Synthesis and Characterization of SiC/Al_2O_3 Reinforced AA5083 Metal Matrix Composite by Friction Stir Processing

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Abstract: ***By the use of Friction Stir Processing (FSP), in the following paper aluminium alloy 5083 will be reinforced using silicon carbide (SiC) and alumina (Al_2O_3) to form a metal matrix composite. Through FSP only the surface of the material is altered making it possible to withstand higher strength-to-weight ratios. SiC and Al_2O_3 have both the properties such as low densities and high strengths, therefore, through the combination of both particles a hybrid composite will be achieved. In this study, several numbers of passes will be used in each sample which is going to be characterized by different proportions of the reinforcement particles while parameters such as, traverse speed and rotational speed are fixed.***

Keywords: ***Friction Stir Processing; Wear rate;Ultimate Tensile Strength,Micrographs***

I. INTRODUCTION

The high demand for light but strong materials in aerospace, automobiles, aircraft and other application areas has drawn attention to Metal Matrix Composites (MMCs). Composites are mixtures of at least two different materials or phases. In the case of MMCs, the base is a ductile metal where other metals, ceramics or organics are implanted. These incorporations have the objective of enhancing properties such as hardness, strength, wear resistance, corrosion resistance, fatigue etc.[1,2].In order to fabricate the composite, FSP method will be applied which is based on Friction Stir Welding (FSW) [3]. This technique is a solid-state process [4,5] and therefore prevents the formation of unfavorable phases which may occur in liquid phase processing methods. The main advantage of this process are that it reduces porosity, obtaining nano sized particles as a consequence of dynamic recrystallization and that the required properties can be effectively controlled by the adjustment of the tool parameters [6].This process is carried out by a tool that consists of a pin and a shoulder. The pin is characterized by its length and it determines the depth up to which the microstructure will be modified [7]. The function of the tool is to generate enough frictional heat to cause plastic deformation of the base material while stirring the reinforcement particles at the same time. This is way parameters such as rotational speed, traverse speed and tilt angle must be thoroughly studied. Aluminium presents exceptional strength after welding. However, its use is not recommended above the melting point and this is why FSP appears to be a reasonable alternative to enhace its properties since it works in a solid state [8-12]. The properties of silicon carbide (SiC) include low density, high strength, high hardness and high thermal conductivity [13-14]. On the otherhand, among the properties of alumina (Al_2O_3) the following properties can be found : high strength, high hardness, good wear resistance and high electrical insulation [15].Adding Al_2O_3 to an aluminium base has been produced to increase the yield strength along side the tensile strength. Also, both of these properties are enhanced by incrementing the number of passes [16]. This improvement is also visible in uniform and total elongation [17], although at a certain pass it starts to decrease again [16].Alumina has also been found to enhance the hardnessand microhardness [18] of pure aluminium and aluminium alloys such as AA 5001 [19,20]. Also, in the case of aluminium alloy AA6082, it was demonstrated that the hardness value could be increased up to 3 times that of the base material used along with decreasing the wear rate and making it less susceptible to fluctuations and lowering the friction coefficient [21].When using α-Al_2O_3, a reduction in thermal conductivity was spotted [22]. However, another study also proved that if helped to decrease the wear rate and the friction coefficient and to increase hardness and microhardness [23]. It has been verified as well, that the wear resistance increases when applying higher loads [24].The incorporation of SiC has been studied as well. It's been proven that the addition of SiC nanoparticles to an aluminium base increases the microhardness of the composite [25] along with the hardness and the strength [26,27]. Another study proved that adding SiC in the surface of aluminum alloy AA 5052 could decrease the wear rate upto 9.7 times that of the base alloy, while increasing the microhardness 55% [28].In the case of aluminum alloy AA356, an improvement in hardness and mechanical properties has been verified [29].SiC particles have also been incorporated to an aluminum base along with graphite (Gr) to analyze the effect of rotational speed. The outcome showed that an increase in rotational speed decreases not only the ductility but also the microhardness in the nugget zone, the ultimate tensile strength, the yield strength and the wear rate [30].

