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Process Parameter Optimization of Friction stir Welded Aluminium 6061 Alloy Plates

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Abstract— **Friction Stir welding (FSW) is a solid state joining process widely accepted to weld difficult to weld materials such as Aluminium. Although the technique is indented to weld Aluminium alloys the process is extended to achieve better joint properties in Steel, Copper, Magnesium and other materials. Friction between the tool surface and work piece surface generate the heat necessary to bring the material to plastic state and then material is stirred to make the joint. The heat generation and material flow in the weld zone depends mainly on the tool Rotation speed, Welding/Traverse speed and Tool Geometry. In this work the fundamental understanding of the FSW process and the effects of these parameters in the joint strength of Aluminium 6061alloy plates is presented. The process parameters are selected according to Taguchi Method, which is an effective and efficient method to optimize the response variable. According to Taguchi orthogonal array the parameters and their levels are selected and the experiments are conducted. The joint is tested for its Ultimate Tensile Strength in UTM. The Rockwell Hardness at various positions in the weld is checked. Microstructure Analysis of the weld zone justify the variations in strength for different welds. Finally the process parameters for Friction Stir welding of Aluminium Alloy 6061 are optimized for maximum strength.**

Keywords—**Tool Pin, Welding Speed, Rotational speed etc….**

I. INTRODUCTION

FRICTION STIR WELDING (FSW) was invented in 1991 at The Welding Institute (TWI) United Kingdom as a solid-state welding technique. It was initially applied to weld aluminum alloys. A no consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of plates to be joined and subsequently traversed along the joint line Figure1 illustrates process definitions for the tool and work piece The parts have to be clamped rigidly onto a backing bar in a manner that prevents the abutting jointfaces from being forced apart. The length of the pin is slightly less than the weld depth required and the tool shoulder should be in intimate contact with the work piece surface. The frictional heat is generated between the wear resistant welding tool shoulder and pin, and the materials of the work-pieces. This heat, along with the heat generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without reaching the melting point, hence it is cited a solid-state process. As the pin is moved in the direction of welding the leading face of the pin, assisted by a Special pin profile, forces plasticized material to the back of the pin whilst applying a substantial forging force to consolidate the weld metal[l]. The welding of the material is facilitated by severe plastic deformation in the solid state involving dynamic re-crystallization of the base material .

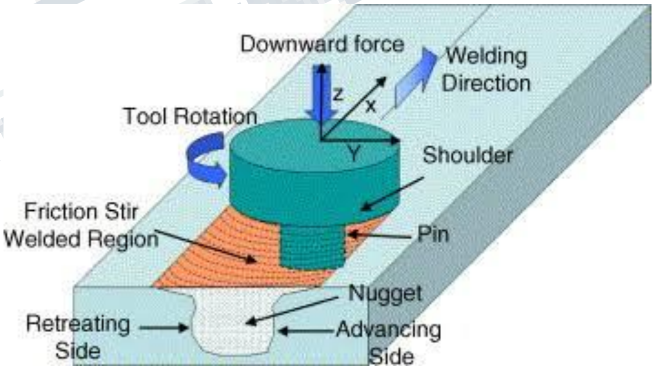


Fig. 1Schematic drawing of friction stir welding

Recent experimental works have provided significant understanding about various interesting features of materials flow in FSW and the welding process[1]. Most of the material flow occurs through the retreating side and the transport of the plasticized material behind the tool forms the welded joint. Three types of flow effects the overall transport of plasticized materials during FSW[2, 3], First, near the tool, a slug of plasticized material rotates around the tool. This motion is driven by the rotation of the tool and the resulting friction between the tool and the work piece. Second, rotational motion of the conical pin tends to push material downward close to the pin which drives an upward motion of an equivalent amount of material somewhat farther away. Finally, there is a relative motion between the tool and the work piece. The overall motion and mixing of the plasticized material and the formation of the weld joint, result from the simultaneous interaction of these three effects.

