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Analyze Process Parameter of Friction Stir Welding of Alluminium Alloy by FEM and Experiment

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Abstract

This present work focused to evaluate the effect of process parameters such as tool rotational speed; welding speed and shoulder diameter on yield strength and tensile strength of 6 mm thickness friction stir welded AA7075-0 aluminium alloy joints. As an initial step thermomechanical model was developed using hyper work 14.0 simulation software and simulation process was carried out. Out of different response from the analysis two responses were selected i.e. peak temperature of joint and yield strength. It was observed from the result that the peak temperature of joint is below the melting point of parent metal. After that, experimental work was performed and prepared 27 samples and tensile strength was recorded of all samples. Process parameters were optimized by the full factorial design approach on the basis of high tensile and yield strength. Non-linear regression model was developed to correlate the process parameters to yield strength and tensile strength of joint. The result observed that tool rotation speed, welding speed and shoulder diameter influence on yield strength and tensile strength of welded joints. Then after hardness tests were conducted on three samples of optimized process parameters. Maximum hardness at nugget focus is gotten in test which has optimum parameter so it approves the outcome.

1.0 INTRODUCTION

Many welding processes are used in manufacturing and other industries for joining the different metals. Mainly the welding processes are divided into two main groups (1) fusion welding (2) solid-state welding. Fusion welding processes use intense localized heat source to melt the base metal. Solid-state welding is completed under pressure alone or a combination of heat and pressure. Temperature is generated in solid state welding is below the melting temperature of the joining metal. Friction-stir welding (FSW) is a solid-state joining process and is used for applications where the original metal characteristics must remain unchanged as far as possible. [1]

The basic concept behind FSW is simple: A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of the two parts to be joined and traversed along the line of joint as shown in figure 1. The FSW tool primarily serves two functions: a) heating the work piece, and b) flowing the material to produce the joint. A detailed list of parameters controlling this joining

Process is given in as follows: [2]

1) Shoulder diameter (mm)
2) Welding speed (mm/min)
3) Tool Rotational speed (rpm)

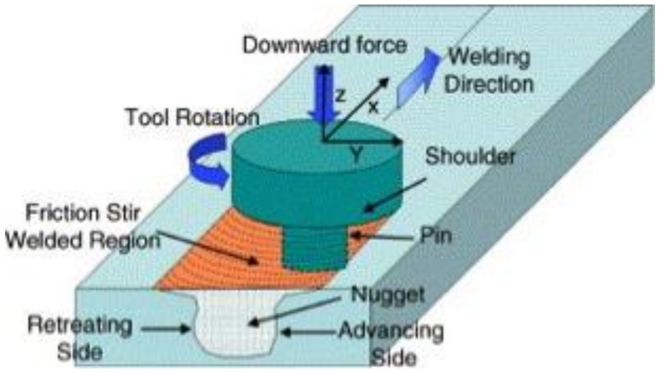


Figure 1. Terminology of the friction stir welding process

2.0 FINITE ELEMENT MODELING AND SIMULATION OF FRICTION STIR WELDING PROCESS

In this work AA7075 with dimension of 300 mm ×100 mm × 6mm plates with chemical composition of the AA7075 is shown in Table 1, is selected to perform virtual FSW experiment using Hyper Works 14.0. The tool geometry was selected with cylindrical pin having a tilt angle 0^0, shoulder length (L=50mm), pin diameter d = 6 mm at top and 3 mm at bottom of pin and pin length (l=5.4mm). Physical and thermal properties of AA 7075 are shown in Table 2. The parameters identified for investigation are tool shoulder diameter, welding speed, tool rotation speed. The selected process parameter and their levels are shown in table 1.

