Macrostructural refinement and subsequent mechanical property change during friction stir processing of AA6061

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ABSTRACT

In the current research, friction stir processing (FSP) of AA 6061 alloy was carried out using two different tool geometries and by varying process parameters like tool rotational speed and traverse speed to determine its influence on the microstructure modification and mechanical properties of the examined alloy. It was noted that the type and distribution of the strengthening precipitates in the friction stir processed Al 6061 alloy appreciably depend on the FSP parameters. The mechanical properties of friction stir processed alloy were investigated using microhardness and tensile test. It was found that, friction stir processed AA6061 under optimum processing conditions exhibits decreased hardness and tensile strength with increased ductility.

Keywords: AA6061, Severe Plastic Deformation, Friction Stir Processing, Microhardness, XRD

1. I. INTRODUCTION

Light metals with high strength are the immediate and future requirements for aerospace, defense as well as automotive industries. Grain refinement, compared to other material strengthening techniques, can deliver combination of ultrahigh strength and ductility which is required for ambient and cryogenic temperature applications. Recently, severe plastic deformation (SPD) has been established as a useful approach to fabricate ultrafine grained (UFG) materials. Broad research has been carried out to develop SPD techniques and which can produce UFG metals and alloys. The significant feature of these techniques is that the external dimensions of the work-piece do not change considerably during the processing. Examples of these methods include equal channel angular extrusion or pressing (ECAE or ECAP)[1], high pressure torsion (HPT)[2], twist extrusion (TE)[3], friction stir processing (FSP), and multi directional forging (MDF) also known as multi-axial compression/forging (MAC/F)[4,5]. In addition, there are several methods of producing UFG sheet metals, such as accumulative roll bonding (ARB)[6] and repeated corrugation and straightening (RCS)[3]. Friction stir processing is one of the SPD techniques developed for producing ultra-fine grain structures in submicron level by introducing a large amount of shear strain into the materials without changing the plate shape or dimensions. Friction stir processing (FSP) has been projected by Mishra et al. [7,8] as a generic tool for microstructural modification based on the basic principles of FSW. Less amount of heat generation, extensive plastic flow of material, mechanical mixing, large forging pressure, proscribed flow of material, very fine grain size and random misorientation of grain boundaries in the stirred region are the unique features of FSW, utilized by Mishra [9].

FSP, is basically a local thermo-mechanical metal working process, in which, a rotating tool with pin and shoulder is inserted in a single piece of material that alters the localized microstructure. It modifies local properties without influencing the properties of the bulk material. Intense plastic deformation at high strain rates in the processed zone generates fine recrystallized grains by means of dynamic recrystallization and results in break-up of constituent particles. Thus FSP generates microstructure containing ultrafine grains with large grain boundary misorientation which leads to Superplasticity [10]. For example, a fine-grained microstructure for high-strain-rate Superplasticity was obtained in the commercial 7075Al alloy during FSP [11, 12]. In addition, the FSP technique has been used for the formation of a surface composite on aluminum substrate, which is also called as Additive FSP [13]. Homogenization of powder metallurgy (PM) aluminum alloys, metal matrix composites, and cast aluminum alloys can also be done using FSP [14-16].

The main process parameters of the FSP method are, rotational speed of the tool, n (rpm), tool travel speed, v (mm/min), angle of tool inclination relative to the material (Tool tilt angle), Plunge depth h (mm) and tool geometry. The FSP process can be performed in a single pass or the surface can be tailored in several passes. Amount of overlap during Multi-pass FSP is very important process parameter which decides interaction of tool for given number of times in a specified portion of specimen and thereby obtain the desired dimension of the modified surface [17, 18].

Aluminium 6061 is one of the commercial Aluminium alloys being especially used in aerospace and automobile industries. Its important advantages include good formability, fairly good corrosion resistance, weld ability. Additionally, since this alloy is heat treatable, it can be strengthened significantly during aging. AA6061, magnesium and silicon as major alloy additions, forms Mg_2Si precipitates which in turn form a simple eutectic system with Aluminium. It is the precipitation of Mg_2Si after artificial aging (temper T6) that allows these alloys to reach their full strength. Their applications include construction of aircraft structures, marine fittings and hardware, hydraulic pistons, couplings, valves, bicycle frames, boat hulls, automotive parts such as wheel spares, cans for packaging food stuffs etc.

