Optimization of Friction Stir Welding Process Parameters Using Taguchi Method

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Abstract- *Friction stir welding is a solid state welding process in which rotating tool is used to mix matrix material across the joint line subjecting it to both heat and deformation considerably improving the weldability of the joint. The process is used in various industries like aerospace, marine and automobile due to its high quality joint.*

The major issue in FSW is high frictional heat which results in excessive softening of aluminium which causes defects and weak heat affected zone leading to degradation of mechanical properties of the joints. This problem can be solved by using water medium surrounding the weld zone.

In this projects, the parameters such as welding speed, spindle speed, plunge depth was varied 3 levels and samples AA5052 and AA2014 was carried out using Taguchi method. The welded samples was tested for its tensile strength and hardness value. The microstructural analysis at the weld zone was carried out.

Keywords- Friction stir welding; Aluminium alloy 5052; Aluminium alloy 2014.

I. INTRODUCTION

Friction stir welding (FSW) is a solid state joining or welding process, the joints are created by the combination of frictional heating and mechanical deformation by using a high strength special rotating tool. A non-consumable or solid rotating tool is pushed in between the two base materials (Centre of contact), to be welded and the central pin or probe, followed by the shoulder, is brought into contact with the two metal parts to be joined. The rotation of the tool heats up and plasticizes the material it is in contact with and, as work pieces travels along the joint line, the material from the front of the tool is swept around the plasticized annulus to the rear, so eliminating the interface.In FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and recrystallized grains [1-2].A rotating tool is used to mix material across the join line, subjecting it to both heat and deformation considerably improves the weldability [3-4].Friction Stir Welding (FSW) technology is used in primary structures of airframes [5-6]. The issue in FSW is it tends to create a softening region in the joints due to the dissolution or growth of the strengthening precipitates during the welding, thus leading to a degradation of mechanical properties of the joints [7-8]. The investigation demonstrates the use of submerged friction stir welding (SFSW) under water as an alternative and improved method for creating fine grained welds, and hence, to alleviate formation of intermetallic phases. The study suggests that submerged friction stir welding under water resulted in lower peak temperature and because of lower heat input intermetallic compounds formation was limited [9-10]. The cooling rate is the key factor influencing the grain growth during post-welding cooling [11-12]. High frictional heat results in excessive softening of aluminium which causes defects and weak heat affected zone (HAZ). Precipitates also get dissolved in the aluminium matrix due to the high frictional heat. In this problem can be solved by using the water medium surrounding the weld zone. The water surrounding the weld zone absorbs the heat at a faster rate which prevents the coarsening of precipitates, yields fine grains and reduces the welding defects [13-14]. In this study, based on the complete investigation of the microstructure, mechanical properties and the microstructure evolution including grain structure and texture from the BM to final weld during the FSW of 1050 Al-alloy by rapid cooling and subsequent annealing, the following conclusions can be drawn. Microstructure control was achieved by RCFSW using liquid CO_2. Significant improvements in the mechanical properties were achieved by utilizing rapid cooling to stop the grain growth and texture change which occur during the natural cooling stage of the C-FSW [15-19]. The shoulder is known to induce the flow of material during FSW which greatly influences the formation of weld nugget [20].

II. EXPERIMENTAL PROCEDURE

2014 ALUMINIUM ALLOY SELECTION

It has easily to machine in certain tempers and among the strongest available aluminium alloys, as well as having high hardness strength. It is difficult to weld and it was subject to cracking. The AA2024 is the second most popular 2000-series aluminum alloys material, after that 2014 aluminum alloy. It is commonly extruded and forged. The corrosion resistance of this alloy is poor. To combat this, it is often clad with pure aluminum.

5052 ALUMINIUM ALLOY SELECTION

Primarily alloyed with manganese and chromium. It had good workability, medium static strength, high fatigue strength, very good corrosion resistance, and a good weldability, especially in marine atmospheres. It has low density and excellent thermal conductivity common to all aluminium alloys.

III. METHOLOGY

Figure 3.1 shows the Methodology.

