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Characterization of the Microstructure and Mechanical Properties of Al/SiC Composite Produced by FSP Technique

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Abstract In this study, Medium strength AA7020 alloy was reinforced with SiC powder particles by Friction Stir Processing (FSP) technique. Samples were subjected to multiple passes with changing direction of rotation of the tool between subsequent passes. Characterization of macrostructure and microstructure was achieved by optical microscopy (OM) and scanning electron microscope (SEM) of the modified surfaces. Tensile test and Vicker's Hardness test were carried out on resulted composite for characterization of mechanical properties. As a result, it was found that SiC particles were good distributed inside the substrate with an average penetration depth of about 5mm. The AMMCs (Aluminum Metal Matrix Composites) produced in this way had excellent bonding between matrix and reinforced particles. Moreover, the grain refinement of matrix and improved distribution of particles were obtained after each FSP pass. The hardness of produced composite surfaces was improved by 1.8 times as compared to that of base alloy.

Keywords AA7020, FSP, SiC, Microstructure, Hardness

1. Introduction

Metal matrix composite (MMC) is an engineered combination of at least two components, namely matrix (usually an alloy) and reinforcement (hard ceramic particle) to get tailored properties [1].

The addition of hard refractory particles (e.g. alumina [2], silicon carbide [3] to a ductile matrix (e.g. aluminium) produces a material whose mechanical properties are intermediate between the matrix alloy and the ceramic reinforcement.

Aluminium based metal matrix composites exhibited high strength and improved resistance to fatigue and wear [4]. Such characteristics make them promising structural materials for aerospace and automobile industries [5].

Previous studies concluded that the homogenous dispersion of ceramic particulates and/or reducing matrix grains from micrometer to nanometer level [6-8] is beneficial to enhance the mechanical properties of composites [9-13].

Among the several methods used to fabricate particulate reinforced Al based surface composites, much attention has been paid to friction stir processing (FSP) as a solid-state, emerging efficient processing technique to fabricate surface composites [14-17]. FSP is a single step process, while other techniques require multiple steps which make FSP easier, novel, green and less time and energy consuming [18]. Most of the published work [14-23] is focused on the effect of processing parameters on surface characteristics and the particle distribution pattern was mainly affected by the FSP parameters such as traverse speed [16], rotational speed [15,24], axial force [22], tool pin profile [23,24], number of passes [17,18], and groove design [25].

The primary aims of this paper is to investigate the possibility of fabricating nano - SiC surface metal matrix composites layer on AA7020 substrate through friction stir processing (FSP). Also, the influence of number of passes and tool rotation direction on particle distribution, hardness and microstructure of composite were experimentally investigated.

2. Experimental Procedure

2.1. Metal Matrix Used

The alloy chosen for this study was 7020-T6 heat treatable wrought alloy introduced as a plate (150 mm x 35 mm x 10 mm thick). This alloy is mainly used in Armoured vehicles, military light bridges, motor cycle and ship construction [5]. The chemical composition (in weight percent) of the parent

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material is shown in Table 1. The mechanical properties with pre-determined values such as listed in Table 2.

Table 1. Alloy composition in weight percent (wt. %)

Elem.	Zn	Mg	Fe	Mn	Cr	Si	Al
wt. %	2.3	1.6	0.46	0.23	0.2	0.12	Bal.

Table 2. Mechanical properties of AA7020-T6

Ultimate tensile strength (MPa)	384.6
Elongation (%)	15.1
Vickers hardness (HV 0.5 kg)	117

2.2. Reinforcement Powder

Fig. 1 shows SEM image of commercial grayish white Silicon Carbide (SiC) Beta Nanopowder (99% purity and 50 nm average diameter). The properties of SiC powder are summarized in table 3.

