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Effects of Process Parameters on the Microstructure and Hardness of 7020/Al_2O_3 Composite Layer Fabricated by FSP

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Abstract— FSP technique was employed to produce Al–10%Al_2O_3 surface nanocomposite on Al7020 substrate. Effects of number of passes and tool direction on nanoparticle distribution and matrix microstructure have been explored. Microstructure and mechanical properties of samples were investigated by optical microscopy (OM), scanning electron microscopy (SEM), and hardness measurements. As a result, it was found that Al_2O_3 particles were good distributed inside the substrate with an average penetration depth of about 1000μm. The surface nanocomposites produced in this way had excellent bonding with the substrate. The hardness of the surface nanocomposite was about 1.5 times that substrate. Moreover, the grain refinement of matrix and improved distribution of nanoparticles were obtained after each FSP pass.

Index Terms— AA7020; FSP; Al_2O_3; nanocomposites; 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 high strength, high modulus refractory particles (e.g. alumina [2], silicon carbide [3] to a ductile metal matrix (e.g. aluminium) produce 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]. A survey of the previous studies indicates that either the homogenous dispersion or decreasing the sizes of ceramic particulates and/or matrix grains from micrometer to nanometer level [6-8] is beneficial to enhance the mechanical properties of aluminum matrix composites (AMCs) [9-13].

Among the several methods used to fabricate particulate reinforced 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]. One of the most important and unique features of FSP is that 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]. Fig. 1 illustrates different steps for fabrication of surface metal matrix composite. In order to form reinforcement layer, reinforceing particles or powders are mixing with a volatile solvent such as methanol. A groove of required depth is made in the substrate Fig. 1.a. The reinforcing powders could also be filled into a groove on the plate Fig. 1.b. In order to prevent the particles from being escaped, surface ‘‘repair’’ was accomplished with a modified FSP pinless tool. For the process of fabricating surface composite by FSP, a rotating FSP tool was plunged into the base metal Fig. 1.c, and traverse along the groove Fig. 1.d. The frictional heat softens the matrix and the ceramic particles are distributed and mixed within the plasticized matrix alloy by the stirring action of the tool [19-22]. 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 - Al_2O_3 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.

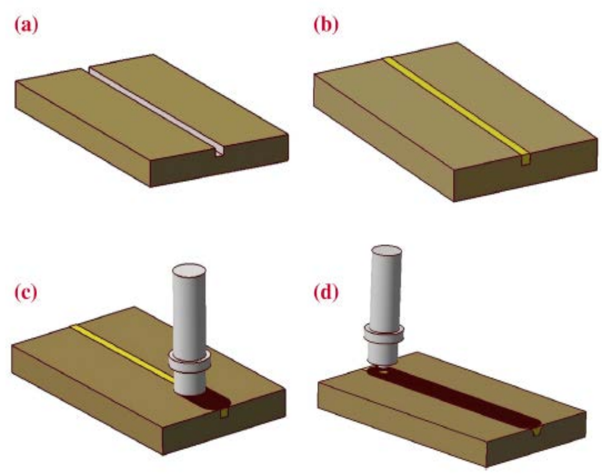

Fig. 1 Steps for fabrication of surface metal matrix composite [22]

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2 Experimental Procedure

2.1 Materials used

The alloy chosen for this study was 7020-T6 heat treatable wrought alloy introduced as a plate of (150 mm x 35 mm x 10 mm thick). This alloy is generally used in armoured vehicles, military light bridges, motor cycle and bicycle frames and also used in aircrafts and ship structure [26-28].
The chemical composition (in weight percent) of the parent 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. %	2.23	1.46	0.46	0.19	0.19	0.121	Bal.

TABLE 2
Mechanical properties of AA7020-T6

Ultimate tensile strength (MPa)	384.6
Elongation (%)	14.7
Vickers hardness (HV 0.5 kg)	115

2.2 Sample preparation

Samples A groove with 1 mm width and 5 mm depth was made in the middle of the plate surface and aligned with the centerline of the rotating probe. Commercially Al_2O_3 powder (99.9% purity and 50 nm average particle sizes) was mixed with small amount of methanol and then incorporated into the groove.

2.3 FS process

In the beginning, upper surface of the groove was closed with a modified pinless FSP tool to prevent the Al_2O_3 nanoparticles from being scattered out of the groove during the FSP.

