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Mechanical Behaviour of Mg/SiC Composite Processed by Friction Stir Processing

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Abstract - Due to their good mechanical and physical properties as well as their low densities, Magnesium Matrix Composites are considered as an attractive option for different aerospace and other commercial applications. Lately, Friction Stir Processing (FSP) which is considered as an effective modification to Friction Stir Welding (FSW) has shown a great protentional as successful alternative for fabricating Metal Matrix Composite (MMC). One major difference between conventional engineering materials and MMC is the addition of reinforcing elements that results in an overall enhancement of the composite's stiffness and strength. This paper discusses the effect of using Silicon Carbide (SiC) reinforcement particles in AZ 31B magnesium alloy base composite using FSP. Effect of reinforcement particles on the thermal profile, microstructure, micro-hardness, tensile properties and impact toughness are discussed. In addition, the effects of tool rotational and translational speeds on the microstructure and micro-hardness of the Mg/SiC surface composite have been examined. Mg/SiC surface composite was successfully fabricated using FSP. Results suggest that Mg/SiC surface composite can be used to significantly enhance the micro-hardness and the ultimate tensile strength within the stir zone.

Keywords**:** Friction stir processing, Magnesium AZ31B, SiC particles, Mechanical behaviour

1. Introduction

As a result of their low density, which is around two third of that of aluminum, in addition to their relatively high strength, magnesium alloys have gained lots of attention. Such properties can reduce the amount of fuel consumption in many aerospace and automobile applications. This can result in a significant reduction of greenhouse emission worldwide [1-3]. Magnesium alloys feature hot formability, excellent machinability as well as good electromagnetic shielding characteristics [4]. Nevertheless, the widespread use of magnesium alloys has been always restricted as a result of their low strength, low modulus and poor creep resistance at elevated temperatures [5, 6]. Hence, lots of scientific research have targeted to study and improve the mechanical properties of magnesium and its alloys. An interesting alternative to both magnesium alloys and Aluminum MMC is the Magnesium MMC. Such composites depend on the use of reinforcements in order to enhance the properties of the base metal. Some of these reinforcements are Aluminum Oxide (Al2O3), Titanium Carbide (TiC) and SiC. SiC reinforcement improves hardness, ultimate tensile strength, yield strength and wear resistance of magnesium and its alloys [7]. The main concept of MMC is to come up with a final product having the desirable properties of both base metals and reinforcements. Although they have valuable combination of mechanical properties, Mg alloys suffer from low stiffness. On the contrary, SiC reinforcement are strong and have high stiffness, but they are brittle. As a result, such a mixture will produce an Mg/SiC MMC with an intermediate mechanical properties that are between those of the Mg alloys and the SiC reinforcement. Such a unique mixture of properties is behind the use of Mg/SiC MMC in the manufacturing of golf tools, space shuttles and electronic substrates [4]. The properties of the Mg/SiC MMC can be improved further by carefully controlling processing parameters as well as the size and distribution of the SiC reinforcement [8].

FSP uses a non-consumable rotating tool with a special design to create a friction between the shoulder of the tool and the work piece. At the same time, the rotating pin stirs the heated material due to friction and subjects the work piece to severe plastic deformation. This will result in a significant grain refinement caused by dynamic recrystallization [9-12].

Ultrafine-grain materials due to severe plastic deformation were successfully obtained by FSP in different studies in literature [13]. Initially, FSP was used to refine the grains of light-weight alloys. Recently, FSP is considered as a powerful fabrication tool to modify the microstructure of MMCs and improve their mechanical properties [14]. FSP is controlled by many parameters like tool rotational and translational speeds. Conventional grain refinement processes such as multi-directional forging change the bulk properties of materials, nevertheless, FSP involves only surface modification without any modification on the bulk characteristics [15].

