Effect of SiC Particles on Microstructure and Wear Behavior of AA6061-T6 Aluminum Alloy Surface Composite Fabricated by Friction Stir Processing

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ABSTRACT. This research studies the effect of SiC particles on the microstructure and wear behavior of AA6061-T6 aluminum alloy surface composite. Friction stir processing (FSP) was used to incorporate micro-sized SiC particles into AA6061-T6 aluminum alloy to form a particulate composite surface layer. Samples were subjected to two passes of FSP with and without SiC powder at the best rotational speed of 1250 rpm, travel speed of 32 mm/min and two passes in the same direction. Microstructural observations were conducted via optical and scanning electron microscopy (SEM) of samples subject to FSP. Mechanical properties, including microhardness and wear resistance, were evaluated. The results manifested that at two passes, the FSP caused a more uniformity in the distribution of SiC particles. The addition of SiC particles to AA6061-T6 improved the hardness (improvement 62.6%) and wear resistance as compared to FSPed sample without SiC particles. The wear behavior was of a mild type or an oxidative type at low loads (5 N), which became severe or metallic wear at higher loads (20 N) for sliding time 20 min.

Keywords: Aluminum alloy; Composite; Friction stir processing; SiC; Wear

1. Introduction
The AA6061-T6 aluminum alloy is widely used in defense, marine, automobile and aircraft applications owing to its light weight, strength and good corrosion characteristics. However, this alloy displays low tribological characteristics in many applications [1]. In comparisons of metal matrix composites (MMCs) with the unreinforced Al alloys, Al alloy matrix composites that were reinforced with ceramic phases revealed greater hardness and strength, enhanced characteristics of tribology, and increased creep and fatigue resistance, along with good wear resistance and enhanced high temperature properties in comparison with the traditional alloys and metals [2].

Al matrix composites (AMCs) that have been manufactured via reinforcement of the Al alloys with particles, such TiB₂, Al₂O₃, SiC are freshly-generated composites. Such composites reveal better characteristics than base alloy, for example in terms of strength, stiffness, and improved tribological properties [3]. Reinforcement by nano and micro particles and their distribution upon the surface of the Al alloy is intricate to perform with techniques of traditional surface modification [4]. The techniques of laser beam and thermal spraying are used for making surface composites but they compromise the characteristics due to the development of undesirable phases. Taking
into consideration such problems, friction processing (FSP) is the best operation by which to prepare the surface composites and surface modification. This technique is a recently-evolved solid-state processing method, which is a variant of the friction stir welding (FSW) operation that began in 1991 at the Institute of Welding (TWI) [5]. A non-consumed rotating tool made with a shoulder and a pin is plunged into the plate of a base metal and it is produced for traversing in a pre-defined direction to cover the target area. The base metal softening and plasticization takes place due to the generation of the frictional heat between the work piece and the rotating tool. The blending action of material and the thermo-mechanical feature of the process thus give the ability to incorporate the particles of the second phase in SZ and to produce a surface composite [6-7].

In 2016, Kishan et al. [8] studied the effect of volume percentage of nano sized particles on the mechanical, microstructure and tribological behavior of Al alloy AA6061-T6 surface nano composite made via FSP. It was found that the increase in the volume percentage of TiB2 particles increased the microhardness more than the as-received aluminum alloy. Also in 2016, Rathee et al. [9] investigated the manufacturing of surface composites AA6061/SiC with the influence of the tool implant depth upon the reinforcement particles’ dispersal pattern into the matrix of metal. Six different tool plummets depths were selected, at fixed levels of tilt angle and shoulder diameter, to observe the specific influence of implant change. That study found that the lower levels of plummets depth resulted in insufficient generation of heat and the formation of a cavity towards the center of SZ. From the other side, the higher depth levels of implant led to the reinforcement particles’ ejection, and even in material sticking to the shoulder of the tool.

