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Surface Composite Preparation by Friction Stir Processing

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Abstract: Grooves of 1 mm depth and of different widths 1, 1.5, or 2 mm are made on the surface of AA5083 Al alloy plates and filled with 1.07:112.35 μm alumina powder. Then, the surface is treated with friction stir processing “FSP” to form a composite surface layer of AA5083 matrix reinforced with alumina particles. FSP is carried out using a tool rotational speed of 1400 rpm, processing speed of 25 mm/min and a plunge depth of 4.3 mm. Prepared surface composites are subjected to microstructure investigation, Vickers hardness measurements, and wear rate determination. For comparison, as-received and FSP 5083 Al alloy are subjected, also, to similar tests. The composite layer thickness decreases from 0.8 to 0.7 and to 0.6 mm at 1, 1.5, and 2 mm groove widths, respectively. It seems that, the stirring conditions i.e. 1400 rpm rotation speed, 25 mm/min travel speed and 4.3mm plunge depth are not suitable to specimens with alumina grooves wider than 1mm, where the alumina powder is expelled out of the stir zone, as indicated by micro-structural observations. The surface micro-structure of 1mm alumina groove specimens shows highest alumina volume fraction.

Such specimens possess highest surface micro-hardness numbers of about 120, while those with wider grooves possessed values of only about 100. Moreover, FSP of the surface layer increases the wear resistance of present alloy, especially at higher sliding velocities. However, the wear resistance is dramatically raised when alumina powder is added to form surface composite.

Keywords: Friction stir processing (FSP), Surface composite (SC), A5083 alloy

1-INTRODUCTION

Aluminum alloys are very promising for structural applications in aerospace, military and transportation industries, due to their light weight, high strength-to-weight ratio, and excellent resistance to corrosion. However, low hardness and low strength of aluminium alloys limit their use, especially for tribological applications [1].

Friction stir processing (FSP) is an emerging novel processing technique as a surface treatment, or to fabricate surface composites which is based on the basic principles of friction stir welding (FSW). Some advantages of FSP are micro-structural refinement, densification, homogeneity, accurate control and variable depth of the processed zone. FSP is a green and energy efficient technique without deleterious gases and does not change the shape and size of the processed component [2]

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Friction stir processing (FSP) can be an important enabling technology for the construction of aluminum and magnesium lightweight vehicle substructures. FSP is a means to modify properties of castings. It can dramatically refine grain structures, and improve a variety of properties, that are crucial in vehicle structural applications. Friction stir processing also can be used to modify microstructures to improve the surface properties of metals, a capability that is of particular interest for transportation applications.

Some researchers [2-8] observed that, the addition of particle material to some aluminum alloys improves the mechanical properties and resistance to wear.

N. Murugan et al [2] in 2012 studied the microstructure and micro-hardness of AA1050/TiC surface composite, fabricated using friction stir processing. The microstructure and micro-hardness of the fabricated AMC were analyzed. Scanning Electron Microscope (SEM) micrographs revealed a uniform distribution of TiC particles, which were well-bonded to the matrix alloy. The hardness of AMC was 45% higher than that of the matrix alloy.

Mingzhao [3] in 2001 studied the effect of the addition of alumina and silicon carbide on the mechanical properties of aluminum alloy Al-2618, and the effect of thermal treatment on such properties. Mingzhao [3] noted that, the effect of adding silicon carbide particles on tensile strength and hardness is bigger than that of adding aluminum oxide.

Keesam Shin and Sunghak Lee [4] in 2003 studied property improvement of stainless-steel-base surface composites fabricated by high-energy electron-beam irradiation. Powders and substrate surface were melted and surface composite layers were successfully formed. In specimens fabricated with SiC powders, a volume fraction of $Cr_{23}C_6$ particles (~22 vol.%) were homogeneously distributed along the solidification cell boundaries. The large amount of $Cr_{23}C_6$ particles in combination with solid solution hardening of Si in the matrix strongly improved hardness and wear resistance of the surface composite layer. On the other hand, in specimens fabricated with SiC and Ti+SiC powders, only TiC and $Cr_{23}C_6$ particles were precipitated without precipitation of SiC. Sinha [5] in 2006 studied the effect of adding (Ni-Ti) on the mechanical properties of pure aluminum. The results showed an increase in tensile strength and hardness compared to base metal.

