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Dry sliding wear behaviour of zinc oxide reinforced magnesium matrix nano-composites

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ABSTRACT

The main objective of the present work is to investigate the dry sliding wear behaviour of a magnesium matrix composite reinforced with zinc oxide nano-particles. Magnesium matrix composites have many applications, especially in the automotive and aerospace industries, due to their superior specific properties. A magnesium matrix composite with 0.5 vol.% ZnO nano-reinforcement was prepared using powder metallurgy and was hot extruded to eliminate pores. The wear behaviour of the Mg/ZnO nano-composite was investigated by conducting dry sliding tests as a function of wear with an oil-hardened non-shrinking (OHNS) steel disc as the counterpart on a pin-on-disc apparatus. Wear tests were conducted for normal loads of 5, 7.5 and 10 N at sliding velocities of 0.6, 0.9 and 1.2 m/s at room temperature. The variations of the friction coefficient and wear rate with the sliding distances (500 m, 1000 m and 1600 m) for different normal loads and sliding velocities were plotted and analysed. To study the dominant sliding wear mechanism for various test conditions, the worn surfaces were analysed using scanning electron microscopy. The wear rate was found to increase with the load and sliding velocity.

1. Introduction

Magnesium is the lightest metal, making it very useful for aerospace and automobile applications due to its potential to dramatically reduce the weight of components that would otherwise be made from aluminium, which is 65% denser than magnesium [1,2]. Magnesium and its alloys can be provided with high specific strength, stiffness, damping capacity and dimensional stability and creep behaviour by the addition of reinforcements. Although the implementation of this material in industrial applications faces some practical difficulties, such as the processing temperature needed, magnesium has become a vital metal in some industries. Furthermore, such industries will be forced to use this type of metal to remain economically feasible in the future [3]. Magnesium can solve most of the problems faced by industries in which the strength-to-weight ratio is important, such as the automobile, space and telecommunication industries. The available literature shows that the usage of magnesium is constantly increasing and can be expected to continue to increase in future [4,5]. Metal matrix composites produced by adding ceramic materials for reinforcement exhibit improved mechanical properties, including structural, wear and creep properties, among others, and thereby find many applications. The metal matrix composite properties depend on the matrix metal, reinforcement material, reinforcement method, reinforcement particle size and composite fabrication method [6]. The main drawbacks of magnesium and its alloys are their lower strengths at both room temperature and elevated temperature and, poor wear and corrosion resistances. Among these issues, wear is the most dominant problem in industrial components, leading to a reduced life time for magnesium-based parts and making magnesium unsuitable for use in bearings, gears, pistons and cylinders [7–9]. Particle-reinforced magnesium matrix composites (PRMMCs) are most frequently used in the automobile and aerospace industries due to their high specific tensile strength and modulus as well as high wear resistance. PRMMCs are manufactured using various methods, such as stir casting, powder metallurgy, squeeze casting and spray forming. Superior mechanical properties can be achieved by uniformly dispersing fine and stable ceramic particles in the matrix [10]. Hot extrusion of porous metal matrix composites results in effective reduction of pores and admirable bonding of reinforcements with the metal matrix [11].

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Magnesium is a better metal than Al and Ti in terms of its physical properties, including processing, machining and recycling properties, which can tremendously reduce recurring costs [12]. Zinc oxide (ZnO) is an important material in the metal oxide family due to its prominent mechanical, electrical and optical properties and its wide range of applications [13]. The addition of low volume fractions of nano-particulate reinforcements like nano-Al_2O_3, nano-ZnO to pure Mg/alloys results in enhanced mechanical properties in the extruded Mg-materials [14–16]. Moreover, higher compressive yield strength is obtained for the Mg composite containing 0.5 vol.% of nano-ZnO as reinforcement than that of Mg/ZnO composites containing 1.0 and 1.5 vol.% of nano-ZnO [16]. The literature has proven that the wear resistance and strength of Mg and its alloys can be enhanced by reinforcing ceramic materials, such as alumina, SiC, MgO, TiC, B_4C, TiB_2 and ZnO [17]. The mechanical properties of the most commonly used reinforcement materials are shown in Table 1 [18,33]. Although the wear rate and friction depend on many factors, such as applied load, environmental temperature, specimen geometry, surface roughness, sliding speed, material type, relative humidity and system rigidity, it has been found that sliding speed and normal load had a particularly strong effect on the wear rate [19]. Based on this context, the present work aims to investigate the effect of the sliding speed and normal load on the friction coefficient and wear behaviour of a 0.5 vol.%ZnO reinforced Mg metal matrix nano-composite.

