Production and wear characterization of AA6082-TiC surface composites by friction stir processing

A. Thangarasu\textsuperscript{a*}, N. Murugan\textsuperscript{b}, I. Dinaharan\textsuperscript{c}

\textsuperscript{a}Department of Mechanical Engineering, Sri Ramakrishna Institute of Technology, Coimbatore – 641 010, Tamil Nadu, India.
\textsuperscript{b}Department of Mechanical Engineering, Coimbatore Institute of Technology, Coimbatore – 641 014, Tamil Nadu, India.
\textsuperscript{c}Department of Mechanical Engineering, V V College of Engineering, Tisaiyanvilai – 627 657, Tamil Nadu, India.

Abstract

Friction stir processing (FSP) has originated to be an innovative solid state technique to fabricate aluminium matrix surface composites (AMCs). FSP technique was used to produce AA6082/TiC surface AMCs and analyze the effect of TiC particles on microstructure and dry sliding wear behaviour. Surface AMCs containing five different various volume fractions (0, 6%, 12%, 18% and 24%) were fabricated. FSP was carried out using a tool rotational speed of 1200 rpm, travel speed of 60 mm/min and an axial force of 10 kN to produce surface composite. The microstructure of the AA6082/TiC AMCs was studied using optical and scanning electron microscopy (SEM). The sliding wear behaviour was evaluated using a pin-on-disk apparatus. The results revealed that the TiC particles significantly influenced the distribution of TiC particles, and sliding wear behaviour of the AA6082/TiC AMCs. The effect of TiC particles on worn surface is also reported in this paper.

Keywords: Aluminium Matrix surface Composites; Friction Stir Processing; Microstructure; Wear.

1. Introduction

Due to the excellent properties like specific strength, superior wear resistance and low thermal expansion, Aluminum matrix composites (AMCs) have gained more attention and research focus. AMCs are widely replacing...
conventional aluminum alloys in many applications and components in aerospace, automobile and marine industries. Research is being carried out across the world to improve the properties of AMCs using novel fabrication methods and reinforcements [1–3]. AMCs are conventionally produced by liquid metallurgy routes such as stir casting [4], squeeze casting [5] and compo casting [6]. It is difficult to mix any kind of reinforcement to molten aluminum and keep it in suspension due to the poor wettability of both matrix and reinforcement [7]. The ceramic particle has an affinity to react with molten aluminum or decompose at higher temperatures to form undesirable compounds which deteriorate the properties of AMCs [8]. Though liquid metallurgy routes are inexpensive for mass production, the homogeneous distribution of reinforcement particles across the casting is questionable. The process parameters influence the solidification structure of AMCs which demands precise control.

Friction stir processing (FSP) is a novel solid state technique to fabricate bulk and surface composites [9, 10]. The idea was derived from the principles of friction stir welding (FSW). Grooves [11] are produced on aluminum plates and filled with ceramic particles. A tool is plunged at one end of the plate and traversed across the plate. The frictional heat plasticizes the material and the intense stirring action of the tool pin mixes the ceramic particle to the plasticized material. FSP is a solid state economical process which overcomes the limitations of liquid metallurgy routes. The temperature during FSP is well below the melting point of the materials which avoids interfacial reactions and porosity.

Qu et al. [12] developed AA6061/Al2O3 and AA6061/SiC Nano AMCs using FSP and obtained an enhanced wear resistance. Dolatkhah et al. [13] produced AA5052/SiC AMC using FSP and analyzed the effect of process parameters on the microstructure and mechanical properties. Soleymani et al. [14] formed AA5083/SiC and AA5083/MoS2 AMCs and investigated the tribological behavior of the composites. Devaraju et al. [15] developed AA6061/SiC and AA6061/graphite AMCs using FSP and optimized the process parameters to enhance the wear behavior of the composite. Liu et al. [16] fabricated AA1016/MWCNT AMCs using FSP and examined the microstructure and mechanical properties of the composite.

In the present work, an attempt is made to fabricate AA6082/TiC AMCs using FSP and study the effect of TiC particles and its volume fraction (vol. %) on microstructure and dry sliding wear behavior of the AMCs. TiC is used as reinforcement to prepare AMCs because of its high hardness and elastic modules, low density, good wettability with molten aluminum and its low chemical reactivity [17].

