Effect of Rotation Rate on Microstructure and Mechanical Properties of FSW Al-Mg-Si Alloy Joints

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Abstract—*Friction stir welding (FSW) of Al-Mg-Si plates with 6 mm in thickness was successfully carried out under a rotation speed of 1200, 1400 and 1600 rpm with a constant traverse speed of 66mm/min. Optical microscopy technique were used to analyse the microstructure of FSW joints. Joint prepared at the welding speed of 1600 rpm exhibited superior tensile properties. After FSW, the coarse grains in the parent material were changed into fine equiaxed recrystallized grains at the nugget zone. The hardness values of the Nugget Zone for all the FSW joints were higher than those of the Parent Material, and the lowest hardness values were detected in the heat affected zone (HAZ).*

Keywords: *Friction Stir Welding, Mechanical Properties, Microstructure, Aluminium Alloy*

INTRODUCTION

Aluminium alloys are used extensively in automobile and aerospace industry due to its high specific static and dynamic strength, good corrosion resistance, weldability, good formability, high strength to weight ratio, recycling potential, low density, excellent energy absorption properties, good ductility, and non-magnetic nature [1–6].

During manufacturing of automotive and aerospace parts, welding of Al-Mg-Si alloys (6xxx) is frequently needed [2]. Most commonly used welding processes for welding these types of alloys are tungsten inert gas welding (TIG), metal inert gas welding (MIG), laser beam welding (LBW) and friction stir welding (FSW) [1]. The most significant technical difficulties encountered in attempting to weld aluminum alloys are due to its stable oxide layer as in the case of liquid-state welding it is susceptible to weld cracking as a result of grain boundary film formation. Friction stir welding successfully circumvents these problems since it produces solid-state welds (grain boundary films form only in the liquid-state), and the shearing action of the tool crushes the stable oxide layer and disperses it throughout the weld area, minimizing any deleterious effects [4].

Friction stir welding (FSW) is an innovative solid state welding process invented in December, 1991 by Wayne Thomas at The Welding Institute (TWI), Cambridge, United Kingdom [3]. To make a linear weld in a butt joint configuration, the work pieces are positioned on the backing plate with the edges in contact .The rotating friction stir welding tool is plunged into the weld joint with an axial force until the shoulder of the tool makes contact with the top surfaces of the work pieces. Frictional heat produced by rotating tool in the work piece plastically deforms the material and the stirring action mixes the material of two plates with each other. Then the tool moves in forward direction. After passing the forced rotating tool into the abutting plates the tool is pulled off from the work pieces. Finally the weld is achieved and the pin of the tool leaves behind a hole which is named as pin hole defect [1].

The interaction of non-consumable rotating tool with the work pieces being welded creates a welded joint through frictional heating and plastic deformation at temperatures below the melting temperature of the alloys being joined [7]. The various welding parameters are tool rotation speed, traverse speed, tool geometry and axial force. The microstructure evolution and the resulting mechanical properties depend strongly on the variation of process parameters leading to a wide range of possible performances [8].

FSW is emerging as an appropriate alternative technology due to its low cost, low distortion, easy applicability and high strength of the joint. Also, there is no use of flux or shielding gas and filler material thus making it eco-friendly joining process [3]. The objective of present work is to investigate the influence of tool rotational speed on the mechanical and microstructural properties of Friction stir welding.

EXPERIMENTATION

Al-Mg-Si (6xxx series) alloy plates in a T6 tempered state having dimensions of 100 mm x 50 mm x 6 mm was used as a work piece material. The chemical composition of the alloy and is given in Table 1.

Table 1: Chemical Composition (wt %) of Work Piece Material

Al	Si	Mg	Mn	Cu	Cr	Fe	Ti
Balance	0.6	0.65	0.021	0.03	0.003	0.259	0.003

A pair of Work piece material was cleaned with wire brush and acetone to remove oxide layer and other oily material from it. Then these were clamped and fixed rigidly on specially designed fixture in square butt joint configuration as shown in Fig. 1. Friction stir welding process was performed on a vertical CNC milling machine (Deckel, Germany). In this non-consumable cylindrical threaded pin profiled tool made of high carbon steel was used to fabricate the joint. The specifications of tool are shown in Table 2.