In their paper, Morisada et al. [16] successfully used FSP to obtain multi-walled carbon nanotubes AZ31 surface composites. Results suggest that the distribution of the reinforcement nanotubes was dependent on the tool rotational speed. Both, the nanotubes and the use of FSP enhanced the micro-hardness and promoted grain refinement. Lee et al. [17] used FSP to fabricate Mg AZ61/SiO2 composite. The grain of the resulted composite exhibited a significant refinement. Sharifitabar et al. [18] successfully developed Al 5052-H32 rolled plate reinforced with Al2O3 powder using FSP. It was reported that as the number of FSP passes increases, grain size decreased. Interestingly and although the grain refinement enhanced the ultimate tensile strength and the yield strength, however, dislocation density decreased and sub-boundaries reduced both the strengths. Percentage elongation was also higher for FSPed metal alloy without reinforcement. Both Mg AZ91/ SiC and Mg AZ91/Al2O3 were successfully fabricated by Asadi et al. [19] via FSP. Better hardness values were obtained when SiC reinforcement was used. Nevertheless, the hardness of the Mg AZ91/Al2O3 composite was still higher than that of the metal alloy. Furthermore, the scattered SiC reinforcement inside the Mg MMC slowed the wear rate as they acted like barriers to wear. Ultimate tensile strength as well as the percentage elongation of both the Mg MMCs decreased compared with that of the base metal. The effect of translational speed on the hardness of AZ91/ SiO2 composite developed using FSP was studied by Khayyamin et al. [20]. Grain refinement and enhancement in hardness were obtained at high translational speeds. Abdollahzadeh et al. [21] used FSW to fabricate AZ 31/ SiC composite using different combination of tool rotational and translational speeds. The impact of both speeds on the microstructure and mechanical properties of the composite was examined. It was found that controlling the combination of both speeds is crucial in affecting the mechanical properties of the composite. Raju et al. [22] fabricated Cu/Al2O3 using FSP. Results showed that the hardness as well as the ultimate tensile strength and the yield strength of the composite increased due to grain refinement. On the other hand, impact toughness values and percentage elongation were decreased.

To facilitate the use of Mg MMC in today's application, more analyses on the effect of process parameters of FSP as well as the type and size of reinforcement are required. In this paper, FSP was used to fabricate both AZ 31B alloy and AZ 31B/SiC surface composite using different combination of tool rotational and translational speeds. The effect of both speeds as well as the SiC reinforcement on the thermal, micro-hardness, and microstructural properties is studied and analyzed. The effect of the same on the impact toughness and tensile properties is highlighted. Results are then compared with the properties of the base material

2. Experimental Details

FSP was conducted on 5 mm thick Mg AZ31B sheets. A groove with 0.5 mm depth and 2 mm width was created along the center line of each specimen. FSP tool with a shoulder diameter of 15 mm and a 5 mm diameter pin with a length of 4 mm was mounted in a vertical CNC milling machine. The groove was filled with 250 μm SiC particles and then FSPed Mg AZ31B/SiC composite was successfully attained. Three rotational speeds (1200, 1600 & 2000 rpm) and three translational speeds (25, 75&100 mm/min) were used. K-type thermocouples were used to measure the temperature during the process. To measure Vickers micro-hardness, different transverse sections were taken at 50% of the FSPed pass thickness. QV-1000DM digital micro-hardness tester was used with a load of 1000 gram and a dwell time of 10 seconds. Micro-hardness values were recorded at 25%, 50%, and 75% (from the top edge) of the FSPed Mg AZ31B sheet thickness and at 10%, 16%, 50%, and 75% of the FSPed Mg AZ31B/SiC composite thickness. The longitudinal and through-thickness positions are shown in Fig. 1. The average of three to five readings was considered for each measurement. Tensile tests were accomplished using universal tensile testing machine at a strain rate of 1.5 mm/min. Finally, Impact tester was used to obtain the impact toughness for Charpy U-notch samples. The cross-sectional area before fracture was found to be 1.89 cm^2. Tensile and impact tests were re-conducted using the same conditions to ensure repeatability of results.

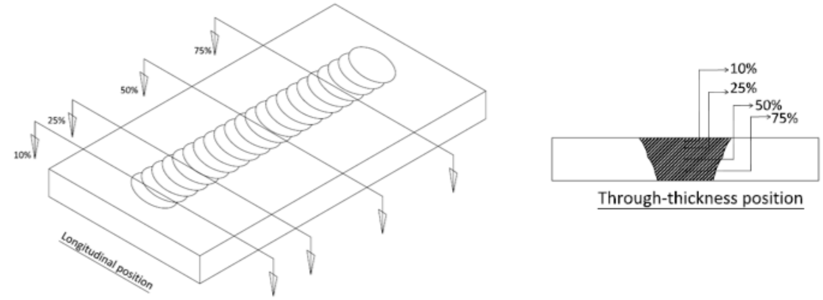

Fig.1: Inspected sections of the FSPed Mg/SiC composite

2. Results and Discussion

Thermal profile was recorded for all trials. Figures 2 (a) and (b) introduce the effect of tool rotational and translational speeds on the thermal profile respectively. As can be seen, the maximum temperature increased when higher tool rotational speeds were used. This is because the amount of frictional heat and the heat generated due to the severe plastic deformation are increased. On the other hand, changing the translational speed did not result in any significant change in the peak temperature. Nevertheless, it had a significant impact on the processing time and hence the amount of heat the specimen was exposed to. For example, at low translational speed the processing time increased which made the specimen subjected to heat for longer period of time and hence, the maximum temperature exhibited an increase. In summary, controlling both the speeds is crucial because in order to achieve grain refinement, enough heat to soften the material but not to cause a significant grain growth is required.