There is sufficient literature available in severe plastic deformation of Aluminium 6061 alloy by multi-pass FSP to obtain the homogeneous properties throughout the plate. It is possible to enhance certain mechanical properties of AA 6061 by tailoring microstructure using FSP.

An attempt is made to optimize certain process parameters during single and multi-pass FSP of AA6061 to fabricate defect free surface and evaluate certain mechanical properties.

2. II. EXPERIMENTAL DISCRIPTION

Rolled, homogenized and aged to condition T651 (solution heat treated, stress relieved then artificially aged) AA 6061 with elemental composition (Table 1), and mechanical properties (Table 2) was used in this experiment, whose composition was confirmed by ICP OES (inductively coupled plasma optical emission spectroscopy). Samples of dimension 150mm x 70mm x 6 mm were cut using power shearing machine. Single pass and Multi-pass FSP was performed on Semi-automatic Vertical Milling Machine. A specially designed and fabricated FSP fixture was used for clamping. Process parameters, Rotational speed and traverse speed, were varied using two different tool geometries as shown in Fig 1.

TABLE 1 CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF AL 6061-T651 ALLOY.

Material	%Si	%Fe	%Cu	%Mn	%Mg	%Cr	%Ti	%Al
Al6061-T651	0.56	0.39	0.27	0.048	1.02	0.19	0.038	97.43

TABLE 2 MECHANICAL PROPERTIES OF AA 6061-T651 ALLOY

Material	UTS	YS	% Elongation	Hardness(Hv)
AA 6061-T651	312	179	12	104

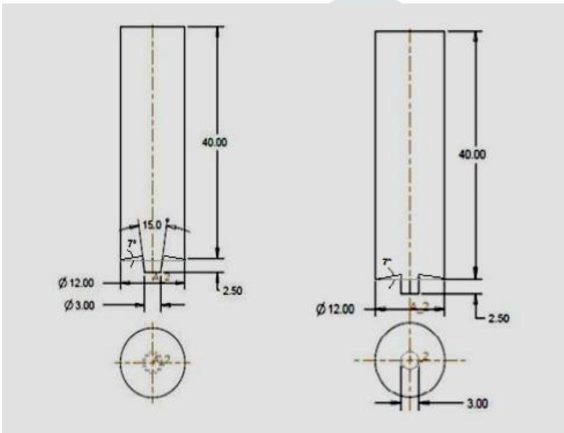

Fig. 1. Drawings of different tool geometries for FSP

For microstructural analysis, mirror polished FSPed and as received samples was etched to reveal microstructure. These samples are first polished (emery paper 200-1500) to the higher degree of polishing needed for such Aluminium alloy. Then the samples are lapped by using diamond paste. The black residue formed during lapping removed by running water, then dried and washed with cotton. The samples were etched using reagent containing 50% water and 50% HF. The prepared samples were analyzed by using image analyzer.

Microhardness of the processed samples were taken on microhardness tester Future Tech FM-700 with a load of 100g and 10s dwell time. The hardness indentation was taken for every 3mm intervals so as to get the exact hardness.

Tensile test of samples decided to take according to ASTM standard. Tensile test was carried out in transverse direction. According to ASTM standard for Aluminium alloys, E8 tensile test was carried out. X-ray Diffraction of as received & FSPed samples taken to analyze the precipitates in the as received and after FSPed sample.

3. III. RESULTS AND DISCUSSION

General Observations:

It was observed that tool geometry plays an important role in microstructural modification during FSP. Optimized process parameters for cylindrical pin geometry are summarized in table 3. For the tool with simple cylindrical pin profile, the material sticks to the tool at lower rotational speeds and hence tunnel defect was observed throughout the NZ. At higher RPM, material becomes more soft and flows easily hence defect free NZ was fabricated. In case of, tool with taper cylindrical pin profile material flow is much easier and hence defect free NZ can be obtained at lower RPM compared to simple cylindrical pin geometry.