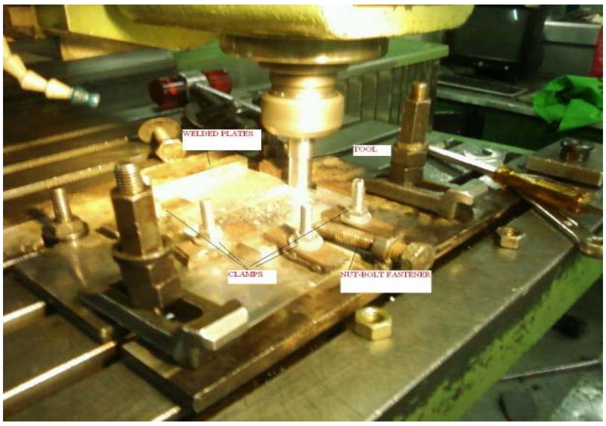

Fig. 1: Friction Stir Welding Setup

Table 2: Specifications of Tool

Tool length	90 mm
Tool diameter	18 mm
Pin diameter	6 mm
Pin length	5.7 mm
Pitch of thread	1.5 mm
Angle	60°
Tool till angle	30°

The tool fixed in collect was mounted on the vertical spindle of CNC milling machine hydraulically and was tilted at an angle of 3° with respect to the work piece attached with the help of fixture on the bed of CNC milling machine. Then the rotating tool was made to plunge into the square butt joint configuration with an axial downward force. The tool is rotated as the pin is forced into a location on a surface until the shoulder impinges into the work piece. Once the pin has fully penetrated and shoulder touches the work piece the tool was traversed along abutting edges to accomplish welding of separate work pieces. A single pass welding procedure was used to fabricate the joint. The bed was given automatic feed and axial force was kept constant. Tool rotation speed was identified as critical welding parameters. So welding was performed by varying the tool rotational speed (1200 rpm, 1400 rpm and 1600 rpm) with tool shoulder diameter of 18 mm, transverse speed of 66 mm/min, tilt angle 3° and other parameters were kept constant;.

After welding the work pieces were removed and sliced on power hacksaw into required sizes for tensile test, hardness test and metallographic tests. The outer parts of 15 mm were discarded from both sides as shown in Fig. 2. For metallographic, the specimens were collected from middle portion of the weldments to ensure a true representation of weld characteristics. Metallographic specimens were then polished by using emery papers having grit sequence of 400, 600, 800, 1000, 1500 and 2000 following standard metallographic procedure. After this the samples were polished using diamond paste of medium micron size on polishing cloth(velvet) on disc polishing machine thus obtaining a mirror image. Then polished specimens were etched with Keller's reagent to reveal the grain structure.

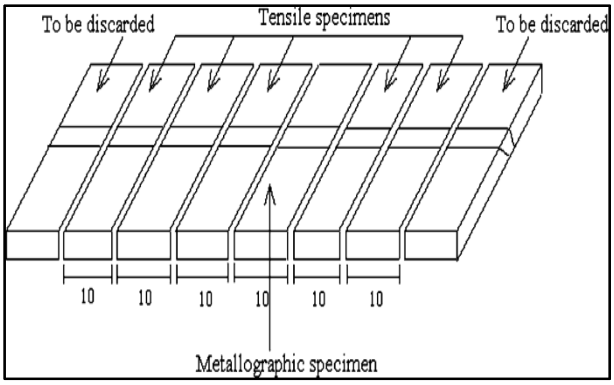

Fig. 2: Schematic Diagram Showing from Where Specimens were Machined

The microstructure on top, stir zone and HAZ was studied under inverted optical microscope (Make: Leica, USA). The samples for hardness test were kept same as that for microstructural analysis. Vickers microhardness tester (Omnitech, Pune) was used to check the hardness from top and cross-section of the weldment. It was done at a load of 100 gms for 10 seconds. X-ray radiography was carried out to see the internal defects like porosity voids and cracks in the weldment. The tensile test was carried out to check the tensile strength of the joint on Universal testing machine 60 KN (Make: Heico, New Delhi) and Fig. 3. shows a typical tensile test specimen. The standards are taken from ASTM Internationals, Designation B 557M–07.

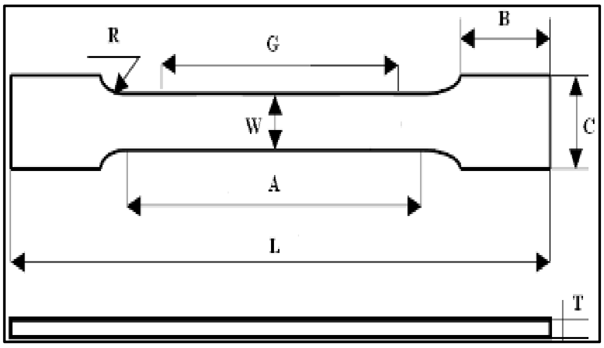

Fig. 3: Standard Specimen Size for Tensile Strength Testing (Singh *et al.*,[3])

L= Overall Length (100mm)
A= Length of Reduced Section (32mm)
B= Length of Grip Section (30mm)
C= Width of Grip (10mm)
G= Gage Length (25mm)
W= Width (6mm)
R= Radius of Fillet (6mm)
T= Thickness of Material (6mm)

RESULTS AND DISCUSSION

Macroscopic Analysis

Almost, all the weld joints prepared by FSW at various defined parameters shows smooth surface finish as shown in Fig. 4.