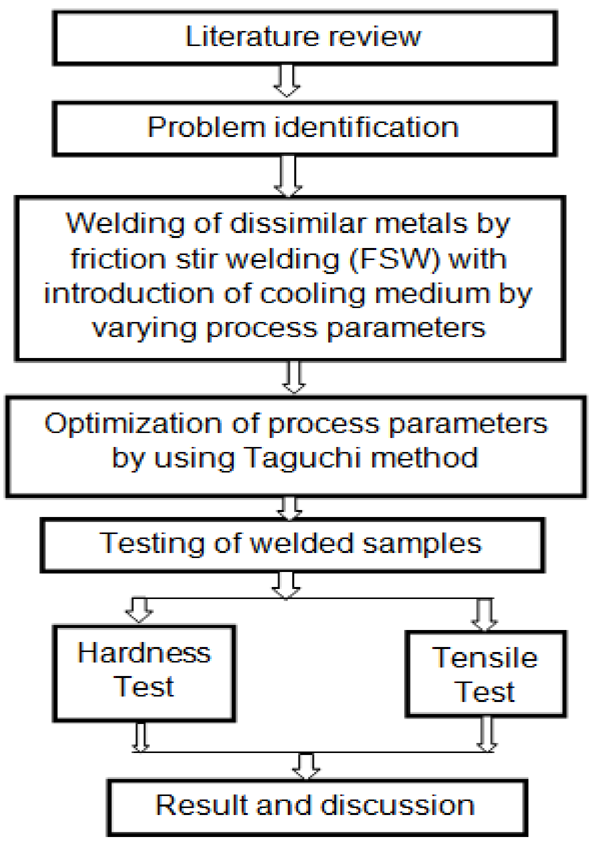

Figure 3.1 Methodology for Friction Stir Welding

IV. EXPERIMENTAL DETAILS

4.1 EXPERIMENTAL PROCEDURE

The experiments were conducted on a vertical milling machine where a tool is mounted in an arbor with a suitable collate. The vertical tool head can be moved along the vertical guide way (Z-axis), the horizontal bed can be moved along X and Y axis. The aluminium alloys (AA2014 and AA5052) has chosen for the study were 6mm thick plate of commercially available aluminium alloy. The weld faces of the test plates are machined and clamped in horizontal bed with zero root gaps aligned with the centre line of the FSW tool with the help of a specially designed fixture and back plate needs to be tightly clamped to one another. Figure 4.1 shows the experimental Setup describing clamping of FSW plate

Figure 4.1Experimental Setup describing clamping of FSW plate

4.2 PROCESS PARAMETERS AND LEVELS

Friction stir welding involves various process parameters. In this project spindle speed (rpm), welding speed (mm/min) and Plunge depth (mm) are chosen as major process parameter and varied to three levels. Table 4.1 shows the welding parameters and their level values.

Table 4.1 Welding process parameters and levels

Parameters	Level1	Level2	Level3
Spindle speed	900	1400	1800
Welding speed	65	100	135
Plunge depth	0.10	0.15	0.20

L9 orthogonal array of the experimental readings are shown in figure 4.2.

Table 4.3 L9 Orthogonal array of the experimental reading

Ex. No.	Spindle speed	Welding speed	Plunge Depth
1	900	65	0.10
2	900	100	0.15
3	900	135	0.20
4	1400	65	0.15
5	1400	100	0.20
6	1400	135	0.10
7	1800	65	0.2
8	1800	100	0.10
9	1800	135	0.15

4.3 PRODUCTION OF JOINTS

The plates used in the present study were AA2014 and AA5052 having thickness 6mm are joined. Nine joints has been produced according to L9 orthogonal array experiment.Figure 4.2 shows the welded specimen.

Figure 4.2 Butt Welded Specimen

4.4 SPECIMEN PREPARATION FOR TENSILE TEST

The welded joints are sliced using power hacksaw and then machined to required dimension to prepare tensile specimen as shown in figure 4.4, these specimen are taken in the normal direction of the weld. the ASTM standard for tensile test specimen is loaded and tensile specimen undergoes deformation. The tensile test of butt joint was conducted by using a universal testing machine of 1000KN capacity. Figure 4.3 shows the tensile testing of welded samples.

b) Specimen at holding c) Specimen at breaking

4.5 OPTICAL MICROSCOPY

Before going to take microstructure, the weld samples were cut into transverse directions and the cross sectional surface were carried out for standard metallographic procedure. Polishing with emery sheets of SiC with grit size varying from 220 to 2000 followed by disc polishing using alumina and velvet cloth were employed on specimen to obtain a mirror finish the weldments. Figure 4.4 shows the specimen prepare for microstructure analysis.