FSW results in severe plastic deformation around rotating tool pin and friction between tool and workpieces. Both these factors contribute to the temperature increase within and around the stirred zone. Since the temperature distribution within and around the stirred zone directly influences the microstructure of the welds, such as grain size, grain boundary character, coarsening and dissolution of precipitates, and resultant mechanical properties of the welds, it is important to obtain information about temperature distribution during FSW. However, temperature measurements within the stirred zone are very difficult due to the intense plastic deformation produced by the rotation and translation of tool[6,13]. Therefore, the maximum temperatures Within the stirred zone during FSW have been either evaluated from the microstructure of the weld or recorded by placing thermocouple in the regions adjacent to the rotating tool pin. An investigation of micro structural evolution in 7075Al—T651 during FSW showed dissolution of larger precipitates and re-precipitation in the weld center. Therefore, they concluded that maximum process temperatures are between about 400°C and 480 °C in an FSW 7075Al-T61. On the hand, some of the precipitates were not dissolved during welding and suggested that the temperature rises to roughly 400°C in an FSW 606Al. plastic deformation around rotating tool and friction between tool and workpieces. Both these factors contribute to the temperature increase within and around the stirred zone. Since the temperature distribution within and around the stirred zone directly influences the microstructure of the welds, such as grain size, grain boundary character, coarsening and dissolution of precipitates, and resultant mechanical properties of the welds, it is important to obtain information about temperature distribution during FSW. However, temperature measurements within the stirred zone are very difficult due to the intense plastic deformation produced by the rotation and translation of tool[6,13]. Therefore, the maximum temperatures Within the stirred zone during FSW have been either evaluated from the microstructure of the weld or recorded by placing thermocouple in the regions adjacent to the rotating pin. An investigation of micro structural evolution in 7075Al—T651 during FSW showed dissolution of larger precipitates and re-precipitation in the weld center. Therefore, they concluded that maximum process temperatures are between about 400°C and 480 °C in an FSW 7075Al-T61. On the hand, some of the precipitates were not dissolved during welding and suggested that the temperature rises to roughly 400°C in an FSW 606Al.

II. OBJECTIVES

- To optimize the process parameters tool rotation speed, welding speed and tool geometry for maximum tensile strength in friction stir welded aluminium6061alloy plates.
- Microstructure analysis of the weld joint with maximum tensile strength and minimum tensile strength in the experiments.

III. MATERIALS

Aluminium 6061 alloy is a precipitation-hardened Aluminiumalloy,the major alloying elements are magnesium and silicon. After analysing different materials, Aluminium 6061 has been selected due to its wide application and low cost.it is commonly available in pre-tempered grades such as 6061-o (annealed), tempered grades such as 6061-T6 (solutionized and artificially aged) and 6061-T51 (solutionized, stress-relieved stretched and artificially aged). The chemical composition of Aluminium 6061 is :

component	Amount (wt. %)
Magnesium	0.8-1.2
Silicon	0.4 – 0.8
Iron	Max. 0.7
Copper	0.15 – 0.40
Zinc	Max. 0.25
Titanium	Max. 0.15
Manganese	Max. 0.15
Chromium	0.04- 0.35
Others	0.05
Aluminium	Balance

Table 1:The chemical composition of Aluminium 6061

The material used for tool is HSS It is superior to the older high-carbon steel tools used extensively through the 1940s . it can withstand maximum temperatures without losing its temper (hardness). This property allows

HSS to cut faster than high carbon steel, hence the name high-speed steel. At room temperature, in their generally recommended heat treatment, HSS grades normally display high hardness (above Rockwell hardness 60) and abrasion resistance (generally linked to tungsten and vanadium content often used in HSS) compared with common carbon and tool steels

IV. PROCESS PARAMETERS

The parameters taken into account must be independent. The change in any of the parameter considered should cause some change in the desired output such as mechanical properties. The relation to the output may be linear or varying .the important independent input parameters are

Rotation speed- The FSW can be slow process than other forms of welding, such as electric arc weldingor laser welding. This is because the cylindrical tool must turn to generate heat on the joint, and then traverse the length of the joint transmitting that heat. The tool is tipped with a probe, called pin or nib, which typically rotates within the range of 200 to 2000 rotations per minute (rpm) [2,3]. In this work the tool rotation speed taken are 800,1000 and 1200 rpm.

Welding speed- is the speed at which the tool moves in the welding direction meter per minute(mm/min). the traverse rate of the tool along the joint line is between 10 to 100 mm/min. the welding speed selected are 50mm/min, 60mm/minand70 mm/min. However , these figures are averages, and rates outside of those ranges are still used. The speed is largely determined by the application and the metal being joined , but they are not mutually exclusive. A slowly rotating tool pin cannot move incredibly fast across the joint line, for instance.

