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Influence of Friction STIR Processing on the Microstructural, Hardness and Tribological Characteristics of A356 Cast Aluminium Alloy

Friction stir processing (FSP) is a surface treatment technology that can eliminate casting defects locally by refining microstructures, thereby improving the mechanical properties of material. The present work investigates the effect of FSP process parameters, typically, the tool rotational and transverse speeds on the microstructure, hardness and tribological behavior of A356 cast aluminum alloy. Three different transverse speeds, typically, 37.5, 60 and 75 mm/min and three different tool rotational speeds, typically, 750, 950 and 1180 rpm were used for FSP. The results revealed that FSP improved significantly the wear resistance of the surfaces of A356 alloy. It has been found that friction stir (FS) processed regions showed finer grain size, better hardness and wear resistance than the as-cast A356 alloy. Increasing the tool rotational and/or the transverse speeds reduces the size α -Al primary grains and increases the hardness and wear resistance of the A356 alloy surfaces.

1. INTRODUCTION

Friction stir welding (FSW), a solid-state joining process invented at the Welding Institute (TWI), UK in 1991, is a technique for joining Al alloys [1]. Friction stir processing (FSP) is a variation of FSW. It applies the same principle; however, it does not join materials but modifies the microstructure of specific areas of the surface to improve its microstructural and mechanical properties [1,2]. FSP has shown significant microstructural refinement and improved mechanical properties of both hypo- and hypereutectic cast Al-Si alloys [3,4]. It has been reported that, FSP almost eliminates the casting porosity and cavities, refines the coarse acicular Si particles in the eutectic structure as well as the primary Si particles by breaking them up and dispersing them into the aluminum matrix [3-6]. Such observations show that FSP is an effective technique that can be used to modify the microstructure in cast Al-Si alloys.

Although there are large number of investigations were conducted to evaluate the effect of FSP on the mechanical and microstructural characteristics of cast

Al-Si alloys [3-8], a fewer investigations were conducted to evaluate the effect of FSP on the tribological characteristics of cast Al-Si alloys [9,10]. For example, Mahmoud et al. [9] reported that the friction stir (FS) processed samples exhibited lower wear rate and coefficient of friction than the as-cast hypereutectic A390 Al-Si alloy. Both the wear rate and the coefficient of friction were found to be reduced by reducing the tool rotational speed and/or increasing the tool transverse speed. Increasing the number of passes reduces the wear rate as well as the coefficient of friction. Also, it has been reported that, the FS processed zones exhibited better mechanical properties as well as dry sliding wear resistance than the as-cast A413 Al-Si base alloy.

The aim of the present investigation is to use FSP to modify the surface structure of A356 hypoeutectic Al-Si cast alloy. The influence of the FSP parameters, typically, the tool rotational speed and tool transverse speed on the tribological behavior of the modified surfaces was investigated.

2. EXPERIMENTAL PROCEDURES

The base material used in the current study is A356 cast Al-Si alloy. The A356 aluminum alloy has a nominal chemical composition of (in wt.-%) 7.2% Si, 0.29% Mg, 0.02% Cu, 0.01% Mn, 0.18% Fe, 0.01% Zn, 0.12% Ti, 0.02% Ni, 0.05% Sn, 0.1% Pb and 92. % Al. The A356 alloy was received in the form of ingots and machined into thick plates having dimensions of [50 mm (width) × 200 mm (length) × 10 mm (thickness)]. The tool was made from H13 tool steel. A schematic illustration of the used tools is shown in Figure 1. The FSP was conducted using a vertical CNC milling machine using three different tool rotational speeds (ω), typically, 750, 950 and 1180 rpm and three different transverse speeds (v), typically, 37.5, 60 and 75 mm/min. In all experiments, the tool angle was fixed to 30 and the friction pressure was held constant.

