Effect of Welding Parameters on Tensile Behaviour of Friction Stir Welded Joints of Aa6082 and Aa5083 Aluminium Alloys

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Abstract—*The development of the Friction Stir Welding has provided an alternative improved way of producing aluminium joints, in a faster and reliable manner. In present investigation the effects of welding parameters on the tensile properties of dissimilar AA6082- AA5083 joints produced by Friction Stir Welding is analyzed. Tool rotational speed (RPM), Tool feed (TF), Shoulder diameter (SD), and Pin depth (PD) have been taken as welding parameters. Mixed factorial design of sixteen runs has been selected for conducting the experiments. Analysis of variance (ANOVA) and main effect plot were used to determine the significant parameters and set the optimal level for each parameter. Confirmation tests were performed on the optimum level. According to the ANOVA results, the most important contributing factors for mechanical properties was found as Tool rotational speed and Tool feed followed by Shoulder diameter and Pin depth. Micro hardness tests were performed in order to characterize the hardness in the vicinity of the weld affected area.*

Keywords*: Friction Stir Welding, Aluminium alloys, Ultimate tensile strength, Micro hardness*

Introduction

Friction Stir Welding (FSW) is a relatively new joining technique developed by The Welding Institute (TWI), Cambridge, in 1991 [1]. FSW is a continuous, hot shear, autogenous process involving a non-consumable rotating tool of harder material than the substrate material. The technique has been used for aluminum alloys, although it has also been applied to the joining of magnesium, titanium and steel [2-5]. The process takes place in the solid state and appears to offer a number of advantages over conventional fusion welding techniques, such as no need for expensive consumables such as filler wire and gas shields, ease of automation on simple milling machinery, good mechanical properties of the resultant joint, and low distortion. In addition, since welding occurs by the deformation of material at temperatures below the melting temperature it is possible to avoid problems commonly associated with the joining of dissimilar aluminum alloys [6].

Joining of dissimilar materials by conventional fusion welding is difficult because of poor weldability arising from different chemical, mechanical, thermal properties of welded materials and formation of hard and brittle intermetallic compounds (IMC) in large scale at weld interface [7]. Since FSW is a solid state welding process, it is best suited for welding of dissimilar material.

Hence, in this investigation an attempt has been made to understand the effects of welding parameters on tensile strength of dissimilar Al alloys (AA6082 and AA5083). In order to increase the welding efficiency, mechanical properties of joints must be maximized and that of the defects minimized by controlling parameters in the FSW process.

Experimental Detail

Material Used

The two most frequently-used aluminium alloys for shipbuilding are AA5083 (AlMg4.5Mn) for plates and AA 6082 (AlSi1Mg) for extrusions. The main alloying element in the 5000 series is magnesium. A magnesium content of around 5% provides good strength and high corrosion resistance in sea water. The 6000 series is mainly alloyed with magnesium and silicon, which results in a hardenable alloy [8-11].

Experimental Setup

The plates of 6mm thickness, AA6082 and AA5083 aluminium alloy, were cut into the required size (200 × 150 × 6 mm) by power hacksaw cutting. Square butt joints were prepared to fabricate FSW joints. The direction of welding was normal to the rolling direction. The single pass welding procedure was followed to fabricate the joints. Non-consumable tools, made of high speed steel, were used to fabricate the joints. CNC vertical milling machine (15 HP; 3000 RPM; 25 KN) was used to fabricate the joints keeping AA5083 on retreating side and AA6082 on advancing side. The tool was fixed in the tool holder of the milling machine and the milling head is kept parallel to the vertical axis. The tool was lowered while in rotation and when the shoulder touches the plate, heat was generated in the interface. After 15 seconds, tool was moved along the length of the sheets to be welded. At the completion of the welding, the tool was withdrawn while in rotation and then stopped.

Experimental Condition

The effects of welding parameters associated with FSW on the Yield & Ultimate Tensile Strength (UTS) were extensively investigated in this study. Moreover, the significant parameters and the optimal combination levels of welding parameters were determined.

Process Parameters Used

From the literature and the previous works done the predominant factors which have a greater influence on the tensile strength of friction stir welded aluminum alloys and some addition parameters were identified [12-15]. These are Tool rotational speed, Tool feed (Transverse speed), Shoulder diameter, Pin depth. Trial experiments were conducted to determine the working range of the above factors. Feasible limits of the parameters were chosen in such a way that the friction stir welded joints should be free from any visible external defects. The important factors that influence the tensile properties of FSW joints and their working range for AA6082-AA5083 aluminium alloys used have been presented in Table 1. Due to a wide range of factors, it was decided to use the mixed factorial design matrix to optimize the experimental conditions. The experimental design was according to an orthogonal array based on the Taguchi method (L16 OA). As prescribed by the design matrix 16 joints were fabricated. The welded joints were sliced using a power hacksaw and then machined to the required dimensions.

