Influence of hybrid pin profile on microstructural and mechanical properties of Al/SiC graded composites produced by friction stir processing

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Abstract. Friction stir processing (FSP) was employed to fabricate a surface graded composite by embedding SiC reinforcement particles in an AA6082-T6 matrix. Conical blind holes were drilled on the surface of the plate with varying inter-hole distances. The processing was performed with the different number of passes by keeping rotational and traverse speed constant. A new hybrid tool with a combination of conventional conical threaded tool and the triangular cross-sectioned tool was used in processing. The microstructural features of the processed samples were examined by a 3D microscope and scanning electron microscope (SEM). Mechanical properties such as microhardness, tensile strength was thoroughly evaluated. It is reported that the number of passes played an essential role in the distribution of reinforcement particles and grain refinement. The hardness value improved by applying multiple passes. The fractured tensile samples showed ductile failure. The sample treated with double passes gave better results with the homogenous distribution of reinforcement particles compared to samples processed with a single pass.

Keywords: Friction stir processing; Graded composites; Hybrid tool; AA6082-T6

1. INTRODUCTION

Friction stir processing (FSP) is a solid-state processing technique developed based on the principles of friction stir welding (FSW). FSW is a patented technology that was established in 1991 by The Welding Institute (TWI), Cambridge UK. The approach to this processing technique is the same as FSW, in which a non-consuming rotating tool that consists of a tool pin and a shoulder rotates and penetrates the material. Then the tool is traversed along a tool path to redefine the microstructure of the material (refer Figure 1). The tool pin can have different geometries and it enables the formation of the defect-free microstructure of the material that was processed [1,2]. FSP is a flexible method through which we can transform the microstructure of the material being processed, repair flaws, and modify surface topography or composition. The potential use of these practices lies in the ocean, aerospace, railways, and automotive industries. FSP can be used for grain refinement which enhances ductility, formability, corrosion resistance and mechanical strength such as yield strength of the material being processed. It induces localized homogenous microstructure of the material with
equiaxed fine grains. During FSP, the friction caused by the rubbing action of the shoulder with the surface of the material generates heat, due to which softening of the material occurs. In addition, during the stirring action of the pin, the material in the processed zone undergoes plastic deformation ensuring a dynamically recrystallized grain structure [3].

Figure 1: Schematic of friction stir processing technique

Recently, FSP has gained popularity in fabricating composites such as metal matrix composites (MMC), surface composites (SC) and functionally graded metal composites (FGMC). In MMC, the particles are distributed in the whole volume of the material while, in SC, the reinforcement particles are distributed only to a specified thickness of the material. In FGMC the volumetric percentage of reinforcement particles gradually decreases or increases along a direction. For example, we can fabricate an FGMC along the length of the plate where the percentage of reinforcement particles changes and thus the mechanical properties would also change along that direction [4].

Sharafitabar et al.[5] investigated the microstructural and mechanical properties of 5052Al/Al2O3 surface composite produced by FSP. Increasing the number of FSP pass affected the equivalent dispersal of Al2O3 particles in the matrix. In the finest settings, tensile strength and elongation of base material enhanced to 118% and 165%, respectively in composite produced by four passes. Rathee et al.[6] fabricated MMC using FSP by different strategies. Groove and cylindrical hole reinforcement strategies were employed with the tool offset method on both the advancing (AS) and retreating sides (RS). It was observed that the groove method with tool offset in RS showed better homogeneity in reinforcement particle circulation among the six reinforcement strategies that were considered. Sharma et al.[7] performed a detailed analysis on developing a surface composite of Al5083 with SiC particles. Different strategies such as variations in process parameters, double tool processing, and tool offset intersection were used. The material flow after FSP showed that the stirring action of the probe plays a foremost role in the distribution of particles. The rotational speed showed the main influence on the distribution of silicon carbide particles. Fernandez et al.[8] developed surface composite using Al6061-T6 as the base metal and Al2O3, SiC as reinforcement particles. The reinforcement particles were incorporated in the square section groove, cut parallel to the length of the plate and sealed before performing FSP. Wear resistance behaviour was studied with two different reinforcement strategies respectively of Al-SiC/Al2O3 composites. The specific wear rate was reduced when multi-pass FSP was done with SiC reinforcements.