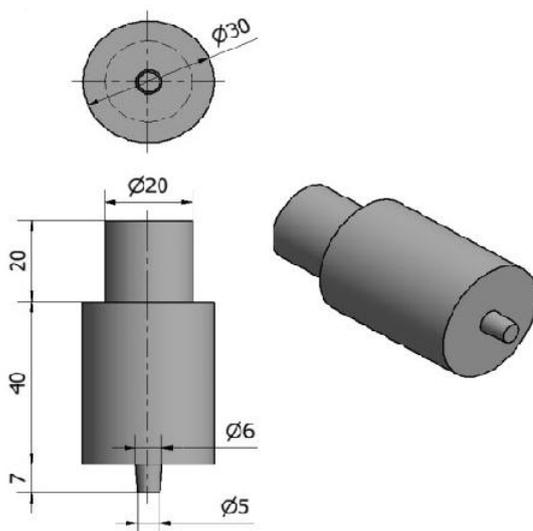


Figure 1: Schematic illustration of the tool used in the present investigation (Dimension in mm)

After processing, the test pieces were cut along the transverse direction and mounted to analyze their microstructures characteristics. The microstructural characteristics of the FS-processed regions were investigated using both optical metallurgical (OM) microscope and scanning electron microscope (SEM).

Vickers hardness profile of the FS-processed regions were measured, on the cross-section perpendicular to the processing direction, using a Vickers indenter with 10 kg load for 10s. Wear tests were performed on a pin-on-ring machine shown schematically in Figure 2. All tests were run under dry sliding conditions. The wear samples have 10 mm (length), 10 mm (width) and a height of 10 mm. The counterface disc was made of 316 stainless steel, of nominal composition (by wt.-%) 0.08% C, 1% Si, 12% Ni, 17% Cr, 2.5% Mo and balance Fe, with a hardness of 184 VHN. All samples were tested for 30 minutes at a load of 20 N. The rotational speed of the disc and wear track diameter were kept constant at 100 rpm and 200 mm, respectively. A standard wear test procedure was employed. Before each test, the cylinder was cleaned with acetone to remove any possible traces of oil, grease and other surface contaminants. The specimen, which was also cleaned with ethanol, was weighed before and after the wear tests using an electronic balance with accuracy of 0.0001 g. The dry sliding weight loss was computed using the weight loss before and after the experiments. The data for the wear tests was taken from the average of three measurements. Friction coefficient measurements were conducted using a force transducer to measure the frictional force developed on the pin holder and caused by the ring rotation. The coefficient of friction was computed by dividing the frictional force (F) by the normal load (W). The worn surfaces of the wear samples were examined using SEM.

3. RESULTS AND DISCUSSION

3.1 Macro- and Microstructural Characteristics

Figure 3 shows typical optical macrographs of the transverse cross-sections of A356 alloy specimens after