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All of this would be a consequence of annealing the stir zone by generating too much frictional heat.A report where SiC and MoS_2 were combined was also carried out. It showed that the hybrid composite had an improvement in the hardness of the composite, although this increase was lower than the one achieved by the SiC on its own. However, the wear resistance obtained a higher value when both of the particles were incorporated. Besides, the analysis of the friction coefficient displayed a decrease which had a lower value for MoS_2 and a higher one for SiC. [31]When analyzing the effect of SiC and Al_2O_3 particles in an aluminium base not many articles could be found, though the results seem to be favorable. With the addition of both Al_2O_3 and SiC, the hardness could be improved up to 20%, the friction coefficient was reduced by 40% which therefore implies a reduction in wear rate [32]. It was also demonstrated that while the hardness can be raised to twice at least the value of the aluminium, this value decreases when Al_2O_3 particles are more abundant and that the wear resistance depends on the load that is applied [33].The combination of alumina and SiC with graphite (Gr) however, results in degradation of the tensile properties tough the microhardness and the wear resistance are still improved in aluminium alloy AA 6061-T6 [34]. A comparison between B_4C and Al_2O_3 proves that while Al_2O_3 has the highest ultimate tensile strength B_4C presents a greater tensile yield strength and a lower ductility [35].Analysing B_4C in an aluminum composite results into an increase in hardness and tensile strength and a decrease in the wear rate and friction coefficient [36]. For aluminium alloy AA5083, the incorporation of B_4C supposed an increase in compressive strength of 15% and 120% in strain [37]. B_4C has also been combined with TiC and the outcome was a reduction in the wear rate and the strengthening of the metal matrix composite [38]. TiC alone can cause an improvement in hardness of 45% [39] but the value of microhardness decrease when increasing the rotational speed of the tool [40]. In the case of TiC reinforcement particles in aluminium alloy AA 6082 an improvement in the mechanical properties is observed and this enhancement increases along with the column fraction of reinforcement particels used [41].In this work two different samples are going to be analyzed. In each of the samples the proportions of the SiC and Al_2O_3 nanoparticles used will be different while rotational speed and the trasverse speed are kept constant at an optimal value. The aluminium matrix will undergo a Friction Stir Process to obtain surface composites. Afterward, the mechanical properties, hardness, wear resistance and microstructure will be evaluated.

2. Experimental Details

2.1 Trail Runs

When carrying out the first expreiments, the reinforcement particels came out of the groove while doing the friction stir processing. To overcome this problem, the particles were mixed with acetone in order to obtain a paste which would be more difficult to take out of the groove. In addition, instead of using a pinned tool from the beginning a pinless tool was used. This tool seals the outside of the groove keeping the particels inside without the stirring taking place. Two passes of this tool were used and the obtained results were favorable. Therefore, the same procedure was used in all of the following experiments.

We can recognize three different areas in Figure 2. In the top part of the image, the material is completely broken due to the length of te pin and we can observe cracks and voids without asmooth or sound surface. In the middle part, we can observe a non-continuous crack with a smoother surface. This crack is the result of inadequate heat generation between the shoulder of the tool and the matrix since it is displaced to the right in

right in comparison with the groove position. In the bottom part, we can distinguish the third area, in which a continuos crack has been formed. This crack is positioned in the groove line which implies insufficient heat generation between the pin of the tool and the aluminium.

Figure 2: 5mm length pin

Figure 3: 3.5mm length pin

In, we can observe two different area. In the top part of the image, we can observe a consideralb ecrack in line with the groove position. Due to the size of the crack we can deduce that the pin length wa too big for the groove depth and therefore, resulted in breaking the material. In the bottom part of the image , however, we can observe a smaller grove and this time it’s no aligned with the groove position. This crack is continuos and created due to deficient heat generation between the shoulder of the tool and the metal matix. In both areas, the formation of an onion ring-like design isn’t noticeable.

As we can observe in Figure 1 the formation of cracks have occurred in the surface of the aluminium base matal. These cracks are the result of insufficient friction heat generation between the tool and the metal matrix. This results in a surface that is neither smooth or sound. However, an onion ring like design made by the tool can ve appreciated although they are eventually interrupted by the cracks.

The temperature was also measured in this sample and during the process it varied between 200 and 400°C. The temperature increased and decreased continuously, when it should only increase. The deduction obtained was that the reinforcement particles used didn’t allow the natural increase of temperature.

2.2 Fabrication of Surface Composite

Aluminium alloy 5083 was used as the base material in the form of rolled plates and with a thickness of 6mm. The composition of this magnesium based aluminum alloy can be seen in Table 1. The nano particles used as reinforcement are SiC and Al2O3 in different proportions as shown in Table 2.

Table 1. Material Composition

Composition	Wt.%	Compositon	Wt.%
Al	92.4 - 95.6	Mg	4 - 4.9
Si	Max 0.4	Cr	0.05 - 0.25
Mn	0.4 – 1	Ti	Max 0.15
Cu	Max 0.1	Zn	Max 0.25
Fe	Max 0.4	Other, each	Max 0.05
Other, total	Max 0.15		

Table 2. Reinforcement particles composition

Sample No.	Composition
1	75% SiC – 25 % Al_2O_3
2	80% SiC – 20% Al_2O_3

All of the samples had a groove in the center whose parameters were 3 mm in depth and 1.4 mm in width. The geometrical characteristics of the groove and the rolled pate can be seen in Figure 4.