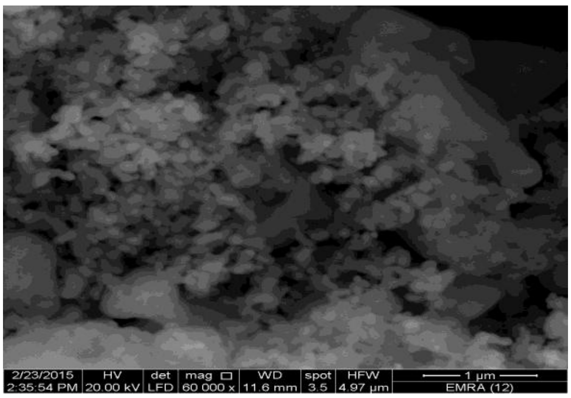

Figure 1. SEM micrograph of the SiC powder nanoparticles

Table 3. Ttechnical Properties of Silicon Carbide (SiC)

Bulk Density (g/cm^3)	0.03
True Density (g/cm^3)	3,32
Specific Surface Area (m^2/g)	80 - 130
Morphology	cubic
Manifacturing Method	laser synthesized

2.3. FSP Process

Fig.2 illustrates different steps for fabrication of surface metal matrix composite. In the beginning, a groove with 1 mm width and 5 mm depth was opened by CNC milling machine in the middle of the plate surface and aligned with the centerline of the rotating probe, Fig 2.a. The SiC powder was mixed with small amount of volatile solvent (methanol) and then incorporated into the groove, Fig 2.b. Upper surface of the groove was closed to prevent the powder from scattering with a modified a modified FSP tool that only had a shoulder and no pin, Fig 2.c.

Multi-pass friction stir processing was performed using a rotating cold work steel tool (K340) with featureless concave shoulder and non- profile pin. In each pass, the tool was plunged into the base metal and advanced along the groove. The frictional heat softens the matrix alloy and the ceramic particles are distributed and mixed within the plasticized matrix alloy by the stirring action of the tool [19-22]. The tool dimensions and the main operating parameters are presented in table 4.

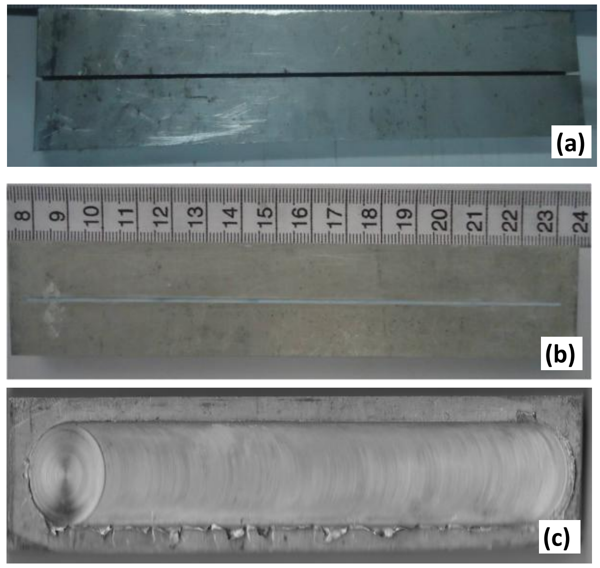

Figure 2. Sequence for fabrication of surface metal matrix composite

Table 4. The tool dimensions and FSP Parameters

Shoulder diameter (mm)	20
Pin length (mm)	6
Pin diameter	7
Rotational speed (rpm)	580
Traverse speed (mm/min)	40
Tool tilting angle	3°
Plunge depth (mm)	6.3

2.4. Microstructure and Hardness Measurement

The specimens for metallographic examination were sectioned transverse to the processing direction, ground, polished, etched with classical Keller's reagent, and then rinsed in water. The investigation of both macrostructure and microstructure was carried out on cross-sections of friction stir processed specimens using optical microscope (OM) and Scanning Electron Microscope (SEM). To have an insight into the mechanical properties, both tensile test using Tinius Olsen machine type and Vickers hardness measurements on Matsuzawa Hardness tester at 500 kgf load (Hv0.5) for 15 sec dwell period were carried out.

3. Results and Discussion

3.1. Macrostructure

Fig. 3 shows the upper surface of the produced composite after FSP. It is evident from the macrograph that the groove is effectively closed and completely bonded along the path subjected to tool movement. The top surface appears very smooth and there is sound, continuous, and defect-free.