Y. Morisada [6] et al in 2007 studied fullerene/A5083 composites fabricated by friction stir processing. The obtained results can be summarized as follows: First, fullerene molecules can be dispersed in A5083 matrix using FSP. Second, onion ring is formed by the convectional flow due to the shoulder. Third, FSP with fullerene obviously increases the microhardness of the substrates by the promotion of grain refinement, due to the pinning effect of fullerene and its extremely high hardness. Fourth, A5083 with a grain size of less than 200 nm is easily obtained using fullerene dispersion.

Seder [7] in 2008 studied the effect of particle size of SiC added to pure aluminum. Silicon carbide particle sizes of 125, 250, 500 microns were used applying powder metallurgy technique. It was found that, the use of 125 microns particulate size gave the highest hardness and wear resistance values.

Essam R. I. Mahmoud [8] et al in 2009 studied the fabrication of surface-hybrid-MMCs layer on aluminum plate by friction stir processing and its wear characteristics. It was found that, the reinforcement particles were distributed homogenously inside the nugget zone without defects, except some voids that appeared around the Al_2O_3 particles. The average hardness decreased with increasing the relative content of Al_2O_3 particles. Regarding wear characteristics, the wear volume losses of the hybrid composites depended on the applied load and the relative ratio of SiC and Al_2O_3 particles. The hybrid composite of 80% SiC + 20% Al_2O_3 showed superior wear resistance to 100% SiC and Al_2O_3 or any other hybrid ratio, under a normal load of 5 N.

The objective of the current research is to study the effect of the addition of alumina particles on the hardness and dry wear resistanes of (A5083) alloy.

2. EXPERIMENTAL PROCEDURE

Friction stir processing of plates 300×200×10 mm of 5083 Al alloy is studied. The alloy contains 4.0-4.9 % Mg and 0.4-1.0 % Mn. The surface of the 5083 Al alloy plate is doped through FSP with alumina powder 1.07:112.35 μm, as indicated in Fig.1, to produce surface composite. The set up used for carrying out FSP consists of a vertical milling machine and a specially designed FSP tool. The fixture for holding the base plate during FSP was designed and fabricated, Fig.2.

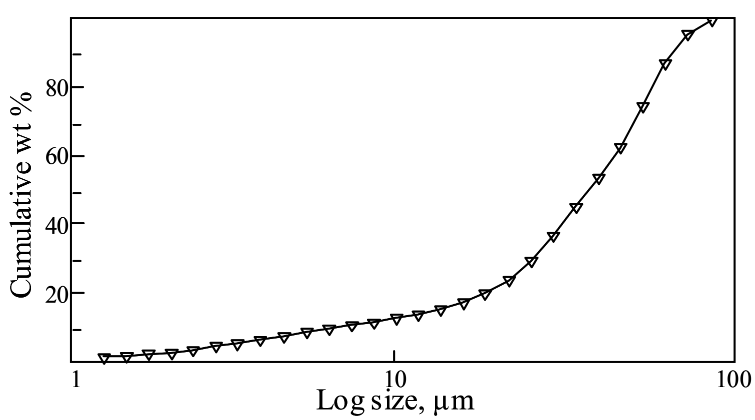

Fig.1 Particle size distribution of alumina powder.

