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Analysis of Tool Geometry Effect on Mechanical Properties of Friction Stir Welded AA6082 Aluminium Alloy

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ABSTRACT

Friction Stir Welding (FSW) is a solid state welding process. In this process, the heat produced due to the relative motion between tool and workpiece is used for joining similar or dissimilar metals. In FSW, the weld quality depends on, tool rotations, tool tilt angle, axial pressure and welding speed. In this study, the effect of tool type, tool tilt angle, and rotational speed on mechanical properties of AA6082 aluminum alloy is studied. Taguchi technique is used for doing the analysis. Use of L9 orthogonal array is made for performing the experimentation. The FSW welded specimens are tested using Universal Testing Machine (UTM) for its tensile strength. After performing the experimentation and testing it was observed that, the transverse tensile samples failed at the nugget/HAZ boundary due to localized softening. Hexagonal tool pin profile welds have shown the highest tensile strength compared to other tool pin profile welds.

Keywords— **Friction stir welding, Process parameters, Taguchi method, weld strength**

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I. INTRODUCTION

Friction stir welding (FSW), a solid state joining technique invented by The Welding Institute (TWI) in 1991, and is one of the most significant developments in joining technology over the last half century. In FSW, the metal joining process occurs without fusion or use of filler materials and is derived from conventional friction welding. AA6082 is a medium strength alloy with excellent corrosion resistance. It has the highest strength of the 6000 series alloys. Alloy 6082 is known as a structural alloy. In plate form, 6082 is the alloy most commonly used for machining. As a relatively new alloy, the higher strength of 6082 has seen it replace 6061 in many applications. The addition of a large amount of manganese controls the grain structure which in turn results in a stronger alloy. It is difficult to produce thin walled, complicated extrusion shapes in alloy 6082. The extruded surface finish is not as smooth as other similar strength alloys in the 6000 series. FSW may produce high tensile stresses elsewhere in the components, FSW results in a much lower distortion and residual stresses owing to the low heat input characteristics of the process.

In FSW process rotating cylindrical tool with a shoulder and a profiled pin is plunged into the abutting plates to be joined and traversed along the line of the joint. The plates are tightly clamped on to the bed of the FSW equipment to prevent them from coming apart during welding. Fig. 1 shows the schematic of the friction stir welding process. A cylindrical tool with a shoulder-pin profile rotating at high speed is slowly plunged into the plate material, until theshoulder of the tool touches the upper surface of the material.

(Kumbhar et al. 2011). A downward force is applied to maintain the contact. Frictional heat, generated between the tool and the material, causes the plasticized material to get heated and softened, without reaching the melting point. The tool is then traversed along the joint line, until it reaches the end of the weld.

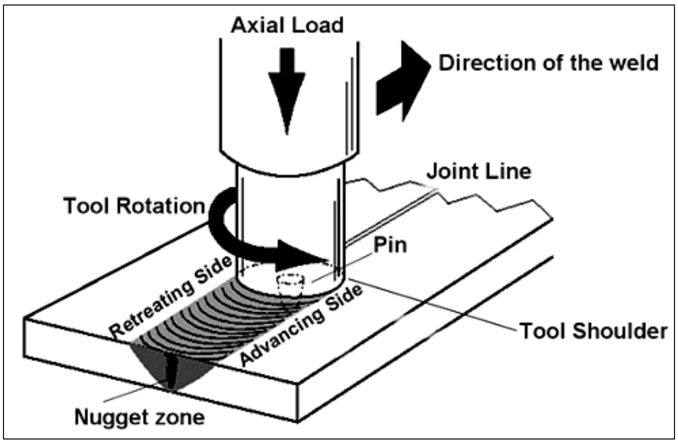

Fig. 1. Schematic of Friction Stir Welding

II. Literature Review

The literature study of Friction stir welding process reveals that the welding process was started a few decades ago. Number of experiments and theoretical studies are carried out on this process. Most of the studies argue over the welding characteristics of aluminum alloy hence this studies have determined the influence of all operational variables on the process effectiveness including process parameter Rotational speed (rpm), Welding speed (mm/min.), Axial force (N), Tool geometry, Pin length (mm), Tool shoulder diameter D(mm), Pin diameter d (mm), Tool tilt angle (◦), D/d ratio of the tool. There are number of researcher worked on friction stir welding and we are going to study few papers.

Jayaraman et al. (2009) discussed use of Taguchi experimental design technique for maximizing tensile strength of friction stir welded cast aluminum alloy A319. Using ANOVA and signal to noise ratio of robust design, effect on tensile strength of FSW process parameter (tool rotation speed, welding speed and axial force) was evaluated and optimum welding condition for maximizing tensile strength is determined. They observed that tool rotation dominant parameter for tensile strength followed by welding speed. Axial force has lowest effect on tensile strength compared to other parameters.

