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Wear and Friction of Advanced Composites

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ABSTRACT

Composites are two-phase materials. They have hard and stiff reinforcements incorporated in metal/ceramic matrices. Composites have superior mechanical properties, which contribute toward the enhancement in their tribological performance. Their enhanced wear and friction properties are attractive in applications such as automobile, aerospace, biomedical, and sports utilities. Wear of composites is determined by the underlying operating wear mechanisms. Friction of composites may/may not follow similar dependence on applied parameters of speeds and loads, as that of wear. In this paper, examples of tribological performance of advanced composites taken from various research works are presented. The discussion presented in the paper provides an overall understanding of the tribological response of representative composite systems.

Key words: *Composites, Wear, Friction, Wear mechanism.*

1. INTRODUCTION

Composites are new age materials. They are synthesized with the main aim of improving material and mechanical properties of metals/alloys to extend their scope of application [1]. With metal matrices and micro/nano-reinforcements, composites exhibit enhanced properties of strength, hardness, toughness, wear resistance, and friction. Under tribological contact conditions, as the response to the traction generated, materials experience friction and undergo wear. In this context, improved strength and hardness increases wear resistance [1]. Composites with enhanced wear and friction properties are attractive in applications such as brakes, clutches, bearings, pistons, gears, biomedical implants, and sports equipment. Popular metal matrices include aluminum, magnesium, copper, and nickel [1]. Reinforcements used include alumina, silicon nitride, silicon carbide, boron nitride, boron carbide, molybdenum disulfide, graphite, and carbon nanotubes (CNTs). [1]. In this paper, they are presented wear and friction behavior of various systems of metal matrix composites highlighting their tribological response to the applied external parameters of sliding speeds and normal loads. A ceramic matrix composite is also discussed.

2. EXPERIMENTAL

Composite systems discussed in this paper include AM100 with δ-alumina short fiber reinforcements, AZ31B having 1-3% Ca reinforced with nano-alumina particles, Mg/AZ31 with nano-alumina particles, Al with B4C nano-particles, Al with CNT additions, Cu and Ni with MoS_2, graphite additions and nano-carbon reinforcements, and Al_2O_3-SiC-(Al, Si) ceramic matrix composite. Details regarding the materials, methods of fabrication, and mechanical properties of the above-mentioned composite systems can be referred [2-10].

3. RESULTS AND DISCUSSION

AM100 magnesium alloy reinforced with δ-alumina short fibers (%V_f 15, 20, 25) shows increase in the hardness from 85 BHN (base alloy) to 170 BHN (%V_f 25) [2]. These composites were produced by squeeze infiltration technique. Results from the tribological tests against En24 steel show that the wear rates of the composites are lower than that of the base alloy. With increase in the %V_f of the reinforcement, the wear rate decreases owing to the increase in the hardness. Increase in hardness suppresses plastic deformation and hence the wear rate reduces. The base alloy undergoes severe wear by adhesive wear mechanism (Figure 1a), and the composites undergo wear by delamination wear mechanism (Figure 1b). Friction of the composites is higher than that of the base alloy. Friction coefficient increases with increase in the %V_f of the reinforcement. During wear as the material is removed from the surfaces of

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the composites, the dislodged δ-alumina short fibers that are hard in nature counter-abrade the surfaces (i.e., third body interaction), and thereby increase the friction force. Thus, friction values increase with the increase in the $\%V_f$ of the reinforcement. Composites such as these are attractive materials for brakes and clutches, which require high, wear resistance and also high friction.

Al_2O_3-SiC-(Al, Si) ceramic matrix composite made by direct melt oxidation method exhibits the formation of a self-protecting film during sliding (Figure 1c) [3]. At sliding speeds >1 m s^{-1}, Al metal-rich tribofilm forms at the surface of the composite. At these speeds, high interface temperatures cause Al metal present at the surface/near surface of the composite to flow toward the interface to form a uniform film. This tribofilm covers the composite surface and protects the composite from further wear. It also reduces the friction coefficient.

Nanocomposites (matrices with nanosized reinforcements) have two important advantages over microcomposites (matrices with micron-sized reinforcements), namely (i) mechanical properties such as hardness, yield strength, and toughness are superior and (ii) absence of third body interaction at the tribo-interface (i.e., counter-abrasion due to wear debris). Magnesium nanocomposites (AZ31B magnesium alloy having calcium reinforced with nano-alumina particles) shows better wear resistance against hardened tool steel, than the AZ31B base alloy due to improved hardness and strength [4]. In addition to the enhanced mechanical properties, the formation of Mg, Al_2 Ca intermetallic, and MgO and CaO oxides contribute toward lowering the wear rates of the nanocomposites. Wear of the nanocomposites decreases as the function of sliding speed. They exhibit a transition from abrasion to adhesion and mild oxidation with an increase in sliding speed.