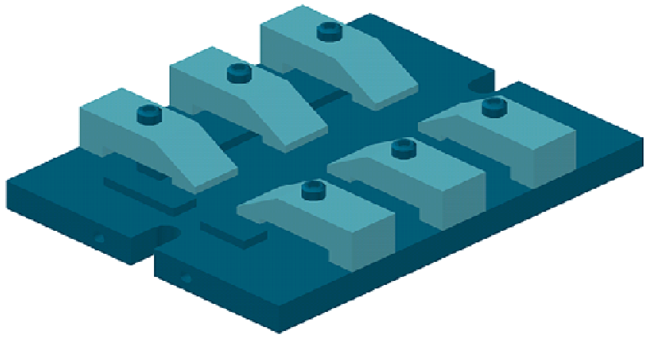

Fig. 2 Fixture for holding specimens during FSP

A specially designed friction stir processing tool, Fig.3, with a shoulder and pin is used. The tool is made of high strength steel of around 61-62 HRC hardness.

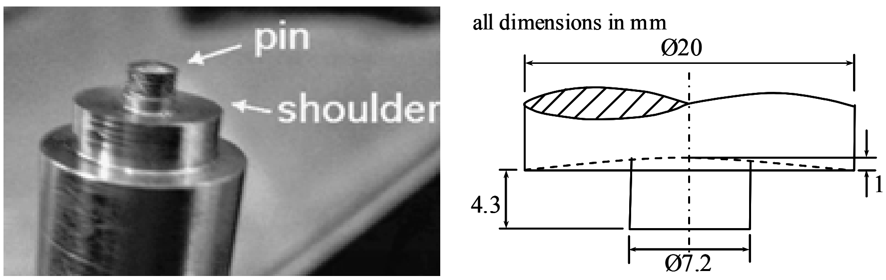

Fig.3 Friction stir processing tool

The fixture containing a duly gripped base plate is placed and tightened to the bed of a vertical milling machine. Grooves, 1 mm deep, are then made on the surface of samples with different widths of 1, 1.5, and 2 mm, and the grooves are filled with alumina powder. Thereafter, the FSP tool is mounted in the spindle of milling machine, and the spindle rotates at 1400 rpm, and the machine bed is moved at a speed of 25 mm/min. The FSP tool is plunged into the base plate, to a depth of 4.3 mm. As the rotating tool moves along the grooves centre line, a layer of 5083 Al–Al_2O_3 composite is produced on the surface of base plate, Fig.4 and Fig. 5.

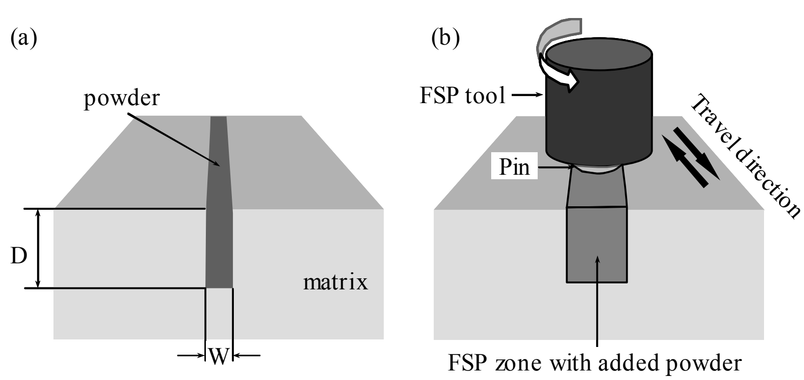

Fig.4 Schematics of FSP, groove depth D is 1 mm and its width W is 1, 1.5, or 2 mm.