Multi-pass friction stir processing was performed using cold worked tool steel (K340) with featureless concave shoulder and non- profile pin. In each pass, the tool was travelled along the same line as the previous one but in the opposite direction. The tool dimensions and the main operating parameters are presented in table 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 Macro- and microstructural analysis has been conducted on both base materials and cross-sections of friction stir processed specimens using optical microscope (OM) and Scanning Electron Microscope (SEM). To have an insight into the mechanical properties, Vicker hardness measurements were carried out at 500 kgf load (Hv0.5) for 15 sec dwell period.

TABLE 3
The tool dimensions and FSP Parameters

Shoulder diameter (mm)	20
Pin length (mm)	6
Pin diameter	7
Rotational speed (rpm)	500
Traverse speed (mm/min)	20
Tool tilting angle	3°
Plunge depth (mm)	6.2

3 Results and Discussion

3.1 Macrostructure

Fig. 2 shows the upper surface appearance of the fabricated SMMC. Since a groove was made at the center of the aluminum plate to incorporate the Al_2O_3 particles, the material has to flow into the groove. It is evident from the macrograph that the groove is effectively closed and completely bonded on all sides subsequent to FSP. Defect-free, sound and continuous stir zone was produce. The top surface shows very smooth quality and there is no prominences or depressions inspite of tool's stirring.

Fig. 2 Picture of as-processed plate with one pass at 500 rpm, 20 mm/min

3.2 Flow mechanism of powder

It was observed from Fig. 3, that the powder appeared 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 shift of 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.

The macrostructure observations Fig. 3 revealed also that, not all the material in the tool path was actually stirred after 1 pass.

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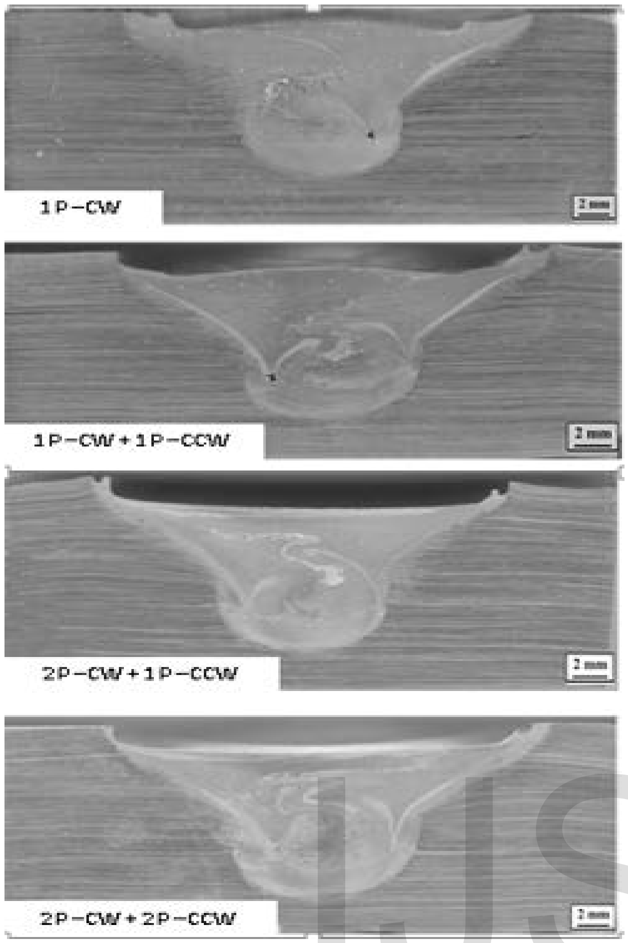

Fig. 3 Optical macrograph of a cross-section of the friction stir surface metal matrix composite at different passes (Pass: P, Clockwise: CW, Counter clockwise: CCW)

3.3 Macrostructure

Previous studies [18-25, 29] 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 isn't enough, so powder particles are not easy to disperse in larger region and move in clustered (unmixed particles) shape. As a result, agglomerated Al_2O_3 particles could be observed in the surface composite layer produced by one FSP pass (Fig. 3). The observed clustering particle size is frequently much larger than the individual Al_2O_3 size.

Fig. 3 reveals a narrow thermomechanically affected zone (TMAZ) with sharp boundary between stir zone and TMAZ, where existence of reinforcing particles can be introduced as primary reason for this phenomenon. It is suggested that the black lines observed are related with the distribution of Al_2O_3 particles.