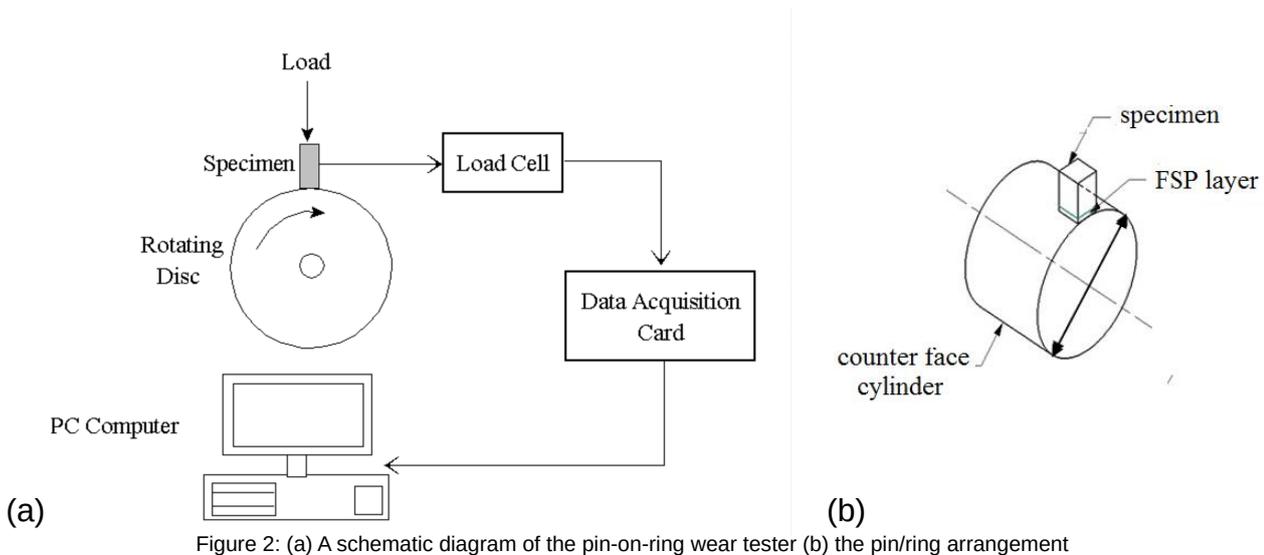


Figure 2: (a) A schematic diagram of the pin-on-ring wear tester (b) the pin/ring arrangement

FSP at different tool rotational and transverse speeds. The stirred zones (SZ) are clearly visible in the macrograph. In some specimens, for example in the specimen shown in Figure 3a, small tunnel defect (cavity) was observed at the bottom of the advancing sides (AS). No defects were observed at the retreating sides (RS) of the FS- processed regions.



Figure 3: Typical macrostructure developed by FSP at tool transverse speed and rotational speed of (a) 37.5 mm/min and 1180 rpm; (b) 75 mm/min and 750 rpm

The tunnel defect was observed in specimens FS-processed at the lowest tool transverse speed (i.e. at 37.5 mm/min) and/or the highest tool rotational speed (i.e. at 1180 rpm). It is believed that the formation of the cavities in the FS-processed zone may attribute to the high heat input during FSP [3,9,10]. Increasing the tool rotational speed and/or decreasing the transverse speed increases the heat input. The high heat input causes turbulent flow of the metal

around the tool pin due to excess plasticization of base metal under the tool shoulder. In this case, defective FS-processed regions are produced. For FSP, to produce defect free FS-processed zones sufficient frictional heat is to be generated in the process zone. In the present investigation, at the lowest tool transverse speed (i.e. 37.5 mm/min) and/or at the highest tool rotational speed (i.e. 1180 rpm), the amount of heat generated by friction was most likely to be high which cases tunnel defect. Figure 4 shows optical micrographs of the microstructure of the A356 as-cast alloy. It is clear that the structure of the A356 alloy consists of the primary α -Al dendrites and eutectic structure. It has been found that the as-cast A356 alloy suffers from cavities. Two types of cavities, typically, porosity cavities (not shown) and

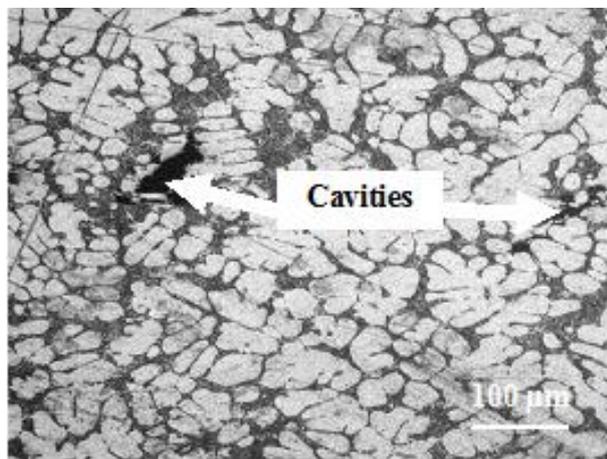


Figure 4: The microstructure of the A356 as-cast alloy

shrinkage cavities (shown in Figure 4) with irregular shapes were observed in the microstructure.