In the present study, an attempt was made to produce property gradients by FSP along the tool traverse direction (longitudinal direction) by drilling holes in an aluminum plate and the holes were positioned to vary the composition of reinforcements from maximum to minimum. Followed by FSP, the characterization of the stirred zone in terms of distribution of reinforcement particles, microhardness and tensile was carried out.
2. EXPERIMENTAL PROCEDURES

Aluminum 6082-T6 alloy, with a thickness of 6 mm and SiC reinforcement particles of size 28 \( \mu m \), was used. The chemical composition of the substrate is shown in Table 1.

| Mg  | Mn  | Cr  | Cu  | Si  | Fe  | Al   |
|-----|-----|-----|-----|-----|-----|------|
| 1.13| 0.75| 0.20| 0.10| 0.97| 0.34| Bal. |

The hybrid tool pin with one conically threaded part and another part triangular profile (total pin length = 5.4 mm) was utilized for this study as shown in Figure 2. The tool material was H13 and it was heat-treated to a hardness value of 61 HV. The shoulder had a diameter of 24 mm. To fill reinforcement particles, holes of diameter 2 mm were drilled to a depth of 4 mm, over a length of 45 mm using an electric discharge machine. After drilling, the holes were positioned to achieve the maximum to minimum variation in composition over a length of 45 mm. FSP was carried out on the FSW machine (Model- FSW-3T-NC). The reinforcement particles were initially mixed with ethanol, filled in the holes and allowed to dry, to prevent ejection of reinforcement particles during FSP. After the holes were sealed, the processing was performed with the hybrid tool. The tool rotation was set to 900 rpm and the traverse speed was 20 mm/min. The tilt angle was taken as 1° along the centreline. The tool traverse direction remained constant in case of multiple passes. The samples were subjected to either one or two passes and were sectioned at the processing zone. The specimen was allowed to cool to room temperature after each pass.

Figure 2. Hybrid FSP tool

Figure 3. Dimensions of a tensile test specimen

The samples were sectioned normal to the processing direction and mechanically polished with different grades of sandpaper. The polished samples were then etched with Keller’s reagent. For
microscopic examination, different microscopic images were taken at three different zones (top, middle and bottom) using a 3D optical microscope of model Huvitz (South Korea). Detailed microstructural examination of the samples was executed using a Vega 3 LMU (Europe) scanning electron microscope (SEM) integrated with energy dispersive X-ray analysis (EDAX) to scrutinise the dispersal of SiC particles and elemental analysis in the stir zone. Microhardness was carried out using a Vickers hardness tester with a load of 100-g for 10 seconds along the thickness of the composite layer. The tensile strength was evaluated using the universal testing machine (UTM) and the dimensions of the testing specimen were as per ASTM standards (Figure 3). The morphology of the fractured samples was analysed by SEM.

3. RESULTS AND DISCUSSIONS

3.1. Microstructure
The microstructural features of graded samples processed with the hybrid tool are shown in Figures 4 and 5. The samples were free from defects like cavities and voids. FSP induced localized homogenous microstructure of the material with equiaxed fine grains. With the stirring action of the pin, the material in the stir zone (SZ) underwent plastic deformation thereby causing dynamically recrystallized grain structure. For the graded sample of a single pass, the formation of onion rings can be observed in the SZ due to material flow near the threaded portion of the tool during stirring action. There was low dispersion of reinforcement particles in the matrix from the top portion to the bottom portion which is visible from Figure 4. (a) – (c). As we moved from the top portion to the bottom portion, it was be seen that the percentage of SiC particles decreased gradually. The SiC particles were coarser in size and the reinforcement particles were more concentrated on the retreating side. To further enhance the uniform particle distribution with fine grains, a double pass was required.

Figure 4. Microstructure of graded sample from top to bottom processed using single pass

Figure 5. Microstructure of graded sample from top to bottom processed using double pass

Figure 5. depicts the microstructure of the SZ obtained with a double pass where fine-sized SiC particles can be seen in the sample with the homogenous distribution. The onion rings that formed in the previous pass was not observed in the second pass. Dynamically recrystallized fine equiaxed grains were visible completely in the SZ because of the high frictional heat and intense plastic
deformation applied due to the pinning action of the hybrid tool. The results conclude that dynamic recrystallization (DRX) and continuous dynamic recrystallization (CDRX) were responsible for the development of fine-grained microstructure in the graded samples during FSP. The pinning effect of SiC particles in the coarse of grain growth hampered the movement of grain boundaries. Also, the SiC particles facilitated the break-up of the grains due to inhomogeneous local deformation [9]. The utilization of the hybrid tool proved that with a fewer number of passes, a defect-free surface composite can be obtained. The reason being that the specially designed tool produced higher heat when compared to the conventional tool thereby increasing the material flow in SZ.