Metals are made into alloys by adding various alloying elements to enhance their mechanical properties, and thereby to meet the demands of several applications. When composites are made from alloys, they exhibit excellent mechanical and tribological properties than their metal-based counterparts. This can be clearly seen from the tribological behavior of Mg and AZ31 alloy-based composites (with alumina nanoparticles) [5]. Figures 2 and 3 show the wear and friction behaviors of the composites. It can be seen from the Figures 2 and 3 that the AZ31 alloy-based composites outperform the pure Mg-based composites in terms of wear resistance and friction property.

Under tribo-conditions where both the mating surfaces undergo material removal, repeated sliding can induce mixing of both the materials (i.e., pin and counterface disc materials), which is similar to the mechanical mixing occurring in a ball-mill. The result will be the formation of a relatively hard tribo-layer known as “mechanically mixed layer” (MML). Such layers are “self-protecting” in nature as they protect the sliding surfaces from further wear. Figure 4 shows the cross section of a worn surface of B4C reinforced aluminum matrix nanocomposite slid against AISI 52100 steel [6]. The white layer seen on the top of the specimen surface is the MML, which constitutes of material from both the mating surfaces.

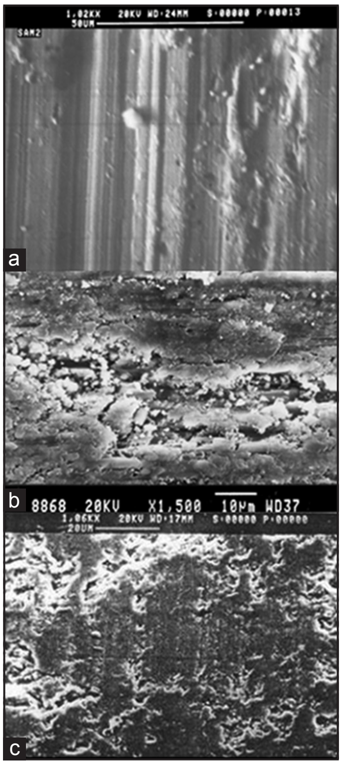

Figure 1: (a) Adhesive wear of AM100 base alloy [2], (b) delamination of AM100 reinforced with δ-alumina short fibers [2], (c) Al metal-rich tribofilm formed at the surface of Al_2O_3-SiC-(Al, Si) ceramic matrix composite [3].

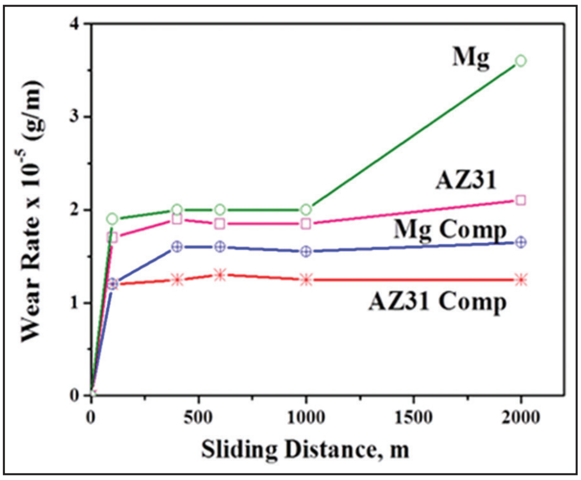

Figure 2: Wear of Mg and AZ31 alloy-based composites with alumina nanoparticles [5].

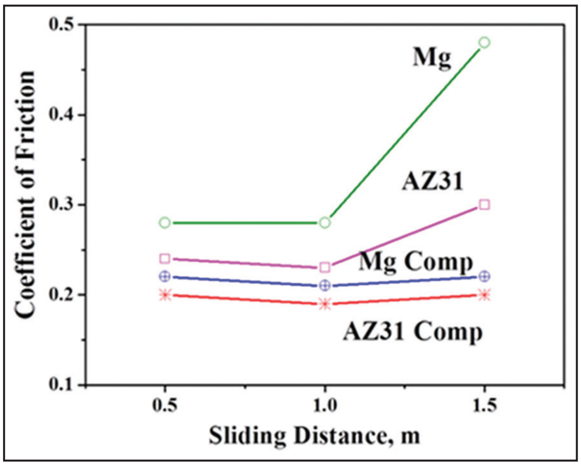

Figure 3: Friction of Mg and AZ31 alloy-based composites with alumina nanoparticles [5].