Figure 5 shows a sample micrograph of the FS-processed region, at the advancing side, for a sample processed at a tool rotational speed 950 rpm and a tool transverse speed 60 mm/min. Beside the base alloy, three regions are clearly visible in the micrograph, typically, the heat affected zone (HAZ), the thermo-mechanically affected zone (TMAZ), and the stir zone (SZ). These regions are formed due to intense plastic deformation at high temperature leading to dynamic recrystallization and complex material mixing during FSP [1]. The SZ experiences a combination of thermal cycle and extensive plastic deformation resulting in an extra-fine microstructure. The TMAZ experiences both temperature and deformation during FSP and characterized by a highly deformed structure. The HAZ is the zone that is believed to be mechanical unaffected but only the thermal effects caused by the frictional heat generated by the should and tool pin rotation. Figure 5 shows also that the SZ exhibited finer α -Al grains when compared with the base alloy. The stirring action of the tool during FSP resulted in fragmentation of the coarse primary α -Al grains to finer grains. Moreover, the stirring action eliminated the shrinkage cavities observed in the base alloy by closing them. Figure 6 shows the variation of the average grain size with the transverse speed at different tool rotational speeds. The results revealed that, at constant tool rotational speed, increasing the transverse speed reduces the average grain size. For example, at constant tool rotational speed of 1180 rpm, increasing the tool transverse speed from 37.5 to 75 mm/min reduces the average grain size from 21.45 to 11.54 μm . Also, it has been found that, at constant tool transverse speed,

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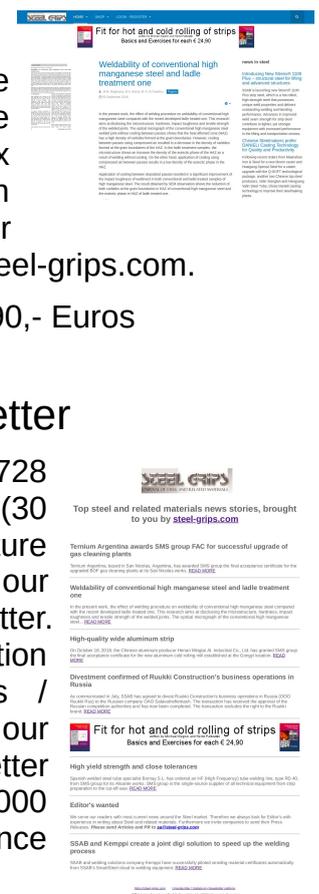
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increasing the tool rotational speed reduces slightly the average size of the α -A1 grains. For example, at constant tool transverse speed of 37.5 mm/min, increasing the tool rotational speed from 750 to 1180 rpm reduces the average grain size from 26.61 to 21.45 μm . According to the aforementioned results, it can be concluded that increasing the tool transverse speed and/or reducing the tool rotational speed reduce(s) the average grain size of the α -A1 grains at the stirred zones.



Figure 5: Optical micrographs of a region FS-processed at tool rotational and transverse speed of 950 rpm and 60 mm/min, respectively

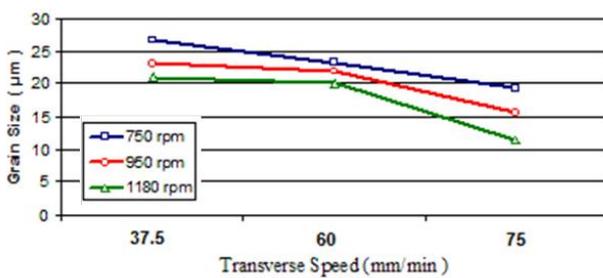


Figure 6: Variation of the size of primary α -A1 grains with the tool transverse speed at different tool rotational speed

3.2 Hardness Measurements

The as-cast A356 alloy exhibited average hardness of about 60 VHN. Figure 7 shows typical example of the transverse section hardness profile of FS-processed regions at constant tool rotational speed of 950 rpm and several tool transverse speeds. The vertical dashed lines indicate the position of the pin during FSP. It has been observed that the FS-processed

regions exhibited higher hardness when compared with the base as-cast alloy. The stirred zones exhibited higher hardness values than both of TMAZ and HAZ zones. Such observation was noticed for both retreating and advancing sides. Figure 8 shows the variation of the average hardness of the stirred zones with tool rotational speed at different tool transverse speeds. The results revealed that increasing the tool rotational speed and/or the transverse speed increase(s) the average hardness of the stirred zones. The enhancement of the mean hardness of the stirred zones in comparison with the A356 as-cast alloy may attribute to the microstructural enhancement due to FSP such as the grain refinement of the α -A1 grains as well as the eliminations of casting defects such as cavities and pores. The enhancement of the hardness of the cast Al-Si alloys due to FSP was reported by many workers [3-10]. The relationship between the hardness (Hv) in the stirred zone and the grain size (d) can be explained using the Hall–Petch equation [11]:

$$H_v = H_0 + H_K d^{-1/2} \quad \dots(1)$$

Where H_0 and H_K are appropriate constants. It is clear from equation (1) that H_v is proportional to $d^{-1/2}$. Accordingly, the finer the grain size is, the higher the hardness value is.

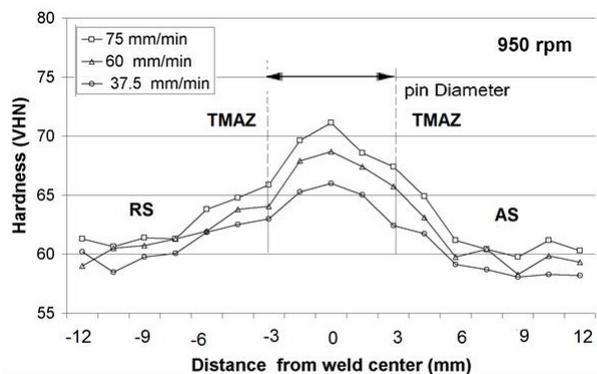


Figure 7: Hardness profiles of transverse section of regions FS- processed at tool rotational speed of 950 rpm and several tool transverse speeds

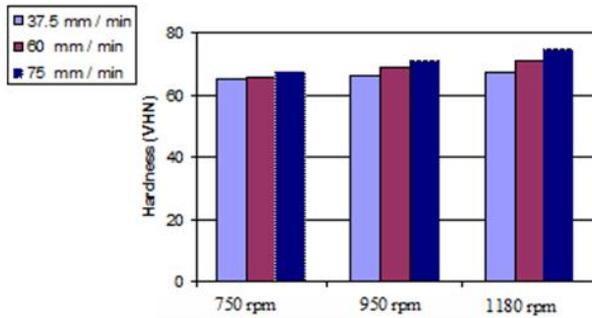


Figure 8: The Variation of the average hardness of the stirred zones with tool rotational speed at different tool transverse speeds

3.3 Tribological Behaviour of FS-Processed Regions

Figure 9 shows typical variation of the coefficient of friction with sliding distance for the sample FS-processed at 750 rpm and 37.5 mm/min under dry sliding conditions. The A356 as-cast alloy exhibited an average coefficient of friction of about 0.135. The FS-processed samples exhibited lower average coefficient of friction when compared with the as-cast alloy. Table 1 lists the values of the coefficient of friction for the FS-processed samples. The results revealed that at constant tool rotational speed increasing the transverse speed reduces slightly the average coefficient of friction. For example, at constant tool rotational speed of 950 rpm, increasing the transverse speed from 37.5 to 75 mm/min reduces the coefficient of friction from 0.138 to 0.133. It has been found also that, at constant transverse speed, increasing the tool rotational speed has practically no effect on the coefficient of friction.

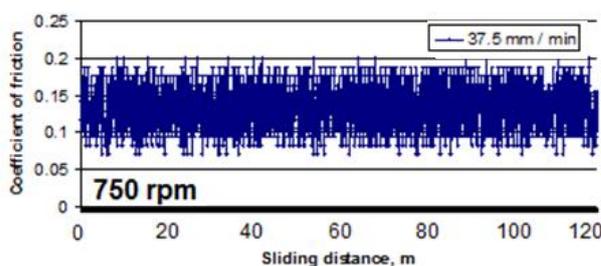


Figure 9: Variation of the coefficient of friction with the sliding distance sample FS-processed at 750 rpm and 37.5 mm/min