Tool geometry- Another important parameter affecting FSW is the tool geometry. The tool has two main parts. The pin and the shoulder. The pin can be designed in several geometries which can vary the material flow in the plasticized zone or the nugget zone. Many geometries are developed as cylindrical, threaded, triangular, square, conical , hexagonal ect. In this work the geometries of tools used are cylindrical, conical and hexagonal tool pins. However the tool pin length and shoulder diameter depended on the thickness of the plate.Tool pin diameter provided as per standards is 5 mm. tool pin length is 5.7 mm, slightly less than thickness of aluminium plates. The tool shoulder diameter is 15mm

.

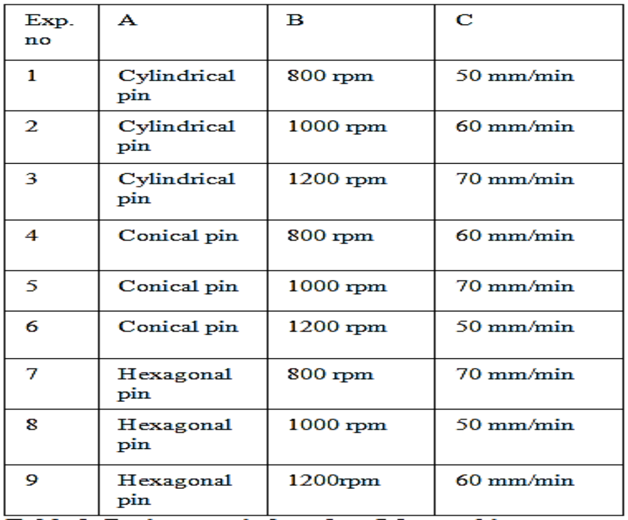
fig 2: HSS tools used in the experiment

shape	Shoulder radius mm	Tool probe radius mm	Tool pin taper angle	Probe height mm
Straight cylindrical	7.5	2.5	-	5.7
Tapered cylindrical	7.5	2.5 (mean)	20	5.7
Straight hexagonal	7.5	2.5	-	5.7

Table 2: Tool details

V. EXPERIMENTAL PLAN, SET UP AND PROCEDURE

Aluminiumalloy 6061 plate is selected as the material for friction stir welding process. Plate of 6 mm thickness is selected. Dimensions of the work piece is determined as100*50*6 mm as per industry instructions since the FSW VMC uses the fixture which can hold the work with specified dimensions. The abutting edges are closely tight together to resist the outward forces generated during the FSW process.no surface preparation and pre heating is needed. To identify the optimal parametric combination for getting good quality of joint, taguchi design has adopted. Hence the taguchi design of three parameters and three levels model choosed. The tool rotation speed, welding speed and tool geometry are taken as parameters.



Exp. no	A	B	C
1	Cylindrical pin	800 rpm	50 mm/min
2	Cylindrical pin	1000 rpm	60 mm/min
3	Cylindrical pin	1200 rpm	70 mm/min
4	Conical pin	800 rpm	60 mm/min
5	Conical pin	1000 rpm	70 mm/min
6	Conical pin	1200 rpm	50 mm/min
7	Hexagonal pin	800 rpm	70 mm/min
8	Hexagonal pin	1000 rpm	50 mm/min
9	Hexagonal pin	1200rpm	60 mm/min

Table 3: Design matrix based on L9 taguchi orthogonal array design of experiment

Fig. 3:FSW welding process

Total nine butt welded joints were done under different input parameters. The nine set of experimental condition is shown in table 3. The specimens for tensile test were cut by conventional milling process. The tensile specimens were cut as per ASME SEC IX : 2015 standard and done on universal testing machine. From tensile test result, optimal condition was made by taguchi SN ratio and by solving regression equation.

Fig.4: Frictionstir welded workpiece (specimen 6)

VI. RESULT AND DISCUSSION

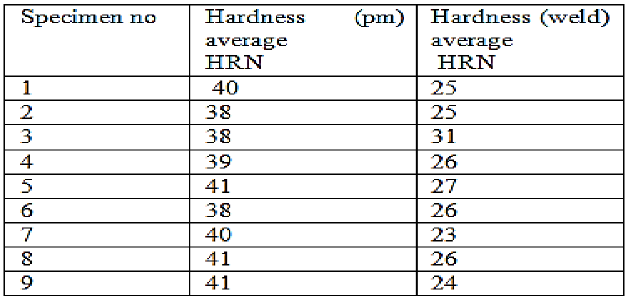
Tensile test-Tensile testing, also known as tension testing, is a fundamental material science test in which a sample is subjected to a controlled tension until failure of the sample. The results from the tests are commonly used to select a material for an application, for quality control, and to predict how a material will react under other types of forces. Properties that are directly measured with a tensile test are ultimate tensile strength, yield strength, maximum elongation and reduction in area.experimental observations of tensile testing is given in the table.