2. Experimental procedure

Aluminum alloy AA6082 plates of 10 mm thickness were used for this study. A groove of 5 mm deep and 0,0.4,0.8,1.2 and 1.6 mm width was made along the centre line of the plate using wire EDM and compacted with TiC powder. The average size of TiC particles used in this work was 2 μm. A pinless tool was initially employed to cover the top of the groove after filling with TiC particles to prevent the particles from scattering during FSP [18]. A tool made of HCHCr steel as shown in Fig. 1(a) was used in this study. The tool had a shoulder diameter of 18 mm, pin diameter of 6 mm and pin length of 5.5 mm. The FSP was carried out on an indigenously built FSW machine. The process parameters employed were: tool rotational speed of 1200 rpm, traverse speed of 60 mm/min and axial force of 10 kN. Five such plates were friction stir processed by varying the width of the groove to have five levels of volume fraction of TiC particles (0, 6, 12, 18 and 24 vol. %). Specimens of 10 mm thickness by cutting for FSPed plates at its centre perpendicular to processing direction were polished as per standard metallographic procedure and etched with Keller’s reagent. The microstructure was observed using a metallurgical microscope and a scanning electron microscope.
The sliding wear behaviour of AA6082/TiC surface composites was measured using a pin-on-disc wear apparatus (DUCOM TR20-LE) at room temperature according to ASTM G99-04 standard. AA6082/TiC pins of size 6 mm x 5 mm x 40 mm were prepared from the FSP zone by wire cut EDM. The wear test was conducted at a sliding velocity of 1.0 m/s, normal force of 25 N and sliding distance of 2500 m. The polished surface of the pin was slid on a hardened chromium steel disc. A computer aided data acquisition system was used to monitor the loss of height. The volumetric loss was computed by multiplying the cross sectional area of the test pin with its loss of height. The wear rate was obtained by dividing volumetric loss to sliding distance. The worn surfaces of the test specimen were observed using SEM. The wear debris which were scattered on the face of the counterface were carefully collected and characterized using SEM.

3. Results and discussion

Fig. 2 illustrates the typical crown appearance of friction stir processed aluminium with TiC particles. There are no voids, cracks on the surface. The top surface seems to be even and good quality with no depression. The aforesaid defect free crown appearance is an evidence for the appropriate selection of sufficient process parameters. A smooth crown appearance is necessary in the processed zone, because surface imperfection causes various internal defects in the AMC.

Fig. 2. Typical crown appearance of friction stir processed aluminium alloy AA6082 using TiC particles.
3.1. Microstructure of AA6082/TiC AMCs

The optical micrographs of the prepared AMCs are shown in Fig. 3.

![Optical micrographs](image)

Fig. 3. Optical photomicrograph of AA6082/TiC AMCs containing TiC: (a) 0 vol.%, (b) 18 vol.%, and (c) 24 vol.%.

Figure 3(a) indicating zero volume fractions shows very fine equiaxed grains formed due to dynamic recrystallization during FSP. The intense plastic deformation and exposure to elevated temperature cause dynamic recrystallization which refines the grains of aluminium alloy AA6082. Dynamic recrystallization is a well-known established phenomenon in FSW and FSP. The average grain size of friction stir processed AA6082 is about 10 μm. Dynamic recrystallization resulted in an extensive grain refinement. The optical micrographs shown in Fig 3(b) and (c) clearly reveal the distribution of TiC particles all over the aluminium matrix.

The SEM micrographs of the prepared AMCs are shown in Fig. 4. The distribution of TiC particles is fairly homogeneous in the AMC. During the initial stages of the formation of the AMC, the plasticized aluminium alloy flows into the groove and forged at the back of the tool. The rotating action of the tool provides a vigorous stirring which causes the packed TiC particles in the groove to be uniformly distributed in the aluminium matrix. Segregation reduces mechanical and tribological properties of the AMC. Since the AMC is formed in the solid state, the free movement of particles due to density gradient is absent. However, an agglomeration of TiC particles was observed at few places. The dark regions in the macrostructure (Fig. 3) exhibit bands of TiC particles. Those regions were present close to the centre of the AMC. The threaded tool causes a vertical flow might have formed the agglomeration of the plasticized composite. The trapped TiC particles during the vertical flow might have formed the agglomeration while the particles in groove were mixed with plasticized aluminium. The grains are not clearly visible in Fig. 3b and c because they are ultrafine in nature.