The as-cast A356 alloy showed average wear rate of about 1.8331×10^{-3} g/m. The FS-processed samples exhibited better wear resistance than the as-cast A356 alloy. The maximum average wear rate was about 1×10^{-3} g/m for samples FS-processed at 750 rpm and 37.5 mm/min. Figure 10 shows the variation of the average wear rate of the FS-processed samples with the transverse speed at several tool rotational speeds. It is clear that increasing the tool transverse speed and/or the tool rotational speed reduces the average wear rate. The improvement of the wear resistance of the FS-processed samples compared with the as-cast A356 samples may attribute to the

Transverse speed (mm/min)	Average coefficient of friction, (μ)		
	Rotational speed (rpm)		
	750	950	1180
37.5	0.136	0.138	0.136
60	0.134	0.135	0.134
75	0.132	0.133	0.133

Table 1: Average coefficient of friction for A356 alloy FS- processed samples

improvement of the hardness due to FSP. It is well known that increasing the hardness of the materials reduces the volume of the material removed from the surface and hence improves the wear resistance of the alloy. In the present investigation, the FS-processed regions showed higher hardness that of the as-cast A356 base alloy which assisted in reducing the wear rate (i.e. improving the wear resistance) of the A356 alloy.

Figure 11 shows SEM micrograph of the worn surface of the FS-processed

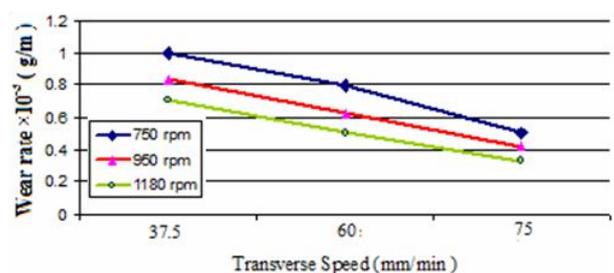


Figure 10: Variation of the average wear rate of the FS-processed samples with the transverse speed at several tool rotational speed

samples. It has been observed that the worn surfaces FS-processed at high tool transverse speeds and/or high tool rotational speed exhibited smoother and less damaged (smaller grooves and crack sizes) surfaces (as shown in Figure 11b, 11d) than those FS-processed at lower tool rotational and transverse speeds (as shown in Figure 11a, 11c). For example, the grooves on the worn surfaces of samples FS-processed at 37.5 mm/min and 750 rpm (Figure 11a) were deep and the plastic deformation at the edge of the groove is heavy when compared with samples FS-processed at the same tool rotational speed but higher tool transverse speed of 75 mm/min (see Figure 11b). and also, the grooves on the worn surfaces of samples FS-processed at 75 mm/min and 1180 rpm (Figure 11d) were smooth and the plastic deformation at the edge of the groove is small when

compared with samples FS-processed at the same tool rotational speed but lower tool transverse speed of 37.5 mm/min (see Figure 11c).

4. CONCLUSIONS

From the present investigation, the following important conclusions are derived:

1. The microstructural characteristics of the A356 alloy was significantly improved using friction stir processing (FSP). FSP assisted in eliminating the structural cast defects such as porosity and shrinkage cavities. FSP produces finer α -Al primary grains when compared with the as-cast A356 alloy. Increasing the tool rotational and/or transverse speeds reduces the size of the α -Al primary grains.
2. The friction stirs (FS) processed regions exhibited higher average