3.4 Microstructure

Previous studies [18-25, 29] 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 isn't enough, so powder particles are not easy to disperse in larger region and move in clustered (unmixed particles) shape. As a result, agglomerated Al_2O_3 particles could be observed in the surface composite layer produced by one FSP pass (Fig. 4). The observed clustering particle size is frequently much larger than the individual Al_2O_3 size.

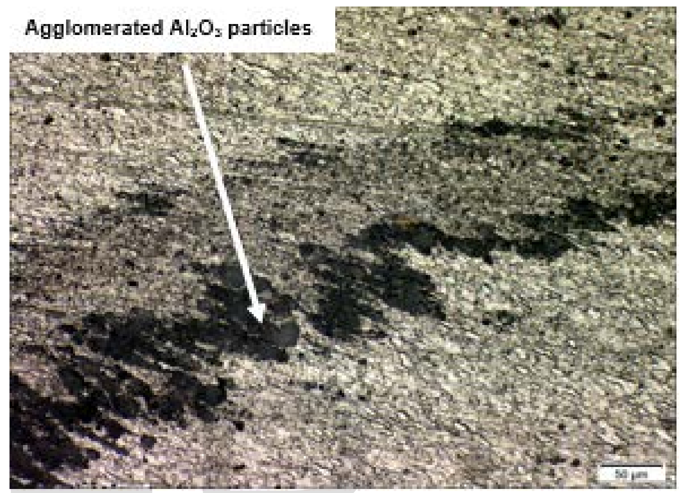

Fig. 4 Optical macrograph of the stir zone for FSPed sample with the Al_2O_3 particles after 1 pass.

Fig. 5 shows the SEM micrograph of the interface zone between surface composite layer and aluminum alloy substrate. The surface composite layer appears to be well-bonded to the aluminum alloy substrate and no defects are visible at the interface.

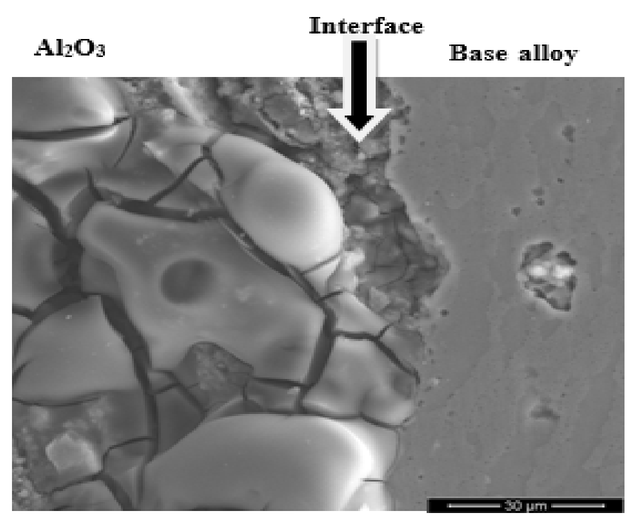

Fig. 5 SEM micrograph of the interface zone between surface composite layer and base metal

Observing the stir zone of surface composite layer produced by one FSP pass in comparison to the stir zone of sam-

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ples FSPed without powder indicates that the presence of Al_2O_3 particles restricts the grain growth and cause severe grain refinement of aluminum matrix as shown in Fig. 6.

As reported by other researchers [12,25, 29], reinforcing particles increases the nucleation sites, break-up the pre-existing grains, and impedes the migration of grain boundaries due to pinning effect of particles.

