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Short communication

Evaluation of wear resistance of magnesium/glass microballoon syntactic foams for engineering/biomedical applications

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ABSTRACT

Friction and wear behaviour of magnesium/glass microballoon (GMB) foams synthesized by Disintegrated Melt Deposition (DMD) were investigated under dry sliding conditions. The coefficient of friction (μ) decreases with increasing GMB content. Mg-25wt.% GMB exhibits ~13% lower μ pure compared to magnesium. Wear resistance of magnesium showed a significant enhancement (~2.5 times) post GMB addition. Abrasion and oxidation were identified as dominant wear mechanisms post worn-surface analysis. Delamination wear, which has traditionally limited the advantages of composites with discontinuous reinforcements in sliding wear conditions for structural and biomedical applications can be effectively addressed by the development of these proposed syntactic foams.

1. Introduction

Magnesium (Mg), being the lightest (density ~1.74 g/cc) among available metals is finding increasing applications in automotive, aerospace and defense sectors demanding weight reduction, higher fuel efficiency and reduction in greenhouse gas emissions [1]. Further, magnesium is gaining increased interest as a biomaterial because of its biocompatibility, biodegradability, and bioresorbability without any toxic by-products post-implantation. This has made magnesium an ideal material for cardiovascular and orthopedic implants [2]. However, owing to lower hardness, magnesium and its alloys exhibit poor wear resistance limiting their suitability for structural and transmission components (bearings, rollers, sprockets seals, gears, and brakes) wherein wear scenarios are prominent [3]. Further, high wear rates of the implants in presence of the body fluid can result wear debris across metal interfaces in joints causing osteolysis and sepsis leading to improper functioning of implants [4]. Therefore, efforts are made by researchers to develop novel magnesium matrix composites to improve their wear resistance [3,5,6]. Yet, it has been reported that incorporation of discontinuous reinforcement into magnesium matrix can have a deleterious effect in resisting delamination wear [7]. Particle-matrix interfaces act as additional void nucleation sites and preferential crack propagation paths leads to increased delamination resulting in higher wear rates [8,9]. Further, the detachment of the hard-reinforced particles acts as third-bodies resulting in more scratching action between the mating surfaces leading to increased abrasion wear.

On the other hand, composites containing hollow particles termed as 'syntactic foams' [10,11] can have significant differences in their tribological behavior and wear mechanisms as compared to those reinforced with other fillers/reinforcements [12]. These hollow particles can provide cushioning action against the applied load [13] impeding the sub-surface crack nucleation and propagation and further act as local debris accumulation sites post particle fracture [14]. Part of the applied load gets consumed/cushioned in compacting the wear debris effectively in the void space available post hollow particle fracture and is a unique scenario in syntactic foams owing to their porous microstructure. Further, it also helps is minimizing undulations during the wear [13]. It was demonstrated that aluminum/cenospheres foams exhibited better wear resistance than aluminum composite reinforced with discontinuous SiC particles in both dry and lubricated conditions [7]. Lower densities, higher energy absorption, and better damping capabilities are some of the crucial properties exhibited by magnesium syntactic foams. It has the potential to replace most of the conventional metallic foams based on their specific properties [15]. Incorporation of porosity through hollow spherical particles in magnesium matrix aids in the tailoring of mechanical properties particularly elastic modulus closer to the bone and their tissues that helps in improving the interface therein as compared to present stainless steel and titanium alloys [16]. However, there is no systematic report in open literature about the effect of reinforcing hollow spherical particles on the wear behavior of

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magnesium-based materials.

This article presents a wear analysis of a magnesium based syntactic foam aimed at quantifying the potential advantages of hollow GMB particles inclusion to overcome delamination wear that has traditionally limited the competitive advantages of magnesium in safety-critical components for transportation vehicles and bio-implantations. In our recent study, significantly higher specific strength is observed for Mg/GMB foams as compared to that of aluminum and titanium based syntactic foams [17]. Further, the aim of this work is to gain an understanding on the role of hollow GMB particles on the wear mechanism processed through DMD technique and to identify critical wear mechanisms that aid in the development of better friction material, in the context of weight saving potential and performance. Our study reveals that the incorporation of hollow GMB particles into magnesium matrix results in a unique wear behavior wherein void spaces enclosed inside the hollow particles can accumulate wear debris and provide a smoother surface enhancing wear resistance. Such a behavior is beneficial especially in the prevention of implants failure occurring because of wear debris release into the surrounding (tissue) that results in bone resorption [16]. Further, controlling the release of debris greatly helps in eliminating the wear particles deposition in the abdominal lymph nodes, liver, or spleen which has been commonly reported previously in patients with implantation [16].