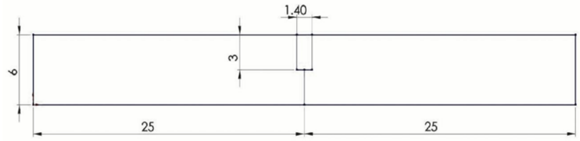

Figure 4: Dimensions of the sample and groove

These grooves were filled with the reinforcement particles before doing the FSP. It has to be considered that at all times the groove was aligned with the center line of the rotating pin. In addition, in order to prevent the particles coing out of the groove when practicing the FSP for the first time, two passes of a pinless tool were used to seal the groove.

The FSP unit consisted of a conventional miller machine in which the tool was fixed. A sketch of the FSP process is available in Figure 5.

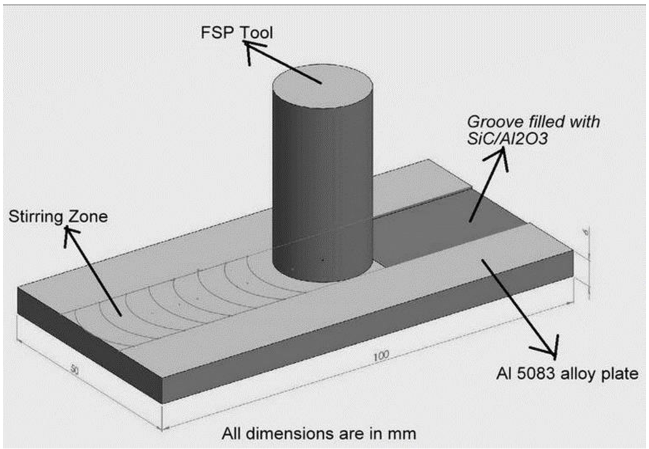

Figure 5: Sketch of Friction Stir Process

The material used for the tool was H-13 steel and after several attempts the optimal parameters were obtained. These parameters are 5.5mm for the length of the pin and 6mm for its diameter while the diameter of the shoulder is 20mm. Pictures of the tool can be seen in Figure 6. The traverse speed used was 20 mm/min and the rotational speed was 1200 rpm, both of them fixed for all the samples.

a)

Figure 6: (a) Top view of the tool (b) side view of the tool

In all of the samples several numbers of passes were used in the FSP. For the first sample two passes were done, while in the case of the second sample three passes were completed. These passes were done changing the direction which consequently changes the position of the advancing and retreating sides of the process in each pass. No time to cool down to room temperature was left between each pass.

2.3 Material Characterization

After the FSP, different tests were carried out to evaluate the results obtained. The particles distribution was evaluated using an optical metallurgical microscope (QS Metrology/XJL-17) after being polished in a twin disc polisher (METCO/PMP009). The microhardness was assessed using yhe Vickers method (Mitutoyo, Japan /HM113). Tensile tesing (TMC Universal Testing Machine/ TMC, Chennai / CUTM-50KN) was also carried out and the nech dimensions are 7 mm in width, 6mm in thickenss and 40 mm in length. The dimensioning can be properly seen in Fig.12. Wear rate was calculated using a pin-on-disc machine (DUCOM/TR-20-LE) whose input was 25 N load, 1.5m/s sliding velocity and 2500m sliding distance while the track diameter was 100 mm.

3. Results and Discussion

3.1 Tensile Test

In order to evaluate mechanical properites such as tensile strength and elongation of AA5083 after the FSP, tensile tests were carried out. In Figure 7 and Figure 8, the pictures of the samples after the tensile testing can be seen.

Figure 7: Sample 1 after Tensile Test

Figure 8: Sample 2 after Tensile Test

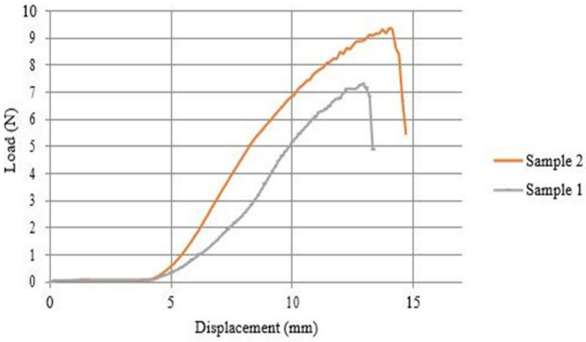

Figure 9: Load/Displacement curve

Figure 9 shows the comparison of the load against the displacement curve obtained from both tensile tests. Tensile strength increases when the number of passes grows from two to three and decreases alongside the alumina nanoparticels. The comparison of the tensile strength of the different sampes with the base aluminium value is shown in Figure 10. The addition of nanoparticles implies a decrease higher than 40% in the tensile strength for both cases.