Ranjit Bauri et al. [2] in 2011 showed that FSP can be employed efficiently to homogenize the particle distribution in Al based in-situ composites. FSP was employed on cast composite, to uniformly disperse the SiC particles in the matrix of Al. This composite was subjected to one pass and two passes. The single pass of FSP was sufficient to break the segregation of particles from boundaries of the grains and enhance spread. Two passes generated a uniformity and removed the defects of casting. Also, the size of grain size was smoothened beyond every FSP pass. The hardness and strength enhanced essentially beyond the FSP.

Narayana Yuvaraj et al. [10] in 2015 produced the Al alloy 5083 with reinforced boron carbide (B4C) layers by FSP. The utilized reinforcements were micro- and nano sized B4C particles. The number of passes and the reinforcement size played a substantial role in the development of surface composites via FSP. The surface composites’ tribological performance was examined via pin-on-disk. The surface composite layer induced via three passes, using nanoparticle reinforcement, had superior hardness characteristics. The properties of wear of AA 5083 alloy were enhanced by the addition of B4C nano particles compared to B4C micro particle, and the nanoparticles’ wear resistance was greater than the alloy AA5083 without reinforcement.

Essam Moustafa [11] in 2017 used sheets of AA2024-O, having a thickness of 3.5 mm and made with Al2O3 nanoparticles using FSP, to develop a surface composite layer, with a three-multipass FSP that improved the surface composite homogeneity. Increasing the number of passes decreased the formed defects in the initial pass. The perfection in the grain refinement was 80% in comparison with the base metal.
This research work investigates the influence of SiC particles on the microstructure modification and wear behavior of aluminum alloy AA6061-T6, fabricated by friction stir processing at a fixed rotational speed of 1250 rpm, a travel speed of 32 mm/min and two passes in the same direction.

2. Experimental Work
Aluminum alloy plate AA6061-T6 was employed in this study. This plate was prepared into dimensions of 150×100×6 mm with a cutting machine. The chemical structure of this alloy was determined with the spectrometer analyzer device from the Examination and Rehabilitation Engineering General Company, as listed in Table 1. The mechanical properties of alloy AA6061-T6 are shown in Table 2.

### Table 1: The chemical analysis of as-received (AA6061-T6) alloy

| The element | (Si) | (Fe) | (Cu) | (Mn) | (Mg) | (Cr) | (Ni) | (Zn) | (Ti) | (Other) | (Al) |
|-------------|------|------|------|------|------|------|------|------|------|---------|------|
| Standard alloy [1] | (0.80) | (0.70) | (0.40) | (0.15) | (1.20) | (0.35) | (0.05) | (0.25) | (0.15) | (0.05) | Balance |
| Used alloy | (0.636) | (0.586) | (0.258) | (0.105) | (0.916) | (0.183) | (0.0032) | (0.035) | (0.05) | (0.0147) | Balance |

T6: Solution heat treatment and artificial aging.

### Table 2: The AA6061-T6 alloy mechanical properties

| Base Alloy AA6061-T6 | Yield strength, YS (MPa) | Tensile strength, TS (MPa) | Elongation (%) | Hardness, HV (Kg/mm²) |
|----------------------|--------------------------|---------------------------|----------------|---------------------|
| Measured value       | 160                      | 314                       | 28             | 58                  |
| Standard value *     | 276                      | 310                       | 12             | 95                  |

* Datasheet for ASM Aerospace Specification Metals Inc.

The FSP was performed on a milling machine (vertical type: WMW-HECKERT-Germany). The specimens were prepared, fixed in a specially-designed and fabricated fixture, and clamped firmly in order to ensure that the plates remained in their places and were not dislodged by the welding forces, as shown in Figure 1. The tool was plunged into the chosen sheet area. A non-consumable cylindrical-shouldered and threaded pin made of high-speed steel (HSS) with a shoulder diameter of 16 mm and 6 mm pin diameter of length 3.2 mm were utilized, as shown in Figure 2, and the tool tilt angle was 2°.
Beyond fixing the plate, the operation was commenced via the tool rotation (cylindrical shouldered with threaded pin), the rotating direction was clockwise, and spindle was located at the center. The machine table was gradually lifted vertically until the shoulder of the tool was plunged with 0.2 mm in the surfaces of plates, and after that, the spindle was rotated at its location for ten seconds (time of dwelling) to pre-heat the plate prior to the process.