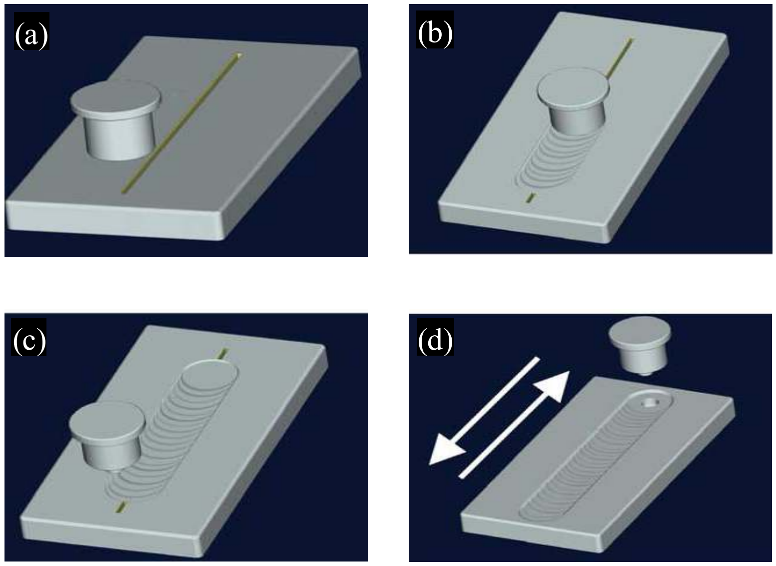

Fig.5 Surface composite preparation procedure. (a) Cutting grooves and inserting powder, (b) Use of a flat tool for surface repair; (c) Use of a tool with a fixed pin for FSP; and (d) Applying multiple FSP passes [9].

2.1 Microstructure Investigation

Samples of prepared AA5083 reinforced with alumina particles are prepared for microstructure investigation. The samples are grinded, successively, with emery papers 180, 320, 500, 1000, then 1200 mesh using Metkon-Gripo2v grinding machine. Microstructure is revealed using Keller's reagent.

2.2 Micro-hardness Testing

Micro-hardness of friction stir processed samples is measured at various locations, from the processed zone to base metal. Before performing the test, the specimen is well polished. The micro-hardness number is then calculated by Matsuzawa Modul DMH'2 device. Each micro-hardness value is the average of at least three readings using 100 gm load.

2.3 Wear Test

The wear rate of friction stir processed test specimens, and of un-processed ones is evaluated on a pin-on-disk type wear testing machine. Flat specimens 8x8 mm in cross section and 10 mm long are cut from the nugget zone of the FSP sample, as well as from the base alloy plate. Such flat specimens fit tightly into a 30 mm long pin shaped holder with 10 mm diameter. The holder is provided with a circular slot to adjust the cut specimen. The pin holding the flat specimen is tightened in the grips provided with the wear testing machine, which is secured inside the loading arm, carrying a normal load of 8.8 N. The sample is held against a rotating disc made of EN32 steel (HRC = 62) at a constant sliding speed of 1, 3, or 5 m/min, and the test duration is 15 min. The weight loss of the sample is measured using an electron weighing balance of accuracy 0.001 mg. Wear rate is calculated from the following equation:

$$\text{Wear rate} = \Delta W / S \quad (\text{gm/cm}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where, ΔW is the weight loss in gm, $\Delta W = W_1 - W_2$ gm,

W_1 is the weight after test, and W_2 is the weight before test gm,

S is the sliding distance = $2 \pi r n t$ cm,

n is the rotation speed rpm,

t is the time = 8.8 min.

Table 1 Wear test conditions

Experiment No.	Test Conditions		
	Speed, m/min	Time, min	Load, N
1	5	15	8.8
2	3	15	8.8
3	1	15	8.8

3. RESULTS AND DISCUSSION

In order to investigate the effect of doping Al_2O_3 particles on 5083Al plate through FSP, the specimens are characterized for microhardness and wear test. The results obtained for friction stir processed samples are compared with those obtained for unprocessed 5083 Al alloy.

Table 2 Test specimen designation

Designation	Description of specimen conditions
S00	Base alloy without FSP and no alumina addition
S0	Base alloy with FSP but no alumina addition
S1	Surface composite groove is 1mm deep and 1 mm wide
S2	Surface composite groove is 1mm deep, and 1.5 mm wide
S3	Surface composite groove is 1mm deep, and 2 mm wide

3.1 Microstructure

Figure 6 shows a cross section of three surface composite samples. It is observed that, the surface composite layer thickness is about 0.08 mm in the case of 1 mm groove width, whereas the thickness decreases to 0.06 in the case of 2 mm groove width. It seems that, the stirring conditions i.e. 1400 rpm rotation speed, and 25 mm/min travel speed, and 4.3 plunge depth are not suitable to higher Al_2O_3 contents, i.e. wider alumina grooves. The alumina powder in the case of groove widths greater than 1 mm may be expelled out the stir zone.