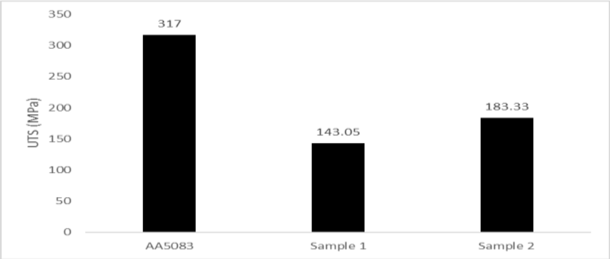

Figure 10: Ultimate Tensile Strength

A graphical comparison of the elongation percentages at break has also been done in Figure 11. As it can be seen, the elongation is highly improved. In the case of 75% SiC the increase in elongation at break is of 107.5% but when the content of SiC and the number of passes increases that value also grows to become 130%.

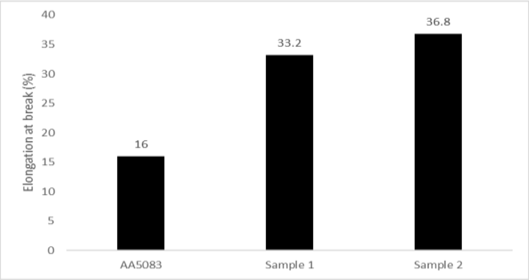

Figure 11: Elongation at Break comparison

Therefore, it can be concluded that the addition of SiC and Al2O3 nanoparticles has a positive effect on elongation although it decreases the tensile strength. The increase in the number of passes and the amount of SiC also contributes to the enhancement of these mechanical properties.

3.2 Microhardness

Using the Vickers tesing method the microhardness of the samples has been measured and then compared to that of AA 5083. Figure 12 shows a graph of this comparison. As it can be seen, the hardness value is in both samples lowe to the one of the base matrix. However, in the case where the number of passes and the content of SiC is bigger this microhardness value is slightly higher.

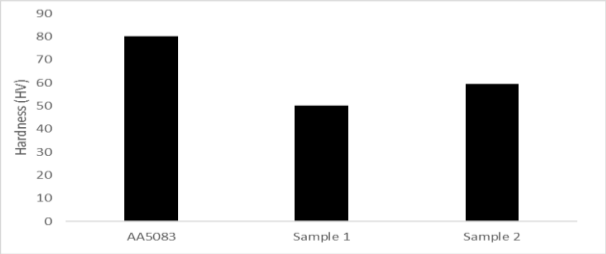

Figure 12: Microhardness comparison

The wear rate of the processed samples was also tested in order to get a better understanding of the tribological properties. Wear can be defined as the damage suffered by a solid surface involving progressive loss of material as a consequence of relative movement between the surface and substance who it is in contact with. The test was carried out by a pin-on-disc machine whose input parameters were 25N normal load, 1.5m/s sliding velocity and 2500m sliding distance, being the track diameter of 100mm.

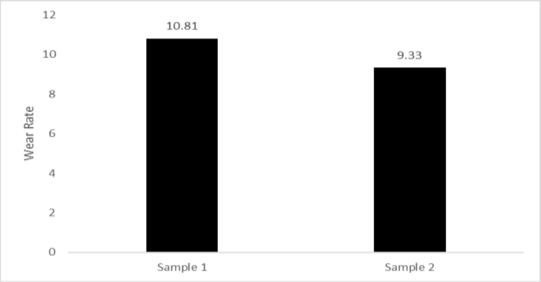

Figure 13: Wear rate comparison

Using the height loss, the volumetric loss and the wear rate were calculated. The results are shown in Figure 13. As it can be observed, the wear rate of the samples is reduced when the number of passes and the content of SiC is increased. Which means that the second sample is more wear resistant than the first one.

The Pin-on-Disc machine also measured the frictional forces and the friction coefficient during the whole sliding distance. Figure 14 shows a comparison of the average friction coefficient obtained during that period of time. The friction coefficient is smaller in the case where the number of passes and the SiC content is bigger. The wear resistance is improved with a lower value of the friction coefficient. Since the friction coefficient is smaller for sample 2, the same occurs with the frictional force.