3.2. Microhardness and Tensile properties
Figure 6. illustrates the plot of microhardness data at different positions for processed graded samples along the direction of the thickness. For Al6082-T6, the average microhardness value was around 96 HV. A gradual variation in the hardness occurred in the gradient direction from top to bottom region. Interestingly, the microhardness value of the processed samples increased in proportion to the addition of SiC particles. The composite layer at the top region showed the highest value of hardness around 131 HV. This value was 1.4 times higher than that of Al6082-T6. In the middle region, the hardness value was around 126 HV which was lower compared to the top region. The hardness value in the bottom region had gradually decreased to 104 HV because of the non-homogeneous distribution of SiC particles and the stirring action of large grains. The pass numbers played an important role in the hardness results. The microhardness values were found to be influenced by the pass numbers and enhanced by 25.31 % for single pass and 36.32 % for double pass respectively, than base material (Al6082-T6). The double pass exhibited higher microhardness values due to refined grains and the homogenous distribution of SiC particles in the base material (matrix). The increase in the hardness can be ascribed to grain refinement which leads to DRX in addition to the Orowan mechanism [10,11].

![Figure 6. Microhardness plots of graded samples using single and double FSP pass](image)

The tensile properties of the samples processed with the hybrid tool with single and double passes are tabulated in the table. The results indicated that yield strength (YS) and ultimate tensile strength (UTS) were 26% and 14%, respectively, more when compared to single pass. By comparing the tensile results of the samples processed with single and double pass it was revealed that the addition of SiC particles in the sample created a major impact on tensile properties. A marginal increase in % elongation (EL) (i.e., from 16 to 19) and UTS (i.e., from 190 MPa to 240 MPa) was noticed for the double passes when compared to single passes. The morphology of fractured samples with single and double passes is represented in Figure 7. The fractography of the two samples showed the presence of
large dimples, indicating ductile failure. The dimple density of the single-pass sample was slightly more compared to double pass. The improvement of the strength and ductility was hindered by the combined effect of DRX during FSP, homogenization and grain refinement.

Table 2: Tensile samples of graded samples with pass number

| Pass number | YS (MPa) | UTS (MPa) | EL (%) |
|-------------|----------|-----------|--------|
| 1           | 147      | 190       | 16     |
| 2           | 163      | 240       | 19     |

Figure 7. Fractured morphology of graded samples (a) Single-pass (b) Double pass

3.3. EDAX analysis

Figure 8. represents the EDX elemental analysis of Al/SiC composite and the results confirmed the existence of SiC particles over the aluminum alloy matrix. The analysis of the matrix revealed the presence of elements such as carbon, magnesium, aluminum, silicon, oxygen and manganese. The SiC reinforcing particles were uniformly distributed in the parent alloy. No other intermetallic compounds were present in the composite. The SiC were present in the form of particles. There is a considerable difference in the densities of aluminum and SiC particles. As a result of these density differences, the SiC particles tended to float on the surface of the layer. The formation of fine grains was attributed to the hybrid tool and an increase in pass number. This causes severe plastic deformation at high temperatures during processing. Therefore, the process softens the material and leads to the homogenous distribution of reinforcement particles. The triangular edges of the hybrid tool stimulated the crushing of particles to form fine grains. Elemental mapping was performed at the SZ of processed graded samples. In Figure 9, the main elements such as C, O, Mg, Al, Si, Mn are pointed out during elemental mapping of Al/SiC graded samples. A detailed assessment of mapping suggested that the FSP was a versatile solid-state method in which reinforcement particles embedded in the matrix were uniformly distributed.

Figure 8. EDAX mapping of graded sample for the double pass
4. CONCLUSIONS

The present reinforcement strategy was found to be feasible in producing Al/SiC graded composites using FSP. Homogenous distribution of SiC particles in Al matrix with strong interfacial bonding was achieved employing a double pass. A progressive gradient in hardness values was observed for single and double pass friction stir processed Al/ SiC surface composite layers. The size effect of the reinforcements was judged based on the mechanical properties of composites which confirmed that SiC particles had contributed to the strengthening of the aluminum matrix through the Orowan mechanism. The Al/SiC composites processed with two FSP passes exhibited an increased percentage of elongation compared to the base material, because of the inclusion of SiC particles and enhanced hardness.

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