Friction stir processing was conducted at the best fixed (1250 rpm) rotational speed, 32 mm/min travel speed with double passes which were used in previous work by researchers Muna and Noor Alhuda [12].

![Figure 1: Sample after friction stir processing](image1)

![Figure 2: The tool used in this work](image2)

When FSP was complete, a series of holes was created in the work-piece center line, for the addition of the micro particles of SiC. These holes were in the plate’s central axis, and the spacing between each hole was 1.5 mm, each hole having dimensions of 2 depth mm and 2 mm diameter. There were 40 holes at length 140 mm, made via a
CNC vertical milling machine (C-TEK). The average particle size of the SiC was fixed at 120.8 nm in this study. The particles of SiC were blended with liquid ethanol, and the holes were then filled with powder. Accordingly, the reinforcement volume percent was 10 vol.% fraction for the FSP composite, and the holes were closed without a pin to avoid the powder sputtering during the FSP. In this study, the percentage of silicon carbide powder added was 10 vol.% depending on the total volume of holes which were made in the samples subject to FSP, and the density of the SiC particle.

The tool was plunged into the drilled hole, which was provided in the base plate, to a predetermined depth of 3.2 mm which represents the layer of friction stir processing, as the tool progressed along the center line of the drilled holes, as shown in Figure 3.

![Figure 3: Drilling holes on the top surface of the plate](image)

3. Microstructure Examination and Microhardness Test
Specimens were examined using an optical microscope, these specimens were made from a cross-section of the FSP and scanning electron microscopy (SEM) of the cross sections of the FSP. The mechanical properties of the surface composite layers were determined via the microhardness profiles across SZ, utilizing the Vickers hardness test. A load of 200 gm was applied to cross-section of SZ of the FSP direction, for 15 sec. The wear tests were performed using a pin-on-disk. The wear test was carried out under the dry sliding condition, varying the exerted load for the whole specimens at a constant speed and time of sliding. The variable loads were 5, 10, 15 and 20 N with a fixed time of 20 min and 5 cm distance with a constant speed of sliding (2.8 m.sec⁻¹).

4. Results and Discussion
4.1. Microstructure Results
Figure 4 (a and b) shows the microstructural characterization of a cross section of friction stir processing, without the addition of SiC particles, at 1250 rpm and 32 mm/min with two passes. It is clear that the FSP sample possesses four specific zones. One is a stir zone (SZ) that is a thermomechanically processed region, which has a very fine size of grain and equiaxed grains or homogenized structure, there is also a friction stir processed zone (FSP zone); a thermomechanically affected-zone (TMAZ), which has an elongated grain because it was deformed in a thermo-mechanical way with the observation of onion rings, and a heat affected-zone (HAZ), which is considered to have
the same grain structure of base metal (BM); and the base metal or AA6061-T6 alloy (unaffected metal) considered as the region, which is not influenced by the FSP process. This microstructure contains very fine precipitates of second-phase particles of $\text{Al}_3\text{Mg}_2$ phase, distributed uniformly in $\alpha$-Al.

![Microstructures of sample after FSP at 100x.](image)

(a) SZ, TMAZ and HAZ zone, (b) Base alloy AA6061-T6.

Figure 4: Microstructures of sample after FSP at 100x.

Figure 5 depicts five regions of different microstructure characteristics observed in the FSP sample that was reinforced by the particles of SiC; the zone of composite material (CMZ), stir zone (SZ), the thermomechanically affected zone (TMAZ), the heat-affected zone (HAZ) and base metal (BM).

Figure 5b reveals some clusters formed at one pass, such that the particles of SiC are in same direction of the onion rings in the TMAZ, due to stirring forces, which bring the mixture to an onion rings flow around the tool pin.

![Microstructures of the FSP specimen that reinforced by particles of SiC](image)

(a) CMZ and SZ, (b) CMZ, onion rings and TMAZ.