Figure 3. Picture of as-processed plate with one pass at 500 rpm, 20 mm/min

3.2. Flow Mechanism of Powder

The macrographs shown in Fig.4 indicate the formation of basin-shaped nugget zone. It was also observed that the powder agglomerated at the top of the advancing side first, and then expanded by stirring action of tool shoulder from the advancing side to the retreating side after additional passes. Therefore, the metal matrix composite appears at the advancing side in arc shape in the samples processed by the first pass. With changing rotational direction between passes, the location which was advancing side in the previous FSP pass will be retreating side in the proceeding pass and consequently this will level out microstructural variations from advancing side to retreating side.

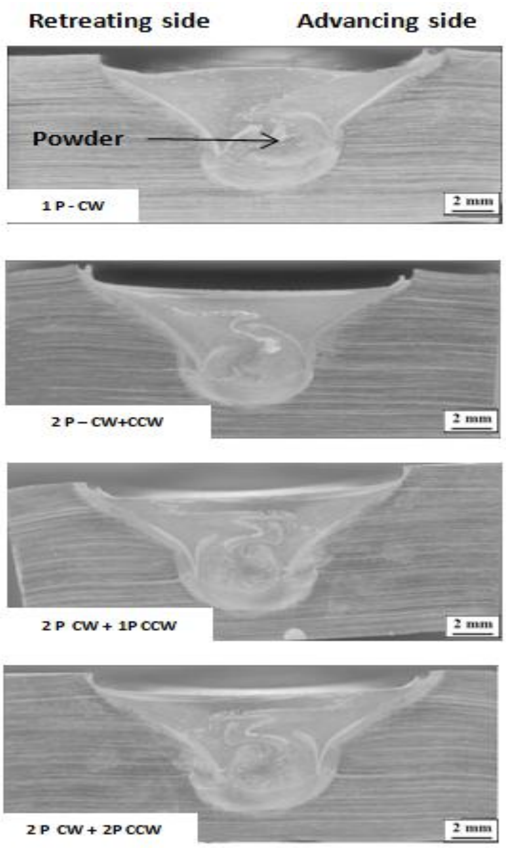

Figure 4. Macrograph of a cross-section of the fabricted composite at different passes (Pass: P, Clockwise: CW, Counter clockwise: CCW)

3.3. Microstructure

Many researches [18-26] demonstrated that the reinforced particles were easily wrapped by softening metal and rotated with the FSP tool. Since there is great physical discrepancy between the covered reinforced phase and the base metal, it is difficult to travel like the same move with softening base metal. Because material stirring and plastic deformation are not enough, so powder particles are not easy to disperse in larger region and move in clustered shape. As observed from Fig. 5, agglomerated SiC particles could be observed in the surface composite layer produced by one FSP pass. The observed clustering particle size is frequently much larger than the individual SiC size.

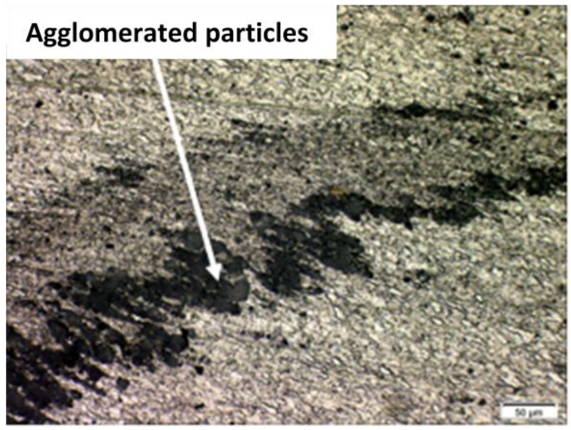

Figure 5. Optical macrograph of the stir zone for FSPed sample with the SiC particles after 1 pass