2. Experimental details

Pure magnesium and Mg/GMB (15 and 25 wt.%) syntactic foams were synthesized by DMD route [5] using commercially available pure magnesium turnings (purity 99.9%, Acros Organics, USA) and GMB particles (mean particle dia. ~11 µm, ~ 1.05 g/cc density, Sigma Aldrich, Singapore). Ingot obtained from DMD was turned to billets (ϕ36 × 45 mm) and then wire cut to obtain ϕ10 mm rods. Archimedes' principle is followed for density estimations. Microhardness measurements were performed on the polished cylindrical specimens (ϕ10 × 10 mm) using a Vickers microhardness tester (Shimadzu-HMV) with 245.5 mN and 15 s, test load and dwell time respectively. Wear test in dry mode was conducted on the cylindrical specimen (ϕ10 × 25 mm) at ambient conditions as outlined in ASTM G99-17 [18] against EN31 steel disc using tribometer (TR-20LF-PHM400-CHM600) procured from DUCOM, Bangalore, India. A normal load of 30N, sliding speed of 3 m/s for a distance of 600 m is maintained constant for all the tests. Scanning electron microscope (SEM) (JEOL, JSM 6010) was utilized for micrography on the worn surface to analyze the dominant wear mechanisms.

3. Results and discussions

Incorporation of hollow GMB particles into magnesium matrix resulted in a significant reduction of density (Fig. 1). With the addition of 25 wt.% GMB particles, density of magnesium decreased from 1.7 to 1.472 g/cc (~13.4% reduction). Further, hardness tests were repeated more than 15 times at different sample locations. Results reveal (Fig. 1), GMB addition enhances hardness by ~127%.

Fig. 2a presents the experimental values of wear rates for pure magnesium and their syntactic foams. Average values of three samples in each composition are reported for the analysis. Wear rate of pure magnesium decreases with increasing GMB content. Lowest wear rate of 0.273 mm^3/N-km (~2.5 times lower than pure Mg) is exhibited by Mg-25GMB. These results indicate the effectiveness of uniformly dispersed GMB particles in significant wear resistance enhancement of syntactic foams even at a higher load of 30N.

Variation of μ for magnesium and its syntactic foams are presented in Fig. 2b. It is seen from Fig. 2b, that with increasing GMB content, frictional coefficient decreases. Mg-25GMB syntactic foams exhibit the lowest μ of 0.273 which is ~13% lower than that of pure Mg (μ = 0.313). Void space within hollow glass microballoons prevents any significant scratching action of the syntactic foam specimen on the

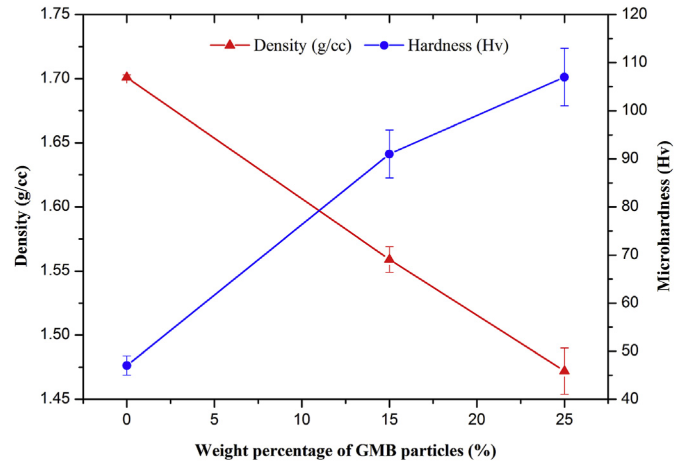

Fig. 1. Density and microhardness for Mg and their foams.

counter surface. Rather, these GMB particles are broken into fine fragments, which roll over the counterface resulting in a reduced frictional coefficient. Further, the void spaces enclosed inside the hollow GMB particles open up due to partial wear resulting from shearing off of the thin porous shell and starts accumulating wear debris to provide a smoother surface leading to lower values of surface roughness and μ [19].