Response Parameters

The effect of selected process parameters were studied on the following response characteristics of FSW process:

- Yield strength
- Ultimate Tensile strength

Tensile Studies

Tensile test specimens were prepared as per ASTM E8 standard. After performing tensile test, the results of yield strength and ultimate tensile strength for two different welded specimens were compiled [11].

Table 1: Process Parameters Used for Work

Process Paramter	Representation	Level 1	Level 2	Level 3	Level 4
Tool Rotational Speed	RPM	800	1100	1400	1700
Tool Feed	TF	25	50	75	100
Pin Depth	PD	15	18	-	-
Shoulder Diameter	SD	5.7	5.8	-	-

Results and Discussion

The experiments were planned by using the parametric approach of the Taguchi's method. The standard procedure to analyze the data based on S/N ratio, as suggested by Taguchi, has been employed. The average values of the S/N ratio of the response characteristics for each parameter at different levels were calculated from the experimental data. In the present study, a larger-the better quality characteristic was used to maximize the Yield strength & Ultimate tensile strength by the following relation

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

Where y is the output response and n is the repeating number of trails in each group. The main effects of process parameters for S/N ratio for each response were plotted by calculating the average values of response characteristics for each parameter at different levels. Analysis of Variance (ANOVA) is performed to identify the process parameters which are more significant.

Yield Strength

After performing tensile test, the results of yield strength for two different welded specimens for each weld were compiled as shown in Table 2. In table 2 Y1, Y2 represents response value for two repetitions of each trail. The average value and main effect of S/N ratio for each level of the parameters are summarized and called the average and main effects of S/N data. It has been listed in Table 3.

Optimal Parametric Contribution Based on Test Results

The optimized process parameters obtained in L16 experiment are as follows:

Tool rotational speed 800

Tool feed (Traverse speed) 50 mm/min

Pin depth 5.8 mm

Shoulder diameter 18 mm

Percentage Contribution of Different Factors

According to the ANOVA results, the most important factor effecting Yield strength was found as RPM (46%), while the Tool feed (TF) was the second ranking factor (36%) and Pin depth (PD) contributed (4%) and last parameter Shoulder Diameter (SD) contributed least (less than 1%).

Table 2: Tensile Test Results with S/N Ratio Indicating the Yield Strength and UTS

Exp. No.	Tool RPM	Tool Feed (mm/min)	PD (mm)	SD (mm)	Y 1 (MPa)	Y 2 (MPa)	S/N Ratio (dB)	T1 (MPa)	T2 (MPa)	S/N Ratio (dB)
1	800	25	5.7	15	91.6	95.2	19.703	101.4	105	20.22
2	800	50	5.7	15	92	99	19.8	110	116	20.531
3	800	75	5.8	18	94.6	96.4	19.8	108.2	107.4	20.326
4	800	100	5.8	18	95.3	93.1	19.741	109.4	111	20.422
5	1100	25	5.7	18	91.8	95.2	19.708	100.5	101.1	19.969
6	1100	50	5.7	18	98	97.2	19.894	105	109	20.294
7	1100	75	5.8	15	89	92	19.567	97.8	97	19.885
8	1100	100	5.8	15	88.6	83.4	19.345	95.5	97.5	19.845
9	1400	25	5.8	15	96.1	92.7	19.749	103.3	101.1	20.094
10	1400	50	5.8	15	99	93	19.823	105	101.8	20.145
11	1400	75	5.7	18	87	83.6	19.309	96.2	98.4	19.881
12	1400	100	5.7	18	86	82.4	19.253	103	99.2	20.047
13	1700	25	5.8	18	77.9	84.1	19.138	94.7	95.3	19.777
14	1700	50	5.8	18	93.2	91.4	19.652	100.3	106.1	20.136
15	1700	75	5.7	15	84	80.8	19.159	97.5	99.3	19.929
16	1700	100	5.7	15	79	83	19.085	86.6	91.4	19.494

Ultimate Tensile Strength (UTS)

After performing the tensile test following results were obtained for UTS: In the Table 2 T1, T2 represents response value for two repetitions of each trail. The average value and main effect of S/N ratio for each level of the parameters were summarized and called the average and main effects of S/N data. It has been listed in Table 5.

