Microstructure and mechanical properties of Al/SiC surface composite with different volume fractions using friction stir process

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Abstract. Friction stir processing (FSP) was used to produce Al/SiC composites on the surface of Al 1050 sheets. SiC particles of 1 µm size were added on the Al sheet surface inside grooves with different sizes in order to obtain different composite volume fractions. FSP was applied with a square shape tool rotating at 1500 rpm and with a feed rate of 116 mm/min. The effect of SiC volume fraction on microstructure, and mechanical properties was investigated and the results were compared with samples treated by FSP but without SiC reinforcement. Different SiC volume fractions were obtained ranging from 7% to 16% depending on the groove size. Optical microscopic analysis (OM) in collaboration with scanning electron microscope (SEM) were used to fully discuss the microstructural changes within each sample. Mechanical properties were investigated through microhardness and tension test (including yield strength, ultimate tensile strength and percentage elongation). The results show significant improvement in microstructure changes in the FSPed composites, where equiaxed and refined grains structure were obtained due to the effect of the severe plastic deformation and continuous dynamic recrystallization caused by FSP compared to the elongated and coarse grains of the base metal. Microhardness and strength of the FSPed composites improved up to 112% and 9.7%, respectively compared to the as-received material.

1. Introduction
Aluminum is a well-known and highly used metal in several industries and applications. Due to the poor mechanical properties and low wear resistance of pure aluminum, alloying is necessary to improve these properties [1]. Preparation and fabrication of aluminum metal matrix composites can be an additional solution for such drawbacks, however, the processes used face a lot of problems [2]. On the other hand, composites may only be needed on the surface of the products in order to improve hardness and wear resistance. FSP (friction stir processing) can be applied to insert a hard phase into the aluminum on the surface, hence, increasing its hardness and wear resistance. This process is based on developing of the friction stir welding process (FSW) [3,4]. In FSP heat and pressure are generated by a rotating non-consumable tool with a special design. The tool includes a pin which penetrates into the material under an applied vertical force and a shoulder which only touches the surface [5], causing severe plastic
deformation through the workpiece top layer [6]. This process offers several benefits by modifying the microstructure, improving the mechanical properties and also by offering the possibility to create a composite material on the surface without the need to melt the material [7]. Due to its effects, FSP is used in wide range of industries such as in the transportation sector, vehicles, electronics industry, defense industries and much more [8]. Composites with aluminum matrix (Al MMCs) by FSP was previously studied by adding SiC particles, which enhanced the mechanical properties through controlling the microstructural features [9-11] resulting in almost double the microhardness of the base material [12,13]. Improvement of the dispersion of SiC particles was also reached with multi FSP passes [14].

In the present study, FSP process was applied under constant process parameters which were selected based on the authors,’ previous research where the process parameters were optimized using RSM [15]. Surface composite was prepared using SiC with 950 nm size with different volume fractions. Investigations include macrostructure, microstructure, hardness and tensile behavior.

2. Experimental work
Aluminum 1050 alloy sheet with 5 mm thickness was cut into square samples 200 mm x200 mm. A CNC vertical milling machine was used to perform the FSP processing using a K100 tool with square tip. In order to incorporate the SiC particles on the surface to prepare the composite, grooves with 2.1mm width were machined with depths of 2, 2.5, 3 and 3.5 mm. These grooves were then filled with 950 nm SiC powder. In order to prevent the SiC powder from escaping during FSP processing, a tool shoulder without a pin was first used to pass on the grooves to close them. This was followed by an FSP pass after adjusting the center of the tool pin to coincide on that of the groove. For comparing, the effect of adding SiC, a sample without SiC was processed (called sample c). All samples were prepared with constant process parameters: 1500 rpm, 116 mm/min, 3 passes and a tool with a square pin. Samples for microstructure investigation and for tensile test were cut and 3 samples of each condition were tested on universal testing machine as per ASTM E8M-04 procedures for tension test. The microhardness test was carried out by Vickers microhardness by load of a 200 g and a 15 s as dwelling time. The hardness distribution was obtained using five microhardness readings measured on the top surface as well as on cross sections. The microstructure was investigated on cross-sections of the samples after standard metallographic preparation and using Keller's reagent for etching. Investigation was carried out using Leco LX 31 and Ceti optical microscopes and by FEI Inspect S 50 for SEM to

3. Results and discussions
3.1. Microstructure
In the longitudinal direction, the coarse and elongated grains of 1050 Al alloy because of the rolling process were changed to refined grains due to the FSP process, figure 1. This achieved grain refinement was attributed to a continuous dynamic recrystallization as found in many previous studies [16]. The overall macroscopic view of a composite sample, figure 2(a) illustrates the known three main zones in the FSP process: stir zone (SZ), thermo-mechanical affected zone (TMAZ), and heat affected zone (HAZ). By investigating, the microstructure in three different zones it is noticed that, the grain size in the SZ zone figure 2(b) where the smallest grain compared to TMAZ area figure 2(c) and HAZ figure 2(d). The fine grain structures in the SZ area were found because of a fully dynamic recrystallization caused by the friction heat produced by the FSP tool and the presence of SiC particles [14]. The TMAZ zone exhibited deformed structure compared to SZ zone; this grain shape is more clear in the HAZ zone where curved and elongated grains size appeared in figure 2(d). The distorted grains in TMAZ region was attributed to a shortage of the plastic deformation [17], where discontinuous dynamic recrystallization has occurred in TMAZ [18, 19] while the major amount of the recrystallization is located in the SZ. As the recrystallization effect decreased gradually, it results in large grain size in HAZ and in TMAZ zone.
Figure 1. Metallographic investigation in FSPed sample C without SiC showing: (a) the base metal and (b) the stir zone.