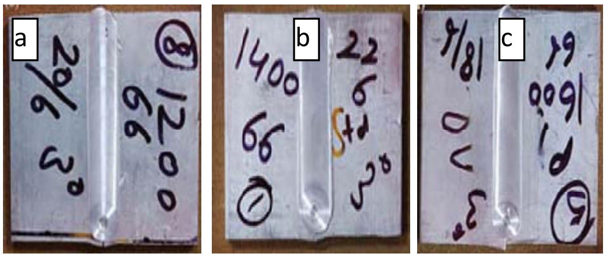

Fig. 4: Macrograph of Welded Work Pieces at Tool Rotation Speed of (a) 1200 rpm & 66 mm/min (b) 1400 rpm & 66 mm/min (c) 1600 rpm & 66 mm/min

X-Ray Radiography

X-Ray radiography was done on all the samples and it was observed that there is no porosity and voids present in the weld zone of friction stir welded samples except a line defect found in weld produced at a tool rotation speed of 1200 rpm Fig. 5. This may be due to the fact that low rotation speed does not generate sufficient heat for plastic flow of material. These results are in agreement with the findings of Ghosh *et al.* [6]. Also voids/defects within the weld nugget are generated owing to difference in material transport and degree of consolidation.

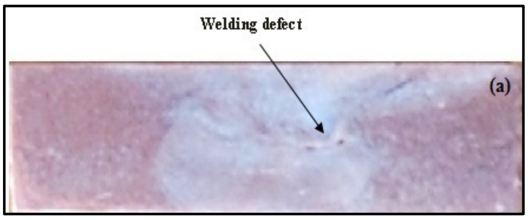

Fig. 5: Defects in Welded Work Pieces Prepared at Tool Rotation Speed of 1200 rpm

Microstructure Analysis

It was observed that fine equiaxed grains were formed in the process performed at tool rotation speed of 1200 rpm Fig. 6(a). With the increase in rotational speed from 1200 rpm to 1400 rpm the grain size reduced and microstructure got refine as shown in Fig. 6(b). Higher rpm of tool resulted in better stirring action and higher temperature which in turn improves the plastic flow of material resulting in fine equiaxed grains. At a tool rotation speed of 1600 rpm the grain size got refined Fig. 6(c) in comparison to grain size produced at tool rotation speed of 1200 rpm and 1400 rpm. This may be attributed due to reason that at high rpm the proper stirring action took place which resulted in grain refinement, also at high rpm the heat generated in weld zone is high which resulted in proper plastic flow of material, resulting in grain refinement.

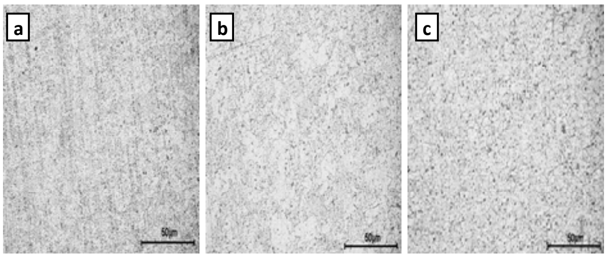

Fig. 6: Microstructure from Top of the Weldments Joined at Tool Rotation Speed of (a) 1200 rpm & 66 mm/min (b) 1400 rpm & 66 mm/min (c) 1600 rpm & 66 mm/min

Observation of microstructure from the cross section shows that four different zones of the microstructure are formed i.e. HAZ, TMAZ, nugget zone and unaffected base metal as shown in Fig.7. In the stir zone the grains of the metal are smaller in size than that of the parent metal. On the either side of stir zone the clear distinct zone can be and referred to as TMAZ, in which microstructure is affected due to thermo-mechanical action of FSW tool. Adjacent to the TMAZ there is a HAZ, which is common in all welding processes. This may be due to thermal action of FSW and the transition between these zones is shown in Fig. 7(b). The difference in grain size in base material and stir zone is clearly visible in Fig. 7(a) & 7(b). The coarse grain size is visible in TMAZ which is affected only by thermomechanical action at solid state (Fig. 7(c). However, fine equiaxed grains are visible in stir zone as shown in Fig. 7(d). It was observed that with the increase in rotation speed the temperature increases in the nugget zone and proper stirring takes place resulting in fine grain structure.

This is consistent with the work reported by Hwang *et al.* (2008). During higher rotation speeds particles would suffer more fragmentation.

Tensile Test

Tensile strength of base material in T6 tempered state was found to be 220 Mpa and a maximum tensile strength achieved by FSW joint was found to be 158 Mpa at rotation speed of 1600 rpm. The highest tensile strength of base metal was due to presence of fine precipitates Mg_2Si. Also the artificial aged T6 tempered state of base alloy was disturbed during FSW, this may be another reason for lower tensile strength of all the weldments as compared to base metal [9]. During tensile test all the specimens failed in the weld region which indicated that weld region is comparatively weaker than other regions and hence joint properties are controlled by weld region composition and microstructure.

