Effect of friction stir processing and hybrid reinforcement on wear behaviour of AA6082 alloy composite

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Abstract

In the present study, microstructure, mechanical properties and wear behaviour of AA6082 alloy reinforced with Yttrium oxide (Y₂O₃) and graphite (Gr) surface hybrid composites produced via friction stir processing have been investigated. Vol.% of Y₂O₃ particles was varied (2, 4 and 6 vol.%) while the graphite content was kept at as 4 vol.%. Microstructure of synthesized composites revealed uniform distribution of Y₂O₃ + Gr particles accompanied by a significant reduction in grain size. Microhardness of the composites was found to be 40% higher than the matrix alloy and tensile strength of the composites increased with increase in vol.% of Y₂O₃ with a marginal decrease in ductility. Wear test results along with SEM micrographs of worn out surface of composites and matrix alloy were compared and correlated with their hardness. Hybrid composites showed better wear resistance.

1. Introduction

6XXX series Al alloys have a wide variety of applications that includes bridges, automobile and milk churns. Among the 6 series alloys, AA6082 alloy is widely used in various structural and transport application due to its excellent mechanical properties [1]. Properties of AA6082 alloy can be further enhanced by Friction Stir Processing (FSP) with the incorporation of ceramic particles as reinforcements [2]. Addition of more than one type of reinforcement to the matrix is named as hybrid composites which will have combined advantage of both the reinforcements [3, 4]. Several authors have reported enhancement in the mechanical and wear properties of hybrid composites. A hybrid composite with hard and soft reinforcement can give superior tribological properties and can be achieved by optimizing the amount of constituents [5]. Mostafapour et al [6] studied the hybrid ratio of graphite and Al₃O₃ on tribological behaviour of AA5083 alloy. Hybrid ratio of 1 was found to give better tensile strength and wear properties. Devaraju et al [7] studied the influence of SiC and graphite addition on the tribological properties of AA6061 alloy developed via FSP. Optimum wear rate was obtained in composites reinforced with 3 vol. % of graphite and 6 vol. % of SiC. Adibpour et al [8] investigated the wear behaviour of A356/Al₂O₃/Gr surface composites produced via FSP. Wear studies, indicated that hybrid reinforcements were found to improve the wear properties of the A356 alloy significantly. Srinivasu et al [9] produced of A356 alloy hybrid composites with B₄C and MoS₂ powder using FSP process and reported that these reinforcements significantly enhanced the hardness and tribological properties of A356 alloy. Sahandi Zangabad et al [10] studied the mechanical properties of via friction stir processed Al–Al₃Ti–MgO hybrid nanocomposites. Microstructural studies showed nanocomposites were composed of fine grained structure (< 2 μm) and hard inclusions (TiO₂, Al₃Ti and MgO) with an average size < 50 nm. Significant enhancement in YS and UTS of 90% and 31% was obtained, with corresponding decrease in the ductility (up to 30%) in the composites. From the literature survey it can be concluded that aluminium alloy reinforced with hybrid particles can improve the tribological behaviour of the composite. In the present study, the effect of friction stir...
processing and Y₂O₃/graphite content on the microstructure, mechanical properties and wear behaviour of AA6082 alloy composites was investigated.

2. Materials and methods

AA6082 matrix alloy (Al-1.2 Si-0.78 Mg-0.53 Mn-0.33 Fe) reinforced with Yttrium oxide (Y₂O₃) with particle size ranging from 1–5 μm and graphite (Gr) with particle size ranging from 10–20 μm. Figures 1(a)–(c) shows the microstructure of AA6082 matrix alloy, Y₂O₃ particles and Gr particles respectively.