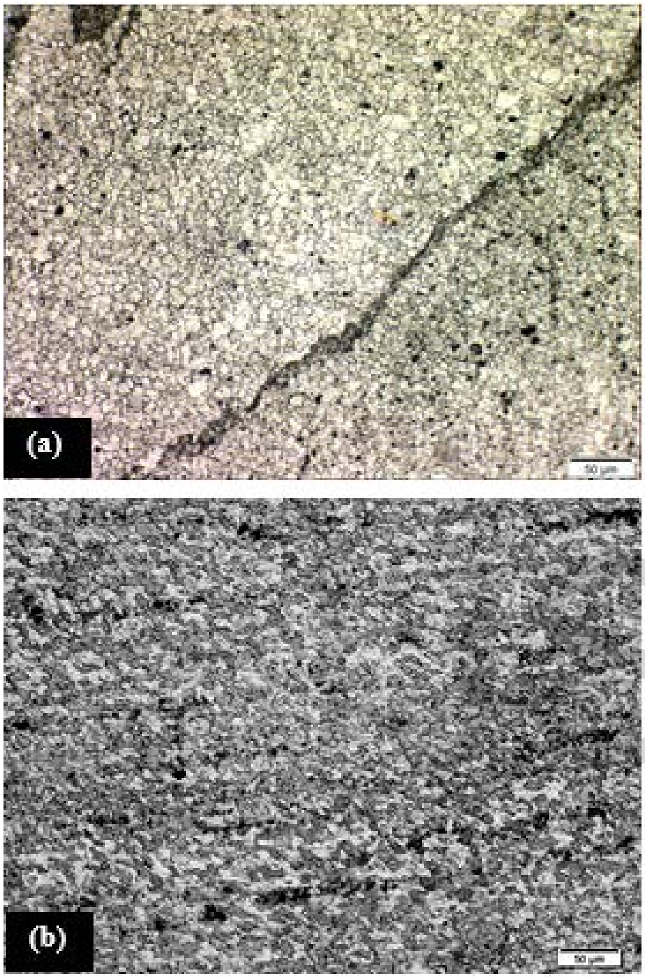

Fig. 6 Optical micrographs of the stir zone for the FSPed alloy after 1 pass (a) With the nano-sized Al_2O_3 particles, (b) Without particles.

3.5 Effect of number of passes and tool direction

Multi-pass FSP remarkably improves cohesive bonding between Al_2O_3 particles and base metal resulting in elimination of interfacial de-bonding (Fig. 7)

With further FSP passes, dispersion of Al_2O_3 particles can be improved and the cluster Al_2O_3 size is reduced. Breaking the agglomerated zones and further separation of particles from the clusters during each passes, resulted in improved nanoparticle distributions in parallel bands (Fig. 8).

On the other hand, there were just a few regions which included the unmixed Al_2O_3 ceramic powders inside the FSP processed zone. As expected, with change of rotational direction between passes, the dispersion of SiC particles in composite layer improved and the reinforcement particles density on the advancing side became almost similar to that on the retreating side.

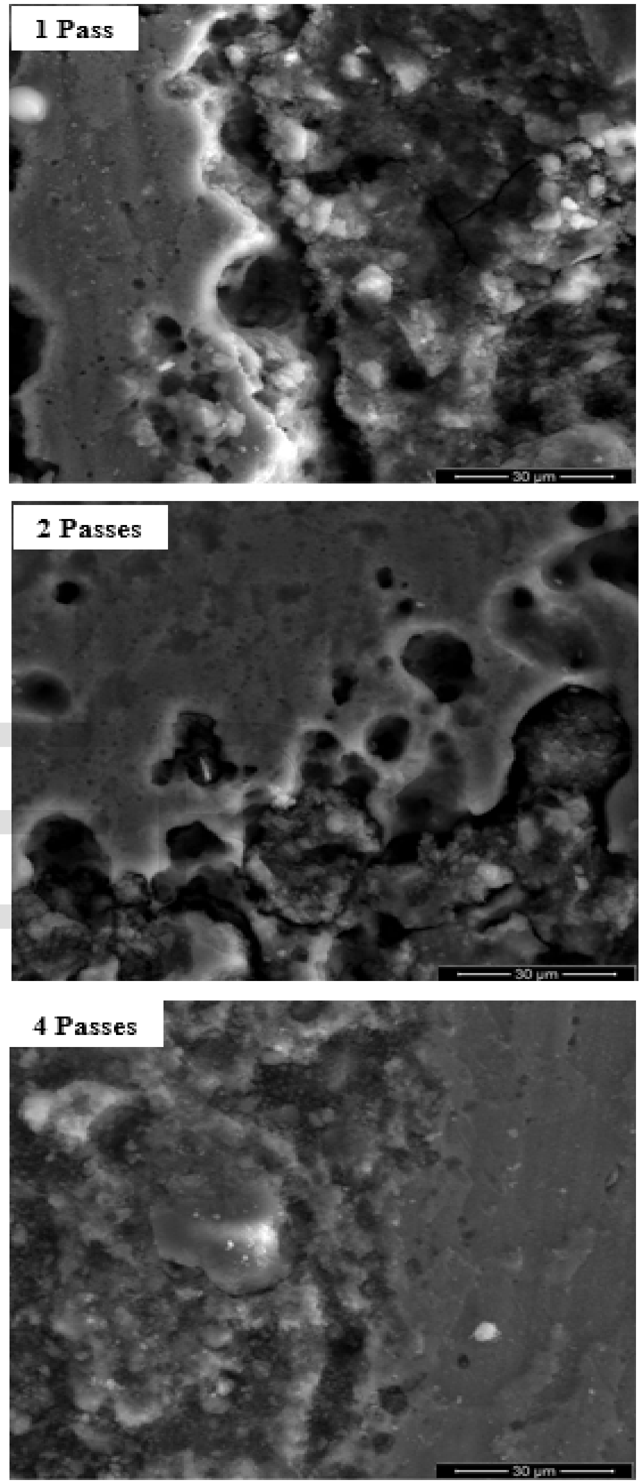

Fig. 7 SEM micrograph of the iterface zone between surface composite layer base metal at different number of passes