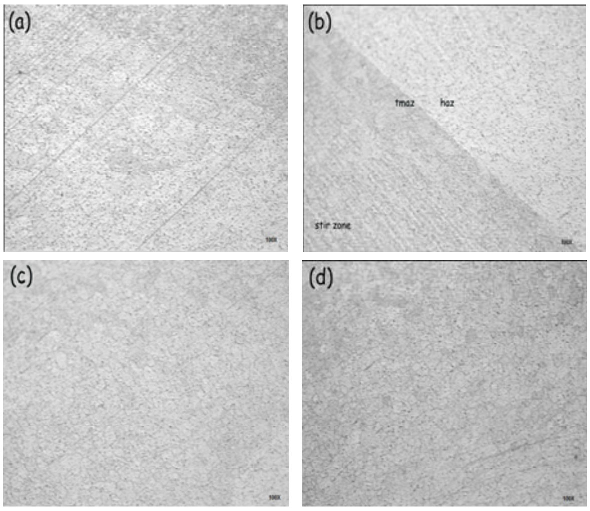

Fig. 7: Microstructure from Cross-Section (a) Unaffected Base Material (b)Transition Zone Showing Stir Zone, TMAZ & HAZ (c) TMAZ (d) Stir Zone

With the increase in rotation speed the temperature within the nugget becomes higher and more uniform. The volume fraction of coarse particles thus decreased which may be responsible for sound welding. Further at higher rpm the fine precipitates were uniformly distributed within the interior of grains and grain boundaries. This may be one of the reason for superior tensile strength at higher rpm. Further, lower value of rpm may result in improper plastic flow and insufficient consolidation of metal in friction stir processing zone which may be reasons for low tensile strength at low rpm.

It is also consistent with Cavaliere *et al.* [10] that by decreasing the temperature in the nugget zone, the force acting on the material was not able to produce a plastic flow properly of a continuous dynamic recrystallisation process, while by increasing the temperature of material for too low travel speed the material is extremely softened. Further Sundaram and Murugan [11] reported the same results that with the increase in tool rotation speed and traverse speed tensile strength increases to a maximum value at certain limit and with further increase in traverse speed results in decrease in tensile strength. As the increase in traverse speed discourages the clustering effect of strengthening precipitates, plastic flow of material and localization of strain.

Hardness

Hardness from top of the weld along centre weld line was measured at different rotational speed as shown in Fig. 8. Hardness of base metal was observed as 74 HV. Hardness of the weld zone is found to be 20-35% less than the base metal. This may be due to softening of weld material at high temperature as during friction stir welding a temperature of the order of 300°-400°C can be attained as reported by Lakshminarayanan *et al.* [4] and strengthening precipitates which are stable upto temperature of 200°C are dissolutioned as reported by Hwang *et al.*[12]. The results shown in Fig. 8 revealed that with increase in rpm there is increase in hardness. As, with the increase in rpm, the stirring action increased which resulted in grain refinement, which may be responsible for higher value of hardness at higher rpm.

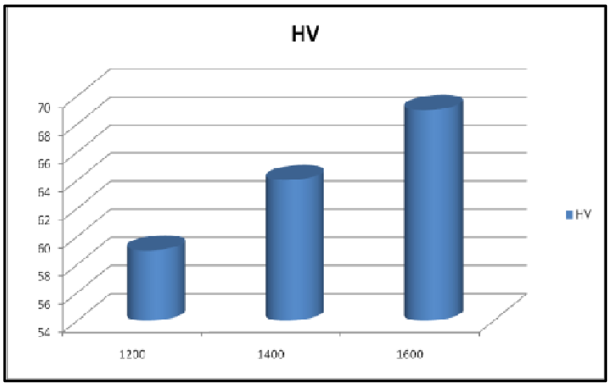

Fig. 8: Comparison of Hardness on the Basis of Tool Rotation Speed

CONCLUSION

The effect of tool rotation speed on microstructure, tensile strength and hardness of friction stir welded Al-Mg-Si (6xxx) alloy were studied in the present paper. It has been found that microstructure within nugget zone is dominated by tool rotation speed. Mechanical properties like tensile strength and hardness also depends upon the microstructure evolution due to various process parameters. However, it shows a trend that with the increase in tool rotational speed the tensile strength increases to a certain limit but with further increase the tensile strength tends to decrease. A drop of 20–35% of hardness is observed as compared to base material. Hardness increases with increase in tool rotation speed. Also the loss of T6 tempered condition of base metal is responsible for low mechanical properties of FSW joints.

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