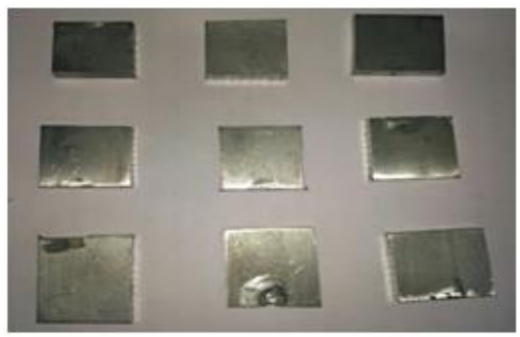

Figure 4.4 Specimen Preparation for Microstructure

4.6 SPECIMEN PREPARATION FOR HARDNESS TEST

The welded joints were sliced using power hacksaw and then machined to a dimension of approximately (20 mm X 20 mm X 6 mm). Specimens are taken in normal direction of the weld. The specimen is loaded and hardness specimen undergoes indentation. The hardness test of butt joint was conducted using a Vicker's hardness testing machine.

4.6.1MICRO HARDNESS TESTER

In this work, hardness of weld zone was taken as one response parameter. Vickers hardness measuring machine was used to measure hardness. The Vickers test is more frequently used than other hardness tests since the required calculations are independent of the size of the indenter and the indenter can be used for all materials irrespective of hardness. It measures macro-hardness of the work piece. As the indenter of Vickers machine is pyramidal shape so it is difficult to enter exact interface point of the welding which is very narrow. Hence measurement of hardness could not be done properly. In order to eliminate this difficulty the pair of samples was polished in such a way that the weld zone would be exposed and the indenter could reach the weld zone. To achieve this shape the material at the upper portion and side portion of the welding were removed by polished the pair at about 450.The indentations were done at three different points of welding in a welding pair and the average of hardness values were taken as final hardness value of a sample. Figure 4.6 the vicker's hardness testing machine.

Figure 4.5Vicker's hardness testing machine

V. RESULTS AND DISCUSSION

The experiments are conducted as per the design of experiments discussed in the previous chapter. In this chapter the microstructure analysis, hardness and tensile strength of FSW are discussed as follows.

5.1 MICROSTRUCTURE ANALYSIS

Metallurgical characterization was performed with the use of optical microscope and inverted microscope on the weldment, compromising of base metal and fusion zone. Standard metallographic procedure was adopted to prepare the sample for examination. The microstructures of AA2014 and AA5052 weldments are shown in Fig. 5.1. Three distinct microstructural zones – stir zone or weld nugget (SZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ) were present in the weld. In the microstructure analysis, porosity is identified.