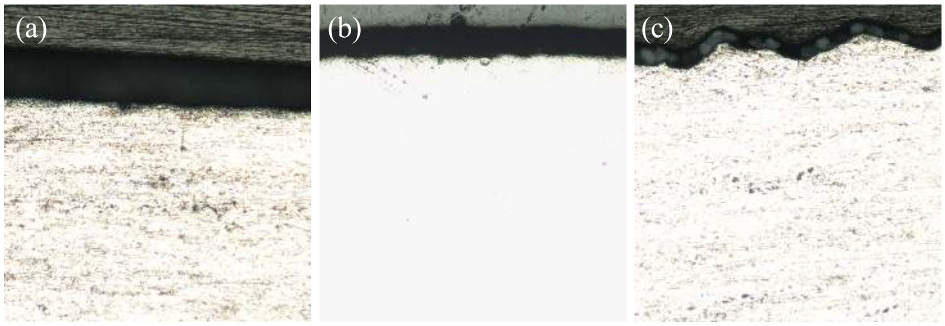

Fig.6 Cross sections of three different surface composites. (a) Groove width 1 mm, composite layer=0. 8 mm. (b) Groove width 1.5 mm, composite layer=0. 7 mm. (c) Groove width 2 mm, composite layer=0. 6 mm.

Figure 7 shows the microstructure on the surface of different surface composites. It is obvious that the alumina volume fraction of the specimen with 1mm groove width, Fig.7a is the largest realized volume fraction. This agrees with previous observation that, the stirring conditions are not suitable to higher Al_2O_3 contents, i.e. wider Al_2O_3 grooves. For specimens with grooves wider than 1mm, alumina powder is expelled out stir zone.

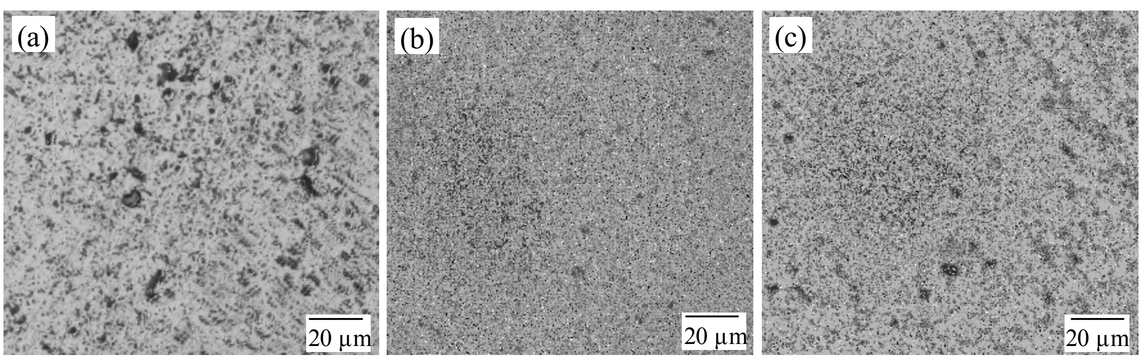

Fig.7 Microstructure of surface composites for specimens with: (a) one mm groove width, (b) 1.5 mm groove width and (c) 2 mm groove width.

3.2 Micro-hardness Measurements

Micro-hardness is measured on the cross-section of test specimens to determine the depth of the composite layer, and the strengthening of the surface layer. Micro-hardness distribution of the subsurface layer of is determined as indicated in Fig.8. Measured values as averages of at least three identical indentations are then plotted against the depth from the surface, as shown in Fig.9. It is generally observed that, the hardness decreases with increasing depth beneath the surface. The depth of the surface layer is about 0.7 mm. The micro-hardness of composites at a depth of 0.7 mm is about 85. However, the surface micro-hardness of specimens with 2 mm groove and those with 1.5 mm groove width is about 100, while that of 1 mm groove width reaches a micro-hardness number of 120.

