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C. Aneja, A. Handa: Effect of tool shape and welding parameters on mechanical properties and microstructure of dissimilar friction stir welded aluminium alloys

# EFFECT OF TOOL SHAPE AND WELDING PARAMETERS ON MECHANICAL PROPERTIES AND MICROSTRUCTURE OF DISSIMILAR FRICTION STIR WELDED ALUMINUM ALLOYS Chetan Aneja<sup>1,\*</sup>, Amit Handa<sup>1</sup>

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#### Resume

In the present experimental study, dissimilar aluminum alloy AA5083 and AA6082 were friction stir welded by varying tool shape, welding speed and rotary speed of the tool in order to investigate the effect of varying tool shape and welding parameters on the mechanical properties as well as microstructure. The friction stir welding (FSW) process parameters have great influence on heat input per unit length of weld. The outcomes of experimental study prove that mechanical properties increases with decreasing welding speed. Furthermore mechanical properties were also found to improve as the rotary speed increases and the same phenomenon was found to happen while using straight cylindrical threaded pin profile tool. The microstructure of the dissimilar joints revealed that at low welding speeds, the improved material mixing was observed. The similar phenomenon was found to happen at higher rotational speeds using straight cylindrical threaded tool.

#### Article info

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# 1. Introduction

Joining of dissimilar metals is one of the most essential needs of industries [1]. In fact, dissimilar joining could be regularly faced in many series of developments including automotive, aerospace, electronics and shipbuilding industries, where fusion welding simply is not appropriate due to the large difference of physical and chemical properties between the components to be joined. Unfortunately, dissimilar metal welding has several fabrication and metallurgical drawbacks that can often lead to in-service failure [2]. Problems including porosity formation, solidification cracking and chemical reaction may occur during fusion welding of dissimilar materials although sound welds may be obtained in some limited cases with special attentions

to the joint design and preparation, process parameters and filler metals.

Friction stir welding (FSW), a solid state joining technology, was invented in 1991 by The Welding Institute (TWI) of UK [3]. It is an eco-friendly fabrication technique, involving energy efficiency and versatility combination provide satisfactory to of microstructure and mechanical properties of assemblies [4]. For joining light metals, especially aluminum and its alloys, this technique avoids the formation of solidification cracking and porosity [5]. FSW also reduces the presence of distortions and residual stresses [6]. Moreover it significantly improves weld properties.

FSW is an appropriate solid state welding technique to effectively join any combination

of dissimilar aluminum alloys [7]. In friction stir welding, a non consumable tool with a profiled pin is rotated and slowly plunged into the joint line between the two pieces of plate material, which are butted together. Frictional heat is generated between the wear resistant welding tool and the material of the work-pieces. This heat causes the latter to soften without reaching the melting point and allows traversing of the tool along the weld line. The plasticized material is transferred from the leading edge of the tool to the trailing edge of the tool pin and is forged by the intimate contact of the tool shoulder and the pin profile. It leaves a solid phase bond between the two pieces [8]. The advancing side (AS) is the side where the velocity vectors of tool rotation and traverse direction are similar and the side where the velocity vectors are opposite is referred as retreating side [9]. FSW parameters are tool geometry, axial force, rotational speed and traverse speed [10]. Characteristics of friction stir welded joints are influenced by material flow and temperature distribution across the weld which are dictated by tool design and welding parameters such as welding speed and tool rotational speed. Tool design is one of the most important factors to consider when designing a FSW joining process. The tool must perform many functions, including generating heat, promoting mixing, breaking up the joint line, dispersing oxide layers, creating forging pressure, containing material within the joint, thereby preventing surface weld flash, and preventing the formation (or minimizing the impact) of defects such as wormholes, sheetthinning, or hooking defects [11]. The rotation of tool results in stirring and mixing of material around the rotating pin and the translation of tool moves the stirred material from the front to the back of the pin and finishes welding process.