Figure 5: Microstructures of the FSP specimen that reinforced by particles of SiC

It can be seen that after applying the second pass in the same direction of passes, the particles are distributed homogeneously. SiC particles are more uniformly distributed
in the stir zone and thermo-mechanically affected zone, as shown in Figure 6. This is due to that the revolving tool provides enough circumferential force and heat for dispensing particles of SiC to be occupied in a broader zone. According to the nature of metal flow in the stirring zone during FSP, some SiC clusters are induced at the SZ, while the multi-pass FSP is regarded as influential process to enhance the ceramic particles’ distribution in the aluminum metallic matrix. Such outcomes are confirmed by the findings of many researchers [11, 13].

![SiC p](image)

**Figure 6:** Microstructures of FSP composite sample showing the reinforcement with SiC particles distributed in stir zone.

### 4.2. SEM Micrographs and EDS Elemental Analysis

The SEM micrograph in Figure 7 visualizes the microstructure of the FSP sample processed at 1250 rpm and 32 mm/min with double passes, and reinforced with SiC having a smoother and highly uniform grain structure. Use of FSP resulted in an enhancement in the mechanical characteristics of processed alloy in comparison with base metal. The contribution of vigorous plastic deformation and the exposure to the elevated temperature inside the processed region during the FSP caused the grains’ recrystallization.

Beyond the double passes, the particle distribution is completely homogenized. Such outcomes are similar to findings in other research [11]. The EDS analyses are shown in Figure 8. Figure 9 illustrates the SEM-mapping of the FSP specimen reinforced by the particles of SiC, obtained with EDS analysis. It is notable that, in various regions of SZ of the FSP specimens, particles of SiC are present in the Al matrix in form of elements Al, Mg, Si and C. These particles had positive effects on the structure regularity and the properties of AA6061-T6.
Figure 7: SEM micrograph of the FSP specimen reinforced by particles of SiC.

Figure 8: EDS elemental analysis of the post-FSP specimen reinforced by particles of SiC
4.3 Microhardness

Figure 10 illustrates the distribution of Vickers microhardness along the FSP cross section. The distribution of microhardness is on the cross-section normal to the tool traverse direction of the FSP sample made at 1250 rpm rotational speed, 32 mm/min travel speed and two passes in the same direction. The stir zone manifested a greater hardness than the TMAZ, HAZ and heat-unaffected zone. The hardness values after the addition of SiC particles increased as indicated in Figure 10. These values can be due to high hardness of SiC particles and very fine grains in stir zone of FSP surface of the alloy.

The peak hardness was 75 HV in the center of SZ, owing to the refinement of grain, and the dynamic recrystallization of stir zone as well as the presence of Al₃Mg₂ phase as precipitated particles of the second phase, as depicted by the XRD in Figure 11. Many researchers [14, 15] have confirmed these results in their studies of FSW welding aluminum alloys. The microhardness values for base alloy FSP and AA6061-T6 aluminum alloy metal matrix composites reinforced by the particles of SiC are listed in Table 3.

| Specimens                                      | Microhardness in center of stir zone | Improvement % |
|------------------------------------------------|--------------------------------------|---------------|
| AA6061-T6 as FSP as compared to base alloy (HV=58) | 75 HV                               | 22.66         |
| AA6061-T6 reinforcement with SiC particles      | 122 HV                              | 62.6          |

The microhardness profiles of the FSP specimen with reinforcement can be found in Figure 10. Notably, the value of microhardness in state of surface composite that reinforced by the particles of SiC was higher than the other composites in the whole FSP regions. In the stir region, thermomechanical affected region and heat-affected region, the hardness reached the peak value (122 HV) in comparison with the parent material (58 HV) and specimen after FSP (75 HV). This is owing to the SiC particles’ dispersion in the SZ and the grain size refinement of the parent alloy, also because the heat of friction and plastic flowing through the FSP created fine equiaxed grains that
are dynamically recrystallized in SZ as well as grains that are elongated and recovered in TMAZ. For raised numbers of passes for the FSP composite, it is observed that hardness is greater than the hardness of one pass. The two passes homogenize the spread of particle, reduce the size of the grain, and create the homogenous profile of hardness. Depending upon the relation of Hall-Petch, the reduction in size of grain raises yield strength that also the hardness value. These outcomes agree with the results of previous studies [11, 16].