It was observed that, tool rotational speed (RPM) has major impact on heat generation and subsequently on microstructure and mechanical properties of FSPed AA6061, compared to that of tool traverse speed (mm/min). Macrostructure of defect free multi-pass friction stir processed AA6061 is shown in Fig. 2

TABLE 3: OPTIMIZED PROCESS PARAMETERS WITH DIFFERENT TOOL GEOMETRIES

Tool Geometry	Rotational Speed (RPM)	Traverse Speed(mm/min)	Hardness Hv	Grain Size (μm)
Simple Cylindrical	1400	60	63	21.8
Cylindrical Tapered	1270	60	61	17.6

Fig. 2 Multi pass Friction Stir Processed Sample

Microstructural Investigations:

The microstructure of parent 6061 Al alloy consists of mainly Mg2Si precipitates. The optical micrographs of parent 6061 alloy and Nugget Zone (NZ) after FSP is shown in Fig. 3(A) and (B) respectively. Elongated grains were visualized in as received material and the equiaxed fine grains were observed in the NZ. Base metal consisted large elongated grains typical of a rolled structure. NZ shows fine recrystallized grains at due to heavy plastic deformation followed by dynamic recrystallization during thermo-mechanical processing [19, 20]. It was clearly seen that Taper Cylindrical tool produced more fine grains due to the pulsating stirring action [21]. Thermo-mechanically affected zone shows heavily deformed and rotated grains. However there was no change in average grain size was observed in HAZ as compared to base material. Grain Size measurement was done by linear and circular intercept method. The circular intercept method was used for elongated grains. As received material shows the grain size of 95 µm of ASTM Grain Size No. 3. After processing refine equiaxed grains of grain size 17.6 µm of ASTM Grain Size No. 8.87 at 1000X were observed.

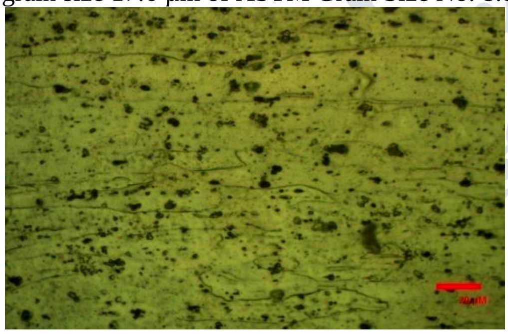

Fig 3 (A) Micrograph of Base metal AA6061

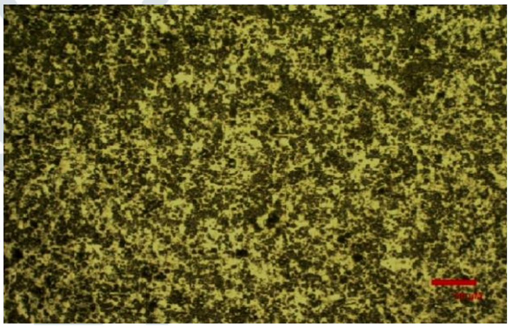

Fig 3 (B) Micrograph of Nugget Zone after FSP

Hardness Traverse:

Microhardness traverses across the friction stir processed zone of AA 6061 produced at 1270 rpm and 60 mm/min with cylindrical taper pin tool is shown in Fig. 4.The microhardness measurements were carried at the mid-section on thickness with 0.3 mm interval of distance. The hardness of the stir zone was significantly lower than that of the parent metal due to dissolution of precipitates which was confirmed by XRD. In general hardness depends on the precipitate distribution rather than grain size. Stir zone temperature ranges from 400 ºC–480 ºC [5]. In AA6061, these temperatures are enough to dissolve all precipitates and cooling rate after processing is amply rapid to retain alloying elements in the super saturated solid solution [5, 21]. The heat affected zone was wide because of high thermal conductivity of the base metal. From the center of processed zone the hardness dips to minimum value about 41Hv and 53Hv for advancing and retreating side respectively. This behavior may be ascribed to precipitate coarsening due to frictional heat.

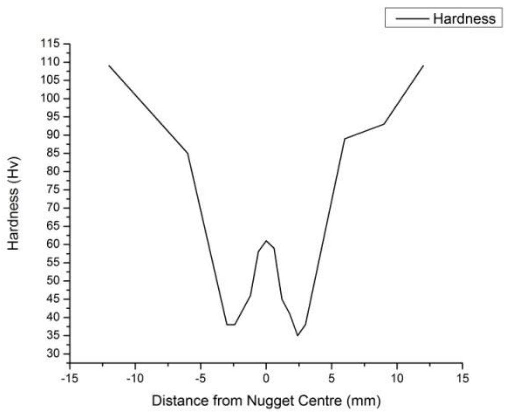

Fig. 4 Hardness traverse of Friction stir processed sample with parameters: RPM-1270; Traverse Speed- 60 mm/sec

Tensile Properties:

Tensile test was carried out for as received, single pass and multi pass FSPed samples as per ASTM E-08 standard. The samples were cut by Wire EDM machine as shown in Fig. 5.