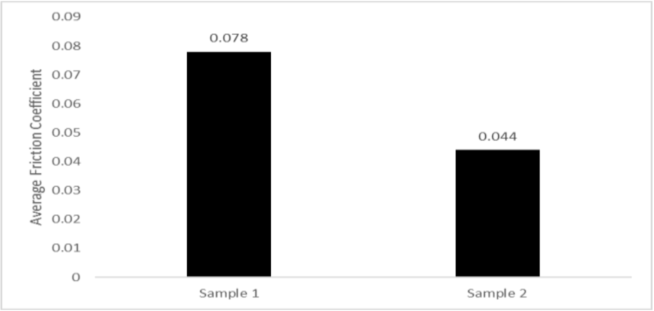

Figure 14: Friction coefficient comparison

3.4 Microstructural Analysis

The microstructures of the surface composite which was fabricated by 2 passes were shown from Figure 15 a) to 15 f). Figure 15 shows the presence of reinforcement particles in the metal matrix, **Error! Reference source not found.**15 c) shows the weld nugget, **Error! Reference source not found.**
5 d) shows the thermomechanically affected zone and, **Error! Reference source not found.** shows the crack formation on the surface due to inadequate heat distribution. The microstructure of the surface composite which was fabricated by 3 passes were shown from **Error! Reference source not found.**15 e) to **Error! Reference source not found.**15 f). **Error! Reference source not found.**
5 e) shows a uniform distribution of the reinforcement particles, **Error! Reference source not found.** shows the shows the weld nugget region and **Error! Reference source not found.**15 f) shows the thermomechanically affected zone.

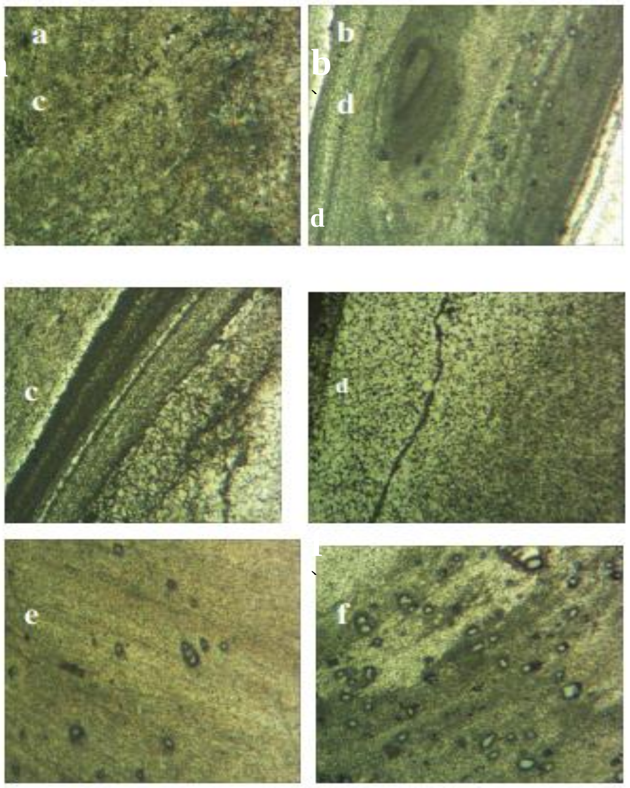

**Figure 15 Optical micrograph of a) Uniform distribution of reinforcement particles b)Nugget Zone c) Thermo Mechanically Affected Zone
d) Crack formation)Three passes with uniform distribution of particles**

From the microstructures we can notice that the surface composite which was farbricated by 2 passes shows more agglomeration of the reinforcement particles in the weld nugget region where as the surface composite fabricated by 3 passes shows less agglomeration and uniform distribution of the reinforcements in the weld nugget region.

4. Conclusions

AA 5083 was successfully reinforced using SiC and Al_2O_3 nanoparticles added to the surface of the base metal through FSP. The results obtained from the tensile test, microhardness test, wear test and microstructural analysis was evaluated.

1.The Ultimate Tensile Strength (UTS) decreased with the addition of the reinforcement particles. However, the ductility of the samples was increased by 107.5% and 130%.

2.Microhardness decreased by more than 40% for both samples, although the increase in the number of passes and SiC content presented better results.

3.Comparing the wear rate, the increase in the number of passes ans in SiC amount results beneficial. Analyzing the frictional force and the frictional coefficient, it can be concluded that in fact the wear resistance is better when the Al_2O_3 quantity is smaller.

4. The number of passes influences the microstructure, the higher the value of the number of passes is the less agglomeration of nano particels will be found. The increase in a number of passes improves the distribution of SiC and Al_2O_3 nano particles in the AA5083 base metal.

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