A study of the effect of various process parameters on mechanical properties of Friction Stir Processed AA6061-T6 aluminum alloy

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***Abstract*—In this study, AA6061-T6 aluminum alloy were processed using friction stir processing with two different tool pin profiles and process parameters were optimized using Taguchi method. The tool rotation, welding speed, tilt angle and number of passes were the parameters taken into consideration. The optimum process parameters were obtained with reference to the tensile strength of the processing sample. The predicted optimal value of tensile strength was confirmed by conducting confirmation run using optimal parameters. Hardness and microstructure analysis were conducted of the optimized sample.**

***Index Terms*—FSP, Hardness, Microstructure, Taguchi, Tensile strength.**

I.INTRODUCTION

Friction stir processing (FSP) is a new micro structural modifications technique; recently it has become an efficient tool for refining and homogenizing the grain structure of metal sheet. FSP is believed to have a great potential in the field of super plasticity. Results have been reported that FSP greatly enhances super plasticity in many Al alloy[1]. Friction stir processing is invented from friction stir welding which was invited by The Welding Institute (TWI) of United Kingdom in 1991[2].Friction stir processing (FSP) is a solid-state process which means that at any time of the processing the material is in the solid state. In FSP a specially designed rotating cylindrical tool having a pin and shoulder dimensions proportional to the specimen thickness. The pin of the rotating tool is plunged into the specimen and the shoulder comes into contact with the surface of the specimen, and then traverses in the required direction. The contact between the rotating tool and the specimen generate heat which softens the material below the melting point of the specimen and with the mechanical stirring caused by the pin, the material within the processed zone undergoes intense plastic deformation.AA6061-T6 is a hardening aluminum alloy containing magnesium and silicon as major alloy additions. Magnesium and silicon forms Mg2Si which in turn forms a simple eutectic system with Aluminum. It is the precipitation of Mg2Si after artificial aging that allows these alloys to reach their full strength. They exhibit good mechanical properties and excellent corrosion resistance along with weld ability. Their applications include construction of aircraft structures, hardware and marine fittings, couplings, hydraulic piston, valves, bicycle frames, boat hulls, automotive parts such as wheel spares, cans for packaging food stuffs etc. [4].

Taguchi techniques were developed by Taguchi and Konishi; these techniques have been utilized widely in engineering analysis to get the optimum values of performance characteristics within the set of design parameters. Taguchi technique is also powerful tool for the design of high quality systems. It introduces an integrated approach that is simple and efficient to find the better range of designs for quality, performance, and computational cost. Some researchers have been performed to optimize the optimum levels of design variables based on orthogonal array experiment of Taguchi's [5].Investigated the application of Taguchi optimization technique to reduce war page problem related to the shrinkage variation depended on process parameters during production of thin-shell plastic components for or those part. They carried out a number of Mold Flow analyses by utilizing the combination of process parameters based on three-level of L27 and L9Taguchi orthogonal design. They used signal-to-noise and the analysis of variance (ANOVA) to find the optimum levels and to indicate the impact of the process parameters on war page and shrinkage. Their results show that war page and shrinkage are improved by about 2.17% and 0.7%. Taguchi method used to find the optimal cutting parameters for surface roughness in turning. They provided experimental outputs to illustrate the effectiveness of this approach.

This study has been conducted to find optimal FSP parameters such as tool rotation (TR), welding speed (WS), tilt angle (TA), and number of passes (NP), in order to fabricate

fine grained aluminum work piece. Taguchi technique was used to analyze the work piece.

I. TAGUCHI METHOD

Robust design is an engineering methodology for obtaining product and process conditions, which is less sensitive to the various causes of variation to produce high-quality products with low development and economic. Taguchi's parameter design is an important tool for robust design. It offers a simple and systematic way to get optimum design for performance, quality and cost [6]. Taguchi methods which combine the experiment design theory and the quality loss function concept have been applied to the robust design of products and process and have solved some complicated problems in manufacturing. To summarize, the parameter design of the Taguchi method includes the following steps: (1) Determination of the quality characteristic to be optimized; (2) determination of the number of levels for the design parameters; (3) designing the matrix experiment and define the data analysis procedure; (4) conduct the matrix experiment; (5) analysis of the experimental results using the S/N and ANOVA analyses; (6) selection of the optimal levels of design parameters; (7) predicting the performance at these levels; (8) verification of the optimum design variables through the confirmation experiment [5].