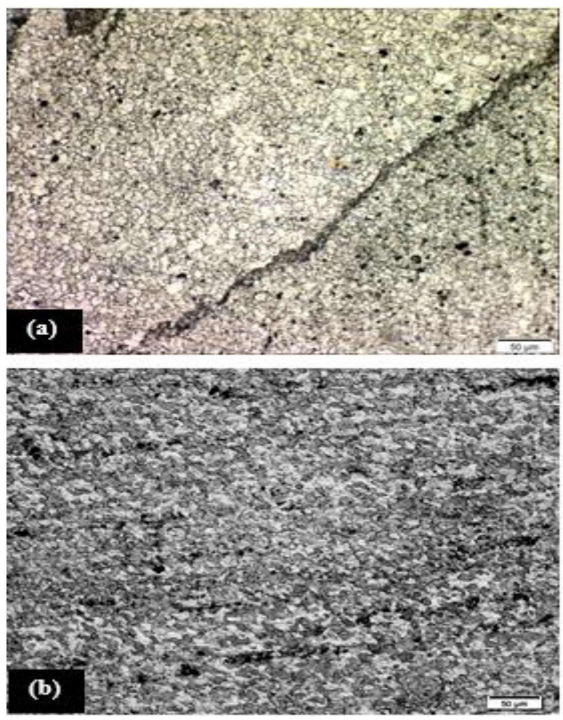

Figure 6. Optical micrographs of the stir zone for the FSPed alloy after 1 pass (a) With the nano-sized SiC particles, (b) Without particles

The reinforcing particles increases the nucleation sites, and break-up the pre-existing grains, and impedes the migration of grain boundaries [19,25]. Fig. 6 shows the stir zone of surface composite layer produced by one FSP pass in comparison to the stir zone of samples processed without powder indicates that the presence of SiC particles restricts the grain growth and cause severe grain refinement of aluminum matrix as shown in.

Fig. 7 shows the SEM micrograph of the interface zone between surface composite layer and aluminum alloy substrate. The surface composite layer appears to be good bonded to the aluminum matrix and no defects are visible at the interface.

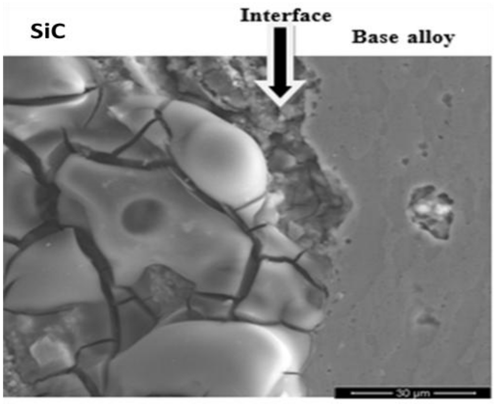

Figure 7. SEM micrograph of the interface zone between surface composite layer and base metal

3.4. Effect of Number of Passes and Tool Direction

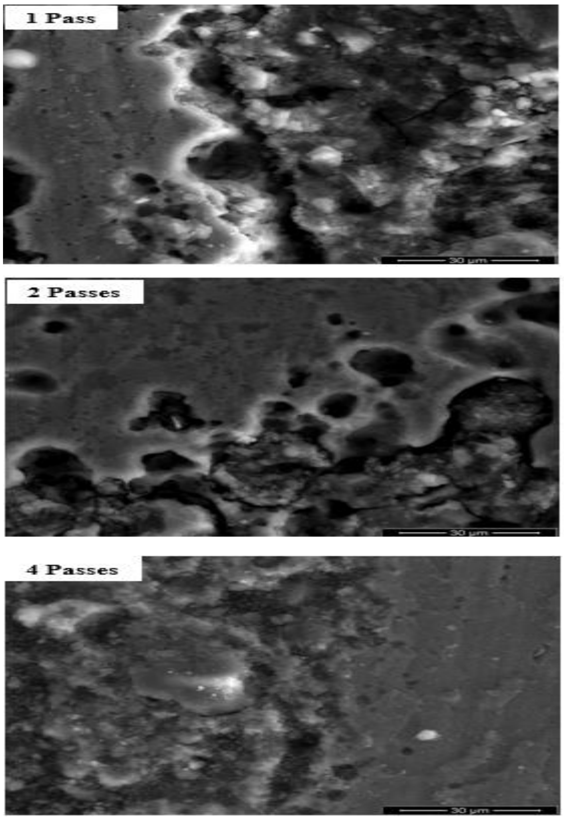

Figure 8. SEM micrograph of the interface zone between surface composite layer and base metal at different number of passes

SEM micrograph of the interface zone between surface composite layer and base metal in Fig. 8 illustrates that multi-pass FSP remarkably improves cohesive bonding between SiC particles and base metal resulting in elimination of interfacial de-bonding.