5.2 TENSILE STRENGTH ANALYSIS

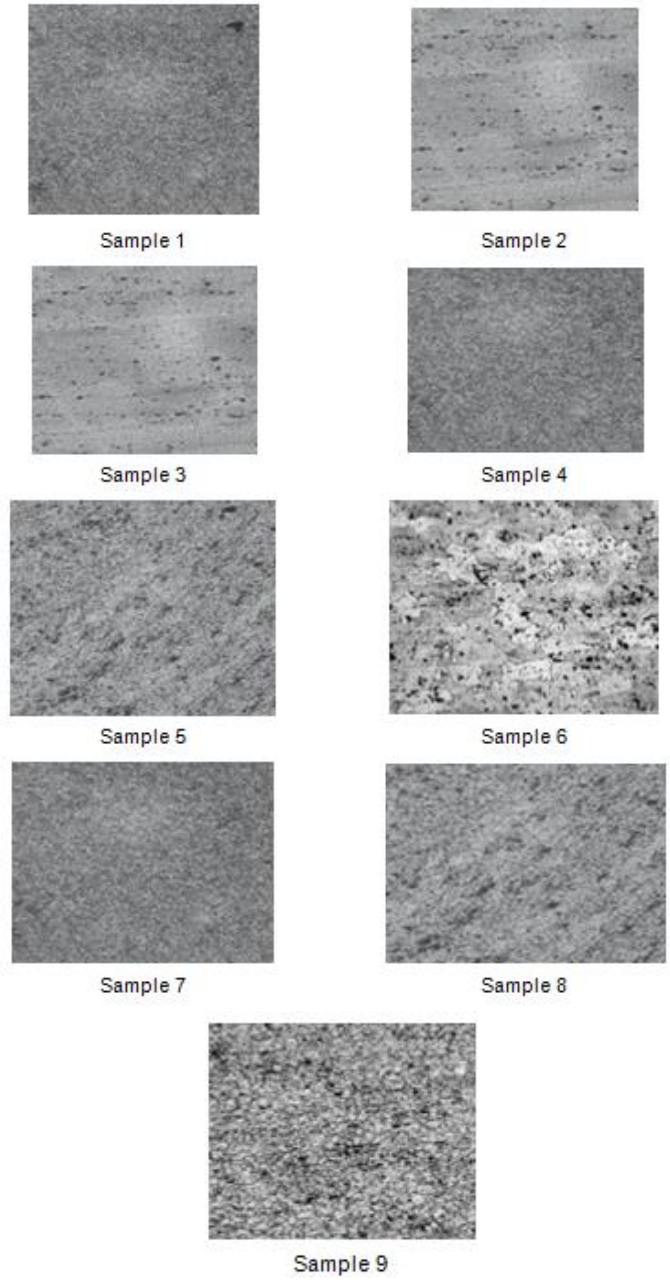

Figure 5.1 Microstructures of the weldments

Tensile testing specimen has made as per ASTM standard, Based on this ASTM Standard, nine specimens are machines using milling machine. From the table 5.1, it is identified that the minimum ultimate tensile strength value 40.92 MPa is obtained at the value of 1400 rpm spindle speed, 135 mm/min welding speed and 0.10 mm plunge depth. The maximum ultimate tensile strength value 136.65 MPa is obtained at the value of 1400rpm spindle speed, 100 mm/min welding speed and 0.20 mm plunge depth**.** Figure 5.3 shows the specimen after tensile test.

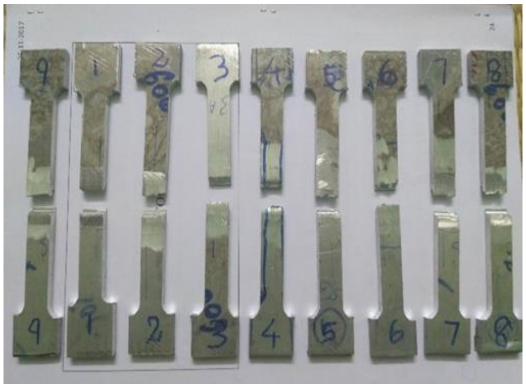

Figure 5.2Specimens after tensile test

Table 5.1 Experimental value of tensile strength and hardness

Exp No.	Spindle speed (rpm)	Welding traverse speed (mm/min)	Plunge Depth (mm)	Ultimate Tensile Strength (N/mm^2)	Hardness value (HV)
1	900	65	0.10	98.32	93.86
2	900	100	0.15	87.65	91.01
3	900	135	0.20	90.56	88.76
4	1400	65	0.15	97.56	97.04
5	1400	100	0.20	136.61	105.99
6	1400	135	0.10	80.93	78.99
7	1800	65	0.20	120.23	92.71
8	1800	100	0.10	98.84	88.32
9	1800	135	0.15	105.99	101.45

5.3 MICRO HARDNESS TEST

Vickers micro hardness tests were conducted across the weld (mid-section, 0.25 mm spacing) to ascertain possible microstructure/property variations among the various regions of the weldment. From the table 5.1, it is identified that the minimum hardness value 75.99 HV is obtained at the value of 1400 rpm spindle speed, 135 mm/min welding speed and 0.10 mm plunge depth. The maximum hardness value 102.99 HV is obtained at the value of 1400rpm spindle speed, 100 mm/min welding speed and 0.20 mm plunge depth**.** Figure 5.4 shows the specimen after hardness test.