Table 1. Chemical composition of AA7075

Element	Mg	Mn	Zn	Fe	Cu	Si	Cr	Al
Wt.%	2.1	0.12	5.1	0.35	1.2	0.58	0.18	90

Altair Hyper Works 14.0 simulation tool is used for simulation and finite element analysis of friction stir welding process. This software has a thermal conduction capability and can be used for a 3-dimensional, steady-state or transient thermal analysis. Transient finite element analysis is performed considering steady state heat source. The finite element model was developed for simulation of friction stir welding. The FSW parameters considered by the simulation suit are pin diameter, pin height, pin rpm, pin tilt, translational speed, shoulder diameter and height. It is assumed that 90% of the work is converted into energy. The developed finite element model has several components with their defined name, no. of elements and ID range. Hyper Works provides an efficient interface for development of finite element model and analyzing friction stir welding with the Hyper Xtrude Solver. The initial temperature of the work piece is assumed equal to the ambient temperature (293K). Convection's coefficient of 30 W/m^2K is applied at the top and side surfaces of the work piece. Since the value of conductive coefficient between the work piece and the backing plate is unknown, convective coefficient of 300 W/m^2K can be applied to the bottom surface of the work piece. The above conditions are adopted from Colegrove [3].

Table 2 . Physical & Thermal Properties of AA7075

Property	**Values**
Density	2810 Kg/m3
Melting Point	635°C
Modulus of Elasticity	40 GPa
Poisons Ratio	0.35
Thermal Conductivity	173 W/m-K
Specific Heat Capacity	960 J/Kg-K
Ultimate Tensile strength	230 Mpa
Elongation	11 %

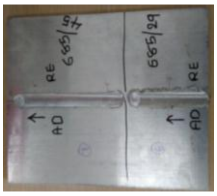
Table 3. Process parameter and their levels

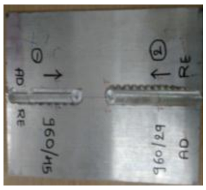
Symbol	**Welding Parameter**	**Level 1**	**Level 2**	**Level 3**
SD	Shoulder Diameter	16	18	20
WS	Welding speed (mm/min)	18	29	45
TS	Tool rotation speed(rpm)	685	800	960

3.0 EXPERIMENT WORK AND RESULTS

All welding experiments were carried out with base plates dimensions 300mm×100mm×6 mm for aluminum alloy AA7075. A vertical milling machine is used to Friction stir welding process. The Experimental setup includes tool tilt arrangement, fixture for clamping the job arrangement. Process parameters (RPM, Welding speed, Tool pin offset) can be adjusted by control-panel. Ranges of the parameters and its capability are as under.

Rotational speed	0 – 3480 rpm
Welding speed	0 – 145 mm/min
Tilt (°)	0 to ± 5°
Motor capacity	HP/3.7KW





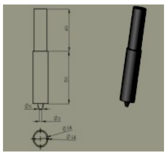
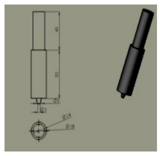
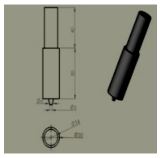
3.1 Tool Designs

Chemical composition of H13 tool steel is shown in Table: 4.important tool Design Criteria highlighted in Table: 5

Table: 4 Chemical compositions (wt %) of tool steel

Material	**C**	**Cr**	**V**	**W**	**Mo**
H13 grades	0.35	5.0	1.0	-	1.50

Table 5: Important tool parameters

Tool Design Features	Tool Number		
	1	2	3
Design			
Tool Material	Tool Steel H13 Grades	Tool Steel H13 Grades	Tool Steel H13 Grades
Shoulder Dimensions (mm)	S.D.= 16 S.L.= 50	S.D.= 18 S.L.= 50	S.D.= 20 S.L.= 50
Pin Dimensions (mm)	R.D.=6 T.D.= 3 P.L.= 5.4	R.D.=6 T.D.= 3 P.L.= 5.4	R.D.=6.2 T.D.= 3.3 P.L.= 5.7
Pin Shape	Conical	Conical	Conical
*Where, S.D. = shoulder diameter; S.L. = shoulder length; R.D. = root diameter;T.D. = tip diameter; P.L. = pin length			

