Effect of Abrasive Medium on Wear Behavior of Al/AlB₂ Functionally Graded Metal Matrix Composite

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Centrifugal casting process was applied for fabricating the functionally graded Aluminium/10% AlB₂ composite under the centrifuging speed of 1200 rpm and hollow cylindrical (150 × 150 × 15 mm) component has been obtained. The outer, middle and inner surfaces of the FGM those were at the distance of 1 mm, 8 mm and 15 mm from the outer periphery were taken for three body abrasive wear test and the applied load was varied (33 N to 80 N) on these surfaces in the presence of silica sand and alumina as abrasive mediums. The wear test results showed that increase in load and increase in distance from the outer periphery of the FGM increases the wear rate. The surfaces of the FGM abraded with silica sand displays higher wear rate than the surfaces abraded through alumina. SEM analysis has been performed on the surfaces abraded by both medium and it was observed that severity of wear was less in the presence of alumina as abrasive medium during the abrasion test.

Keywords: aluminium, functionally graded composite, abrasive wear, abrasive medium, scanning electron microscopy analysis

1. Introduction

Functionally Graded Materials (FGMs) are advanced materials for technological development fulfilling the needs of various applications where the properties of homogenous composites and monolithic alloys are not inadequate. The properties of FGMs are varying continuously in composition and microstructure along the thickness direction and hence it is possible to selectively reinforce the specific location of the component which require better strength and wear resistance. Many fabrication processes are available for fabricating the FGMs such as powder metallurgy, centrifugal casting, thermal spraying, laser cladding etc., [1], out of which the advantages of having the centrifugal casting process as economical route in the production of structural components with Al-Si alloy has been explained [2]. Centrifugal casting is also demonstrated to be effective in redistributing the reinforcement particles in the aluminium matrix. The centrifugally cast external zones exhibited higher superficial Rockwell hardness than the internal zone [3]. Yoshimi Watanabe et al [4] analyzed the control of composition gradient in FGM synthesized through centrifugal route and found that the

greater gradients are obtained in thinner thickness, greater centrifugal forces and smaller size particles. It is also observed that the mixture of particle sizes is useful in controlling the composition. Functionally graded aluminium in-situ composites with Titanium Diboride (TiB₂) and Titanium Carbide (TiC) reinforcements are fabricated using horizontal centrifugal casting method and found the segregation of reinforcements at the outer periphery, as this is due to stirring of molten metal before pouring into the die, while the absence of stirring caused the reinforcements to settle at the inner periphery of the casting [5]. The hardness of these composites increases with increase in volume fraction of reinforcement particles.

To date, one application of such FGM is in the area whereby different tribological properties are required in a component. Wear resistance of functionally graded aluminium/Aluminum Diboride (AlB₂) composite fabricated through centrifugal casting method has been investigated through ball on disk wear tests and found that diboride particles are segregated towards the outer region which leads to greater hardness and high wear resistance [6]. Singh et al [7] investigated the two-body abrasive wear behaviour of aluminium alloy and

aluminium/sillimanite composite with different abrasive sizes and is noted that wear resistance of the composite is superior for finer size abrasives compared with matrix alloy. Aluminium-frit particulate Metal Matrix Composites (MMCs) also showed considerable improvement in hardness and abrasive wear resistance compared to base matrix [8]. Satyabrata Das et al [9] examined the synergic effect of Silicon Carbide (SiC) particle reinforcement on two body abrasive wear of Al-Si alloy under varying loads and abrasive sizes. It is observed that alloy suffers from high wear rate than the composites irrespective of load and abrasive size. The reinforcement of aluminium matrix with SiC improved the three body abrasion wear resistance of composites fabricated by powder metallurgy route. The abrasion resistance of the composites increased with increasing the SiC content [10]. The effect of variables such as applied load and abrasive size are more pronounced on the abrasive wear behaviour of composite than unreinforced aluminium alloy [11]. At the same time, Yusuf Sahin and Ozdin [12], on his studies disclosed that abrasive size is found to be effective for the composite and applied load is dominant for the alloy matrix. Also, the interaction of load and abrasive size is found to be effective than those of other parameters. Ajith kumar Senapati et al [13] had given an overview on the effect of reinforcement on abrasive wear behavior of different aluminium based MMCs and concluded with considerable improvement in wear and mechanical properties. Based on the above studies, it is inferred that abrasive wear resistance of FGMs have not been explored so far, therefore it is valuable to synthesis aluminium/AlB₂ functionally graded composites and to evaluate its three body abrasive wear behaviour under two different abrasive medium of silica sand and alumina.