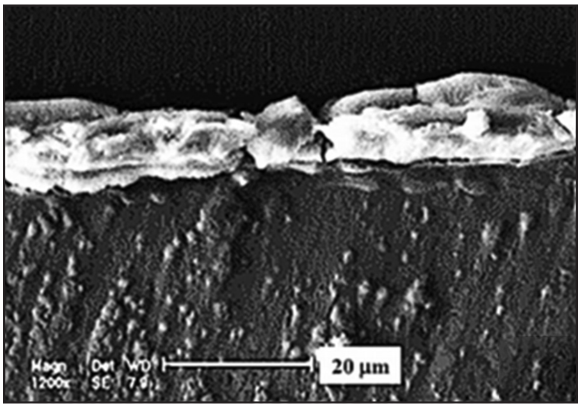

Figure 4: Cross section of a worn surface of B4C reinforced Al nanocomposite showing mechanically mixed layer [6].

CNTs are effective reinforcements for metallic matrices. CNTs enhance mechanical properties such as hardness, modulus, and strength. Under tribological conditions, enhanced mechanical properties contribute toward increasing wear resistance. Addition of CNTs (5 wt.%) to pure aluminum increases hardness by 2.5 times and reduces wear by 4.5 times (slid against En31 steel disc) and friction by 2 times [7]. With increase in the amount of reinforcement addition, hardness increases and thereby wear reduces. Composites with higher wt.% of CNTs exhibit lower friction property. It should be noted that there exists a limiting V_f of reinforcement above which mechanical properties of composites do not improve. Cu-based composites reinforced with CNTs show increase in hardness values until ~15% V_f. However, when V_f is increased to 20%, the hardness value decreases considerably [8]. Tribological tests conducted against En30 steel show good wear resistance and lower friction values until ~15% V_f. Drastic reduction in wear resistance and increase in friction property is seen for composites with 20% V_f. Non-uniform distribution and agglomeration/clustering of reinforcements in the matrices occur beyond a certain critical V_f.

Graphite, MoS_2, and WS_2 are solid lubricants. By incorporating them in metal matrices "self-lubricating," composites can be designed. These solid lubricants can easily shear under traction due to their layered structure and thereby lubricate sliding surfaces (i.e., reduce friction and wear). Cu-graphite composite pins slid against AISI 1045 steel disc exhibit low friction coefficient values of about 0.15-0.2, with an increase in sliding speed from 0.001 m s^{-1} to 8 m s^{-1} [9]. Similarly, Ni matrix composites with graphite and MoS_2 reinforcements show low wear and friction coefficient values of 0.2-0.5 when tested at 600°C [10].

Wear and friction of materials are system responses and are not material properties, unlike modulus and Poisson's ratio. Modeling of wear and friction is not easy and therefore to arrive at these values, experiments need to be undertaken. Making of composites is a reliable route to enhance wear resistance and lower friction property of metals/ceramics. Selection of materials (matrices and reinforcements) and design of composites depends on the application; they are meant to be used for. The amount of critical V_f depends on the matrix-reinforcement system. Composites with light metal matrices (Al, Mg) are attractive for weight critical applications such as in automotive and aerospace sectors. Ni matrix composites are meant for high-temperature applications. Ceramic reinforcements are usually preferred in composites as they provide high hardness and are chemically inert. Solid lubricants as reinforcements induce self-lubricity to the composites. Wear and friction of composites may/may not follow similar trends as the function of applied external parameters (i.e., sliding speed and normal load). Most of the tribological investigations on composite systems have been conducted in dry sliding conditions. Studies on wear and friction of composites under liquid lubrication are very few.

4. CONCLUSION

The following conclusions can be drawn from the examples of tribological investigations on various composite systems:

a. Composites provide higher hardness than metals/alloys. They have higher wear resistance than their metal/ceramic counterparts. Wear of composites is inversely proportional to hardness
b. Friction of microcomposites is higher than metals/alloys due to third body abrasion. Nanocomposites exhibit lower friction property
c. Formation of tribofilms and MMLs promotes "self-protecting" capability
d. Solid lubricants when incorporated in metallic matrices induce "self-lubricating" capability
e. Critical V_f of reinforcement depends on matrix-

reinforcement system

f. Metals/alloys undergo wear by abrasion and adhesion. Dominant wear mechanisms in composites are delamination and oxidation.

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***Bibliographical Sketch**

Dr. Arvind Singh is a career tribologist. He received his doctoral degree from the Indian Institute of Science (IISc), Bengaluru, India (2003). He has extensive research experience in both academic institutes and R&D establishments. He has been a Materials Scientist, Visiting Scientist, Research Fellow, and Lead Engineer at the John. F. Welch Technology Center (GE India), Korea Institute of Science and Technology (KIST) Seoul, South Korea, National University of Singapore (NUS), Vestas Global R&D, Singapore, Energy Research Institute (ERIAN) at the Nanyang Technological University (NTU), Singapore. Currently, he is a Professor at the Aeronautical Engineering Department, Bannari Amman Institute of Technology, Tamil Nadu, India. His research interests include tribology and surface engineering at macro- and micro/nano-scale related to aerospace, automotive, biomedical, renewable energy, nuclear systems, and micro/nano-electro mechanical systems. He has contributed 80 technical communications to international journals and conferences.