Some studies on friction stir welding of aluminum alloy joints were reported in the literatures. Aval et al. [12] reported that at low tool rotational speed, insufficient material transportation as well as low heat generation by plastic deformation and friction at tool/workpiece interface may be responsible for producing poor quality of welds. Yuqing et al. [13] observed that tool pin profile could significantly influence material flow and peak temperature of the nugget zone which further effect microstructure evolution and mechanical properties of the weld. Dinaharan et al. [8] reported that tool rotational speed was a significant FSW parameter. Khodir and Shibayanagi [14] revealed that the grain size decreases with increasing welding speed. Grain size decreases due to the lower temperature caused by the lower heat input associated with faster welding speed. Sharma et al. [15] evaluated that at low welding speed, weld nugget was more homogeneous because high heat input per unit weld length resulted in more homogeneous temperature distribution and effective recrystallization. Palanivel et al. [7] studied that friction stir welding at higher welding speeds resulted in a shorter exposure time in the weld area with insufficient heat and poor plastic flow of the metal and caused some voids like defects in the joint. Ilangovan et al. [16] investigated that each pin profile had its own material flow characteristics like higher mixing of materials, reduction of TMAZ, HAZ regions. The joining of the materials of the weld interface is achieved by the frictional heat generated between the tool and the work-piece and the material flow.

The present work is aimed to the evaluation of the welding speed and tool rotational speed effect by varying tool shape on mechanical properties and microstructural behaviour of aluminum alloy AA5083 and AA6082 welded plates with thickness 6 mm, obtained by friction stir welding.

# 2. Experimental Methodology

The Friction stir welding set up was fabricated on CNC Vertical Milling Machine installed at Central Tool Room, Ludhiana. A clamping Fixture was utilized in order to fix

the specimens to be welded on a milling machine. The tool was mounted on the vertical spindle. Friction stir weld was made of 5083 and 6082 aluminum alloy plates using welding speed of 20, 40 and 60 mm min<sup>-1</sup> and tool rotary speed of 1000 and 1200 rpm. AA5083 aluminum alloy was placed in the advancing side and AA6082 aluminum alloy was placed in the retreating side. The dimensions of aluminum alloy plates were 75 mm in width, 120 mm in length and 6 mm in thickness. The two prepared aluminum pieces were firmly clamped into the fixture. The rotating tool was made to pass through from the butt joint. Afterwards within a fraction of time, the sufficient heating was achieved due to the rubbing action between tool and plates. The bed was given automatic feed, along the joint direction. In this way welding was achieved. Friction stir welding process of two aluminum plates is shown in Fig. 1.



*Fig. 1. Friction stir welding process. (full colour version available online)* 

The two tools were prepared from EN8 Carbon steel material. One tool has straight cylindrical threaded pin and second tool has square pin as it was desirable that the tool must be hard to wear, tough and strong. Two types of EN8 carbon steel tools are shown in Fig. 2. The shoulder diameter and the shoulder height of the tool for FSW were 18 mm and 65 mm. The probe had a diameter of 6 mm and a height of 5.7 mm.



Fig. 2. EN8 carbon steel tool. (full colour version available online)

5083 Aluminum-magnesium alloys are strain hardenable and have excellent corrosion resistance, toughness, weldability and moderate aluminum-magnesium-silicon strength. 6082 alloys are heat treatable and have high corrosion resistance, excellent extrudibility and moderate strength (Gungor et al., 2014). Especially with their high corrosion resistance and moderate strength, these alloys are widely used in shipbuilding industry. In this experimental the plates were prepared work, with  $150 \times 120 \times 6$  mm<sup>3</sup> dimensions. The chemical composition of AA5083 and AA6082 aluminum alloys presented in Table 1 and Table 2.

								Table 1
Chemical composition of 5083 aluminum alloy (wt %).								
Cu	Si	Zn	Mn	Mg	Fe	Ti	Cr	Al
0.03	0.1	.03	0.66	4.5	0.16	0.07	0.06	Balance

Chemical composition of 6082 aluminum alloy (wt %).								
Cu	Si	Zn	Mn	Mg	Fe	Ti	Cr	Al
0.05	1.0	0.05	0.70	0.8	0.16	0.05	0.06	Balance



a) tensile test specimens



b) dimensions of Tensile test specimen Fig. 3. Tensile test specimens (full colour version available online)

# 2.1 Mechanical Testing and Microstructural Analysis

Friction stir welded parts were subjected to variety of mechanical tests to determine their suitability for the anticipated service applications. They were necessary to carry out so as to ensure the quality, reliability and strength of the welded joints.