Micrographs of worn pin-surfaces were taken to gain better insight into wear characteristics of these magnesium foams (Fig. 3). The worn surface of pure Mg depicts the formation of extensive cracks that are perpendicular to the sliding direction (Fig. 3a) indicating delamination wear. Higher sliding speed and loads result in increasing dominance of delamination wear in magnesium-based materials and is a fatigue related wear mechanism as reported in Ref's [16,20]. At higher loads of 30 N, continuous deformation of the material by repeated sliding embrittles the surface and leads to nucleation and growth of sub-surface cracks. This results in eventual shearing off the surfaces leading to higher wear values. Further, the onset of adhesive wear can also be seen in pure magnesium samples. Fig. 3a shows the features of delamination wear gradually getting replaced by induction of rows of furrows, smearing sign and localized plastic deformation. Also, the wear track on the counter tool steel disc was covered by a discernible layer of transferred materials suggesting adhesive wear. It has been previously observed for magnesium based materials that the delamination and adhesive wear are associated with surface oxidation of the worn surface and are preferentially located in the oxidized region as seen by dark grey zones in Fig. 3a [21].

Analysis of the worn specimen for the syntactic foams suggests that delamination and adhesion wear mechanism in magnesium can be effectively addressed with the GMB addition. Oxidative and abrasive wear are predominantly operative for syntactic foams. As shown in Fig. 3b and c, worn surfaces of foam were covered with shallow scratches and numerous grooves parallel to the sliding direction, which is associated with abrasive wear. Detailed examination of the worn surface revealed that the abrasion took place by plowing as shallow scratches accompanied with plastic deformation are evident. Also, the occurrence of ribbon-like debris on the pin surface as seen for Mg-25GMB syntactic foam specimen (Fig. 3c) indicate plowing as the cause of abrasive wear wherein without being removed, the material is displaced on either side of the abrasion groove [22]. Plasticity and adhesion seem to be less significant for Mg-25GMB as compared to Mg-15GMB resulting in improved wear resistance. Further, the improved hardness of the syntactic foams with the addition of GMB particles contributes to the decreased wear rates by preventing large-scale plastic deformation in accordance with the Archard's principle [22].

For the syntactic foam specimen, a large fraction of applied load

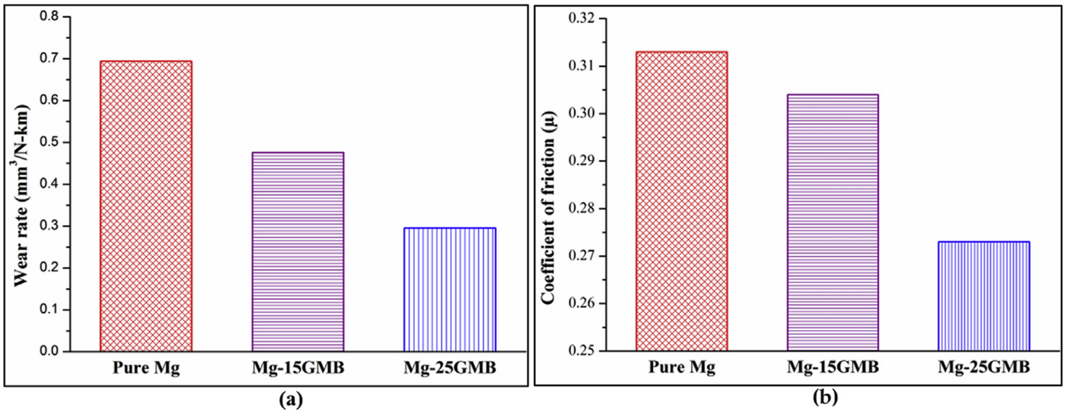

Fig. 2. (a) Wear rates and (b) friction coefficient values for pure Mg and their foams.

governs the compaction of GMB particles on the surface and sub-surface providing a cushioning effect against the applied load (Fig. 3e). It can also be seen from Fig. 3f that a fraction of the load applied is spent on compaction of GMB particles. As a result, the load-carrying capability of these syntactic foams is improved restraining large-scale shedding and shearing off of Mg matrix. This prevents easier initiation and cracks propagation in the matrix resulting in a delayed onset of delamination wear in foams. Once the GMB particles are compacted, craters of the broken GMB particles act as reservoirs for accumulating wear debris and provide a smoother surface which subsequently lowers wear rate