Optimal Parametric Contribution Based on Test Results

The optimized process parameters obtained in L16 experiment are as: Tool rotational speed 800, Traverse speed 50 mm/min, Pin depth 5.8 mm, Shoulder diameter 18 mm

Percentage Contribution of Different Factors

ANOVA analysis for UTS depicts following results:

According to the ANOVA results, the most important factor effecting UTS was found as RPM (58%), while the Tool Feed (TF) was the second ranking factor (24%) and Shoulder Dia (SD) contributed (3%) and last parameter Pin Depth (PD) contributed least (less than 1%).

Table 3: Average of S/N Values for Yield Strength

Process Paramter	Representation	Level 1	Level 2	Level 3	Level 4
Tool Rotational Speed	RPM	19.761	19.628	19.621	19.338
Tool Feed	TF	19.575	19.792	19.458	19.356
Pin Depth	PD	19.489	19.589	---	----
Shoulder Diameter	SD	19.528	19.562	----	-----

Table 4: ANOVA Table for Yield Strength

Process Paramter	DOF	Sum SQ.	Mean SQ.	F Ratio	% Contribution
RPM	3	0.543	0.181	7.901	46.041
TF	3	0.421	0.14	6.123	35.684
PD	1	0.05	0.05	2.217	4.307
SD	1	0.004	0.004	0.19	0.37
Error	7	0.16	0.023		
Total	15	1.178			

Table 5: Average S/N Ratio Table for UTS

Process Paramter	Representation	Level 1	Level 2	Level 3	Level 4
Tool Rotational Speed	RPM	20.374	19.998	19.992	19.96
Tool Feed	TF	20.015	20.276	20.005	19.952
Pin Depth	PD	20.046	20.066	---	----
Shoulder Diameter	SD	20.018	20.106	----	-----

Table 6: ANOVA Table for UTS

Process Paramter	DOF	Sum SQ	Mean SQ.	F Ratio	% Contribution
RPM	3	0.616	0.205	9.815	58.542
TF	3	0.254	0.085	4.047	24.137
PD	1	0.004	0.004	0.211	0.419
SD	1	0.031	0.032	1.5	2.983
Error	7	0.146	0.021		
Total	15	1.052			

Table 7: Micro Hardness Variation Across the Weld Nugget (Data on a Cross Section Perpendicular to the Weld Line, at Mid Thickness) for Sample (1 to 16)

Distance from Weld Center in mm	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16
-15	103	105	101	104	103	102	100	102	105	105	102	103	102	102	102	101
-12	100	101	100	100	102	100	99	100	102	103	100	102	100	100	101	100
-9	99	99	98	99	99	97	97	99	101	102	99	100	97	99	100	98.6
-6	74	78	77	79	72	74	73	72	75	78	71	70	73	77	76	72
-3	103	112	108	114	106	113.8	98	99	102	105	94	89	87	100	88	85
0	105	117	112	116	107	114	96	102	109	110	96	89	87.5	104	90	86
3	104.4	112	109	115	108	112	100	100	106	108	99	91	89	101	94	88
6	111	116	116	114	113	113	113	111	111	112	109	109	100	109	104	105
9	119	118	121	124	124	125	117	116	113	118	122	122	121	122	113	112
12	120	120	120	123	121	125	121	119	120	120	120	120	119	119	118	119
15	122	126	124	125	125	127	123	122	123	123	121	124	121	121	123	121