# 2.1.1 Tensile Test

Tensile test was performed on universal testing machine, Model UT100, capacity of 1000KN, least count is 0.05 KN at CITCO Chandigarh. Tensile test specimens and dimensions of tensile specimen are present in Fig. 3(a) and 3(b). The standards were taken from ASTM (American society for testing and material) Internationals. Dumbles for tensile test were cut on FN2U Horizontal Milling Machine. The rotational speed used for dumble cutting was 450 rpm and Milling Cutter was used.

# 2.1.2 Micro Hardness

A Vickers micro hardness tester (Make FIE, Model No HV 50, CITCO Chandigarh) was employed for measuring the hardness across the transverse section of the joint with a load of 9.8 N and dwell time of 15 sec.

#### 2.1.3 Microstructure

Metallographic specimens were cut mechanically from the welds and polished using abrasive disks and cloths. The chemical etchant to reveal the microstructure of the weld region was the Keller's reagent (1 ml hydrofluoric acid, 1.5 ml hydrochloric acid, 2.5 ml nitric acid and 95 ml water). The microstructures were observed on optical microscope.

#### 3. Results and Discussion

The Friction Stir welding has been done by varying tool pin profile, tool rotational speed and welding speed. The different combinations of tool pin profile, tool rotational speed and welding speed were taken. In this way 12 different friction stir weld joints were fabricated in this research work. The welding parameters were selected as per the Table 3. After the experiments, the pieces were cut into the samples of required dimensions for performing the tensile tests, microstructure observation and micro hardness testing.

# 3.1 Tensile Test Results

The ultimate tensile strength of FSW joints by varying tool pin profile, welding speed and tool rotational speed is shown in Fig. 4 (a-b). The results show that the tensile strength of the welded joints was improved by decreasing welding speed and by increasing tool rotational speed when the straight cylindrical threaded pin profile tool was used. The highest tensile strength of 121 MPa was reached for the joint produced by straight cylindrical threaded tool at welding speeds of 20 mm min<sup>-1</sup> and tool rotational speeds of 1200 rpm. This might be due to the reason that the welding speed influences the heat input per unit length of weld which further controls the degree of softening as well as the flowability of the plasticized material. At lower welding speeds, the quantity of heat supplied to the plasticized deforming material in the weld zone is greater and therefore wider is the softened area around the stirring tool leading to more improved metal flow and hence more effective bonding in the weld. This improved of the material flow and effective bonding leads to more homogeneity of the weld zone which resulted in higher tensile strength as the welded joints having higher heat input per unit length. A lower tensile strength of 102 MPa was observed in the joints made by square tool at welding speeds of 60 mm min<sup>-1</sup> and tool rotational speeds of 1000 rpm. At higher welding speeds, tool results in lower heat input per unit length of weld which in turn reduces stirring action of the material due to poor flowability in the weld area resulting in poor tensile strength, which decreases significantly when welding speed is increased and attributed the same to the formation of voids due to poor consolidation of weld interface at higher welding speed hence low heat input per unit weld length. Similar results were obtained by Sharma et al. [15]. Table 3 presents, the effect of tool pin profile, tool rotational speed and welding speed on the ultimate tensile strength.

Table .	3
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Guinale Tensue Strength Results.									
S No.	Tool Rotational Speed (rpm)	Welding Speed (mm·min <sup>-1</sup> )	Tool Pin Shape	Ultimate Tensile Strength (MPa)	S No.	Tool Rotational Speed (rpm)	Welding Speed (mm·min <sup>-1</sup> )	Tool Pin Shape	Ultimate Tensile Strength (MPa)
S-1	1000	20	Straight Cylindrical Threaded	119	S-7	1200	20	Straight Cylindrical Threaded	121
S-2	1000	40	Straight Cylindrical Threaded	113	S-8	1200	40	Straight Cylindrical Threaded	117
S-3	1000	60	Straight Cylindrical Threaded	103	S-9	1200	60	Straight Cylindrical Threaded	108
S-4	1000	20	Square Pin	110	S-10	1200	20	Square Pin	112
S-5	1000	40	Square Pin	110	S-11	1200	40	Square Pin	110
S-6	1000	60	Square Pin	102	S-12	1200	60	Square Pin	107

Ultimate Tensile Strength Results.