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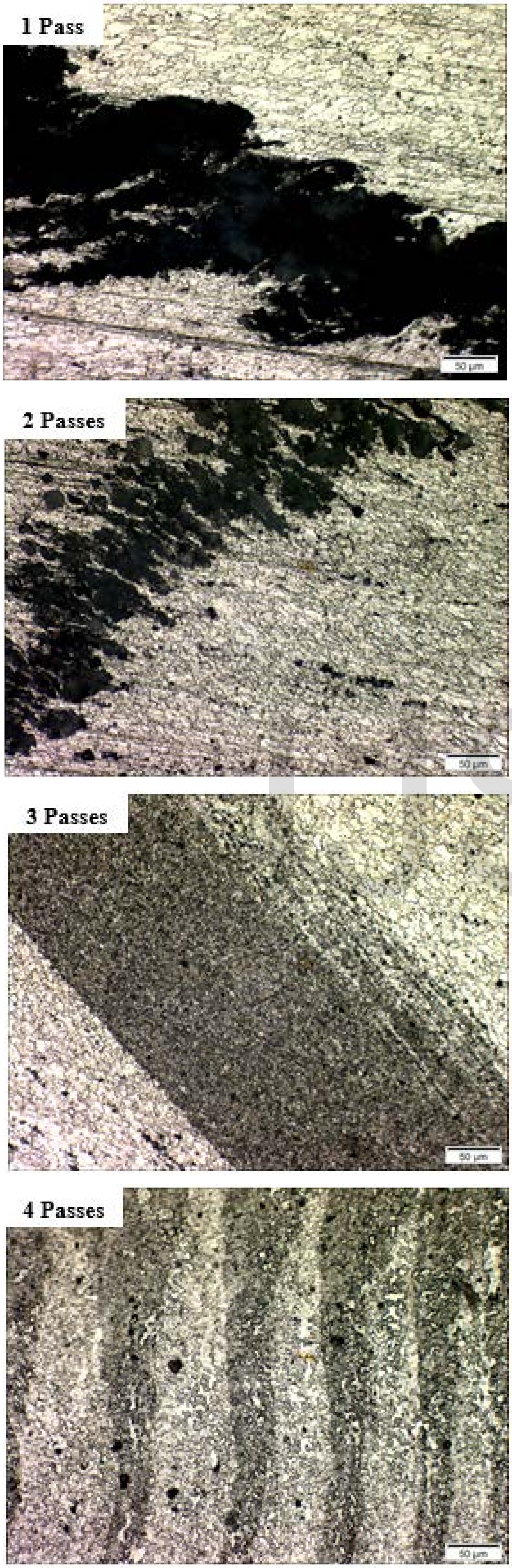

Fig. 8 Effect of number of passes on the distribution of particle

3.6 Hardness

The hardness value depends mainly on the presence and uniform distribution of Al_2O_3 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 to the obtained results in Fig. 9, the average hardness values of surface composite after 1 pass, 2 passes, 3 passes and 4 passes are increased about 1.14, 1.22, 1.24 and 1.3, respectively times that of the as-received aluminum matrix.

