Microstructure and wear behaviour of aluminium surface composites fabricated using friction stir processing

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Abstract. In this study, wear behavior of AA6082 matrix composite reinforced with titanium carbide particles (TiC) produced by friction stir processing was investigated. The main objective of this study is to compare the microstructure and wear behavior of Aluminium alloy 6082 with AA6082 - TiC surface composites. FSP was carried out using a threaded pin tool with 1200 rpm tool rotational speed, whose processing speed of 60 mm/min and an axial load of 10 kN. The microstructure analysis exhibited that the fine grains and uniform distribution of TiC particles in friction stir processed AA6082 matrix with and without TiC particles, respectively. A pin on disc equipment was used to study the wear properties. It was observed that the wear resistance of the FSPed aluminium composites samples improved significantly as compared to that of the AA6082 matrix alloy. With this the effect of TiC particles on worn surface and wear debris is also reported in this study.

1. Introduction

Aluminum matrix composites (AMCs) have gained more popularity and research emphasis due to the excellent properties like precise strength, superior wear resistance and low thermal expansion. The hard ceramic particles are commonly documented to improve the hardness and wear resistance of the surface composites by acting as load-bearing components. AMCs are generally used in many aerospace, automotive, and marine applications. Research is being carried out across the world to improve the properties of AMCs using modern fabrication methods and reinforcements [1–3]. Friction stir processing (FSP) is a novel technique to produce bulk and surface composites [4, 5]. This standardized method was derived from the FSW (Friction Stir Welding) concepts. Grooves [6] are formed on aluminum plates and packed with ceramic particles. At one end of the plate, a tool is plunged and traversed around the plate. The frictional heat plasticizes the material, and the tool pin’s rapid stirring action blends the ceramic material with the plasticized material. FSP is an economical solid state method that overcomes the limitations of liquid metallurgy routes. During FSP, the temperature is well below the melting point of the materials which prevents interfacial reactions and porosity. Qu et al. [7] used FSP to develop AA6061 / Al2O3 and AA6061 / SiC Nano AMCs and obtained an improved wear resistance. Dolatkhah et al. [8] manufactured AA5052 / SiC AMC using FSP and analyzed the effect of process parameters on the mechanical and microstructure properties. Soleymani et al.[9] developed the AMCs AA5083/SiC and AA5083/MoS2 and investigated the composites’ tribological behavior. Devaraju et al.[10] developed AA6061 / SiC and AA6061 / graphite
AMCs using FSP, and optimized process parameters to improve the composite's wear behaviour. Liu et al.\cite{11} manufactured AA1016 / MWCNT AMCs using FSP, and reviewed the composite's microstructure and mechanical properties.

An attempt is being made in the present work to manufacture AA6082/TiC AMCs using FSP and to study the effect of TiC particles on the AMCs' microstructure and dry sliding wear behavior. Because of its high strength and elastic modules, low density, better wettability with molten aluminum and low chemical reactivity \cite{12}, TiC is used as reinforcement for processing AMCs.

2. Materials and Experimental Procedure

Commercially available 10 mm thick AA6082 plates with a nominal composition of 0.78Mg-1.06Si-0.21Fe-bal Al (in wt. percent) were used as the substrates. Using wire cut EDM a groove of 5 mm deep and 0.8 mm wide was made along the center line of the plate and filled with TiC powder. Because of its high hardness the average size of 2 μm TiC particles was used as strong reinforcements. After filling with TiC particles, a pinless tool was initially used to cover the top of the groove to prevent the particles from scattering during FSP. A tool made of HCHCr steel as shown in figure 1 (a) was used for this study. The tool was 18 mm in shoulder diameter, 6 mm in pin diameter and 5.5 mm in pin length. For the manufacture of surface composites an indigenously designed FSW machine was used. The process parameters used were: 1200 rpm rotational tool speed, 60 mm / min traverse speed and 10 kN axial force. Specimens of 10 mm thickness were polished as per standard metallographic procedure and etched with Keller's reagent. Microstructures were analyzed using the scanning electron microscope (SEM).