2.1. Friction stir processing of hybrid composites

Wire Electric Discharge Machining (WEDM) was used to prepare a groove of 0.7 mm width and 2.7 depth in 100 × 50 × 6 mm Al alloy AA6082 plates. The groove was filled with reinforcement particles (varied as 2, 4 and 6 vol. % Y₂O₃ and a constant 4 vol.% Graphite particles) and sealed with a pinless tool to prevent the falling of particles during FSP. FSP was carried out using a tungsten carbide tool having 8 mm diameter and 5 mm length, with an axial load of 10 kN, a rotational speed of 1200 rpm and with a traverse speed of 30 mm min⁻¹. Metallographic examination on FSP samples were carried out using standard metallographic procedure (ASTM E3-11). The polished specimens were then etched using Keller’s etchant and viewed under a metallurgical microscope (MA-100, Nikon) at various magnifications. XRD studies were carried out using a Shimadzu make x-ray diffractometer (XRD 6000) with Cu Kα (λ = 1.5409 Å) radiation. A scan speed of 2° min⁻¹ with the step scan of 0.02° was used with 40 kV potential. The samples were scanned with 2θ values ranging from 10° to 80°. Scanning Electron Microscope (SEM) examination was carried out using a (JSM-6510LV, JEOL) to study the distribution and bonding between the matrix and reinforcement. Hardness test was conducted as per ASTM E384 standard using a Zwick Vicker’s microhardness tester under a load of 100 g for 15 s and the average of five readings was taken as the hardness. Tensile tests were performed according to the ASTM E8 standard using an INSTRON 1195 tester. Standard tensile test specimens were cut from the stir zone using a wire EDM. The tensile strength of the samples was taken as the average of three readings. SEM examination was carried out on the fracture surface to find the fracture mechanism. Compression test was carried out as per ASTM standard E9-09 with 1 mm min⁻¹ cross head speed. Wear behavior of the alloy and the samples were studied using a pin-on-disc wear tester. Pin samples with a height of 15 mm and diameter of 6 mm were tested against a steel disc counter surface made up of oil hardened nickel steel having hardness of 60 HRC and diameter 55 mm were used in the present study. Room temperature (30 °C) wear test was performed with varying loads of 20, 40 and 60 N at constant sliding speed and sliding distance of 1.0 m s⁻¹ and 2 000 m respectively. The frictional traction encountered by the pin during sliding was measured continuously by a PC-based data-logging system for analysis. Initial weight and final weight of the pin sample were measured using an electronic balance having an accuracy of 0.1 mg. Weight loss method was used to calculate the wear rate of the prepared samples.

3. Results and discussion

3.1. XRD analysis of hybrid composites

XRD of the base alloy and 6 vol % Y₂O₃ + 4 vol. % Gr reinforced hybrid surface composites is shown in figure 2. The XRD pattern confirms the presence of Y₂O₃ and graphite particles.
3.2. Microstructure of AA6082/Y$_2$O$_3$+Gr hybrid surface composites

The optical images of the hybrid composites revealed homogeneous distribution of the reinforcement in the stir zone as seen in figure 3. Significant refinement of grain structure was observed in FSPed hybrid surface composites due to the vigorous stirring action of rotating tool which in turn induces high plastic strains at Stir Zone (SZ). Friction between FSP tool and AA6082 matrix alloy produces very high temperature and stirring action of FSP tool causes plastic deformation of matrix alloy. Significant refinement in grain size can also be attributed to dynamic recrystallization through FSP and uniformly distributed reinforcement particles in turn will restricting the grain growth by pinning effect thus leading to a higher degree of grain refinement.

The mechanism of reduction in grain size with fine particle dispersion has been explained by Titus et al[11] in their study on friction stir processing AlN + BN hybrid reinforcements in copper matrix. Figures 4(a)–(d)
shows the micrograph of the Y₂O₃ + 4 vol. % Gr added AA6082 alloy surface composites. The samples were etched with special reagent (25 ml CH₃OH, 25 ml HCl, 25 ml HNO₃, 1 drop HF) to reveal grain boundary [12]. In comparison to matrix alloy AA6082, the surface composites exhibited significant grain refinement along with a fine and equiaxed structure. The matrix alloy showed an average grain size of about 80 μm whereas the average grain size of the AA6082/6 vol.% Y₂O₃ + 4 vol. % Gr added composites was about 20 μm (figure 4(d)), a reduction in grain size by 75%, which is expected to enhance the hardness and wear resistance of the composite.

3.3. Microhardness of AA6082/Y₂O₃+Gr hybrid surface composites

Figure 5 shows the microhardness of the matrix alloy and hybrid surface composites along the cross-section of specimen. It can be seen that the stir zone exhibits a higher and uniform hardness compared to the adjacent region. It may be due to uniform dispersion of hybrid reinforcement without any agglomeration. Similar properties can be achieved on the whole surface with chosen set of tool rotational speed and feed. The hybrid surface composites exhibited a higher hardness of HV 132 as compared to the hardness of the matrix alloy (HV 88) and increase of 50%. This increase in hardness can be attributed both to grain refinement and the presence of hard Y₂O₃ particles and reduction in SZ grain size.

The significant improvement in hardness of the developed composites can be attributed by the following strengthening mechanisms, primarily due to Orowan particle strengthening caused by hard Y₂O₃ particles and secondly Hall–Petch relation related to grain size reduction. In addition, the difference in coefficient of thermal expansion between the hybrid reinforcement and the AA6082 alloy leads to work hardening effect leading to a further increase in the hardness of the hybrid composites. However, it can be seen that the hardness of Heat Affected Zone (HAZ) is lower than that of SZ and it may be due to the occurrence of grain coarsening caused by annealing.