2. Materials

The cast aluminium LM25 alloy is selected as the base matrix since it has been applied for the development of cylinder block and cylinder head. The AlB₂ reinforcement particles (10% and 45 µm) are chosen to incorporate in the matrix for the improvement of abrasive wear resistance due to its high wear resistance nature. The aluminium alloy and AlB₂ particles have the densities of 2.68 g/cm³ and 3.19 g/cm³ respectively.

3. Fabrication process

The aluminium alloy is taken in the graphite crucible and kept for melting in an electric resistance furnace which is equipped with mechanical stirrer. The melting chamber of the furnace is connected with the argon gas cylinder which provides inert gas atmosphere (88% argon and 12% Carbon di-oxide (CO₂)) during melting of the aluminium alloy. The preheating has been conducted on the reinforcement particles simultaneously in order to remove the moisture content in the particles. After

Fig. 1 a) Centrifugal casting setup and b) Cast hollow cylindrical specimen

attainment of the molten stage of the alloy, the preheated reinforcement particles are added to the molten metal and stirred for 10 minutes at 250 rpm to uniformly disperse the particles in the matrix to obtain homogeneous composite. The centrifugal casting setup (Figure 1(a)) which has a rotating die is preheated simultaneously that facilitates avoiding the solidification front by providing the less temperature gradient at the molten metal and die interface. The die is rotated at 1200 rpm prior to pouring of the molten metal and the rotated till the end of solidification. The hollow cylindrical component (Figure 1(b)) of dimensions 150 mm length, 150 mm outer diameter and 15 mm thickness has been obtained after the solidification process.

4. Abrasive wear test

The surfaces from the FGM are taken from the thickness of the casting by taking the outer periphery as the reference. The surfaces at the distance of 1, 3, 5, 8, 10, 13 and 15 mm are having hardness of 142, 134, 123, 119, 114, 109 and 105 HV respectively. From these, the surfaces at the distance of 1, 8 and 15 mm from the outer periphery are taken for testing abrasive wear performance in dry abrasion tester (Figure 2(a)). The specimen is initially sectioned across the thickness of

FGM as indicated in Figure 3 and machined out accordingly to the surfaces (1, 8 and 15 mm) required for the test. The surface roughness of the specimen ($75 \times 25 \times 12$ mm) is made below $0.8 \mu\text{m}$ using surface grinding process. The tester is composed of chlorobutyl rubber wheel which is having the diameter of 228 mm. The specimen is fixed by the specimen holder which produces continuous contact with the rubber wheel by the application of load through the lever. The abrasive

Fig. 2 a) Dry abrasion tester and b) Surfaces abraded at different conditions

Fig. 3 Illustration of sectioning of specimen from the cast FGM

mediums such as silica sand and alumina (Figure 4(a,b)) are preferred for conducting the abrasive wear test to study their effect on the wear rate of the different surfaces of FGM. The abrasive mediums have the mean grain size of $50 \mu\text{m}$ and they fall at the rate of 354 g/min between the specimen and the rubber wheel which acts as a third body that produces abrasion on the surface of the specimens. The different loads (33 N, 45 N, 57 N, 68 N and 80 N) are applied on the surfaces of the FGMs in the presence of both abrasive mediums individually to study the effect of abrasive medium as well as the effect of load (Table 1). All the tests are conducted for the constant time of 5 minutes and at the speed of 150 rpm. Each abrasion test has been repeated for three times and the average value is considered for evaluation. The specimens of abrasive wear test are measured for its mass before and after test, and the abrasive wear rate is calculated from their corresponding mass difference. The outer surface of the FGM abraded at low load and high load with two different abrasive mediums are shown in Figure 2(b).

Fig. 4 a) Silica sand and b) Alumina

Table 1 Experimental layout for abrasive wear test

Abrasive medium	Surfaces of FGM	Applied load (N)
Silica sand	Outer, Middle and Inner	33, 45, 57, 68 and 80
Alumina	Outer, Middle and Inner	33, 45, 57, 68 and 80

5. Results and discussion

The abrasive medium plays a great role in the abrasive wear test which produces the loss of material from the specimen by its different abrading actions. The abrasive medium that falls between the specimen and the rubber wheel tends to roll, slide and subjected to various actions depending upon the parametric conditions. The load is applied on the rubber wheel through specimen at constant force and trapping of these moving abrasive medium between the rubber wheel and the specimen causes extreme pressure. The effect of load and the abrasive mediums (silica sand and alumina) on the abrasion wear rate of the surfaces of FGM has been discussed below.