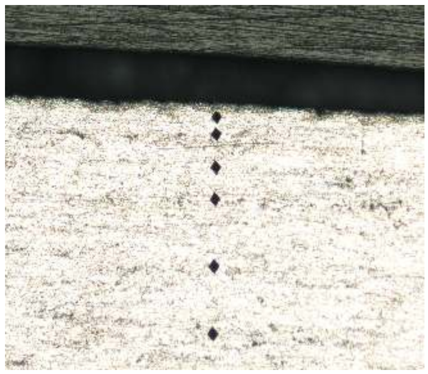

Fig.8 Micro-hardness indentations on SC sample cross-section

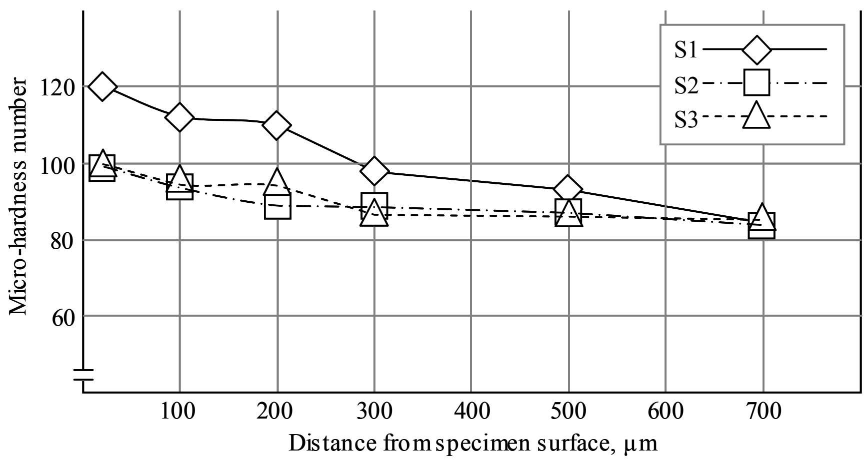

Fig.9 Micro-hardness distribution through the cross section of the SC samples (zero distance stands for the micro-hardness on the surface).

3.3 Wear Rate Determination

The rate of wear is experimentally determined for surface composite specimens S1, S2, S3 containing different contents of alumina. For comparison, the wear rates of as received 5083 Al alloy “S00”, and FSP 5083 Al alloy “S0” are also determined. To study the effect of sliding speed, three speeds 5, 3, 1 m/min are applied. The obtained results are plotted in Fig.10 (5 m/min speed), Fig.11 (3 m/min speed), and Fig.12 (1 m/min speed).

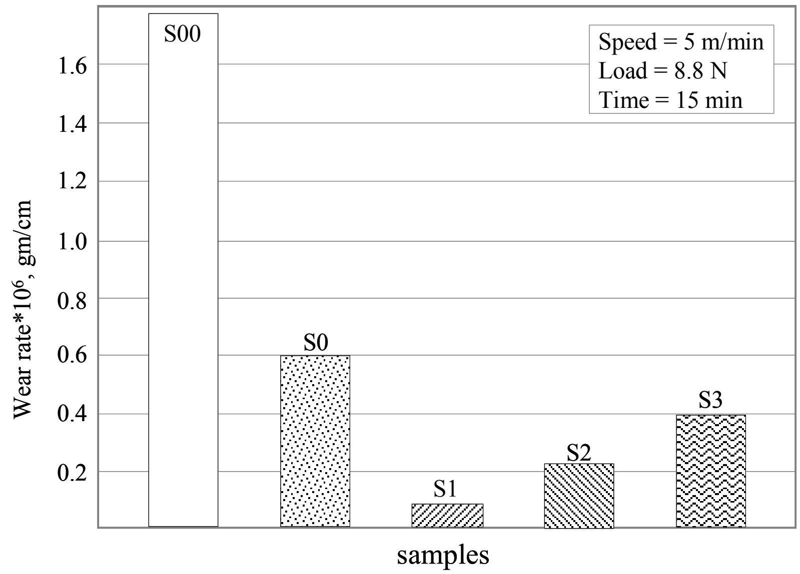

Fig.10 Wear rate of surface composite specimens (S1, S2, S3), and base metal with and without stirring (S0, S00) at 5 m/min speed.