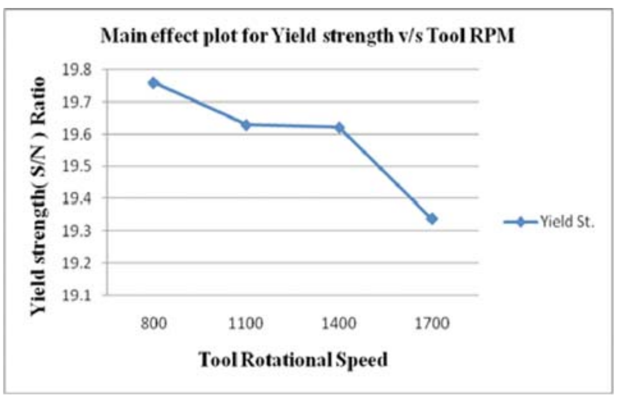

Fig. 1: Effect of Tool RPM on Yield Strength

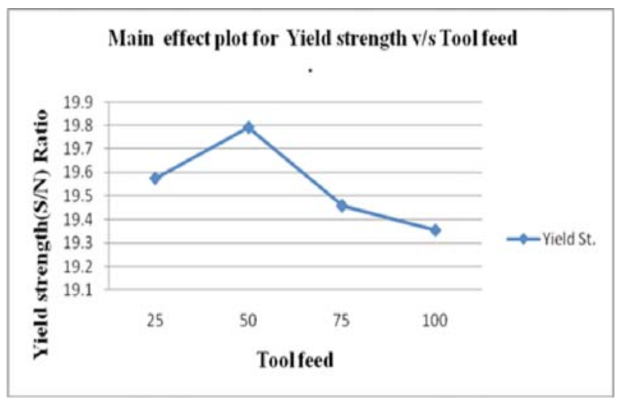

Fig. 2: Effect of Tool Feed on Yield Strength

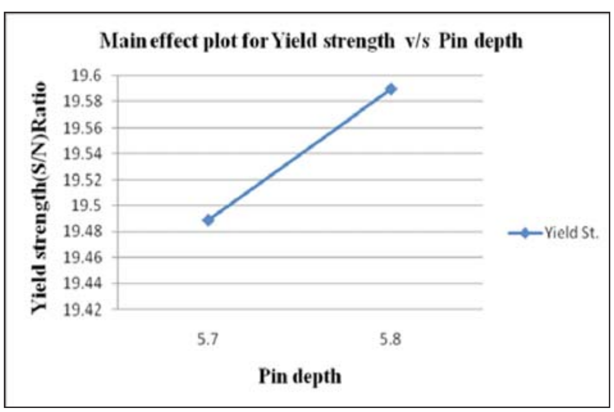

Fig. 3: Effect of Pin Length on Yield Strength

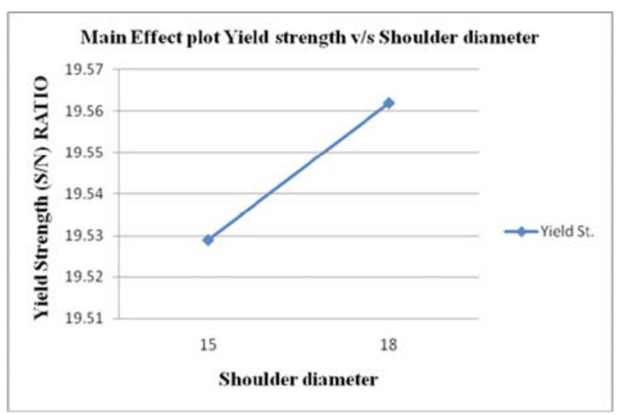

Fig. 4: Effect of Shoulder Diameter on Yield Strength

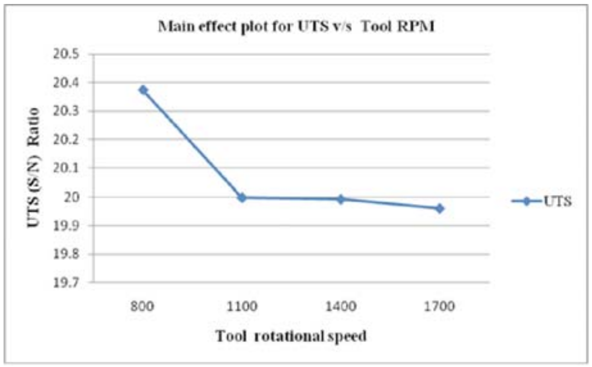

Fig. 5: Effect of Tool RPM on UTS

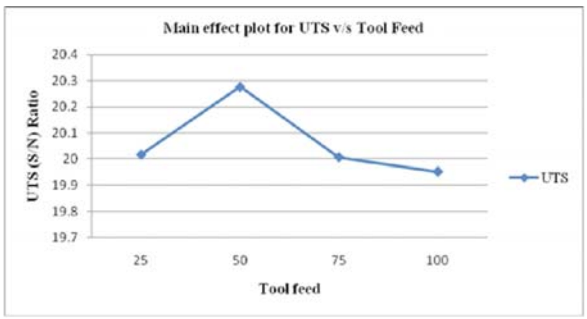

Fig. 6: Effect of Tool Feed on UTS

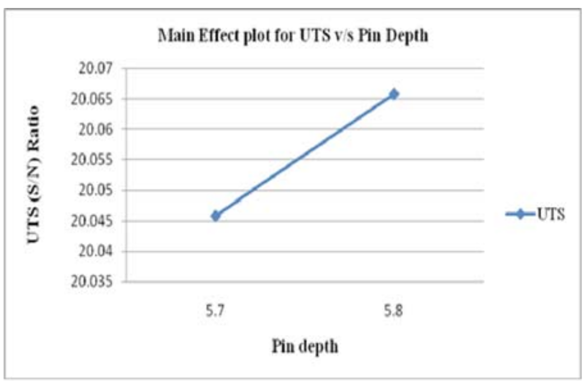

Fig. 7: Effect of Pin Depth on UTS

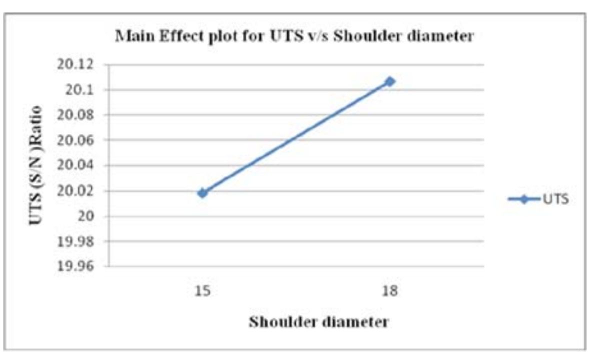

Fig. 8: Effect of Shoulder Diameter on UTS

Effect of Tool Rotational Speed

The joint fabricated at a rotational speed of 800 RPM gave higher Yield and Ultimate tensile strength. Fig. 1 and Fig. 5 revealed the effect of Tool rotational speed on Yield & UTS of friction stir welded aluminum alloy.

It can be concluded that with increase in RPM from 800 to 1700 there was significant decrease in the yield strength & UTS. This might be due to the fact that with increase in tool RPM more heat will generate as a result amount of gases generated would lead to porosity in the welds. The high input rate and relatively low cooling rate results in coarse grained structure. Moreover, a higher-rotational speed causes excessive release of stirred materials to the upper surface, which resultantly left voids in the weld zone. This results in decrease in Yield and UTS. Increase in tool rotation speed cause more heat input in turn enlarges the and (Thermo mechanically affected Zone (TAMZ) and Heat Affected Zone (HAZ) consequently, results in low tensile strength [16]. Previous work done by Sarsılmaz and Cydas on FS welding of AA 1050/AA 5083 couples showed similar behavior [17].

Effect of Tool Feed (Welding or Transverse Speed)

