 2007. Optimization of squeeze casting process parameters using Taguchi analysis. *International Journal of Advanced Manufacturing Technology*. Vol. 33, pp. 1122-1127.
- Wang J.-M., Yan H.-J., Zhou J.-M., Li S.-X., Gui G.-C. 2012. Optimization of parameters for an aluminum melting furnace using the Taguchi approach. *Applied Thermal Engineering*. pp. 33-43.
- Wu F.C., Chyu C. 2002. A comparative study on Taguchi’s SN ratio, minimising MSD and variance for nominal-the-best characteristic experiment. *International Journal of Advanced Manufacturing Technology*. Vol. 20, pp. 655-659.

Nomenclature

FSW	Friction Stir Welding
SZ	Stir Zone
HAZ	Heat Affected Zone
TMAZ	Thermo Mechanically Affected Zone
UTS	Ultimate Tensile Strength

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