Patil and Soman (2010) investigated the effects of different welding speeds and tool pin profiles on the weld quality of AA6082-O aluminum. Tri-flutes and taper screw thread pin are used as tool pin profiles during the experiments. The friction stir welded plates of AA6082-O by using the taper screw thread pin profile reaches the ultimate tensile strength of 92.30% of the base metal.

Krishna et al. (2013) focused on the Taguchi experimental design technique of friction stir welds of dissimilar aluminum alloys (AA2024-T6 and AA6351-T6) for tensile properties. It was found that the tool rotational speed had 67.31% contribution, traverse speed had 13.7% contribution and axial force had 14.5% contribution in yield strength of welded joints.

Rajakumar et al. (2010) studied the influence of process and tool parameters on tensile strength properties of AA7075-T6 joints produced by friction stir welding. The joint fabricated using the FSW process parameters of 1400 rpm (tool rotational speed), 60 mm/min (welding speed), 8 KN (axial force), with the tool parameters of 15 mm (shoulder diameter), 5 mm (pin diameter), 45 HRc (tool hardness) yielded higher strength properties compared to other joints. The maximum strength properties of 315 MPa yield strength, 373 MPa of tensile strength, 397 MPa of notch tensile strength, 203 HV of hardness and 77% of joint efficiency were attained for the joint fabricated using above tool and process parameters. Defect free fine grained microstructure of weld nugget is important factor forthe higher tensile strength of the joint.

Jayaraman et al. (2009) states the effect of friction stir welding (FSW) process parameters on tensile strength of cast LM6 aluminum alloy. Secondly the quality of weld zone was investigated using macrostructure analysis. They observed that twelve joints fabricated, using the process parameters such as 900 rpm (tool rotation speed), 75 mm/min (welding speed) and 3 KN (axial force) yielded higher tensile strength compared to other joints.

Chand and Bunyan (2013) found the optimum tool material for joining of butt joint aluminum alloy AA6061. By considering the three major factors at three levels namely tool material, rotational speed and axial force. They concluded that a maximum equivalent stress of 208.77 MPa exhibited with optimal process parameters (tool rotational speed, 1200 rpm; axial force, 1000N). Axial force is the dominant parameter for equivalent stress developed on the tool followed by rotational speed.

Hwang et al. (2007) studied experimentally to explore the thermal histories and temperature distributions in a work piece during a friction stir welding process involving the butt joining of aluminum 6061-T6. The appropriate temperature for a successful FSW process was between 365 and 3900C. Temperatures on the advancing side are slightly higher than those on the retreating side. The tensile strength and the hardness at the thermo-mechanically affected zone (TMAZ) are about one-half of the base metals.

Barcellona and Palmeri (2006) performed experiments using FSW for butt joints of two different materials, namely AA2024-T4 and AA7075-T6. They concluded that the percentage of insoluble particles locally decreases due to the tool pin action; the recrystallization phenomena occurring in the nugget zone contrast the material softening due to precipitates density decrease.

III. Experimental Procedure

A. Base Material used for experimentation

The base material used in this study was aluminum alloy 6082-T6 plates thickness of 5 mm. A pair of work pieces of dimension 120 mm × 55 mm × 5 mm were abutted and clamped rigidly on the clamp mounted on the bed of Milling machine, having chemical composition as shown in Table 1. The plates were examined using spectrometer. Aluminum alloy 6082-T6 has very good weldability but strength is lowered in the weld zone. It is extensively used in aerospace applications, rocket motors, and spacecraft as well as in nuclear reactors. The base material tensile strength is 240 N/mm^2. FSW trial was carried out on vertical milling machine with butt joint. Fig. 2. Shows the pair of plates abutted in to the required dimensions, the plates held tightly on the clamp placed on the bed of Vertical milling Machine, and the specimens after completion of the FSW process.