Taguchi has established OAs to describe a large number of experimental situations. The symbolic notation for these arrays carries the key information on the size of the experiment. As three levels and three factors are taken into consideration, L9 OA is used in this investigation. The number 9 indicates 9 trials are required. The array handles up to 4 factors at 3 levels each. For situations demanding a larger number of factors, mixed levels as well as higher levels, a number of other OAs are available. In this investigation the three parameters such as tool rotation, welding speed, tilt angle and number of pass are taken into consideration and the values and their symbols and levels are listed in Table 1.

II. EXPERIMENTAL SETUP AND PROCEDURE

The materials selected in the current study were AA6061-T6 aluminum alloy with the size of 170*190*5 mm. The chemical composition of the aluminum alloys is given in Tables 2. The aluminum alloy plate was placed on the fixture, and then rotating tool was plunged and travel along a given direction. The plates were processed parallel to the rolling direction.

The rotating tool was made up of H13 [4]. Tool having a shoulder of 15 mm diameter. Two types of tools were used for the processing of aluminum alloy. First one is a conical pin profile and second one is a square pin profile having pin length of 4.7 mm, base diameter of 6 mm, Tip diameter of 3.6 mm and cone angle of 28^0. The specifications of the tools are presented in Fig. 1. For the purpose of metallurgical analysis, the specimens were prepared and microscopic test was utilized to investigate the microstructures [7]. To characterize the mechanical properties of the processing sample tensile test was conducted [8].In addition, the hardness of the processed samples was measured at different points along the weld and through the thickness by using Vickers micro hardness tester [9]. The processed samples are presented in Fig.2.

III. ANALYSIS AND EXPERIMENTAL DATA

A. *Signal to Noise ratio*

Taguchi technique uses the S/N ratio approach to measure the quality characteristic deviating from the desired value. The S/N ratio characteristics divided into three stages: the nominal-the better, the smaller-the better, and the higher-the better when the quality characteristics are continuous for engineering analysis. Since the objective of this study is to maximize tensile strength through optimum process parameters in friction stir processing, higher-the better quality characteristic is employed in this research. The formula used for calculating the SN ratio is given below.

$$\frac{S}{N} = -10\ \log_{1o} \frac{1}{N} \sum_{i=1}^{n} \frac{1}{yi^2}$$

where yi is the value of tensile strength for the i th test, n is the number of tests and N is the total number of data points. The tensile strength of the friction stir processing values is analyzed to study the effects of the FSP process parameters [10].

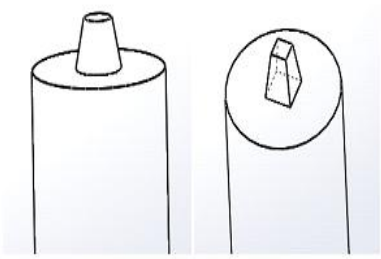
The tensile strength of the FSP values is analyzed to study the effects of the FSP process parameters. The experimental data are converted into S/N ratio. The calculated S/N ratio values are given in Table 4 and Table 7. For this analysis made using the popular software known as MINITAB 15. The larger S/N Ratio refers to the better quality characteristics. Based on S/N ratio values the optimum level setting was obtained at1400 rpm tool rotation, 101.6 mm/min of welding speed, 1^0 tilt angle and single pass processing for conical tool. 1035 rpm tool rotation, 215.9 mm/min of welding speed, 2^0 tilt angle and single pass processing for square tool.

Table 1
Process parameters values and there levels

Level	A Tool Rotation (rpm)	B Welding speed (mm/min)	C Tilt Angle (0^0)	D No. of Passes
1	910	101.6	1	1
2	1035	152.4	2	2
3	1400	215.9	3	3

Table2
Chemical composition of the base material.

Mg	Si	Fe	Cu	Zn	Ti	Mn	Cr	Others	Al
0.8-1.2	0.4-0.8	0.7	0.15-0.4	0.25	0.15	0.15	0.04-0.3	0.05	Balance



Conical Tool Square Tool

Fig.1 Tool used in FSP

Fig.2 FSP processed samples

B. Analysis of variance

The aim of the analysis of variance is to evaluate the significance of process parameters on tensile strength for this study. It gives a detailed film show how far the process parameter affects the response and the level of significance of the factor to be considered. Statistically, there is a tool called an F test to see which design parameters has a significant effect on the quality characteristic. Usually, when F > 4, it means that the change of the design parameter has a significant effect on the quality characteristic. In this study number of passes is a highly significant factor and plays a major role in affecting the tensile strength of the processed sample.