3.2 tensile testing of welded joints

After the welding, the transverse tensile specimens are prepared with reference to ASTM E8M-04 standard and test specimens were machined from both the rolling and transverse directions of the base metal, and in the transverse direction for the weldments. The tensile test was carried out at room temperature with reference to ASTM D 557 M- 94 at a crosshead speed of 1.5 mm/min using a computer-controlled testing machine at Metallurgical testing laboratory. During testing, ultimate tensile strength is measured from averages of the three specimens and % elongations were recorded. Table 6 shows the tensile strength and joint efficiency for each experiment.

Table 6. Results of Tensile testing

Sample No.	Shoulder Diameter (mm)	Welding Speed (mm/min)	Tool Speed (rpm)	Yield stress (Mpa)	Tensile stress (Mpa)	Joint efficiency (%)
1	16	18	685	87.15	152.15	66.15
2	16	18	800	86	151	65.65
3	16	18	960	84.53	149.53	65.01
4	16	29	685	83.15	148.15	64.41
5	16	29	800	81.85	146.85	63.85
6	16	29	960	80.79	145.79	63.39
7	16	45	685	79.66	144.66	62.90
8	16	45	800	78.53	143.53	62.40
9	16	45	960	77.15	142.15	61.80
10	**18**	**18**	**685**	**87.68**	**206.52**	**89.79**
11	18	18	800	87.2	152.42	66.27
12	18	18	960	86.09	146.53	63.71
13	18	29	685	84.41	149.63	65.06
14	18	29	800	83.24	147.99	64.34
15	**18**	**29**	**960**	81.76	**162.37**	**70.60**
16	18	45	685	80.27	145.42	63.23
17	18	45	800	79.17	144.39	62.78
18	18	45	960	77.82	143.04	62.19
19	20	18	685	**88.06**	152.9	66.48
20	20	18	800	86.65	151.87	66.03
21	20	18	960	85.34	150.56	65.46
22	20	29	685	85.38	150.6	65.48
23	20	29	800	84.33	149.55	65.02
24	20	29	960	82.98	148.2	64.43
25	20	45	685	80.77	145.99	63.47
26	20	45	800	79.71	144.93	63.01
27	20	45	960	78.38	143.6	62.43

3.3 JOINT EFFICIENCY

Joint efficiency of welded joint is ratio of strength of the weld metal to the strength of the parent metal. The strength of parent metal is taken as 230 Mpa and strength of weld metal is taken from tensile test report. The joint efficiency of FSW at different welding speed shown in Table 6.

$$\text{Joint Efficiency} = \frac{\text{Strength of weld metal}}{Strength\ of\ parent\ metal}$$

4.0 Optimization of Process Parameters

In present study general full factorial method was adopted for the design of experiments to identify important factors affecting the response and to optimize the response using MINITAB 16 software. Three factors i.e shoulder diameter (mm), welding speed (mm/min) and tool rotation speed (rpm) are selected as variables and yield strength obtain from virtual experiment and tensile strength obtain from tensile test are selected as response parameters.

4.1 Analysis of Variance

Analysis of variance (ANOVA) test was performed to identify the process parameters that are statistically significant. The purpose of the ANOVA test is to investigate the significance of the process parameters which affect the yield strength and tensile strength of FSW joints. In addition, the F-test can also be used to determine which process has a significant effect on tensile strength. Usually, the change of the process parameter has a significant effect on the quality characteristics, when *F* is large.

4.1.1 Regression Analysis: yield strength (Mpa) versus SD, WS, TS

In order to show a relationship of process parameters and yield stress of joints, a nonlinear regression model was developed to predict YS of FSW AA7075 alloy based on experimentally measured YS. Regression coefficients were calculated using statistical software, MINITAB 16. After determining significant coefficient (at 95% confidence level), final model was developed using only these coefficients to estimate YS.