Fig. 4. Ultimate tensile strength. (full colour version available online)

Furthermore it has been noticed that as the rotational speed increases, the heat input within the stirred zone also increased. This might be attributed that at higher frictional conditions, more heat has been generated which resulted in more intense stirring and mixing of materials. As the spindle speed increased from 1000 rpm to 1200 rpm, the strength of the welded joints improved resulting higher heat generation which resulted in turn improved bonding. This behavior might be attributed to increase in solute concentration and number of new grains in the weld nugget due to higher heat input which led to improved tensile properties. Tang et al. [17] reported that peak temperature increased by 40°C within the weld zone with increase in rotary speed from 300 rpm to 650 rpm at constant welding speed of 120 mm $\cdot$ min<sup>-1</sup>.

The dissimilar joints fabricated using the straight cylindrical threaded tool have higher values of the tensile strength when compared to the joints fabricated using square tool. The straight cylindrical threaded type of tool pin profile allow good material stirring quality and mixing of dissimilar plasticized metals during welding. The severe plastic deformation due to intense stir of cylindrical threaded pin profile results in higher strain energy relative to square pin profile. Square type of tool pin profile allow insufficient mixing of dissimilar plasticized metals because tool pin is incapable of deforming appropriate amount of metal during rotation which leads to low tensile strength. Same trends have been noticed by Ilangovan et al. [16] for ultimate tensile strength of friction stir welded joints of aluminum alloys.

# 3.2 Micro Hardness Test Results

Micro hardness test was performed order characterize the hardness to in 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 base material, using 9.8 N load for a dwell period of 15 sec. The micro hardness variation across the weld nugget is shown in Fig. 5. The Vickers micro hardness varied from 90 HV to 95 HV in the base metal of AA5083 and varied from 98 to 105 HV in the base metal of AA6082. In the weld nugget zone hardness varied between 63 to 83 HV. The micro hardness measured from these welds showed that the microhardness was higher on the AA5083 side and lower on the AA6082 side. The thermo mechanically affected zone (TMAZ) on the AA6082 side had the lowest hardness and was found to varied from 51 to 68 HV. The graph indicates the decreasing trend of hardness from AA6082 HAZ to TMAZ region.

The average microhardness in the weld nugget decreased with increase in welding speed from 20 to 60 mm $\cdot$ min<sup>-1</sup> and completely reverse trend was notice with the increase in tool rotation speed from 1000 to 1200 rpm. In the AA6082 side rapid decrease in hardness can be observed which may be attributed to the imposed thermal cycles as well as severe hot deformation. This leads to elimination of the precipitation hardening effect in the alloy owing to partial or complete dissolution of the hardening particles. Because dissolution of the hardening phases of in the TMAZ softening has been observed. On the stir zone, the increase in microhardness was associated with re-precipitation of fine particles. In the AA5083 side, because of recrystallization and generation of fine grains in the weld nugget the microhardness was found to be higher. As the tool rotational speed increased and welding speed decreased, more efficient mixing of the material were happened. The decrease in welding speed and increase in tool rotational speed would increase the heat input per unit weld length. The improved weld nugget hardness was due to the reduction in the density of coarse second phase strengthening particles. Similar results have been revealed by Aval et al. [12] for microhardness of friction stir welded joints. Gungor et al. [18] also made similar observations.

The hardness variation of each region of both tool pin profile was plotted and presented in Fig 5. The graphs indicate the decreasing trend of hardness from NZ to TMAZ in AA6082. The TMAZ zone of AA6082 was identified as the soften region in microhardness plot for both the pin profile. In the AA5083 side, no such variation in hardness was observed. The straight cylindrical threaded pin profile showed higher hardness than that of with square pin profile in the stir zone. The straight cylindrical threaded type of tool pin profile produces good material stirring quality and mixing of dissimilar plasticized metals during welding. Square type of tool pin profile produces insufficient mixing of dissimilar plasticized metals because tool pin is incapable of deforming appropriate metal during rotation leads to low micro hardness. Similar results have been investigated by Rajkumar et al. [19].



Fig. 5. Effect of Tool shape and welding parameters on Microhardness variations across friction stir welded joints.