A pin-on - disc wear apparatus (DUCOM TR20-LE) was used to test the sliding wear action of AA6082 / TiC surface composites at room temperature as per ASTM G99-04 standard. The 6 mm x 5 mm x 40 mm AA6082 / TiC pins were made of the as-received substrate surface (AA6082) and the produced composite surface from the FSP region using wire cut EDM. The polished pin surface slid onto a hard chromium steel plate. The counterpart disks were made of En-32 steel with a approximately 65 HRC hardness value. The prepared pins were polished using fine grade emery paper to eliminate surface irregularities. Before carrying out the examination, both the disk and the pins were washed. The wear analysis was carried out at a sliding speed of 1.0 m/s, and sliding distance of 2500 m. The dry sliding wear properties of the samples were analyzed through varying normal conditions of load. For evaluate the height loss, computer-aided data acquisition software was used. The volumetric loss was determined by the multiplication of the test pin's cross sectional area with its height loss. By dividing volumetric loss to sliding distance the wear rate was obtained. Using SEM the test specimen's worn surfaces were observed. The wear debris were collected and characterized by using SEM. The coefficient of friction between the specimen and the disk was determined by using a stress sensor to measure the frictional force.
3. Results and Discussion
Aluminum with and without TiC particles was successfully achieved by FSP. Figure 1 (b) shows a typical crown appearance of fabricated aluminum surface composites. There are no imperfections on the surface, including voids, cracks etc. The top surface with no depression tends to be even and perfect finish. The crown is smooth in shape.

The top surface i.e crown of the friction stir processed zone contains curved structure. This structure is similar to conventional milling, because FSW was derived from the conventional milling process. Several trial tests were initially performed to pick a set of optimized process parameters that were used to produce the composites. The abovementioned defect free crown appearance is an evidence for the appropriate selection of process parameters. A smooth appearance of the crown in the processed zone is important, as surface imperfection in the crown causes numerous internal deficiencies in the AMC. A continuous black line marks the boundary of the FSP zone which contains the AMC. An image analyzing software was used to measure the processed area.

![Figure 2. Optical micrograph of FSPed aluminium (a) FSPed AA6082 (b) with TiC (c) SEM micrograph of FSPed AA6082/TiC surface composite.](image)

Figure 2. Displays the optical micrographs of friction stir processed aluminium with and without TiC particles. The TiC particles that are incorporated form a composite surface layer. The interface between the composite layer and aluminium is free of defects of any type. The interface demonstrates strong bonding between the composite layer and the aluminium. Figure 2 (c) reveals that the absence of any defect along the interface indicates strong bonding between the composite surface layer and the aluminium. The banded structure present adjacent to the interface indicates the TMAZ, which is a unique feature of FSW. The frictional heat produced by the rotating tool and high stress application during the FSP result in the stretching of TiC particles along the direction of the shear stress. These particles are homogeneously distributed in the composite layer and fused well with the matrix of aluminium. The tool's stirring action induces high plastic strain, rearranging TiC particles compacted in the groove into homogeneous distribution in the stir region.

FSP is considered a hot working process in which the workpiece undergoes extreme plastic deformation through the pin and shoulder that rotates. The high temperature and severe plastic deformation result in TiC particle fragmentation. The large variation in TiC particle size gives an
evidence of fragmentation. Unbroken, partially broken and thoroughly broken TiC particles are visible.

![Figure 3](image)

**Figure 3.** Weight-loss data (a and b) and rate of wear (c and d) of the received aluminium substrate and the surface composite.

The wear behavior of the obtained surface composite AA6082 and AA6082 / TiC was determined using a pin-on-disk system under different loads of 10, 25 and 50 N applied. Figure 3 shows the weight loss data and the wear rate of the specimens as a function of the sliding distance under the various loads applied. It may be found that weight loss is substantially reduced for surface composites compared to that of the received AA6082. The maximum difference in the weight loss data of the two cases can be noted at the applied load of 50 N. The superior wear behaviour of the surface composite can be attributed to its greater microhardness value; this was achieved due to the uniform distribution of hard TiC particulates. Also, the hardness and wear rate are correlated by the established Archard's law as given below. According to this law, volume loss is inversely proportional to the hardness of the AMC. The higher the material's hardness, the lower the wear rate because the resistance to material removal increases during sliding.