3.4. Tensile properties of AA6082/Y₂O₃+Gr hybrid surface composites

The composites were tested for tensile properties including Yield Strength (YS), Ultimate Tensile Strength (UTS), and % elongation. From the figures 6(a) and (b), it can be observed that the YS and UTS of the composites increased with an increase in the vol.% of reinforcement while ductility showed a decrease. Significant improvement in tensile properties resulted from good bonding between the matrix and reinforcement, reduction in grain size and dislocation density generated during solidification due to thermal mismatch between the matrix and reinforcement. Figure 7(a) shows the photograph of tensile tested specimens and figures 7(b), (c) shows the SEM fractograph of surface of AA6082/2Y₂O₃ + 4 Gr and AA6082/6Y₂O₃ + 4 Gr hybrid surface.
Fracture surface of AA6082/2Y2O3 + 4 Gr (figure 7(b)) revealed predominantly ductile failure as indicated by dimples. Dimple formation results from micro voids nucleation, growth and its coalescence that in resulted in ductile fracture. Plastic deformation prior to failure has been confirmed by the SEM micrographs.
3.5. Compressive strength of the composites

Compressive strength of the composites was found to increase with increase in vol.% of Y$_2$O$_3$ particles (figure 8). It is observed that the hybrid composites exhibit a higher compressive strength compared to the matrix alloy. Incorporation of hard Y$_2$O$_3$ particles serves to increase the resistance to dislocation movement thereby increasing the strength\cite{13}.

3.6. Wear behavior of the surface composites

Wear rate of the surface hybrid composites AA6082/Y$_2$O$_3$ + 4 Gr (figure 9(a)) under different loads shows that the addition of Y$_2$O$_3$ significantly reduces the wear rate of the matrix alloy. Composites containing 6 vol.% Y$_2$O$_3$ and 4 vol.% graphite exhibited minimum wear rate (0.002 mm$^3$ m$^{-1}$ at 60 N load) about 50% lower than that of the AA6082 matrix alloy (0.004 mm$^3$ m$^{-1}$ at 60 N load). Compared to the matrix alloy, the wear rate of hybrid composites decreased with an increase in the applied load. At higher loads, contact pressure between the pin surface and the rotating disc increases leading to an increase in the surface temperature of the sample surface and consequently the specimen undergoes significant deformation. Decrease in wear rate in case of the composites is mainly due to the presence of graphite and formation of graphite lubricating thin film on the pin surface. While Y$_2$O$_3$ particles effectively bear the applied load and presence of thin graphite lubricant film significantly reduces the wear rate in the hybrid composites, by reducing the shear stress between the pin surface and the rotating disc which in turn minimises the plastic deformation of the pin surface thus decreasing the wear rate. Figure 9(b) shows the effect of graphite addition on coefficient of friction of surface hybrid composites. From the figure, it can be seen that the addition of graphite significantly reduces the coefficient of friction by acting as a solid lubricant. Compared to the matrix alloy coefficient of friction was found to be 50% lower in hybrid composites.
3.7. Morphological analysis of worn out samples

Figure 10 shows the SEM images of the wear tested sample surface of (a) AA6082 alloy (b) AA6082/2Y₂O₃ + 4 Gr and (c) AA6082/6Y₂O₃ + 4 Gr hybrid surface composites. The worn out surfaces of the matrix alloys shows delamination wear and heavy plastic deformation indicating severe wear. The worn out surfaces of the hybrid composite samples reveals the wear mechanisms to be mild delamination and abrasion. Worn out surface of the hybrid composite shows the detachment pin surface material by decohesion, formation of small cavities and abrasive grooves along the sliding direction. Presence of graphite minimizes the direct contact of pin with the rotating disc and avoids the fracture of the Y₂O₃ particles. With an increase in vol.% of the Y₂O₃ particles, plastic deformation of the matrix material is reduced and in addition Y₂O₃ particles also hinder the dislocation motion leading to reduced wear loss in the hybrid composites.

4. Conclusions

AA6082 alloy reinforced with Y₂O₃ and Gr hybrid surface composites was successfully fabricated using friction stir processing. XRD analysis confirmed the presence of Y₂O₃ and graphite particles. Significant reduction in grain size was observed in composites containing 6 vol.% Y₂O₃ + 4 vol. % Gr (20 μm) compared to that AA6082 alloy (80 μm). Hardness, tensile strength and yield strength of hybrid composites significantly improved with the addition of Y₂O₃ particles with a corresponding decrease in ductility. Addition of graphite significantly reduces the wear loss and friction coefficient by forming lubricating tribofilm on the pin surface. Wear mechanism of the matrix alloy changed from delamination to abrasive wear as the volume fraction reinforcement increased.

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