Table 7. ANOVA for yield strength

Source	DF	Adj SS	Adj MS	F Value	P Value
Model	6	287.198	47.866	295.87	0.00
Linear	6	287.198	47.866	295.87	0.00
SD	2	9.225	4.612	28.51	0.00
WS	2	251.764	125.882	778.09	0.00
TS	2	26.21	13.105	81	0.00
Error	20	3.236	0.162		
Total	26	290.434			

Table 8. ANOVA for regression analysis of yield stress

source	DF	Adj SS	Adj MS	F Value	P Value
Regression	3	285.63	95.21	95.21	0.00
SD	1	8.556	8.556	8.556	0.00
WS	1	250.909	250.909	250.91	0.00
TS	1	26.165	26.165	26.165	0.00
Error	23	4.804	0.209	0.209	
Total	26	290.434			

Regression Equation

Yield stress (Mpa) = 92.23 + 0.3447 SD - 0.27499 WS - 0.008730 TS

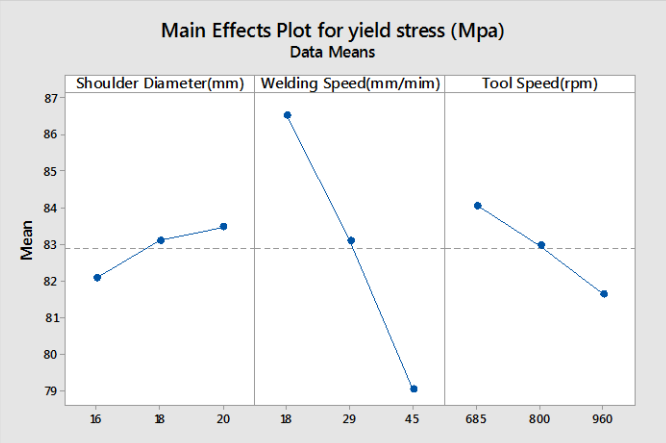


Figure 2. Main effect plot for yield stress

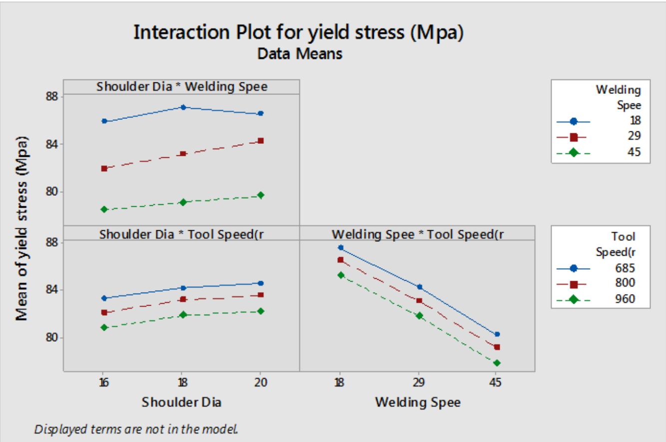