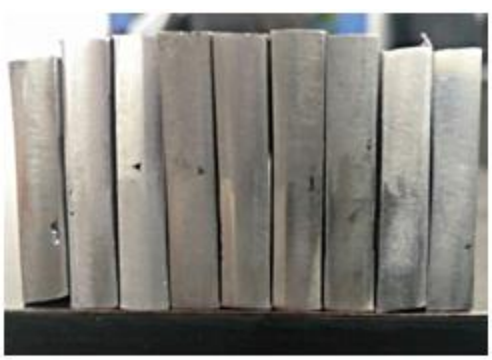

Figure 5.3Vicker's hardness

5.4 OPTIMIZATION OF PROCESS PARAMETERS USING RESPONSES IN TENSILE STRENGTH AND HARDNESS

The tensile test and hardness values were imported into MINITAB software and result of main effect of parameters on tensile strength and hardness was calculated using S/N ratio shown in table 5.2

Table 5.2 Main effect of parameters on tensile strength and hardness (S/N ratio)

Exp NO	Spindle Speed	Welding Traverse Speed	Plunge Depth	UTS (N/mm^2)	SNRA1	Hardness (HV)	MEAN1
1	900	65	0.10	91.227	39.6465	90.85	96.09
2	900	100	0.15	85.613	39.0153	89.98	89.33
3	900	135	0.20	75.560	39.0507	85.96	89.66
4	1400	65	0.15	97.640	39.7622	95.01	97.30
5	1400	100	0.20	136.653	41.4691	103.85	121.30
6	1400	135	0.10	40.920	38.0555	76.10	79.96
7	1800	65	0.20	115.310	40.3263	95.71	106.47
8	1800	100	0.10	92.720	39.3825	91.23	93.58
9	1800	135	0.15	98.560	40.3110	98.35	103.72

5.4.1 OPTIMIZATION OF PROCESS PARAMETERS USING RESPONSES IN TENSILE STRENGTH

The tensile test values shifted into MINITAB software and result of main effect on tensile strength was calculated using S/N ratio shown in table 5.3

Table 5.3 Main effect on tensile strength(S/N ratio)

Parameter	Level 1	Level 2	Level3	Delta	Rank
Spindle speed	39.24	39.76	40.01	0.77	3
Welding speed	39.91	39.96	39.14	0.82	2
Plunge Depth	39.03	39.70	40.28	1.25	1

In the present study, the ultimate tensile strength data were analyzed to find the impact of FSW weld parameters. The trial results were then converted into means and signal-to-noise (S/N) ratio. In this work, 9 means and 9 S/N ratios were computed and the estimated tensile strength, means and signal-to-noise (S/N) ratio are given in Table 5.3.

Every experiment will give the analysis of mean for better combination of parameters levels that guarantees a high level of ultimate tensile strength according to the experimental set of data. The mean response indicates to the average value of execution characteristics for every parameter at various levels. The mean for one level was computed as the average of all responses that were fund with that level.

5.4.2 MAIN EFFECT PLOT

The main effect plot is the graph of the average or means of response at each level of the factor or input parameter. The main effect plot helps one to determine the influence of individual input parameters on the responses measured, by disregarding the effect of any other input parameter present. The main effect plots of each response are explained below. Figure 5.4 shows the Main effects plot of S/N ratios for tensile test.

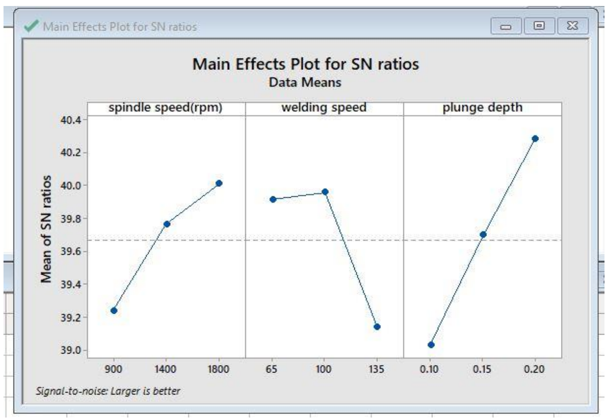

Figure 5.5 shows theMain effect on tensile strength (means).