The grain modification can be attributed to the presence of TiC particles in the AMC because TiC particle acted as an effective grain refiner. The TiC particles pin the movement of the grain boundary and retard the grain growth subsequent to dynamic recrystallization. This is known as pinning effect which produces finer grains in AMCs [19]. The stirring action of the tool and the intense plastic strain were known to break the ceramic particles
during FSW/FSP and change their size and morphology [20].

![SEM micrographs of AA6082/TiC AMCs containing TiC](image)

TiC particles retained the original size and morphology which can be attributed to their initial smaller size. This result agrees with the findings of Chen et al. [21] who did not observe fragmentation of B₄C particles in FSW of AA6063/ B₄C AMC due to its smaller size.

3.2. Sliding wear behaviour of AA6082/TiC AMCs

The wear rate of AA6082/TiC AMCs at various volume fractions of TiC particles is calculated using equation (5) and is shown in Fig. 5. The dry sliding wear behaviour of the AA6082/TiC AMCs was evaluated by a pin-on-disk apparatus against a hardened steel disk under applied load of 25 N.

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\text{Wear rate} = \text{Height loss (mm) x Cross sectional area of specimen (mm}^2)/\text{Sliding distance (m)}
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Fig. 5 shows the observed weight-loss data and rate of wear of the wear specimens as a function of sliding distance under the applied load (25 N). It is observed that weight loss significantly reduced for 24 Vol. % specimens compared to the other specimens. The maximum difference in the weight loss data of the two specimens can be observed at 0 vol. % and 24 vol. %. The rate of wear was measured to be 0.00697 mg/m at 0 vol. % and 0.00303 mg/m at 24 vol. %. The greater wear behaviour of the AMC can be attributed to its superior micro hardness value; this was achieved due to the uniform distribution of TiC particles which in turn refined the AMC matrix grains. 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. Higher the hardness of the material, lower will be the wear rate because, the resistance to remove material during sliding increases.
In addition, Fig. 5(a) shows that the tendency of weight loss with sliding distances can be divided into two stages for AMCs. The first one is related to a sliding distance in the range of 0 – 500 m which shows a relatively low rate of wear. The transition from the first stage to the second stage is associated with a significant increase in wear rate at a sliding distance longer than ~500 m; the first stage wear rate of the zero vol. % was found to be approximately one to two orders of magnitude lower than that of the second one. Fig. 5(c) shows the steady state wear rate as a function of the applied load. The wear rate of all specimens was found to decrease with increasing the vol. % of TiC particles. The wear rate decreases with the addition of TiC particles to form the AMCs.

The worn surface of AA6082/TiC AMCs at various volume fractions of TiC particles is depicted in Fig. 6. The worn surface of friction stir processed AA6082 AMCs (Fig. 6a) shows large amount of plastic flow of matrix alloy. Frictional heat is developed between the surface of the sliding pin and the counterface which plasticizes the matrix. As sliding proceeds, the plasticized matrix is squeezed along the direction of sliding. The wear mode is observed to be adhesive. The plastic flow on the worn surface diminishes and a distinct groove like pattern starts to form (Fig. 6c) as the volume fraction of TiC is increased to 12%. The reinforcement of TiC particles offers resistance to the movement of plasticized matrix and reduces the contact areas. Hence, parallel grooves are formed. The wear mode gradually shifts from adhesive to abrasive.

The metal removal rate during sliding is less in abrasive mode compared to the adhesive mode of wear. The parallel groove pattern is well pronounced (Fig. 6d and e) with further increase in the volume fraction of TiC particles. The plastic flow totally disappears on the worn surface. The worn surface of the AMC at high volume
fraction of TiC particles is covered with numerous debris due to the formation of fine wear-debris.

4. Conclusions

AA6082/TiC AMCs were fabricated using FSP and the effect of TiC particles and its volume fraction on microstructure and sliding wear behaviour were analysed. The following conclusions are derived from the present work.

- The distribution of TiC particles was fairly homogenous in the composite irrespective of the volume fraction. AA6082/TiC AMCs exhibited a reduction in the average grain size during FSP.
- A clean interface was noticed between TiC particles and the AA6082 aluminium matrix.
- TiC particles improved the wear resistance of the AMC. The rate of wear reduced when the volume fraction of TiC particles is increased. The rate of wear was found to be 0.00693 mg/m at 0 vol. % and 0.00303 mg/m at 22 vol. %.
- TiC particles influenced the wear mode as well as the morphology of the wear debris. The increase in the volume fraction of TiC particles altered the wear mode from adhesion to abrasive.

References