2. Experimental details

2.1. Composite fabrication

The Mg–ZnO nano-composite samples used to study wear behaviour were produced through powder metallurgy. Magnesium powder of 60–300 μm having a purity of 98.5% and 50–200 nm sized ZnO particles were blended at 200 revolutions per minute for 1 h in a high energy ball mill. The blended powders were cold compacted at a pressure of 510 MPa using a 1000 kN press to produce green compacts of 35 mm diameter and 40 mm height. The green compacts were sintered at 640 °C for 14 min by a hybrid microwave sintering technique [16]. The sintered compacts were then extruded with an extrusion ratio of 13:1 at 350 °C to produce rods of 10 mm diameter. The mechanical properties of pure magnesium and the Mg–ZnO composite as described elsewhere [16] are provided in Tables 2 and 3.

2.2. Pin and disc preparation

The diameter of the fabricated Mg–ZnO nano-composite extruded rod was machined from 10 mm to 8 mm, and wear pin samples were created for a length of 15 mm. The pin ends were verified to be free of burrs and sharp corners, which could damage the disc surface during sliding. The contact surface of the pins and OHNS discs were smoothened using 600-grit SiC paper and then cleaned with acetone. The flatness and perpendicular orientation of the pin surfaces were checked to ensure that the pins at perfectly on the disc surface. The surface roughness of the pins was maintained at 0.8 μm (Ra) to obtain uniform wear results. The surface roughness of the OHNS disc, with a hardness of 60 HRC, was also maintained at 0.45 μm. The Mg–ZnO nano-composite sample's cross section was prepared for metallographic examination to study the microstructure. The sample was ground using a series of graded SiC abrasive papers in the order of 180, 320, 600, 800 and 1200 grit. The grinding debris from the composite surface was removed using acetone in between two consecutive SiC grit paper grinding processes. After the grinding, the rough and fine polishing were done using diamond paste having particle sizes of 5 μm and 1 μm respectively using a mechanical polishing machine as per ASTM: E3. The polished surface of composite sample was immersed in an acetic-picral etchant until a brown film forms on the surface and finally rinsed in ethanol and dried in hot air.

Table 1
Mechanical properties of commonly used reinforcements Refs. [18,33].

Material	Density (g/cm^3)	Modulus of rupture[a] (MPa)	Modulus of elasticity[a] (GPa)
Alumina (Al_2O_3)	3.97	689	365
Magnesium oxide (MgO)	3.58	97	214
Silicon carbide (SiC)	3.22	166	469
Boron carbide (BC)	2.52	345	290
Zirconia (ZrO_2)	5.60	138	152
Beryllium oxide (BeO)	3.03	138	310
Molybdenum silicate ($MoSi_2$)	6.20	689	345
Boron nitride (BN)	2.25	48	83
Thoria (ThO_2)	10.00	83	145
Carbon	2.22	21	14
Zinc oxide (ZnO)	5.605	–	111.2

[a] Temperature at 21 °C.

Table 2
Tensile properties from Ref. [16].

Material	0.2TYS (MPa)	UTS (MPa)	Tensile failure strain (%)	Micro hardness (HV)
Mg	121	179	11	45
Mg–0.5 vol.%ZnO	119	203	16	53

[a]TYS: tensile yield strength; UTS: ultimate tensile strength.

Table 3
Compressive properties from Ref. [16].

Material	0.2CYS (MPa)	UCS (MPa)	Compressive failure strain (%)
Mg	103	263	22
Mg–0.5 vol.%ZnO	111	344	14

[a]CYS: compressive yield strength; UCS: ultimate compressive strength.

2.3. Wear test

All experiments were performed in air at (28 ± 1) °C according to ASTM:G99 in a DUCOM pin-on-disc wear-testing machine. The prepared pin samples were set in a slot in the arm above the rotating disc. The surface contact between the samples and disc surface was maintained at 100%. The pin masses were measured using a sensitive electronic balance with an accuracy of ±0.1 mg. The experiments were conducted under normal loads of 5 N, 7.5 N and 10 N at sliding velocities of 0.6 m/s, 0.9 m/s and 1.2 m/s on the disc surface over a sliding distance of 1600 m [19]. At the end of every sliding distance interval, the pins were carefully cleaned using acetone to remove the burrs and particles produced during the sliding of the pin on the disc surfaces. The exact mass of the pin was measured after the wear debris on the pin surface was removed, and the mass losses were calculated at every sliding distance interval for each combination of normal load and sliding velocity. Prior to each test, the contact surface of the disc was ground with 600-grit SiC paper and then cleaned using acetone to remove the accumulated particles on the disc surface due to the prior sliding of the pin surface. The experiments were repeated thrice to minimize the possible experimental error and error bars have been shown in Figs. 1–4. All of the worn pin surfaces were analysed using scanning electron microscopy (SEM) to study the dominant wear behaviour.