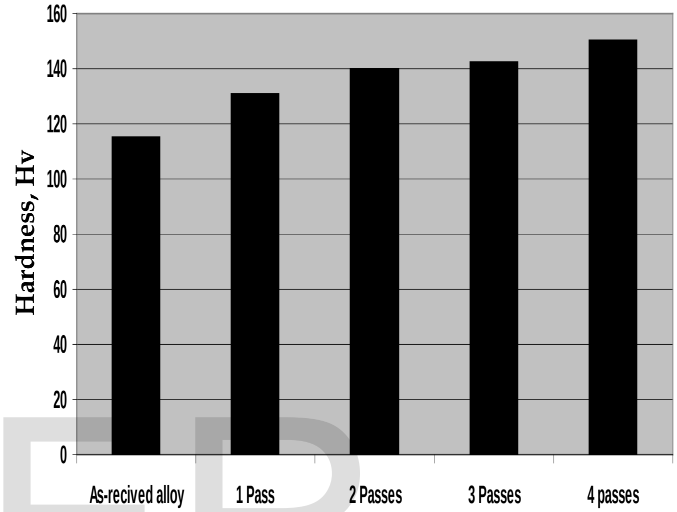

Fig. 9 Effect of number of passes on average hardness number of stir zone

The hardness distribution profile through the fabricated composite after 1 pass (Fig. 10.a) 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. 10. b, c, d). These results imply that the pin efficiently dispersed the nano-sized Al_2O_3 powders in a reasonably uniform manner.

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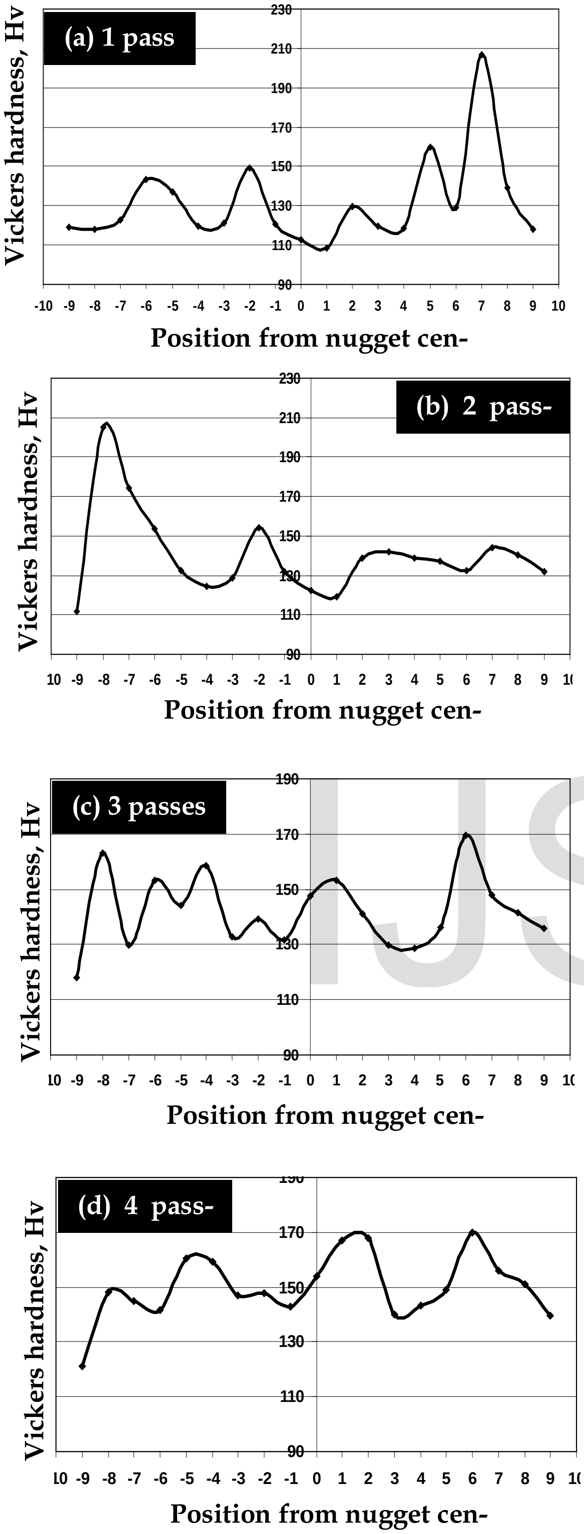

Fig. 10 The hardness profiles along the cross section of the surface composite layers.

4 CONCLUSIONS

In this investigation an attempt has been made to study the effect of friction stir processing on the mechanical behavior of AA7020 aluminum alloy.

From this investigation, the following conclusions are derived:

1- The Al_2O_3/AA7020 wider and deep bulk composite was fabricated successfully by using friction stir process.
2- Good interface between particles and base metal were formed during this process. The surface composite layer is well bonded to the aluminum alloy substrate. Defects were not visible validating that FSP is an effective way for composite fabrication in Al alloys.
3- The hardness of surface composite is found to be at least 18% higher than that of the base metal.
4- By increasing the number of passes, the dispersion of Al_2O_3 particles in the stir zone became more homogenous and the average hardness increased.

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