The effect of welding speed on Yield and UTS of friction stir welded aluminum alloy has been represented in Fig. 2 and Fig. 6. When the welding speed increased above 25 mm/min the Yield and UTS also increased and reached a maximum at 50 mm/min. With increase in welding speed above 50 mm/min., the Yield and UTS of the joint decreased [3].

FSW at higher Tool feed resulted in short exposure time in the weld area with insufficient heat and poor plastic flow of the metal, resulting in smaller TMAZ and HAZ which lead to lower Yield and UTS and caused some voids like defects in the joints. It seemed that these voids were due to poor consolidation of the metal interface when the tool traveled at higher-welding speeds. The reduced plasticity and rates of diffusion in the material might have resulted in a weak interface. The softened area was narrower for the higher-welding speed than that for the lower welding speed.

When the welding speed was lower than a certain critical value (50 mm/min), the Yield and UTS was less because of less mixing of materials at the interface. With welding speed faster than the critical value, welding defects could be produced in the joints. The defects act as a crack initiation site during tensile test. Therefore, the tensile properties and fracture locations of the joints are determined by the welding speed [12]. In the previous work done by Sakthivel et al. [18] similar parameter gave good results for FSW of aluminium alloys.

Effect of Pin Depth

The primary function of the non consumable rotating tool pin is to stir the plasticized metal and move ahead leaving behind same in order to have good joint. Pin length plays a crucial role in material flow. The effect of tool pin depth on yield strength and UTS of friction stir welded aluminum alloy has been represented in Fig. 3 and Fig. 7. The joints fabricated by cylindrical pin length 5.8 mm tool exhibited highest Yield and UTS irrespective of welding parameters [13]. This might be attributed to greater pin depth which leads to more mixing upto root level of dissimilar aluminum alloys which resulted in better yield strength and UTS.