Figure 3. Interaction plot for yield stress

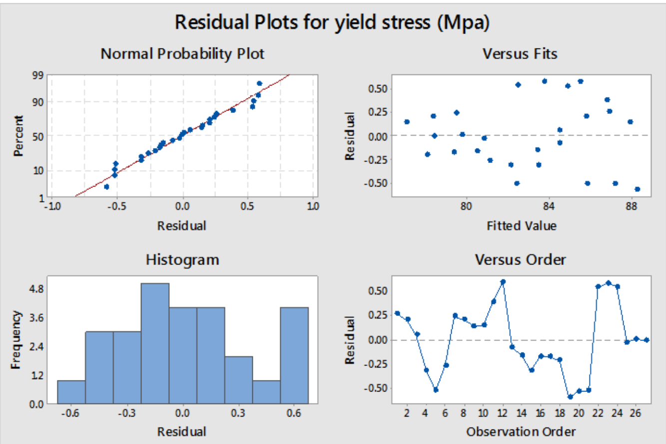


Figure 4. Residual plots for yield stress

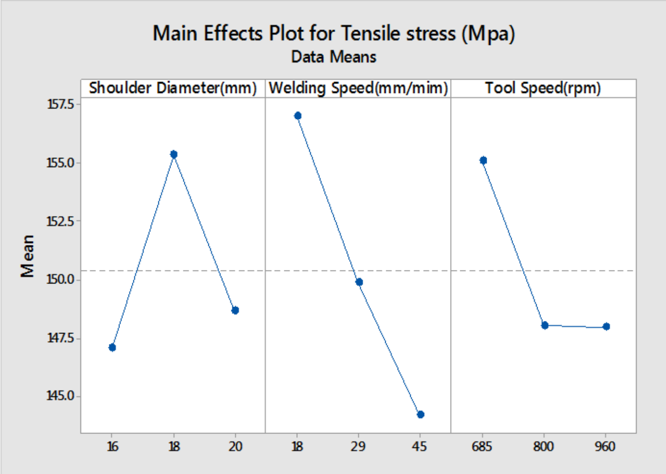


Figure 5. Main effect plots of tensile stress

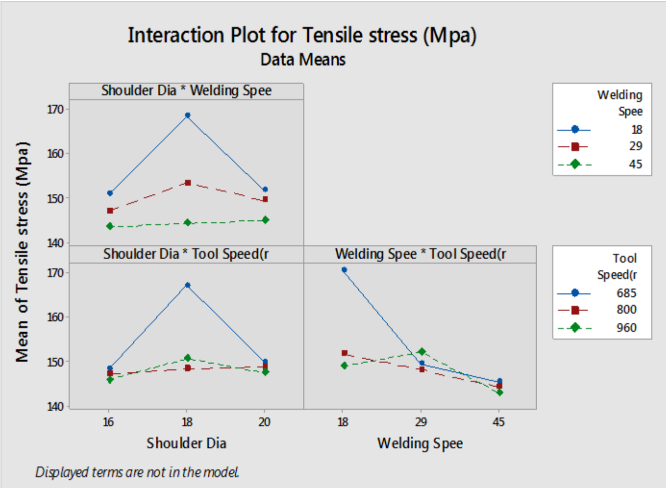


Figure 6. Interaction plot for tensile stress

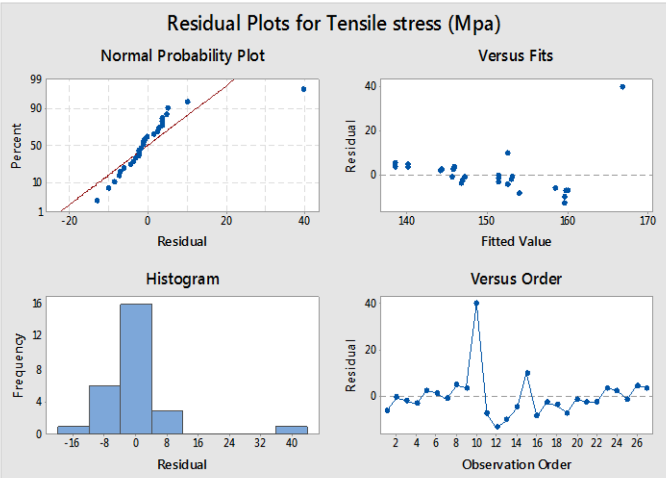


Figure 7. Residual plots for tensile stress

4.1.2 Regression Analysis: Tensile stress (Mpa) versus SD, WS, TS

Table 9. ANOVA for tensile strength

Source	DF	Adj SS	Adj MS	F Value	P Value
Model	6	1397	232.8	1.99	0.115
Linear	6	1397	232.8	1.99	0.115
SD	2	347.1	173.5	1.48	0.15
WS	2	747.7	373.8	3.2	0.062
TS	2	302.2	151.1	1.29	0.196
Error	20	2337.3	116.9		
Total	26	3734.2			