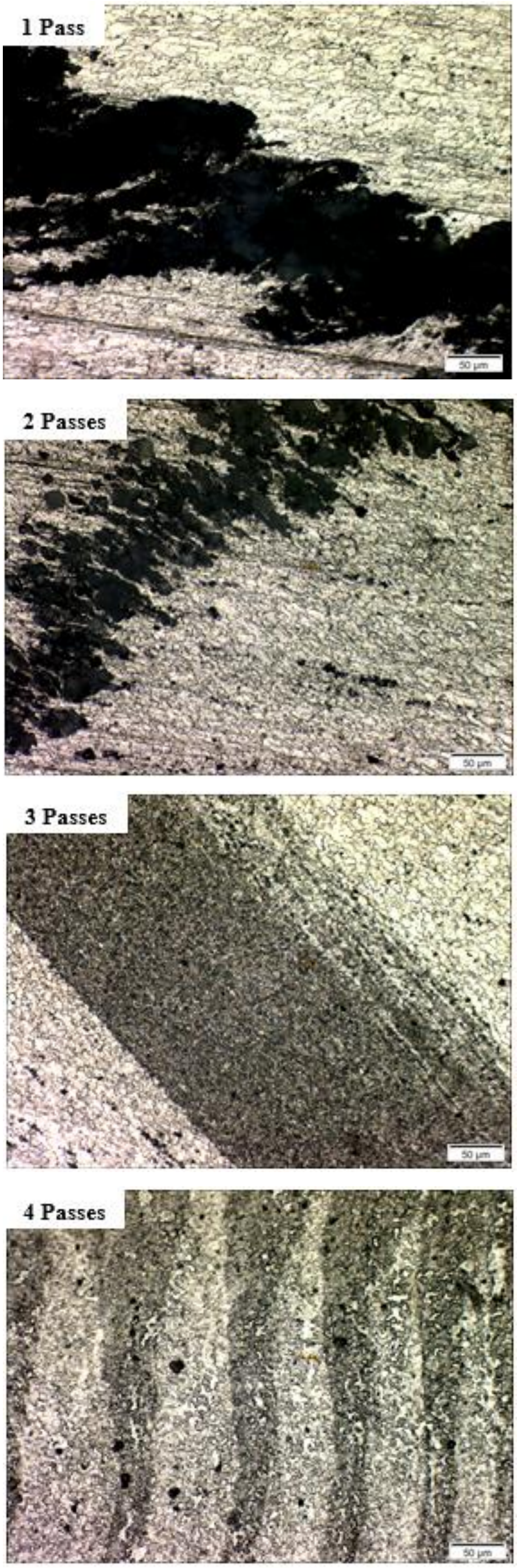

Figure 9. Optical micrographs of the surface composite layer at different number of passes

As shown in Fig. 9, increasing the FSP passes expands the stir zone and breaks the agglomerated SiC clusters during each pass. Also, the tool rotational direction is changed between subsequent passes which causes a change in the material flow and improves particles' distribution in parallel bands. On the other hand, there were just a few regions which included the unmixed SiC ceramic powders inside the stir zone.

3.5. Hardness

The hardness value depends mainly on the presence and uniform distribution of SiC particles according to Orowan strengthening theory [2]. The existence of reinforcing particles makes the dislocations movement difficult [4,12,18]. As a result, the indenter is not able to penetrate as much as it could do in an as-received aluminum matrix, and hardness value increases. According Fig. 10, the average hardness values of surface composite increased with increasing number of passes due to more homogenization and uniformly distribution of SiC reinforcement particles over wide regions.

The hardness distribution profile through the fabricated composite after 1 pass (Fig. 11) shows great scatter of hardness, implying that the nano powder was not efficiently dispersed into a reasonably uniform manner. The hardness peaks observed can be attributed to occasional particles clustering and agglomerations.

Furthermore, results show that change of tool rotational direction between passes, and increase in number of passes, increases the average hardness value and reduces hardness curve fluctuations or scattering of Hv within the FSP stirred zone (Fig. 11). These results imply that the pin efficiently dispersed the nano-sized SiC powders in a reasonably uniform manner.