5.1. Effect of load on wear rate

The abrasion wear rates for the load transition on the surfaces of the FGM in the presence of different abrasive mediums (silica sand and alumina) are shown in Figures (5,6). The increase in wear rate is observed for transition of load on all the surfaces of the FGM for both the abrasive mediums. The low load of 33 N subjects the interacting surfaces to limited contact pressure and the falling abrasive medium easily rolls between the specimen and the rubber wheel as likely stated in the previous study [14]. These freely falling abrasive medium has only less effect of ploughing on the surfaces of the specimen and thereby produces less material removal. When load of 45 N is acted on the rubber wheel,

Fig. 5 Effect of load on the surfaces of FGM in the presence of silica sand

Fig. 6 Effect of load on the surfaces of FGM in the presence of alumina

the abrasive medium gets crushed at the middle zone of the interfaces where the contact pressure is maximum. This in turn causes the abrasive medium to produce increased cutting and ploughing effect on the surface of the specimen which results in increased abrasion rate. The increase of load to 57 N on the surface yields further increase in wear rate as this is due to increase in the physical contact between the interacting surfaces as observed in the earlier report [15]. This causes the abrasive medium to get crushed at the entrance zone of the surfaces and produce abrading action earlier which eventually removes more material from the surface. When the load is turned to 68 N, these crushed particles gets reduces in the sizes due to more compression effect that takes place between the surfaces. These abrasive medium which are smaller in size are effective in producing the deeper cutting and abrading action on the surfaces of the specimen due to the action of high range of load. On further increase of load to 80 N, the abrasive medium gets compressed more at the interfaces and the vibration of tribosystem also takes place. This situation causes more uncertainties on the surfaces of the specimen which thereby leads to high material removal and results in more abrasion on the surfaces. Thus, increase in load causes the abrasion wear rate to increase on all the surfaces of FGM however the outer surface of the FGM displays the minimum order of wear rate, middle surface shows intermediate wear rate and inner surface shows the higher order of wear rate (Figures (5,6).

5.2. Effect of surface on wear rate

The surfaces at the distance of 1 mm, 8 mm and 15 mm from the outer periphery of the casting are examined through the optical microscope to observe the dispersion of the AlB_2 reinforcement particles in the aluminium matrix (Figure 7(a-c)). From these micrographs, it is observed that outer periphery (1 mm) of the FGM is particle enriched (Fig. 7(a)) and inner periphery (15 mm) of the FGM is particle depleted (Fig. 7(c)) which is due to the action of centrifugal force. These surfaces (1, 8 and 15 mm) are also examined through the image analyser and found concentration of the AlB_2 particles as 31%, 12% and 9% respectively. This image analysis ensures that reinforcement concentration is more on the surface at the distance of 1 mm and it decreases towards the inner periphery. This confirms that the compositional gradient obtained across the thickness of the casting under the action of centrifugal force.

The difference in the order of wear rate on different surfaces of FGM (Figures (5,6)) is attributed to the reinforcement particles compositional gradient formed across the thickness of the casting. The reinforcement particles and the molten metal are of different densities and thereby the rotating effect of the centrifugal die produces centrifugal force on the molten metal and the reinforcement particles suspended in it. Thus, the denser reinforcement particles experience throwing effect

Fig 7 Optical micrographs of the surfaces from the outer periphery a) 1 mm, b) 8 mm and c) 15 mm

towards the inner surface of the die and therefore the particles are enriched at the outer periphery of the casting, and similar pattern is observed [16]. It is understood from this concept that, particle concentration is decreased towards the inner periphery and forms particle depleted region at the inner periphery of the casting. The outer region of the FGM is composed of major portion of hard reinforcement zone with very less matrix area. During abrasive wear test, when the abrasive medium contacts with this harder reinforcement zone, it gets deflects towards the rubber wheel. This protects the softer matrix area from the abrading action of the abrasive mediums till these reinforcement particles are supported by the matrix and the similar pattern is observed [17,18]. The lower order of wear rate of this surface ensures that these reinforcement particles are greatly supported by matrix due to its uniform dispersion and good bonding. The middle surface displays intermediate wear rate among the surfaces of the FGM and this is due to the decrease in the reinforcement concentration when compared to the outer surface of the FGM. The inner surface shows higher wear rate and this is due to major matrix area with depletion of reinforcement particles. The inability of this surface to resist the abrading action of the abrasive medium in turn causes the abrasive medium to abrade easily on this surface and results in more material removal. Hence, the particle enriched outer region with greater wear resistance can be used as cylinder liners in the cylinder block by machining out the particle depleted inner zone of the FGM. Thus, the LM25/ AlB₂ FGM can be used as the replacement of cylinder block which are made of LM25 aluminum alloy for high wear resistance and increased life.