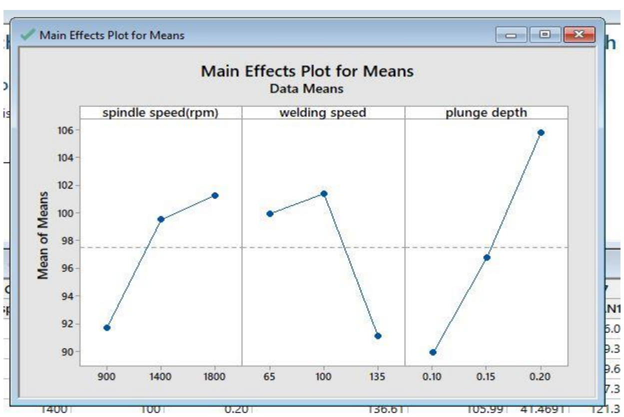

Figure 5.5 Main effect plot of means for tensile strength

5.4.3 OPTIMIZING THE PROCESS PARAMETERS

Analysis of mean for experiments gives better combination of parameter levels. Means response refers to average value of performance characteristics for each parameter at different levels. Analyzing means and S/N ratio of various process parameters it is observed that a larger S/N ratio corresponds to better quality characteristics. Therefore, Effect of process parameter is level highest S/N ratio. Mean effect and S/N ratio Plunge depth calculated by minitab software indicated that Plunge depth was at maximum.The optimum process parameter is found to be a combination of Spindle speed of 1800 rpm, welding speed of 100mm/min, and plunge depth of 0.20mm.

5.4.4 OPTIMIZATION OF PROCESS PARAMETERS USING RESPONSES IN MICRO HARDNESS

The hardness test values were imported into MINITAB software and result of main effect on hardness was calculated using S/N ratio shown in table 5.5.

Table 5.5 Main effect on hardness (S/N ratio)

Parameter	Level 1	Level 2	Level3	Delta	Rank
Spindle speed	39.20	39.40	39.46	0.26	3
Welding speed	39.51	39.54	39.01	0.52	2
Plunge Depth	38.77	39.68	39.60	0.91	1

In the present study, the hardness data were analyzed to find the impact of FSW weld parameters. The trial results were then converted into means and signal-to-noise (S/N) ratio. In this work, 9 means and 9 S/N ratios were computed and the estimated hardness, means and signal-to-noise (S/N) ratio are given in Table 5.5.Every experiment will give the analysis of mean for better combination of parameters levels that guarantees a high level of hardness according to the experimental set of data. The mean response indicates to the average value of execution characteristics for every parameter at various levels. The mean for one level was computed as the average of all responses that were fund with that level.

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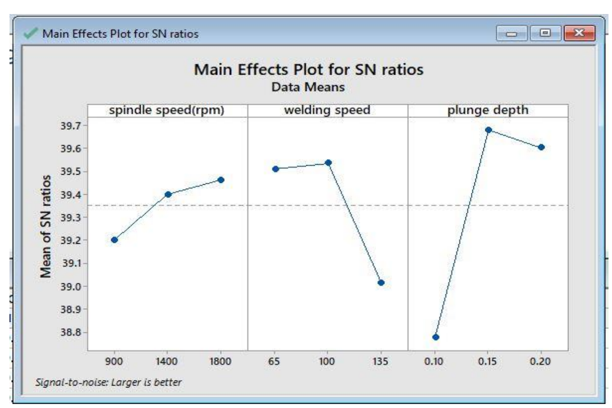

Figure 5.6 Main effects plot of S/N ratios for hardness

5.4.6 RESPONSE TABLE FOR OUTPUTS

Response table can also indicate which process parameters has greater influence on the responses measured by giving the process parameter a rank. Also one can infer the optimal condition from the response table 5.6 and figure 5.7.

Table 5.6 Main effect on hardness (means)

Parameter	Level 1	Level 2	Level3	Delta	Rank
Spindle speed	91.21	94.01	94.16	2.95	3
Welding speed	94.54	95.11	89.73	5.37	2
Plunge Depth	87.06	96.50	95.82	9.44	1