Tool geometry	Rotation speed (rpm)	Welding speed (mm/min)	Ultimate tensile strength (MPa)
Cylindrical	800	50	105.021
Cylindrical	1000	60	115.223
Cylindrical	1200	70	143.336
Conical	800	60	146.384
Conical	1000	70	120.939
Conical	1200	50	178.024
Hexagonal	800	70	81.781
Hexagonal	1000	50	58.581
Hexagonal	1200	60	24.010

Table 4: tensile test results

From the results obtained, the highest value for ultimate tensile strength is 178.024MPa for the specimen welded at 1200 rpm tool rotation speed , 50 mm/min welding speed.The minimum UTS is obtained for specimen which is welded at 1200 rpm, 60 mm/min welding speed and hexagonal tool. UTS obtained is 24.01 MPa only.

Hardness test-iThere are many methods to find out the hardness of a material. The commonly used methods are Rockwell hardness test, Brinnel hardness test and Vickers hardness test. In this work Rockwell hardness test is used for finding out hardness of the specimen(machine no. CL/ME/ROCK05, model MSM).the hardness test results are given in the table.



Specimen no	Hardness (pm) average HRN	Hardness (weld) average HRN
1	40	25
2	38	25
3	38	31
4	39	26
5	41	27
6	38	26
7	40	23
8	41	26
9	41	24

Table 5: hardness test results

Optimization

Signal to noise ratio method - Dynamic parameter design introduced by Taguchi (1987) is one of the most important tool in quality engineering. It is also known as parameter design in signal-response systems The name suggests that the interest lies in a signal-response relationship rather than a single value of the response. Here LARGER-THE-BETTER criteria is used

n = -10 Log10 [mean of sum squares of reciprocal of measured data].

From this s/n ratio larger the better method the optimum condition obtained was [2 1 3] that is welding with conical tool pin at 800rpm tool rotation speed and 70mm/min welding speed.

Level	**A**	**B**	**C**
1	41.59	40.66	40.26
2	43.32	39.41	37.38
3	33.74	38.58	41.01
delta	9.58	2.08	3.63
rank	1	3	2

Table 5: Response Table for Signal to Noise Ratios Larger is better

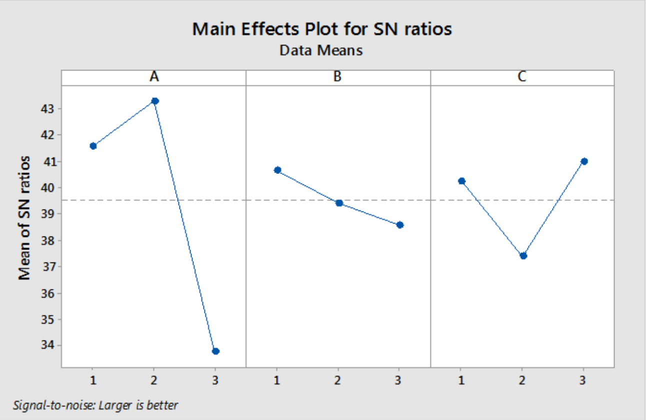


Fig 5: main effect plot for SN ratios

Experiment is done with the obtained optimum condition and tensile test is done. The ultimate tensilestrength obtained is 140.354 MPa.

Based on solving non linear regression equation- the equation is obtained using MINITAB17 software . Step wise method is used to get the equation.

$Uts=-101.0+274.2A+48.3B-32.18C$
$60.46A*A+10.39B*B-1.435C*C-41.69A*B+8.909A*C$

A - tool geometry
B - tool rotation speed
C - welding speed
Constraints :
1<= A <=3, A is an intiger
1<= B <=3
1<= C <=3

By solving the equationfor maximum ultimate tensile strength, the optimum codition obtained is
Tool geometry: cylindrical
Tool rotation speed : 1200 rpm
Welding speed : 50 mm/min

The tensile strength obtained by solving the equation is 201.374 MPa.

Experiment is done with the obtained optimum condition and tensile test is done. The ultimate tensilestrength obtained is 187.052 MPa.

Using the equation mathematical model created and from that graph is plotted to find the effects of parameters in UTS of the welded joint in the selected range.line chart is plotted to show the effect of parameters in tensile strength. For this, two parameters kept constant and one parameter is varied.