5.3. Effect of abrasive medium on wear rate

The effect of different abrasive mediums such as silica sand and alumina on the surfaces of the FGM has been studied and the obtained results are shown in Figure 8. The severity of the abrading action of the abrasive mediums is determined from its shape and hardness. The alumina particles are found with higher hardness and smooth curvy edges (Figure 4(b)) while the sand particles are found with slight decrease in hardness but have sharp angular edges (Figure 4(a)) on all the sides. The abrasive wear rate is observed high on all the surface of the FGM abraded with sharp sand particles rather than

Fig. 8 Effect of abrasive medium on the surfaces of FGM at constant load of 80 N

smooth curved alumina particles. This evident that sharpness of the abrasive medium dominates more on the abrading action than the hardness of the abrasive medium and the similar phenomena is observed [19]. Thus, these sharp angular sand particles are effective in deeper penetration on the surfaces of the FGM and displays high material removal. This situation does not allow the material to get work hardened and hence observed with more wear rate. The alumina particles are unable to plough the material as much due to its curve shape and results in less material removal. These curve edged particles majorly rolls and slides on the surface of the specimen rather than removal of material which makes the material work hardened even with small abrading time and therefore less wear rate is observed.

6. Scanning electron microscopy analysis

The Scanning Electron Microscopy (SEM) analysis is performed to determine the impact of load and abrasive medium on the wear mechanisms. The outer surfaces of the FGM abraded at different loads in the presence of silica sand (Figure 9(a-c)) and alumina (Figure 10(a-c)) are shown. The surfaces abraded at 33 N (Figure 9(a) and 10(a)) reveals less wear rate as this is attributed to less physical contact between the rubber wheel and the specimen. The surfaces shows small number of grooves with less material removal as this is due to less effectiveness in ploughing with dominant rolling behaviour of the abrasive mediums. The increase in load to 57 N on the surfaces (Figure 9(b) and 10(b)) reveals

Fig. 9 SEM analysis on the outer surface of FGM in the presence of silica sand a) 33 N b) 57 N and c) 80 N

Fig. 10 SEM analysis on the outer surface of FGM in the presence of alumina a) 33 N b) 57 N and c) 80 N

increase in the material removal with continuous grooves and more cutting action on the surfaces. These surfaces are affected by the crushing effect of the abrasive mediums that erode the surface of the specimen and remove more material. The transition of load to 80 N on the surfaces (Figure 9(c) and 10(c)) reveals deeper penetration, pitting and grooving of abrasive medium which is the cause of high compression action of the abrasive medium between the interacting surfaces. Thus, the transition of low load to high load on the surfaces produces a transition from mild wear to severe wear in the presence of both abrasive mediums.

The surfaces abraded with silica sand (Figure 9(a-c)) displays severe abrasive wear comparatively to the surfaces abraded with alumina (Figure 10(a-c)) at all loads. This is attributed to the curve shaped alumina particles which are less effective in ploughing on the surfaces and the sharp angular silica sand particles those are highly effective in abrading the surface. The silica sand particles abraded surfaces shows higher penetration whereas alumina abraded surfaces reveals lesser depth of penetration. Hence, it is observed that shape of the abrasive mediums highly governs the abrasion rate of the specimens.

7. Conclusion

Functionally graded aluminium/ AlB_2 composite has been successfully produced through centrifugal casting method. The abrasive wear test has been performed effectively in dry abrasion tester using silica sand and alumina as an abrasive mediums. The wear test results on the different surfaces of functionally graded composite shows that increase in load increases the abrasion rate. The abrasion wear is found with higher order of magnitude in case of silica sand as an abrasive medium due to its sharp angular shape and in case of alumina the

wear rate is found lower order due to its curvy edges. At all test conditions, the outer surface of the FGM exhibits maximum wear resistance due to concentration of AlB_2 particles, whereas the inner surface shows high wear rate owing to particle depletion under the centrifugal force. Hence, achieving wear resistance at the desired location of the FGM paves the way for many tribological applications where high wear resistance is of greater importance.

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