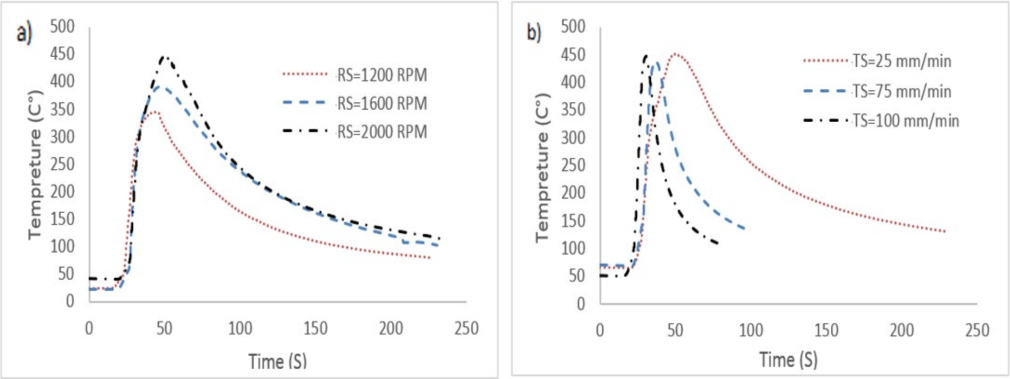

Fig. 2: a) Effect of rotational speed on the thermal profiles and b) Effect of translational speed on the thermal profiles

To understand the effect of FSP parameters on the grain size of the resulted composite, microstructural analysis was carried out. FSP was able to successfully refine the grain size from an average grain size of approximately 13.1 µm to as low as 6.7 µm after only one FSP pass. The effect of tool rotational speed on the grain size of the FSPed samples is shown in Fig 3 (a). Results suggest that more grain refinement is achieved at lower rotational speed. As discussed earlier, higher values of rotational speeds generate more heat which leads to more grain growth. Similarly, Fig 3 (b) shows the effect of the translational speeds. It is noticed that at higher translational speeds, smaller grain sizes are achieved. This is due to the fact that shorter processing time is required at high translational speeds, thus the sample is exposed to heat for a shorter period of time leading to less grin growth. Such observations are supported by the thermal profiles presented earlier. Surprisingly, the average grain size of some combination of tool rotational and translational speeds like 2000 rpm and 75 mm/min gave an average grain size higher than that of the as-received. Hence, controlling both the speeds is crucial in order not to revise the process from a grain refinement to a grain coarsening process. Similar observations were reported in literature [24, 25].

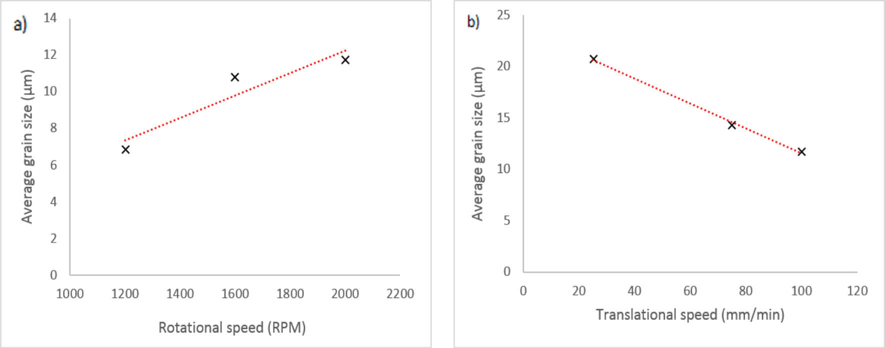

Fig. 3: a) Effect of rotational speed on the grain size and b) Effect of translational speed on the grain size