Table 10. ANOVA for regression of TS

Source	DF	Adj SS	Adj MS	F Value	P Value
Regression	3	941.31	313.77	2.58	0.078
SD	1	11.5	11.5	0.09	0.161
WS	1	726.06	726.06	5.98	0.023
TS	1	203.74	203.74	1.68	0.108
Error	23	2792.92	121.43		
Total	26	3734.23			

Regression Equation

Tensile stress (Mpa) = 177.4 + 0.40 SD - 0.468 WS - 0.0244 TS

5.0 CONFIRMATION TEST

After finding the optimum value of process parameters affecting the yield strength and tensile strength, hardness test were conducted to find the BHN value at different distances from weld center as per IS 1500:2005. Table 11 shows samples selected for the hardness test. Three reading were taken from each zone and average and integer values of three readings were taken as result of respective zone.

Table 11. Details of Samples for hardness test

Sample No.	SD mm	WS mm/min	TS rpm	Yield strength (Mpa)	Tensile strength (Mpa)
Sample 1	18	18	685	88.06	206.52
Sample 2	18	29	960	81.76	162.37
Sample 3	20	18	685	87.68	152.9
SD-Shoulder Diameter, WS-welding speed, TS-tool rotation speed					

5.1 Results of Hardness Test

Table 12. Brinell hardness number at different level

Weld zone	BM	HAZ	TMAZ	Nugget	TMAZ	HAZ	BM
Distance from the weld centre (mm)	**9**	**6**	**3**	**center 0**	**3**	**6**	**9**
sample 1	145	108	107	105	105	106	147
sample 2	148	102	103	100	101	103	147
sample 3	148	106	104	103	105	106	148
Average	147	106	105	103	104	105	147
BM- base metal, HAZ- heat affected zone, TMAZ- thermo-mechanical heat affected zone							

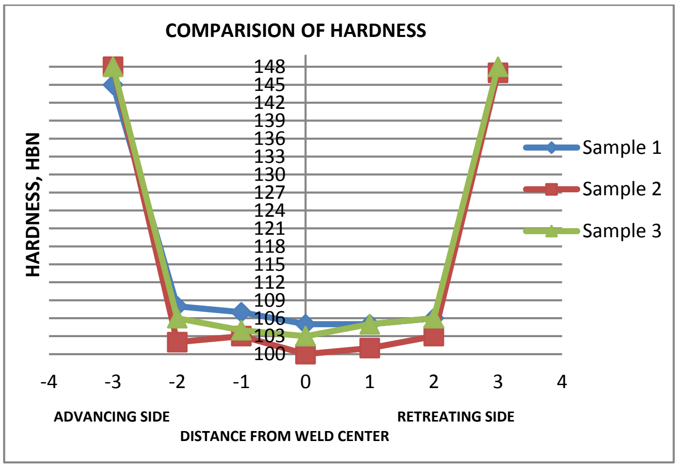


Figure 8. Graph showing comparison of hardness

6.0 RESULT AND DISCUSSIONS

Following results are obtain by Analysis of FSW in Hyper works as shown in table 8 In present investigation, we analyzed influence of all parameter on yield stress of FSW joints. It was observed that most influence parameter is welding speed followed by tool rotation speed and shoulder diameter. Maximum yield stress is achieved at minimum welding speed i.e 18 mm/min.

6.1 Results of tensile testing

If the axial force was increased beyond a threshold value, a large amount of flashing and excessive thinning was observed due to the higher heat input.

We analyzed from the result that welding speed and rotational are most influence parameter for tensile strength and joint efficiency. When welding speed is increasing then tensile strength and joint efficiency are decrease. Similarly when the rotational speed is increasing then tensile strength and joint efficiency are decrease. We can achieve maximum tensile strength and joint efficiency at minimum welding speed and rotational speed.

The outcome of ANOVA show that the maximum F value is for welding speed followed by tool rotational speed and shoulder diameter. Welding speed has significant effect on yield strength.