Figure 2. Microstructure of Sample 1 containing SiC particles: (a) the overall view of the FSP zones, (b) SZ: stir zone in zone 1, (c) TMAZ: thermo-mechanical affected zone 2 and (d) HAZ: Heat-affected zone 3.

The average volume fraction of SiC particles in the SZ was found to be $\approx 9\%$, $11\%$, $7\%$ and $16\%$ for samples 1, 2, 3 and 4, respectively. This indicates that FSP tool shoulder was effective to block the
leakage of SiC particles from the grooves. Furthermore, when the groove depth was increased from 2 mm to 2.5 mm (25%), the volume fraction of SiC was increased by 22.2%, and the increase of groove depth from 2 mm to 3.5 mm (75%), the volume fraction of SiC was increased by 77%. It is clear from the results that the groove depth can be a successful method to obtain a controllable specific volume fraction of the added particles in the surface composite using FSP.

3.2. Mechanical properties
From the values of tensile strength and elongation %, Table 1, it can be deduced that, applying FSP only didn’t improve the UTS of the as-received original material as it can be seen in sample c results, while the addition of SiC affected the strength. The UTS value was clearly increased in sample 4 where the Vf of SiC was ≈ 16% (the UTS recorded an increase of 9.7% compared to the original material). Sample 3 containing the least % of SiC (≈ 7%) exhibited the lowest UTS value among all FSPed samples with SiC particles. This strength enhancement is attributed to the presence of reinforcing SiC and to the refined grain size generated by FSP [20, 21]. The percentage elongation of FSPed composites decreased strongly due to the existence of the ceramic SiC particles, that strongly reduces the material plasticity in the FSPed composites due to the non-deformable SiC; this behavior is very common in the FSPed Al/SiC composites and mostly occurred accompanied with an increase of the strength [22]. The distribution of the microhardness around the SZ for the different SiC Vf are plotted in figures 3 and 4 together with that of the base metal. Obviously, the maximum microhardness values are found in the stir zone due to the existence of SiC particles as previously found [23] and due to formation of fully recrystallized grains attributed to dynamic recrystallization, which is a result of the FSP passes in the SZ. The stirring action has also a large effect on distributing the SiCp in the stir zone causing hardness increase as it is found in the previous work [13]. The peak VHN listed in Table 1 was 41 for sample 1, 33 for sample 2, 33 for sample 3 and 52 for sample 4. The hardness values decreased gradually in TMAZ and HAZ, which are depleted in SiC and exposed to less amount of plastic deformation compared to the SZ, figure 4. It is noticed that, FSP improved the microhardness on top of the FSPed samples by 46% for sample c and by 38% to 112% for the composites samples, Table 1. The hardness improvement is obviously related with the increase of SiC Vf, and the maximum hardness value was found in sample 4 with the maximum Vf (≈ 16%) which enhanced the properties of the surface. So, the general improvement in top surface microhardness is attributed to the combined effect of plastic deformation and the existence of SiCp [24, 25].

![Figure 3. Micro hardness in sample C at different distances away from the SZ and at different depths from the top.](image-url)
Table 1. Mechanical properties and corresponding SiC volume fraction

| Sample name | Y.S (MPa) | UTS (MPa) | %El (MPa) | Microhardness (HV) (on top of the surface) | VF (%) |
|-------------|-----------|-----------|-----------|------------------------------------------|-------|
| As-received | 73.9 ± 0.1| 84.3 ± 0.6| 67.08 ± 2.6| 27.3                                      | 0     |
| c           | 37 ± 1.5  | 75.6 ± 0.2| 72.9 ± 3.1| 39.8                                      | 0     |
| 1           | 54.5 ± 4.9| 91.22 ± 1.2| 27.82 ± 5.1| 41.18                                    | 9     |
| 2           | 62.85 ± 0.1| 91.84 ± 2.1| 29.8 ± 3.4| 50.24                                    | 11    |
| 3           | 62 ± 1.4  | 80.5 ± 6.7| 18.28 ± 1.3| 37.76                                    | 7     |
| 4           | 50.95 ± 2.8| 92.05 ± 5.8| 42.16 ± 3.6| 58.08                                    | 16    |

Figure 4. Micro hardness at different distances away from the SZ and at different depths from the top measured in FSPed samples together with those of original base metal, where a, b, c and d correspond to sample 1, sample 2, sample 3 and sample 4, respectively.

4. Conclusions

- Friction stir processing (FSP) can be successfully applied to create surface Al/SiC composites in addition to improving the mechanical and microstructure properties of as-received metal.
- Severe plastic deformation caused by FSP and SiC both enhanced grain refining on the surface.
- The existence of SiC particles achieved 9.7% enhancement in UTS value compared to the original metal and up to 112% increase in the microhardness.
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