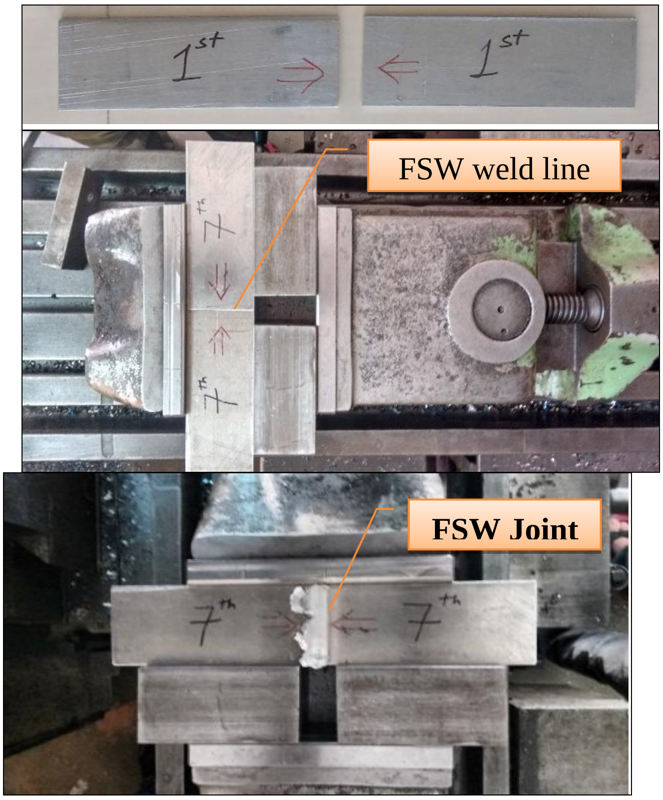

Fig. 2. I). Pair of base material workpiece, II). Pair of welding plates clamped on the clamp of a Vertical Milling machine, III). Plates after completion of weld.

TABLE I
COMPOSITION OF ALUMINIUM AA 6082 – T6

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Al
0.75	**0.18**	**0.01**	**0.4**	**0.42**	**0.01**	**<.005**	**0.01**	**98.1**

B. *Material for Tool*

The welding tool material is High Carbon High Chromium Steel (C 1.55%, Si 0.40%, Mn 0.30%, 11.55% Cr) of hardness 50 to 55 HRC. Tapered Hexagon pin was selected for experimentation. The diameter of tool is 20 mm, having length 80 mm, Length of each side of Hexagon 3 mm and taper angle of 14°, length of pin 4.5 mm. HCHCr tool steel has extremely high wear resisting properties. HCHCr used in blanking dies, forming dies, coining dies, slitting cutters, heading tools and long punches. The CAD model and the actual manufactured tool is as shown in Fig. 3.

Fig. 3. CAD Model and actual Manufactured Hexagon pin profile tool

C. *Experimental Setup for FSW*

The experiment were carried out on vertical milling machine of BFW machine tools cooperated limited, develop at Pratik Engineering Works, Pune. The capacity of bed of on milling machine which is used for experiments is 320*1320 mm. The photograph of friction stir welding which is developed on vertical milling machine. The system is controlled with two motors only, namely spindle motor and feed motor. These motors are linked to drive controllers. The spindle motor is rated at 22 kW and the feed bed motor is rated at 2.2kW. Both these motors use mechanical gearboxes to increase the torque on the output shaft. The main spindle motor provides the spindle rotation while the feed bed motor supplies power to all the three axis movements of the bed. The spindle speed is available from 30 to 1500 rpm and feed rate available from 12 to 430 mm/min.

D. *Design of Experiments (DoE)*

Trial experiments were performed to verify the effect of selected process parameters. Based on the results obtained from trial experiments, the process parameters for main experiments are decided. After finalizing the values for parameters, Design of Experiments (DoE) using Taguchi method is done to get orthogonal array. Considering the obtained array, the main experiments are performed.

Based on the literature review, the parameters and their levels were selected for final experimentation. Final experiments were done on milling machine using various tools on Al 6082 plates.Table II shows the values of the selected machining parameters, three parameters with three levels of each parameter. All these values were selected on the basis of literature review and results of trial experiments. By using Design of Experiments by Taguchi Method, L9 orthogonal array is selected for final experiments.

TABLE III
PROCESS PARAMETERS AND THEIR LEVELS

Process Parameters	**Levels**		
	1	**2**	**3**
Tool rotation speed(rpm)	**355**	**500**	**710**
Welding speed (mm/min)	**30**	**45**	**60**

Tilt Angle (°)	1	2	3

IV. EXPERIMENTAL RESULTS AND ANALYSIS

A. *Tensile Strength*

Tensile strength is one of the main characteristic considered in this investigation described the quality of FSW joints. The welded joints were sliced using hand hacksaw and then tensile test samples were prepared from welds joints according to the ASTM specifications, E-8M-08 [ASTM-2008] by milling machine. Fig.4 shows the stir welded specimen prepared for tensile strength. The tensile test measurement was carried out on universal testing machine. The tensile strength of parent material Al 6082-T6 was 240 N/mm2. The results of tensile strength for L9 orthogonal array are shown in Table 3.

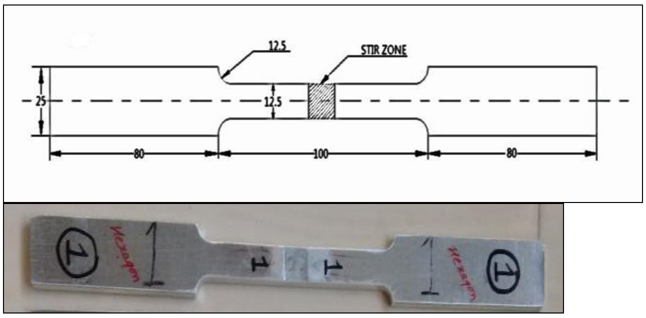

Fig. 4.Dimensions of the Tensile Test Specimens [ASTM E8M-08]

TABLE IIIII
TENSILE STRENGTH OF FSWFOR HEXAGON TOOL PIN PROFILE.