(full colour version available online)

#### 3.3 Microstructure Analysis

Thermal and mechanical stresses caused by tool stirring and axial force resulted in the formation of weld nugget zone (WZ), thermo mechanically affected zone (TMAZ) and heat affected zone (HAZ) in friction stir welded joints. On the basis of the results obtained during mechanical characterization, the best parameters were selected and microstructure evaluation was carried out on specimens welded using chosen parameters. The micrographs of the centre of weld nugget zones, thermo mechanically affected zone and heat affected zone for material welded using speed of 20 mm·min<sup>-1</sup> and tool rotational speed of 1200 rpm with straight cylindrical tool pin profile are shown in Fig. 6. The microstructure of aluminum alloys joined by FSW was studied by employing optical microscopy at 100  $\mu$ m. Images of weld zones cross section when AA5083 is kept in the advancing side and AA6082 is kept in the retreating side are outlined. The weld nugget zone showed proper material mixing because of severe plastic deformation and high temperature sufficient to cause dynamic recrystallization which was caused by rotation and traversing of FSW tool during welding. Therefore, the coarser grain structure of the base material is transformed into the fine and equiaxed grain structure in weld nugget.

Changing the welding speed and tool rotational speed have significant effect on the flow of the material within the stir zone. The extent of mixing and interface disrupsion increases as the tool rotational speed was increased and the welding speed was decreased. The rubbing of the tool shoulder on the plate material creates frictional heat. The rotary action of the tool leads to stirring and mixing of plasticized material around the tool pin. As a result, the welds produced with tool rotational speed of 1200 rpm and welding speed of 20 mm·min<sup>-1</sup>exhibited the formation of onion ring and superior material mixing. When the tool rotational speed increases, the quantity of plasticized material and material transportation from advancing side to retreating side increases. Our results are in the agreement with those found by Park et al. [20].

In friction stir welding the heat generation is due to the rubbing of the tool on work piece and the plastic deformation of the material. Tool pin profile has a remarkable effect on the rubbing and the effect on the welded material plastic deformation. The microstructure of the dissimilar aluminum alloy joints prepared by friction stir welding by straight cylindrical threaded pin profile at rotational speed of 1200 rpm and welding speed of 20 mm  $\cdot$  min<sup>-1</sup> is shown in Fig. 6. From the investigations, it was found that the joints fabricated by cylindrical threaded pin tool are defect free and onion ring are observed in the weld nugget zone. It was also found that the tool having straight cylindrical threaded tool profile causes larger plastic deformation to make more plasticized materials due to stronger stirring actions during FSW. Threaded cylindrical pin yielded the defect free joints. This may be yielded due to proper flow of plasticized material around the tool pin during stirring. In case of square pin profile the deformation included heat generation during the welding is marginally insufficient compared to cylindrical threaded pin profile.



*Fig. 6. Microstructure of various regions in weld zone using straight cylindrical threaded pin profile at welding speed of 20 mm·min<sup>-1</sup> and rotational speed of 1200 rpm (AA5083-AS, AA6082-RS). (full colour version available online)* 

# 4. Conclusion

In the present work the effect of tool shape and welding parameters on the microstructure and mechanical properties of dissimilar friction stir welded aluminum alloys AA5083 and AA6082 were investigated. The results can be summarized as follows:

- At low welding speed and high tool rotational speed, the joints exhibited satisfactory tensile strength and micro hardness. Joints prepared by low welding speed (20 mm·min<sup>-1</sup>) and high rotational speed (1200 rpm), resulted in high heat input provided microstructurally and mechanically better joints.

- Friction Stir Welding tool with two different pin profiles suitable for dissimilar frictions stir welding of aluminum alloys were fabricated. Straight cylindrical threaded pin profile is preferred over square pin profile due to the superior performance of the joints.

- Maximum tensile strength of the joint of 121 MPa was achieved at low welding speed of 20 mm·min<sup>-1</sup> and high tool rotational speed of 1200 rpm, when straight cylindrical threaded pin was used.

- The temperature field in dissimilar FSW of AA5083 and AA6082 is distributed asymmetrically producing larger thermally affected region in the heat treatable aluminum AA6082 alloy.

- Welded materials were more properly mixed and onion ring structure was formed at lower welding speed and higher rotational speed.

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