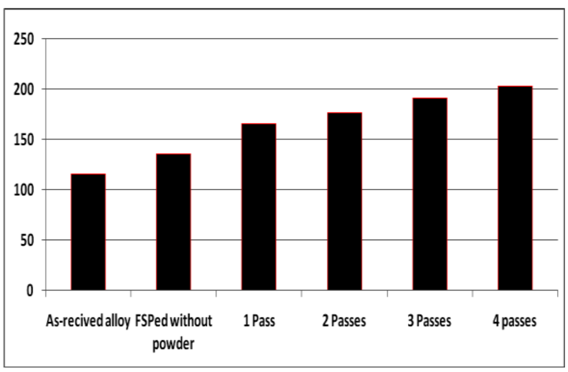

Figure 10. Effect of number of passes on average hardness number of stir zone

alloys. The hardness of the base alloy AA7020 was doubled by reinforcing the alloy with SiC nano-particles after 4 passes.

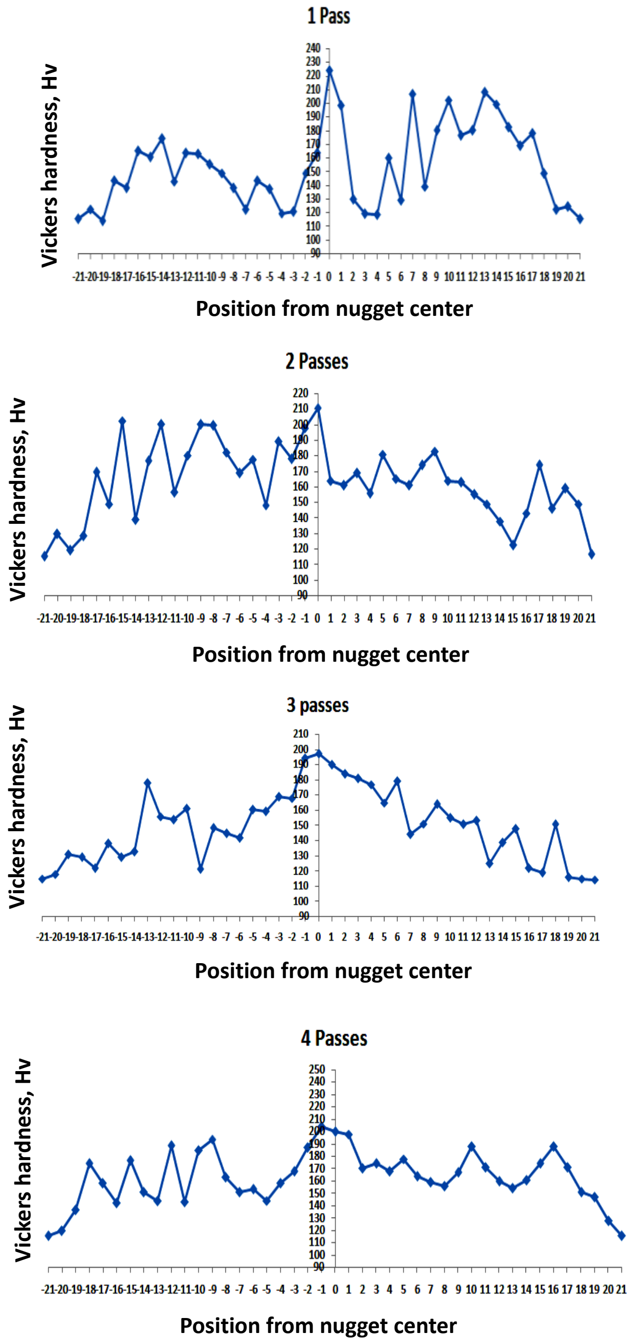

Figure 11. The hardness profiles along the cross section of the surface composite layers

4. Conclusions

Friction stir processing was successfully utilized to fabricate SiC/AA7020 surface-nanocomposites. The new surface nanocomposites showed good interface between particles and base metal. Defects were not visible validating that FSP is an effective way for composite fabrication in Al

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