C. Confirmation Test

As the set of optimum level of the design variables has been selected, the final stage is to verify the improvement of the quality characteristic using set of optimum design variables. The predicted optimal processing parameters and corresponding tensile strength values are given in Table 3.

Table 3
Result of confirmation test

	Optimal parameters(Estimated and experimental)	
	Estimated	Experimental
Tensile strength by conical tool (mpa)	264.71	250
Tensile strength by square tool (mpa)	226.48	235

D. For Conical Tool

The strength, S/N ratio and mean values for given processing parameters by using conical tool are given in Table 4. The response table for signal to noise ratio larger is better for conical tool is given in Table 5.

Table.4
Experimental Layout- L9 orthogonal array, S/N ratio and mean value

TR (rpm)	WS (inch)	TA	NP	STRENGTH (mpa)	S/N (ratio)	MEAN
910	4	1	1	188.57	45.5094	188.57
910	6	2	2	92.87	39.3575	92.87
910	8.5	3	3	96.51	39.6914	96.51
1035	4	2	3	197.78	45.9236	197.78
1035	6	3	1	184.41	45.3156	184.41
1035	8.5	1	2	209.83	46.4373	209.83
1400	4	3	2	206.78	46.3101	206.78
1400	6	1	3	204.96	46.2333	204.96
1400	8.5	2	1	194.63	45.7842	194.63

Table.5
Response table for signal to noise ratio larger is better

LEVEL	TR	WS	TA	NP
1	41.52	45.91	46.06	45.54
2	45.89	43.64	43.69	44.04
3	46.11	43.97	43.77	43.95
Delta	4.59	2.28	2.37	1.59
Rank	1	3	2	4

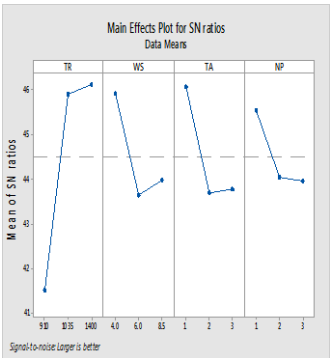


Fig.3 Main effect plot For S/N ratio (conical)

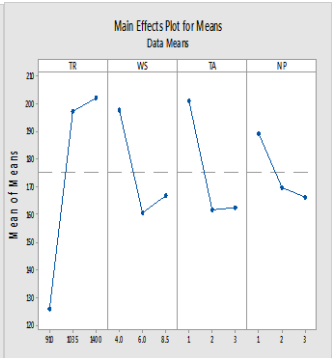


Fig.4 Main effect plot for means (conical)

The main effect plot for S/N ratio and Main effect plot for means are given in Fig 3 and Fig 4. Optimum design variables based on these plots are given by $A_3B_1C_1D_1$.

The tool rotation, welding speed, tilt angle and number of passes were set at 1400 rpm, 101.6 mm/min, 1^0 and single pass respectively. Two tensile test specimens were subjected to tensile test and average value should be taken. Regarding verification test, it can be observed that some error is observed between predicted value and maximum tensile strength.

E. For Square Tool

The strength, S/N ratio and mean values for given processing parameters by using square tool are given in Table 7. The response table for signal to noise ratio larger is better for square tool is given in Table 6.

Table.6
Response table for signal to noise ratio larger is better

LEVEL	TR	WS	TA	NP
1	44.90	45.05	44.74	46.23
2	45.58	44.87	45.41	45.88
3	44.95	45.50	45.28	43.32
Delta	0.68	0.63	0.67	2.91
Rank	2	4	3	1

Table.7
Experimental Layout- L9 orthogonal array, S/N ratio and mean value

TR (rpm)	WS (inch)	TA	NP	STRENGTH (mpa)	S/N (ratio)	MEAN
910	4	1	1	188.15	45.4908	188.15
910	6	2	2	191.27	45.6329	191.27
910	8.5	3	3	150.99	43.5789	150.99
1035	4	2	3	157.19	43.9285	157.19
1035	6	3	1	212.17	46.5336	212.17
1035	8.5	1	2	205.75	46.2668	205.75
1400	4	3	2	193.64	45.7399	193.64
1400	6	1	3	132.6	42.4508	132.6
1400	8.5	2	1	215.29	46.6604	215.29