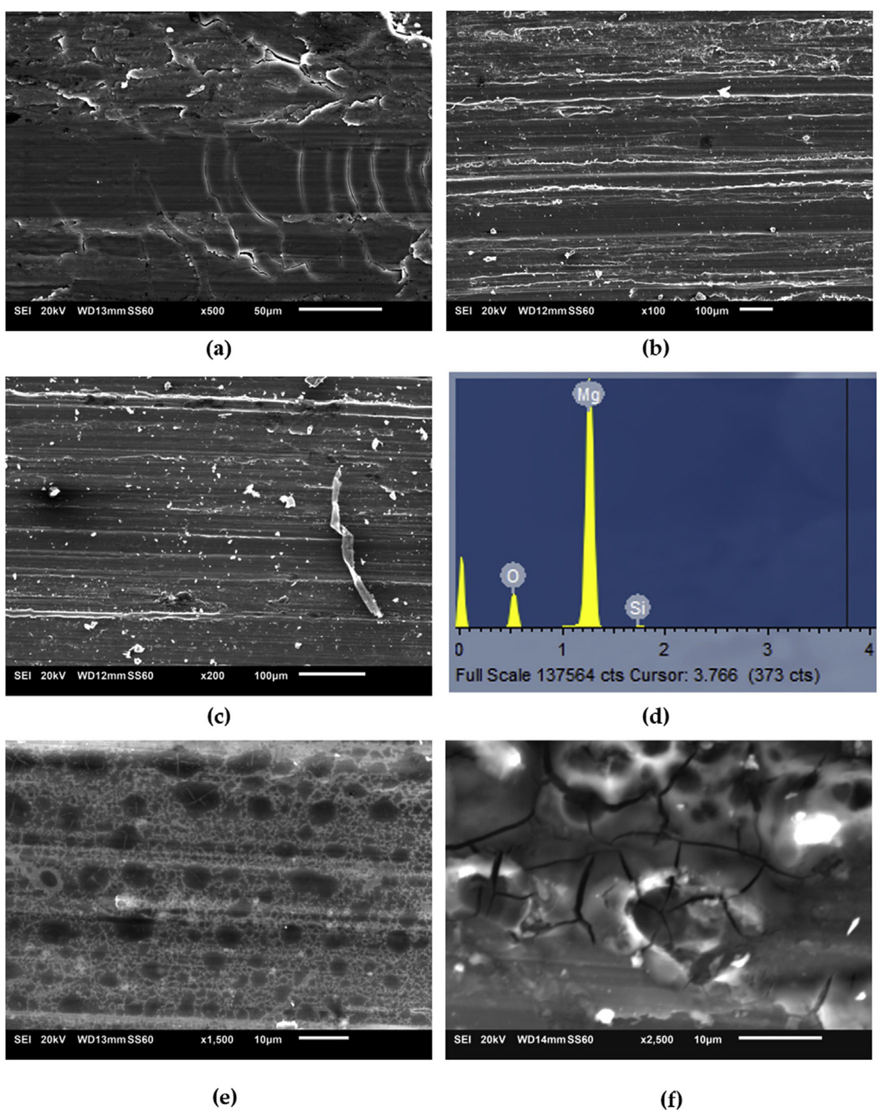

Fig. 3. Micrographs of worn-out surface of (a) Mg (b) Mg-15 wt.%GMB (c) Mg-25 wt.%GMB (d) EDS mapping of (c) indicating presence of MgO (e) Cushioning effect observed in case of Mg-15 wt.% GMB and (f) Cracking of GMB particles under the applied load.

[21]. Significant reduction in wear rate is achieved with an increase in the GMB content from 15 to 25 wt.% owing to higher void space availability for accommodating wear debris. Delamination wear is not so evident in Mg-25GMB foams as most of the applied load is utilized in the GMB particles compaction indicating that the wear behavior is greatly influenced by the filler content.

The wear track in syntactic foams depicts the occurrence of partial and discontinuous oxide films caused by the frictional heat due to sliding action between the mating surfaces. In the corresponding EDS analysis (Fig. 3d), the appearance of strong peaks corresponds to the presence of magnesium oxides. Formation of oxide layer helps in reducing the wear partially by minimizing direct metallic contact between the mating surfaces.

4. Conclusions

In summary, the envisaged study provides evidence that the incorporation of hollow GMB particles into magnesium matrix enhances wear resistance (~2.5 times compared to pure Mg). Mg/GMB foams with higher GMB contents were effective in preventing detrimental delamination wear that is generally observed in composites with the high volume fraction of discontinuous reinforcements. Lower density and wear rates observed in syntactic foams signify their suitability in weight sensitive applications subjected to wear environments.

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