Further figure 3(a) shows that the weight loss phenomenon with sliding distances can be split into two stages for AMCs. The first is related to a sliding distance of 0 - 500 m which shows a relatively low wear rate. The transition from the first stage to the second stage is correlated with a substantial increase in wear rate at a sliding distance longer than 500 m; it was found that the first stage wear rate of the obtained AA6082 matrix was approximately one to two orders of magnitude lower than the second one. In the case of surface composites, however, the two-stage trend was not noted.
Figure 4 displays a steady state wear rate depending on the load applied. With the addition of TiC particles the wear rate of all the specimens decreased. With the incorporation of TiC particles, the wear rate decreases to form the AMCs.

Figure 5. Worn-out surfaces of the received AA6082 matrix under wear loads of 25 N (a, b), and worn-out surface of AA6082/TiC surface composite under loads of 25 N (c, d)

Frictional heat is developed between the sliding pin surface and the counterparts that plastises the matrix. As sliding continues, the plastized matrix is squeezed along the sliding direction. The worn surface of a load of 25N obtained matrix AA6082 is shown in figure 5. As-received matrix AA6082 is much softer than the material on the disc; the slider could penetrate and cut the surface, causing plastic deformation and material loss. Long abrasion grooves were observed, and a number of pits formed parallel to the sliding direction. The wear mode is looked at as adhesive. In addition, it experiences large pits and local delaminating. Additionally, trapping of wear debris is noted in the pits. These indicate that with increasing load, the wear mechanism changes from mild to severe wear. In the case
of surface composite, the presence of TiC particles which have a far greater hardness than that of the obtained particles. The matrix AA6082 offers wear protection by strengthening the matrix of aluminium. The plastic flow of the worn surface is decreasing, and a distinct groove like pattern is beginning to form figure 5 (d) when TiC particles are present. The strengthening of TiC particles provides resistance to plasticized matrix movement and reduces the contact areas. Hence, that parallel grooves are formed. The mode of wear changes slowly from adhesive to abrasive. The plastic flow onto the worn surface completely disappears. Due to the formation of fine wear debris, the worn AMC surface at high volume fraction of TiC particles is covered with numerous debris.

**Figure 6.** Wear debris of the received AA6082 matrix under wear loads of 25 N (a, b), and worn – out surface of AA6082/TiC surface composite under loads of 25 N (c, d)

From figure 6 (a, b) The wear debris of the obtained AA6082 matrix at a load of 25 N is found to show a thin plate like morphology along with a small amount of fine debris. The plasticised matrix is exposed to the counterface's cutting action. The plate like morphology shows that during sliding the material removal rate is high and indicates that the working wear mechanism adhesively. The deterioration of asperities during the initial stages of sliding wear can be due to a small amount of fine debris. It is evident from figure 6 (c, d) the TiC particles in the AMC greatly affect wear debris morphology and size. The spherical morphology indicates that the AMC working wear system is abrasive. Compared to unreinforced matrix alloy, surface contact between the composite specimen and the counterface is low. TiC particles protrude outside of the surface and initially bear the load. The protruding particles are either fragmented or detached from the surface of the specimen as sliding proceeds and trapped between the counterface and the sliding specimen. Afterwards a new layer of protruding particles will contact the counterface. The trapped particles turn into three body abrasion wears and produce fine spherical wear debris. Spherical wear debris forming is similar to conventional ball milling. The wear debris is ground to fine till the specimen covers the distance of sliding set. The spherical wear debris can be attributed to the AMC’s reduced wear rates compared to matrix alloy. Because they tend to change sliding contact into rolling contact, and decreases the rate of material removal. The effects discussed above magnify as the volume fraction of TiC particles increases. The net result is finer spherical wear debris forming and lower wear rate.
4. Conclusion
In this investigation, Friction stir processing technique was successfully applied to fabricate AA6082-TiC surface composite. The dry sliding behaviour of the composite was studied. The findings can be summed up in the following way:
1. The distribution of TiC particles within the composite was relatively homogeneous.
2. There was a noticeable clean interface between TiC particles and the aluminum matrix AA6082.
3. The incorporated TiC particles enhanced the wear resistance of the Surface composites.
4. The wear rate increased with the load applied.

5. References
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