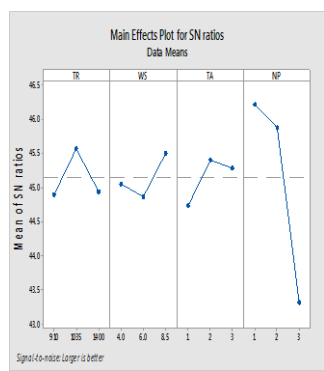


Fig.5 Main effect plot For S/N ratio (Square)

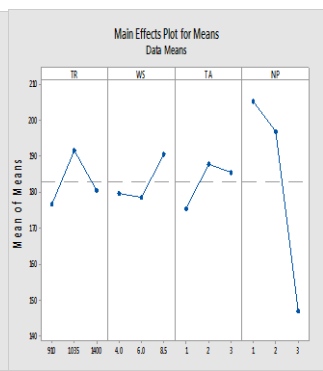


Fig. 6 Main effect plot for means (Square)

The main effect plot for S/N ratio and main effect plot for means are given in Fig 5 and Fig 6. Optimum design variables based on these plots are given by $A_2B_3C_2D_1$.

The tool rotation, welding speed, tilt angle and number of passes were set at 1035 rpm, 215.9 mm/min, 2^0 and single pass respectively. Two tensile test specimens were subjected to tensile test and average value should be taken. Regarding verification test, it can be observed that some error is observed between predicted value and maximum tensile strength.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. *Microstructure*

Micrograph of Friction stir processed AA6061-T6 aluminum alloy are shown in fig. 7-9. Microstructure study was carried out on friction stir processed samples. The micrograph of friction stir processed sample of AA6061-T6 alloy plate showed distinct zones namely stirred zone, thermo-mechanically affected zone, and heat affected zone. 0.5% HF was used as a etching agent during microstructure analysis. The micrograph of base metal shows a alpha aluminium alloy structure with fairly uniform distribution having AlFeSi complex precipitation present. Intermediate structure is in between 6-7%.The micrograph of processed plate with optimum value of conical tool shows a alpha aluminium alloy structure with fairly uniform distribution having AlFeSi complex precipitation present with parting line. Intermediate structure is in between 6-7% at weld zone and in between 8-10% at base metal. The micrograph of processed plate with optimum value of square tool shows a alpha aluminium alloy structure with fairly uniform distribution having AlFeSi complex precipitation present without parting line. Intermediate structure is in between 5-6% at weld zone and in between 7-8% at base metal.

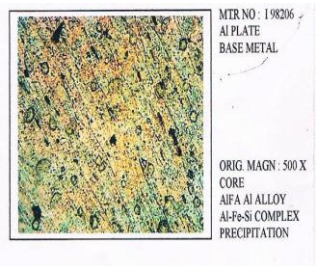


Fig. 7 Micrograph of base metal

Fig. 8 Micrograph of optimum value of conical tool processed sample.

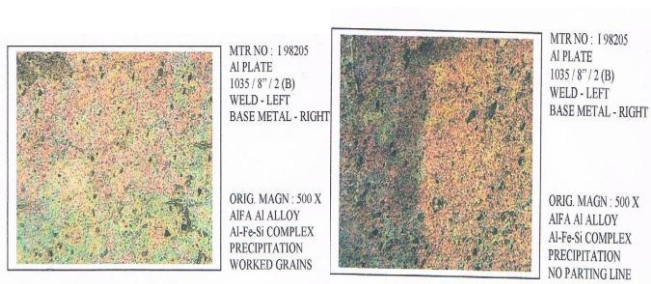


Fig. 9 Micrograph of optimum value of square tool processed sample

B. *Tensile Strength*

The tensile test of friction stir processed and unprocessed samples of AA6061-T6 alloy revealed that the friction stir processing decrease ultimate tensile strength. From the given study we have obtained that the tensile strength of the processed sample was increased as we increase the tool rotation and tensile strength of the specimen decreased as we increase the number of passes. Reduction in tensile strength of an alloy after friction stir processing can be attributed re crystallization and reversion caused by friction heat generated during processing.

C. *Hardness Study*

The hardness of base metal and friction stir processed sample was measured by using Vickers's hardness tester. Hardness test perform on base metal, optimum values obtained by conical tool processed sample and optimum values obtained by square tool processed sample. Hardness of the processed sample measured at surface as well as at inner side. And at each side the hardness was measured at three locations i.e. weld, HAZ, core.