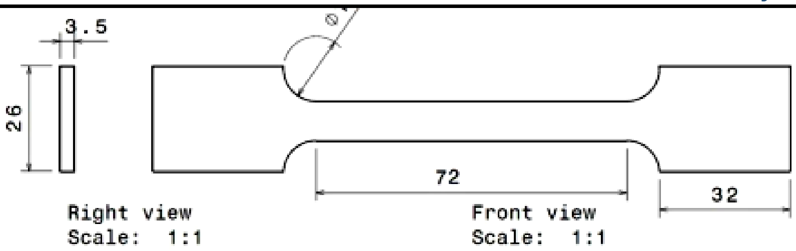

Fig. 5 Tensile Test ASTM E8 Sample drawing with dimensions

Tensile test was performed on UTM machine of capacity 100 tonnes. Test conditions and tensile test results are given in below table 4. It was observed that, tensile strength (UTS) of all the processed samples decreases but ductility (% Elongation) of samples without defect (Optimized Process Parameters) drastically increases. Reduction in tensile strength can be attributed to dissolution of all the precipitates in the processed zone.

TABLE 4: TENSILE TEST RESULTS OF SAMPLES PROCESSED USING CYLINDRICAL TAPER TOOL WITH PARAMETERS: RPM-1270; TRAVERSE SPEED- 60 MM/SEC

Sample Description	Tensile Strength (N/mm2)	% Elongation	% Reduction in C/S area
As Received	317.8	9.2	30.5
Single pass	145.7	8.3	37.4
Multi pass 50% Overlap	176.2	13.4	56.7
Multi pass 60% Overlap	183.6	15.1	60.3

XRD Analysis:

X-ray diffraction (XRD) pattern of as received material, as shown in Fig 6(A), clearly shows typical aluminium intermetallic phases. The strengthening precipitate, Mg2Si, was present in aluminium 6061 T651, as received condition whereas, XRD pattern of nugget zone after FSP, shown in Fig 6(B), clearly shows absence of Mg2Si precipitates. This indicates that, during FSP, due to severe plastic deformation at high strain rates precipitates get dissolved, because of which, hardness after FSP decreases.

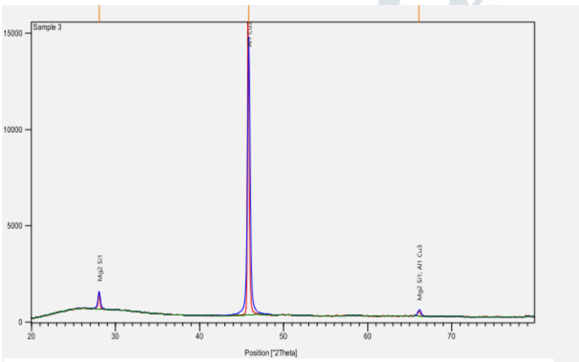

Fig 6 (A) XRD pattern of Base metal AA6061

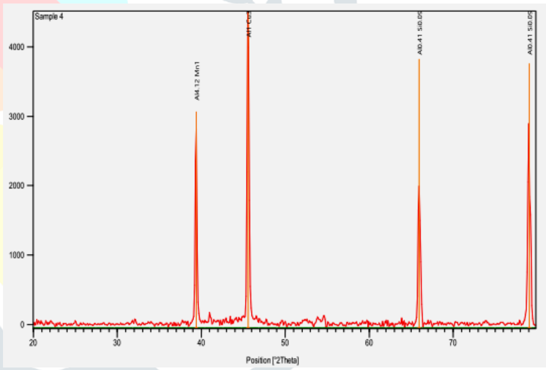

Fig 6 (B) XRD pattern of Nugget Zone after FSP

4. IV. CONCLUSION

- By using Simple Cylindrical pin tool geometry, higher rotational speeds are required to get defect free processed zone, as material sticks to pin at lower rotational speed. Due to higher RPM heat generation is more which leads to grain coarsening in HAZ.
- Tool with Cylindrical tapered pin geometry gives defect free nugget at lower rotational speeds during single and multi pass FSP.
- The decrease in hardness is due to the dissolution of strengthening precipitates observed in all processed samples at room temperature.
- Tool Rotational speed has more impact compared to that of tool traverse speed on microstructure modification and subsequent mechanical properties.
- The optimized process parameters are found to be 1270 RPM and 60 mm/min of travel speed to obtain defect free nugget zone with lowest grain size and highest hardness with cylindrical tapered threaded pin.

5. V. References

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