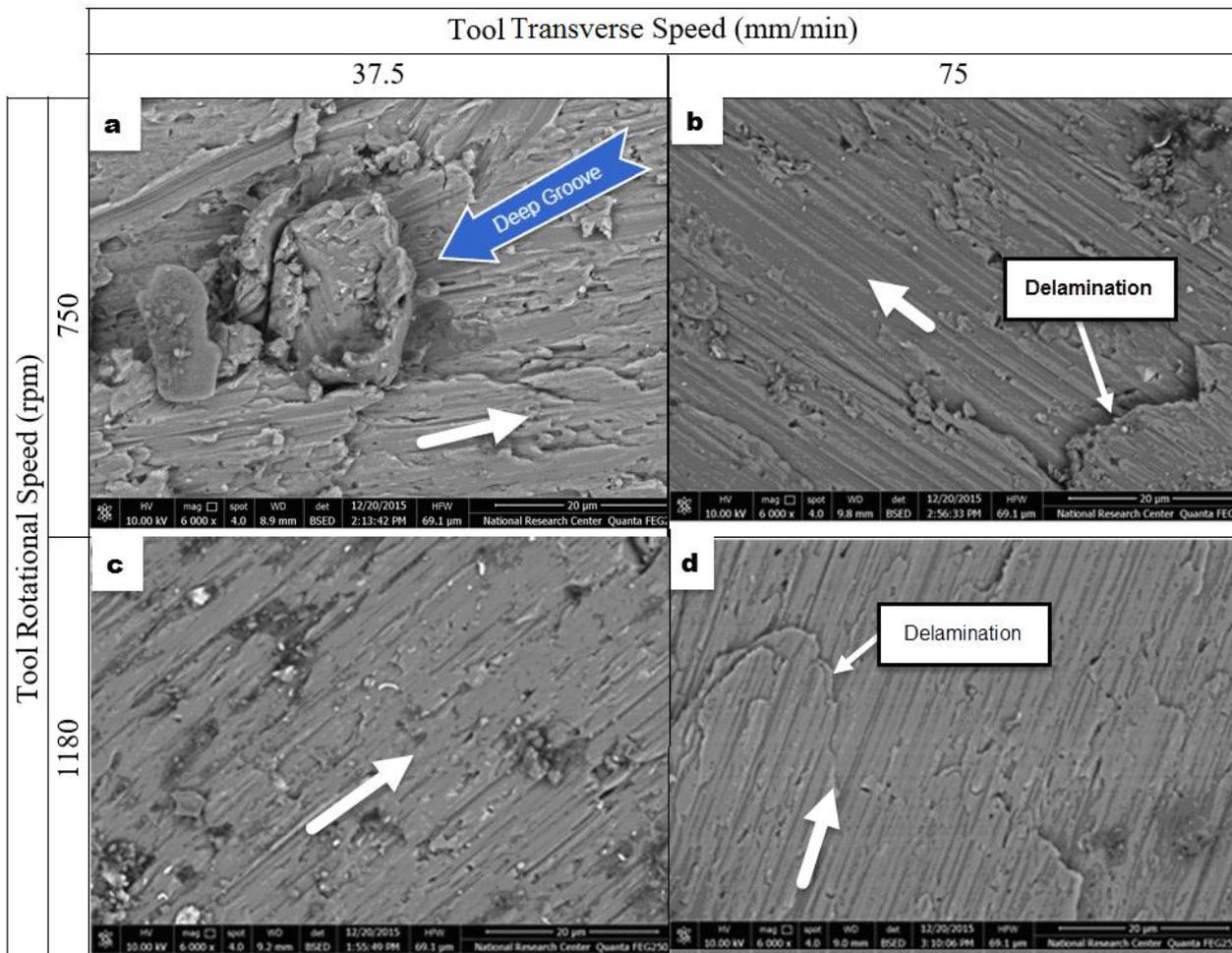


Figure 11: SEM micrograph of the worn surface of samples FS-processed at different tool rotational and transverse speeds (arrows indicate the sliding direction)

hardness and better wear resistance than the as-cast A356 alloy. Increasing the tool rotational and/or transverse speeds increases the hardness and improves the wear resistance of the A356 alloy.

3. The FS-processed samples exhibited lower average coefficient of friction when compared with the as-cast samples under dry sliding conditions. Increasing the transverse speed reduces slightly the average coefficient of friction while increasing the tool rotational speed has practically no effect on the coefficient of friction.

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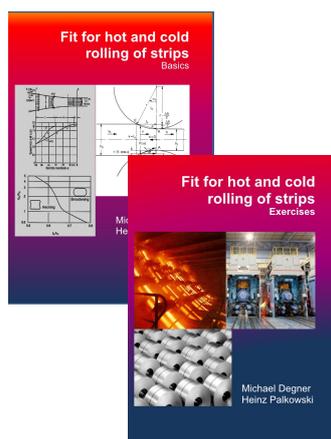
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