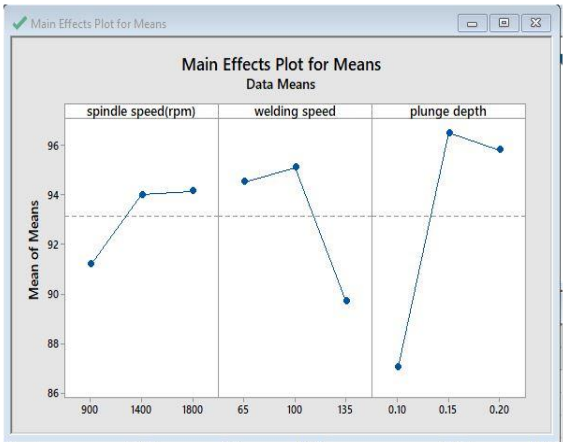

Fig 5.7 Main effects plot for means

5.4.7 OPTIMIZING THE PROCESS PARAMETERS

Analysis of mean for experiments gives better combination of parameter levels. Means response refers to average value of performance characteristics for each parameter at different levels. Analyzing means and S/N ratio of various process parameters it is observed that a larger S/N ratio corresponds to better quality characteristics. Therefore, Effect of process parameter is level highest S/N ratio. Mean effect and S/N ratio Plunge depth calculated by minitab software indicated that Plunge depth was at maximum.the optimum process parameter is found to be a combination of Spindle speed of 1800 rpm, welding speed of 100mm/min, and plunge depth of 0.15mm.

5.5 ANALYSIS OF VARIANCE (ANOVA)

ANOVA developed by Sir Ronald Fisher is a very powerful statistical tool to determine the significance of the process parameters on the responses measured. The F-test in the table assesses which process factors are significant and insignificant. Generally a large F-value signifies the higher significance of the process parameters on the performance characteristics.

Percentage of contribution of each factor can also be deducted from the ANOVA table which is calculated by following expression:

$$\%\ contribution = \frac{Sum\ of\ square\ of\ variation}{Total\ sum\ of\ square\ of\ variation}$$

In factorial design technique, analysis of variance (ANOVA) is usually carried out to determine the significance of model and model terms. A model or model term is significant when its p value is less than 0.05. The ANOVA for the weld strength (response) as influenced by the input variables is shown in Table 5.7. It is seen from Table 5.8 that the linear effects of spindle speed, welding traverse speed and plunge depth also the quadratic effects of the spindle speed, welding traverse speed and plunge depth are significant.

5.5.1 ANALYSIS OF VARIANCE IN TENSILE TEST

In addition, the F–test named after Fisher can also be used to determine which process parameter has a significant effect on the tensile strength. Usually the process parameters have a significant effect on the quality characteristics when F is large .The results of ANOVA indicate that the considered process parameters are highly significant factors affecting the tensile strength of FSW joints in the order of axial force, traverse speed and tool rotation speed. The percentage of contribution is the portion of the total variation observed in the experiment attributed to each significant factors and/or interaction which is reflected. The percentage of contribution is a function of the sum of squares for each significant item it indicates the relative power of a factor to reduce the variation. If the factor levels are controlled precisely, then the total variation could be reduced by the amount indicated by the percentage of contribution. Table 5.7 shows the ANOVA for tensile strength. Table 5.8shows the model summary for tensile strength.Table 5.9 showsthe coefficient for tensile strength.

Table 5.7ANOVA for tensile strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Regression	3	3562.3	1187.4	3.02	0.133	64.42%
Spindle Speed	1	481.7	481.7	1.22	0.319	8.54%
Welding speed	1	1324.2	1324.2	3.37	0.126	23.84%
Plunge Depth	1	1966.8	1756.4	4.47	0.043	36.76%
Error	5	1756.4	393.4			30.56%
Total	8	5529.2				

Table 5.8 Model summary for tensile strength

S	R-sq	R-sq(adj)	R-sq(pred)
19.8334	64.43%	43.09%	0.00%

Table 5.9 Coefficient for tensile strength

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	56.7	42.1	1.35	0.236	
Spindle Speed	0.0199	0.0180	1.11	0.319	1.00
Welding speed	-0.424	0.231	-1.83	0.126	1.00
Plunge Depth	342	162	2.11	0.043	1.00

5.5.2 MULTIPLE REGRESSION ANALYSIS

The mathematical relationship among the friction stir welding process parameters and desired performance measures arederived based on the values obtained from the experimentation.RegressionEquationforTensileStrength=(56.7 + 0.0199 Spindle Speed424 Welding speed+342 Plunge Dept)