Value of P in table 7, 8, 9 and 10 show the model is significant at 95% confidence level and also value of the determination coefficient R^2 indicates the quality of the fit for the model. The value of the adjusted R^2 is also high, indicates a high importance of the model. The predicted R^2 is also in good agreement with the set R^2.

Figure 2 shows that yield strength increases with decrease in welding speed and tool rotation speed

It is seen from the Figure 3 that there is very good interaction between process parameter affecting the yield strength since the responses at different levels of process parameters for a given level of parameter value are almost parallel.

Figure 4 shows the residual plots for yield stress. They are used to evaluate the data for problems such as non-normality, non-random variation, non-constant variance, higher-quality relationships, and outliers. From figure 4, it can be seen that the residues of a straight line follow the normal likelihood course and the approximate symmetrical nature of the histogram indicates that the residues are normally distributed. Residuals even have variance since they are randomly scattered by zero in residues as compared to the adjusted values. Since residuals do not show a clear pattern, there is no error due to time or data acquisition.

Figure 5 shows that tensile strength increases with decrease in welding speed and tool rotation speed and maximum tensile strength is obtain at shoulder diameter 18mm.

Figure 7 shows the residual plots for tensile stress. They are used to evaluate the data for problems such as non-normality, non-random variation, non-constant variance, higher-quality relationships, and outliers. From figure 7, it can be seen that the residues of an approximately straight line follow in the normal probability course and the approximate symmetrical nature of the histogram indicates that the residues are normally distributed. Residuals have a constant variance since they are randomly scattered around zero in residues compared to the adjusted values. Since residuals do not have a clear pattern, there is no error due to time or data acquisition.

6.2 Results of Hardness Test

As seen in the Table 12, the weld is softer than the parent. The hardness joint efficiency is 70%.The friction stir tool material did not have an effect on the hardness of the welds. The hardness profile of the friction stir welds were lower than the parent material but were not as low as the other welds because they do not melt the material or add filler material.

It can be seen the hardness in the nugget zone is slightly lower than that in HAZ and TMAZ, and an area of minimum hardness is located around the center of weld, whereas outside of this region, hardness increases slightly in TMAZ and HAZ, and then rises sharply, moving towards base metal.

There are two low hardness zones on the two sides of the weld center, but the minimum hardness value exists in the low hardness zone on the retreating side,

Maximum hardness at nugget center is obtained in sample 1. Which have optimum parameter so it validates the result.

7.0 CONCLUSION

In the present work, the modeling of FSW is carried out using the transient finite element analyses. A moving heat source with a heat distribution simulating the heat generated from the friction between the tool shoulder and the workpiece is used in the heat transfer analysis.

- It is experiential that the greatest temperature close to the weld increments as the tool holding time and rotational speed are expanded. Temperature diminishes as the tool transverse speed increments.
- Influences of process parameter on yield strength and tensile strength were assessed and welding speed is most impact parameter took after by tool revolution speed and shoulder diameter.
- Maximum yield strength 88.06 Mpa was get at shoulder diameter 20 mm, welding speed 18 mm/min and tool turn speed 685 rpm.
- Maximum tensile strength 206.52 Mpa was get at shoulder diameter 18 mm, welding speed 18 mm/min and tool pivot speed 685 rpm.
- We finish up from the outcome that welding speed and rotational speed are most impact parameter for tensile strength and joint productivity. When welding speed is expanding then rigidity and joint productivity diminish, also when the rotational speed is expanding then tensile strength and joint proficiency diminish.
- Joint effectiveness is extending from least 61.80 % to most extreme 89.79 %.
- Joint created utilizing the upgraded procedure parameters, shoulder diameter 18mm, welding speed 18mm/min and tool revolution speed 685 rpm, displayed most elevated elasticity.
- Regression examination model may utilize effectively to design process parameters of FSW.
- The weld is milder than the parent metal.

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