![Microhardness distribution](image1.png)

**Figure 10:** Microhardness distribution on the FSP cross section for the base material and specimens with reinforcement SiC particles

![XRD analysis result](image2.png)

**Figure 11:** XRD analysis result for base alloy post-FSP AA6061-T6

### 4.4. Results of Wear Test

The rate of wear was measured via the method of weight loss for the base material and the specimens subjected to FSP, processed at 1250 rpm rotational speed and 32 mm/min travel speed with double passes in the same direction. The aluminum alloy metal matrix composites reinforced with SiC particles as a function of different loads (5, 10, 15 and 20 N) and fixed period of time of 20 min and sliding speed 2.8 m/sec were investigated. The weight loss and wear rate continuously increased with increasing the loads at fixed speed and sliding time. From Figure 12, it may be observed that the wear behavior is
identical to that for the whole specimens. This figure shows three regions of wear: mild wear, transition wear and severe (metallic) wear at loads higher than 10 N at fixed time and speed. There is a transition in the behavior of wear from a mild type of wear (oxidative wear) to a vigorous type of wear over 10 N. The FSP specimen wear rate was less than the base material. That is owing to the obtaining of tiny grains in the FSP specimen in comparison with the as-received aluminum alloy 6061-T6, due to the vigorous plastic deformation and dynamic recrystallization.

The rates of wear of the FSP composite specimens that were reinforced by the particles of SiC are lower than that for the FSP base alloy; this is due to the reinforcement particles of SiC, which act as strengthening particles of aluminum alloy 6061-T6 dispersed in matrix of the Al. A proper particle dispersion in matrix decreases the rate of wear rate and enhances the resistance to wear. The SiC has the best resistance to wear due to the improved hardness via its particle spread. The addition of reinforcing particles decreases the rate of wear, because the hard particles are pulled out from the specimen of composite by the pin during the process of wear, created on the steel disc and work as barrier.

Furthermore, it changes the wear from the adhesive type to the abrasive type that causes a higher quantity of worn-out material from the specimen of composite via the pin. The whole specimens have the same wear behavior, but in different values. The wear behavior is first a mild wear or an oxidative wear at lower loads (5 N), then transforms to transition wear, and after that it becomes a severe or a metallic wear at greater loads. Such results agree with the findings of other researchers [17, 18]. The same results were obtained via the researcher [19] for Al5083/B4C and via the researcher [20] for Al5083/SiC in fabricating the surface composites via the FSP.

Figure 12: Effect of applied load on the wear rate for base alloy, AA6061-T6, FSP and with SiC reinforcement particles for a sliding time of 20 min

4. Conclusions
1- Microstructure modification and refinement were observed for samples subjected to FSP at the best fixed parameters of 1250 rpm rotational speed, and 32 mm/min travel speed with double passes by using a cylindrical threaded pin profile.
2- The highest hardness was noticed in the stir zone (SZ) and decreased toward the thermomechanical-affected zone (TMAZ) and heat-affected zone (HAZ) and then toward the base alloy AA6061-T6 for samples after FSP.
3- The SiC particles addition to AA6061-T6 led to increase in the microhardness and wear resistance, in comparison with the base material.
4- The rate of wear increased as the exerted load was increased from 5 N to 20 N at a fixed time of sliding (20 min) and speed of sliding (2.8 m/sec) for the whole specimens (FSPed of the parent material and the composites).
5- The outcomes manifested that the composite specimen that reinforced by the particles of SiC elucidated microhardness and resistance to wear better than the base alloy AA6061-T6 (62.6% improvement in hardness) as compared to FSPed sample.
6- The addition of SiC particles to the base aluminum alloy 6061-T6 improved the resistance to wear and changed the wear behavior from the adhesive type to the abrasive type.

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