Tool rotation speed(rpm)	Welding speed (mm/min)	Tool Tilt Angle (°)	Tensile Strength (N/mm^2)
355	30	1	158.50
355	45	2	162.41
355	60	3	173.10
500	30	2	167.10
500	45	3	173.53
500	60	1	157.90
710	30	3	170.62
710	45	1	153.65
710	60	2	161.59

B. *Analysis of Variance (ANOVA) for Tensile Strength*

Analysis of FSWjoints tensile strength is carried out using MINITAB-16 software. The effect of various process parameters on response variables was analysed using analysis of variance (ANOVA) and mean effect plot. Analysis of variance (ANOVA) test was performed to identify the process parameters that are statistically significant and which affect the tensile strength of FSW joints. The ANOVA results for tensile strength S/N ratio are given in Table 4. The results of ANOVA indicate that the considered process parameters are highly significant factors affecting the tensile strength of FSW. Main effect plot for tensile strength is shown in Fig. 5. It indicates that as tool rotation speed increases tensile strength also increases. The ultimate tensile strength of butt weld reaches to 73% of the base metal ultimate tensile strength.

TABLE IVV
ANOVA FOR TENSILE STRENGTH.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tool Rotation Speed(rpm)	2	27.487	27.487	13.743	15.64	0.060
Welding Speed (mm/min)	2	7.348	7.348	3.674	4.18	0.193
Tool Tilt Angle (°)	2	372.75	372.75	186.37	212.12	0.005
Error	2	1.757	1.757	0.879		
Total	8	409.34				

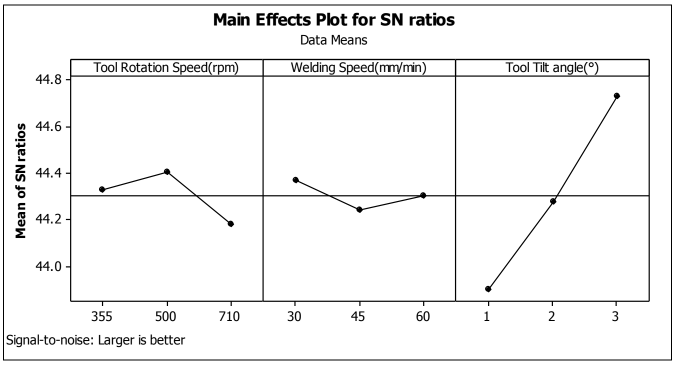

Fig. 5. Main Effects Plot of SN Ratios for Tensile Strength (N/mm^2)

Main effect plot for tensile strength is as shown in Fig 5. As welding speed increases tensile strength also increases, highest tensile is obtained at 173.53 (N/mm^2). Main effect plots for SN ratio are as shown in Fig. 5. It is clear that as the tool rotation speed goes on increasing, tensile strength also increases up to 500 rpm but decrease with the further increase in the speed, whereas, the effect of welding speed is exactly opposite of tool rotation speed. It was observed that as welding speed goes on increasing, the tensile strength goes on decreasing up to 45 mm/min but from there onwards the tensile strength again rises. The effect of tilt angle is entirely different than the above two. The Fig. 5 reveals that increase the tensile strength increases with the increase in the value of the tool tilt angle. In order to produce a successful weld, it is necessary that the material surrounding the tool is hot enough to enable the extensive plastic flow required and minimize the forces acting on the tool. The joint fabricated with the tool tilt angle of 1°and 2° results in tunnel defect at the centre of the weld zone due to insufficient material flow. No defect was observed in weld joints prepared with tilt angle of 3°.

V. CONCLUSIONS

Based on the experiments performed for tensile strength of butt weld on Al-6082-T6 material using FSW process the following conclusions are drawn:

1. From the above results it can be concluded that in FSW, the process parameters play a key role in influencing the weld strength and therefore must be selected carefully depending on the plate thickness and the base material characteristics.

2. The joints produced by FSW using process parameters of 500 rpm(Tool rotational speed), 45mm/min (Welding speed), 3° (Tool tilt angle) provided the highest tensile strength of 173.53 N/mm^2

3. The ultimate tensile strength of butt weld reached up to 73 % of the base metal ultimate tensile strength.

4. Analysis showed that the tool tilt angle is the most influencing parameter affecting the weld strength.

5. The problem of tunnel defect was seen in the joints produced by using Tool tilt angles of 1° and 2°.

6. An important factor is the choice of the pin length of tool. The welding will not be successful if the pin length is equal to the base material thickness.

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