Fig.6line chart shows the effect of welding speed ranges from 50 to 70 mm/min. the tool rotation speed is kept constant as 1000rpm. Here the tensile strength is decreasing as the welding speed increasing from 50 to 70 mm/min. the tool shape have much effects in tensile strength.

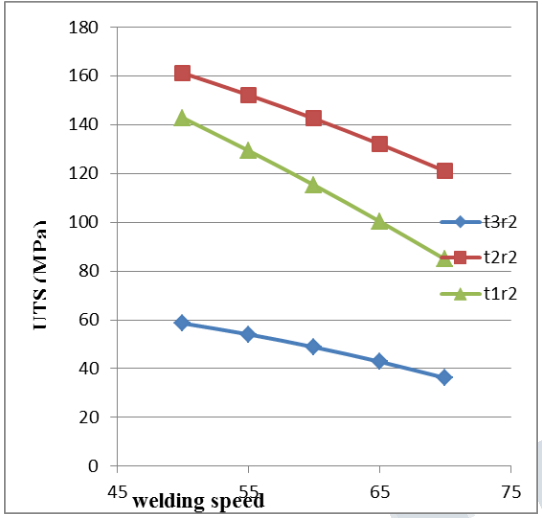


Fig. 6effect of welding speed in UTS

the effect of welding speed in UTS is decreasing as welding speed changing from 50 mm/min to 70 mm/min. as the welding speed increases enough heat is not generated for plastic flow of the material and uniform stirring action of the tool

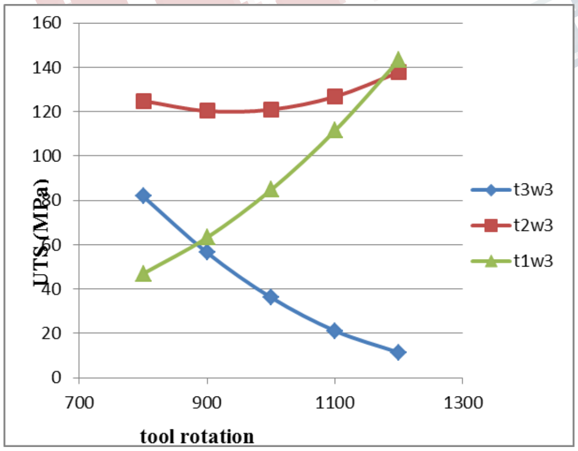


Fig. 7:effect of tool rotation speed in UTS

The above three charts it shows the effect of tool rotation speed ranges fromm800 rpmto1200 rpm. And in this the parameters tool geometry and welding speeds are set constant to observe the effect of tool rotation speed. From these graph it is observed that for each the effect of rotation speed in UTS is changing with different curves. For cylindrical tool UTS increases as speed increases. For conical tool pin as speed increases from 800 to 100 UTS slightly decreases and then increases when speed increased to 1200 rpm. For the hexagonal tool pin the UTS is decreasing as the tool rotation speed increases from 800 rpm to 1200 rpm. The variations are obtained in the UTS is due to heat generated during the welding process is different in different combinations.

Micro analysis-Micro structural analysis is carried out to two specimen for in depth of reasoning of maximum and minimum strength joints. The micrograph is taken from optical microscope to a magnification of 100X at the weld zone. small grain size indicating material flow and distribution is uniform throughout the weld zone. The fine grain size indicates the proper re-crystallization and the temperature generated at the weld zone is adequate and sufficient for the uniform distribution of plasticized Aluminum throughout the nugget zone. Thus the joint produced is strong and capable of withstanding higher loads.

fig. 7: micrograph of specimen 6 (max. UTS)

fig.8:micrograph of specimen 9 (min. UTS)

In this the possibility of dislocation movement is higher compared to the specimen6. Due to this dislocation movements the strength of the weld is less and it cannot withstand higher loads.

VII. CONCLUSION

Experiments were conducted according to the design of experiments using Taguchi method L9 array, considering the process parameters rotation speed of tool, welding speed and different tool geometries.

- Each parameter have significant effect on the tensile strength of the friction stir welded joint.
- The optimization using non-linear regression equation gives better results than optimization using Taguchi signal to noise ratio method. The optimum conditions(maximum ultimate tensile strength) obtained by solving nonlinear regression equation for the material aluminium 6061 alloy for friction stir welding is with cylindrical tool pin is at 800 rpm tool rotation speed and 50 mm/min welding speed. Validation of the optimum condition is done experimentally.

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