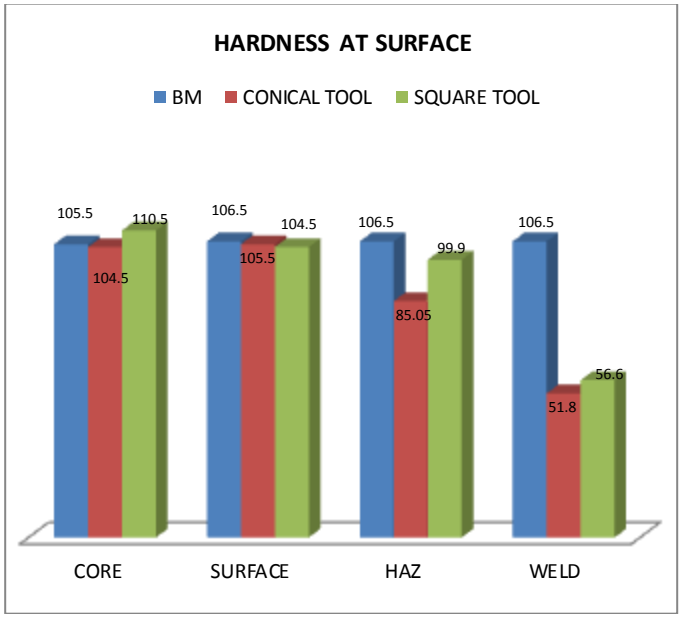


Fig. 10 Graph showing hardness of samples at surface.

Hardness of base metal is greater than that of the optimum value of conical tool processed sample. Whereas, hardness of optimum value of square tool processed sample is greater than base metal and optimum value of conical tool processed sample at core section and measuring at surface as well as measuring at inner side. The detail variation of the hardness values at surface is shown in Fig 10. The detail variation of hardness values at inner side is shown in Fig. 11.

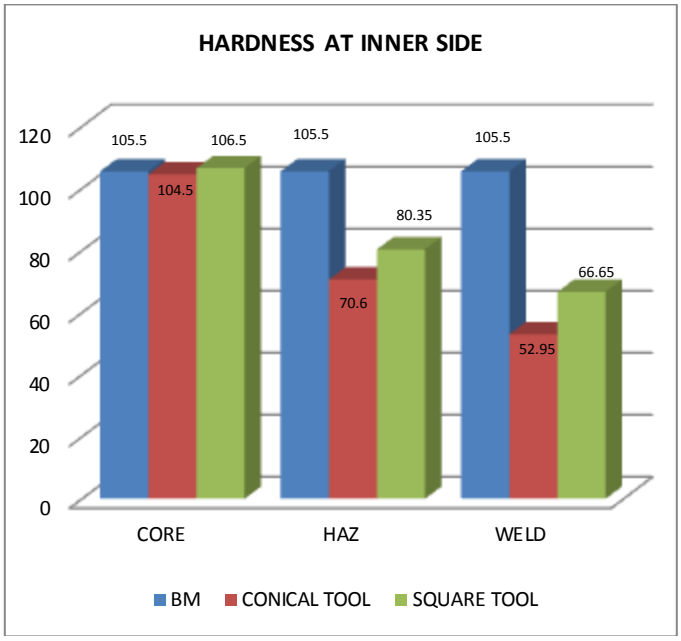


Fig. 11 Graph showing hardness of sample at inner side.

V. CONCLUSIONS

A Friction stir processing was conducted on AA6061-T6 aluminum alloy. The study of given processing can be concluded that:

(1) Taguchi optimization method was used to find optimum level of design variables in Friction stir processing. The optimum value s for conical tool processing sample is tool rotation, welding speed, tilt angle and number of passes are 1400 rpm, 101.6 mm/min, 1^0, single pass whereas for square tool processing sample are 1035 rpm, 215.9 mm/min, 2^0, single pass respectively.

(2) In this study, Tool rotation and number of passes plays a important role in the processing.

(3) During confirmation test, there is an error observed between predicted value and maximum tensile strength.

(4) Microstructure investigation shows that, the finer grain structure without parting line was seen by square tool processed sample as compared to other two.

(5)Hardness of base metal is greater than that of the optimum value of conical tool processed sample. Whereas, hardness of optimum value of square tool processed sample is greater than base metal and optimum value of conical tool processed sample.

(6) 100% overlap multi pass friction stir processing reduces the tensile strength of the specimen.

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