Effect of Shoulder Diameter

With increase in diameter from 15-18 mm, the Yield and UTS also increased as shown in Fig. 4 and Fig. 8. This might be because of the increased contact area with the increase of shoulder diameter and this might be the reason for the increase of the higher temperature region. The temperature distribution under the shoulder becomes more uniform with the increase of the shoulder size. With the increase of the shoulder size (18 mm), the higher temperature region might be increased. Although the material flows at retreating side and the advancing side were different, it might be estimated that the temperature distribution was nearly symmetric to the welding line. In the work done by Zhang et al. , they studied the effect of shoulder size on the temperature rise and the material deformation in friction stir welding and suggested bigger diameter shoulder for better results [19].

Confirmation Test for Yield Strength

Once the optimal level of the process parameters is selected, the final step is to predict and verify the improvement of the performance characteristic using the optimal level of the process parameters. The estimated S/N ratio $\hat{\eta}$ using the optimal level of the process parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{q} (\overline{\eta_i} - \eta_m)$$

Where η_m is the total mean of the S/N ratio, $\overline{\eta_i}$, is the mean S/N ratio at the optimal level, and q is the number of the process parameters that affect the performance characteristic.The estimated S/N ratio using the optimal parameters for yield strength can then be obtained and the corresponding yield strength can also be calculated by using equation given below

$$\hat{\eta} = \eta_m + (\overline{\eta_1} - \eta_m) + (\overline{\eta_2} - \eta_m) + (\overline{\eta_3} - \eta_m) + (\overline{\eta_4} - \eta_m) = 20.068$$

After substitution of $\hat{\eta}$ in equation no. 1, we will get the value of yield strength corresponding to estimated S/N ratio using the optimal parameters ($\hat{\eta}$):

$20.068 = - 10 \log (1/y^2)$

$y = 101.6$ MPa

This is the predicted value of yield strength for optimal welding parameters. Now we take initial welding parameters as RPM1 TF2 PD2 SD2 i.e. RPM 800, Tool feed 50mm/min., pin depth 5.8mm & Shoulder Dia. 18mm and conduct experiment according to above values of parameters keeping previous experimental conditions same. After actual experimentation average yield strength for two samples was found to be 103.2 MPa which has been found to be very near to the predicted value. So, good agreement between the predicted welding performance and actual welding performance has been obtained.

Confirmation Test for UTS

Similar confirmation test was performed for UTS and it was found that predicted value (115.6 MPa) for UTS was very close to the values obtained after actual test conditions on optimum levels (117.4MPa).

Microhardness Test

The hardness results assist the interpretation of the weld microstructures and mechanical properties. Microhardness tests were performed in order to characterize the hardness in the vicinity of the weld affected area. The micro hardness tests were performed on a cross-section perpendicular to the weld line, at mid thickness across the weld zone and into the parent material, using a 1.96 N load. 7 Micro hardness variation across the Weld Nugget is shown in Table 7. The microhardness measured from these welds showed that the microhardness was higher on the AA 5083 side and lower on the AA 6082 side. The microhardness varied from 121 HV to 127 HV in the base metal on AA 5083, the base metal of AA 6082 has a micro hardness 100 HV to 103 HV and the weld nugget hardness varied between 86 HV to 117 HV. The TMAZ on the AA 6082 side has the least hardness around (70-79 HV) which might be due to the local dissolution of strengthening particles and a reduction in the dislocation density. On the stir zone, the increase in microhardness was associated with re-precipitation of fine particles. The softening was mostly evident in the TMAZ on the advancing side (AA6082) of the welds. This zone corresponds to the failure location in tensile tests. In most of the experienced cases, fracture in tensile tests was located in the TMAZ which corresponds to failure location in tensile tests.

Conclusion

The following conclusions have been made from the above investigation

- A CNC milling machine has been demonstrated to be capable of performing FSW and producing reasonable weld to join 6 mm thick AA6082 and AA5083 aluminium.
- The Yield Strength and UTS was increased with traverse speed up to 50mm/min but decreased after that.
- The Yield Strength and UTS decreased with increase in tool rotational speed.
- From the ANOVA results it may be concluded that Tool RPM and Tool Feed were most dominating factors in terms of mechanical properties.
- According to S/N ratio results, the combination of RPM1 TF2 PD2 SD2 was the optimal welding conditions for Yield Strength and UTS.
- For most of the cases, fracture in tensile tests was located in the TMAZ on the advancing side of the welds. This zone corresponds to the failure location in tensile tests.

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