It is obvious from Fig.10 that, the wear rate of specimen S1, i.e. surface composite with one mm groove width is the lowest rate (0.0887 x 10^{-6} gm/cm). Specimen S1 has the highest micro-hardness on the surface, Fig.9. It is also observed that, FSP without the addition of alumina lowers the wear rate of the as-received alloy to one third of its value.

When the sliding speed is lowered to 3 m/min, some variation of the wear rate results takes place, as shown in Fig.11. It is obvious from Fig.11 that, the wear rate of specimen S1, i.e. surface composite with 1 mm groove width is the lowest rate (0.0689 x 10^{-6} gm/cm)

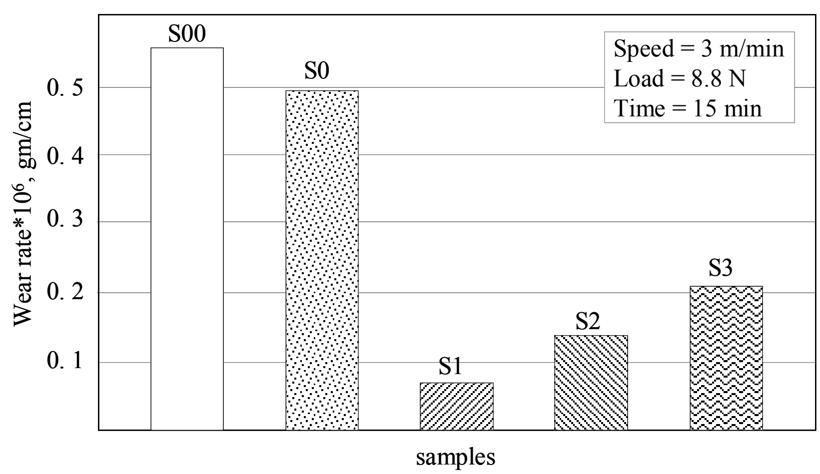

Fig.11 Wear rate of surface composite specimens (S1, S2, S3), and base metal with and without stirring (S0, S00) at 3 m/min speed.

It is obvious from Fig.12 that, the wear rate of specimen S1, i.e. surface composite with 1 mm groove width is the lowest wear rate ($0.00033 x 10^{-6}$ gm/cm), and lowest wear rate when compared with speed 3 m/min and speed 1 m/min .