The effects of both the tool rotational and translational speeds on the micro-hardness are shown in Figs 4 (a) and (b) respectively. It is noticed that the micro-hardness values increased at lower rotational speeds. When it comes to translational speed, an improvement in the micro-hardness was obtained when high translational speed was used. These observations agree with the well-known Hall-Petch relationship. Thus, the challenge in FSP is to be able to control process parameters to end up with significant grain refinement and hence good mechanical properties. Both the rotational and translational speeds shall be set to achieve extreme plastic deformation and cause enough softening of the material without resulting in grain growth. In this study, the results showed that the maximum hardness was attained at a rotational speed of 1200 rpm and translational speed of 100 mm/min. Figures 4 (a) and (b) also highlight the effect of through-thickness position on the micro-hardness. Enhanced micro-hardness values were noticed at deeper through-thickness positions. Again, such a variation in the micro-hardness values at different depths can be related to the deviation of temperature. The further from the top surface, the lower the temperature and the more grain refinement attained. Similar observations were reported in literature [26-29].

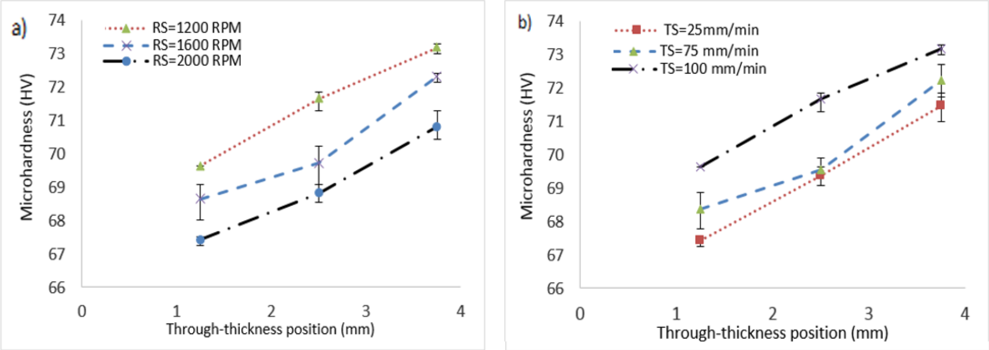

Fig. 4: a) Effect of the rotational speed on micro-hardness and b) Effect of the translational speed on micro-hardness

Figure 5 introduces a comparison of the micro-hardness values between as-received, FSPed and FSPed Mg AZ31B/SiC composite at 1200 rpm and 100 mm/min. At 0.5 mm from the top edge, that is the region containing the SiC reinforcement particles, micro-hardness values reached the maximum. Out of the different combinations of rotational and translational speeds, micro-hardness values recorder at 0.5 mm from the top edge were also the maximum when process parameters of 1200 rpm and 100 mm/min were used. A percentage increase of 37.7% and 52.3% in the micro-hardness when compared to the samples prepared with FSP and the as-received sample was obtained. This suggests that FSPed Mg AZ31B/SiC can be successfully used to increase the micro-hardness of both the base metal and FSPed samples. Due to the minor concentration of the reinforcement SiC particles at 0.7 mm depth from the top edge, higher micro-hardness values from FSPed and as-received samples were noticed. Micro-hardness values of the Mg AZ31B/SiC composite at 2.5 mm and 3.75 mm from the top surface match those values reported for FSPed samples without reinforcement. Obviously, such matching is predicted as no SiC reinforcement was existed at these through-thickness positions.

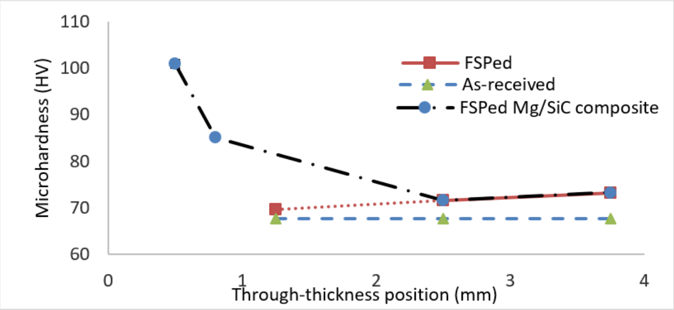

Fig. 5: Micro-hardness values for as-received, FSPed and FSPed Mg/SiC composite

Figure 6 compares the ultimate tensile strength and percentage elongation for as-received, FSPed and FSPed Mg MMC. Figure 7 shows the impact toughness comparison. For Mg MMC composite, maximum ultimate tensile strength and percentage elongation are obtained when tool rotational speed of 1200 rpm and translational speed of 100 mm/min are used. This is in line with the obtained grain size results. This can be explained by both the Hall-Petch and the Orowan-Ashby equation. Orowan-Ashby equation indicates that strengthening by second phase particles is linked with interparticle spacing as shown in Equation 1. $K^{'}$ is a material constant and λ is the interparticle spacing [21].