5.5.3 ANALYSIS OF VARIANCE IN HARDNESS TEST

In addition, the F–test named after Fisher can also be used to determine which process parameter has a significant effect on the hardness. The results of ANOVA indicate that the considered process parameters are highly significant factors affecting the hardness of FSW joints in the order of plunge depth,welding traverse speed and tool rotation speed. The percentage of contribution is the portion of the total variation observed in the experiment attributed to each significant factors and/or interaction which is reflected. The percentage of contribution is a function of the sum of squares for each significant item it indicates the relative power of a factor to reduce the variation. If the factor levels are controlled precisely, then the total variation could be reduced by the amount indicated by the percentage of contribution.Table 5.8shows theANOVA for hardness, table 5.9shows the model summary for hardness**,** table 5.10 shows the coefficient for hardness.

Table 5.10ANOVA for hardness.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Regression	5	232.58	46.52	0.53	0.752	56.77%
Spindle Speed	1	13.88	13.88	0.16	0.718	11.31%
Welding speed	2	166.43	83.22	0.94	0.481	18.96%
Plunge Depth	2	52.27	26.13	0.30	0.763	37.97%
Error	3	264.68	88.23			28.76%
Total	8	497.27				

Table 5.11 Model summary for hardness

S	R-sq	R-sq(adj)	R-sq(pred)
9.39298	46.77%	0.00%	0.00%

Table 5.12 Coefficient for hardness

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	83.9	13.6	6.18	0.009	
Spindle Speed	0.0037	0.00850	0.40	0.718	1.00
Welding speed 100	0.57	7.67	0.07	0.945	1.33
135	-4.80	7.67	-0.63	0.576	1.33
Plunge Depth 0.15	9.44	7.67	1.23	0.306	1.33
0.20	8.76	7.67	1.14	0.336	1.33

5.5.4 MULTIPLE REGRESSION ANALYSIS

The mathematical relationship among the friction stir welding process parameters and desired performance measures are derived based on the values obtained from the experimentation.

Regression Equation for hardness = (83.9 + 0.00337 Spindle Speed0.57 Welding speed+9.44 PlungeDepth)

Experiments were conducted according to L9 orthogonal array which was suggested by Taguchi. Optimum parameters for optimum tensile strength, hardness were found with the help of S/N ratios. Therefore optimization of input process parameter is required to achieve good quality of welding. In this experiment the effect of process parameters on welded joint was studied and optimizes the parameter by using Taguchi method for tensile strength, hardness. Assign the rank to each factor which are having more influence on the mean tensile strength, hardness.

VI. CONCLUSION

The analysis presents effect of spindle speed, welding traverse speed and plunge depth on weld quality. Tensile strength and hardness of friction stir welded dissimilar aluminium alloy have been evaluated under different conditions using Taguchi experimental design.

- Plunge depth has found to be the most dominant parameter which affects tensile strength. The other parameters which influence the tensile strength in order of ranking are welding traverse speed, spindle speed.
- From this analysis, it is revealed that plunge depth is prominent factors which affect the strength of welding for the selected aluminium alloys. The Plunge Depth (P = 36.76 %) is the most influencing factor in determining the tensile strength of the sample followed by Welding traverse speed (W = 23.84 %) and Spindle speed (S = 8.54 %). The tensile

strength of the specimen has a direct relation with the strength of the joint.

- Optimum condition for high tensile strength are found to be Spindle speed= 1800 rpm, Welding traverse speed =100 mm/min, Plunge Depth= 0.20mm by Taguchi analysis.
- Plunge depth has found to be the most dominant parameter which affects hardness. The other parameters which influence the hardness in order of ranking are welding traverse speed, spindle speed.
- From this analysis, it is revealed that plunge depth is prominent factors which affect the strength of welding for the selected aluminium alloys. The Plunge Depth (P = 37.97 %) is the most influencing factor in determining the hardness of the sample followed by Welding traverse speed (W = 18.96 %) and Spindle speed (S = 11.31 %). The hardness of the specimen has a direct relation with the strength of the joint.

Optimum condition for high hardness are found to be Spindle speed= 1800 rpm, Welding traverse speed =100 mm/min, Plunge Depth= 0.15mm by Taguchi analysis.

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