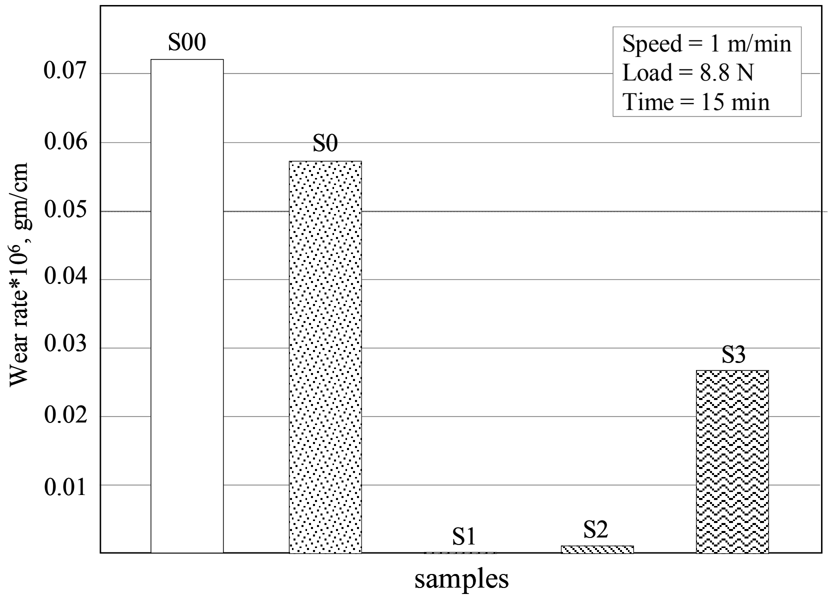

Fig.12 Wear rate of surface composite specimens (S1, S2, S3), and base metal with and without stirring (S0, S00) at 1 m/min speed.

It is clear that, best wear resistance is achieved when the alumina groove width is 1mm. So, the variation of the wear resistance with speed is indicated in Fig.13. the figure indicates that, the wear rate at a load of 8.8 N is strongly dependent on speed. At 1 m/min the wear rate is $0.0033 * 10^{-6}$ gm/cm. Increasing the speed to 3m/min increases the wear rate to $0.069 *10^{-6}$. Further increase of the speed to 5 m/min raises the wear rate to $0.089 *10^{-6}$ gm/cm .

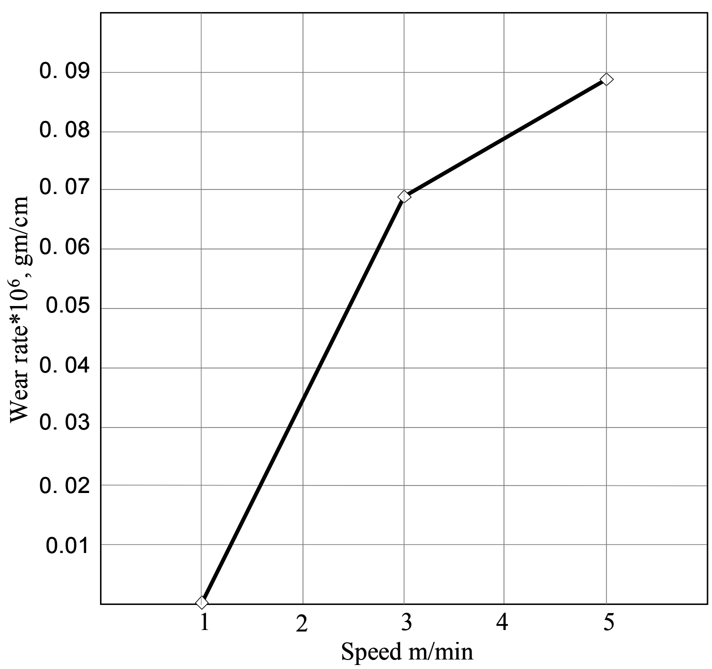

Fig.13 Wear rate of surface composite specimens (S1), at 1 m/min speed.

4. CONCLUSIONS

Based on present results the following could be concluded:

1) Grooves, 1 mm deep, are made on the surface of A5083 matrix specimens with different widths of 1, 1.5, and 2 mm, and filled with alumina powder, then friction stir processing is applied to form surface layer composite.
2) Stirring conditions, 1400 rpm rotation speed, 25 mm/min travel speed and 4.3 mm plunge depth, are not suitable to specimens with alumina grooves wider than 1mm. In case of wide grooves, alumina powder is expelled out of the stir zone, as indicated by micro-structural observations, and supported by micro-hardness measurements.
3) Friction stir processing of 5083 Al alloy significantly raises its wear resistance. However, the addition of alumina powder to form surface composite by FSP, dramatically raises its wear resistance.
4) The wear rate at 1 m/min is 0.0033 * 10^{-6} gm/cm. Increasing the speed to 3m/min increases the wear rate to 0.069 *10^{-6}. Further increase of the speed to 5 m/min raises the wear rate to 0.089 *10^{-6} gm/cm.

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