$$\sigma = K^{'} \lambda^{-1/2} \qquad (1)$$

Therefore, strength increases when grain size and interparticle spacing are low. Moreover, the ductility and percentage elongation increase as the grain size and interparticle spacing decrease. Therefore, during processing of the current Mg AZ31B/SiC composite, neither a low heat generation that promotes a large interparticle spacing nor a high heat generation which promotes grain growth can lead to the optimum mechanical properties of the FSPed Mg MMC. Nevertheless, a careful control of both can lead to the optimum parameters that leads to optimum mechanical properties [21]. Results suggest that the ultimate tensile strength of the Mg MMC increased when compared with that of the FSPed samples without reinforcement. Such increase in the ultimate strength of the surface composite is as a result of the grain refinement which can be associated to the interaction between the reinforcement particles and dislocations within the MMC. The percentage elongation and the impact toughness of the MMC decreased when compared to that of the FSPed. This can be attributed to the dispersion of large number of SiC reinforcement particles that severely restricted the movement of dislocations and decreases the ductility [22].

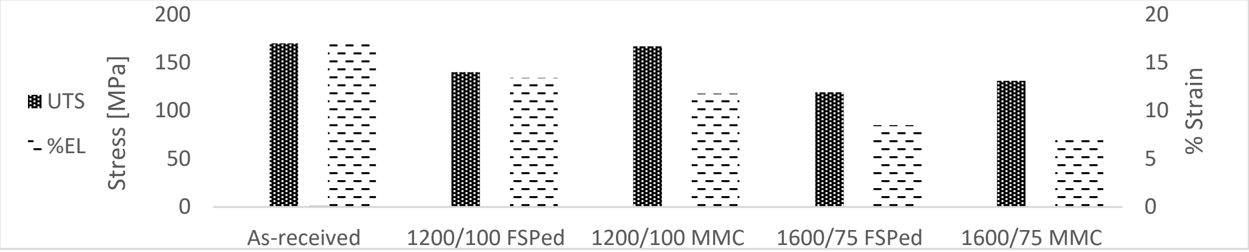

Fig. 6: Ultimate tensile strength and percentage elongation for as-received, FSPed and FSPed Mg/SiC composite

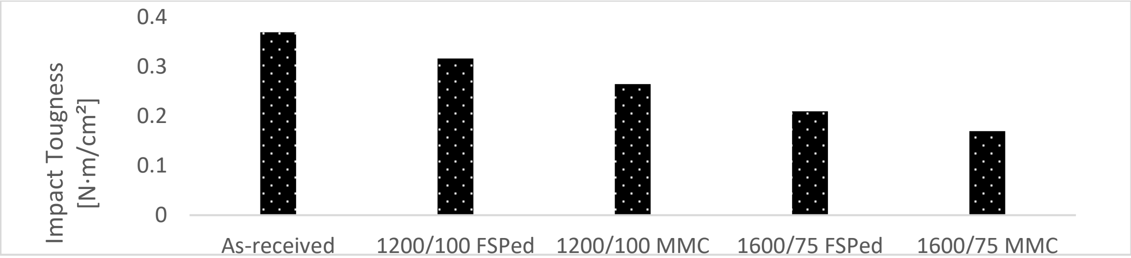

Fig. 7: Impact Toughness for as-received, FSPed and FSPed Mg/SiC composite

4. Conclusion

In the current study, AZ31B/SiC MMC was successfully produced using FSP. The impact of tool rotational and translational speeds on the thermal profiles, microstructure, micro-hardness and other mechanical properties were examined. The followings were concluded:

- FSP is an effective tool to fabricate Mg/SiC composite.
- The heat generated during FSP affected the grain structure and is dependent on the process parameters; hence, a careful control of the combination of both speeds is required to achieve the desirable modifications.
- The micro-hardness of FSPed Mg AZ31B/SiC was increased by up to 37.7% and 52.3% when compared to FSPed and as-received samples respectively.
- The addition of the reinforcement particles in addition to the refined grain structure led to an increase in both the strength and hardness. However, ductility was reduced.

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