Effect of Controllable Parameters on the Tribological Behavior of Ceramic Particulate Reinforced Aluminium Metal Matrix Composites: A Review

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Abstract

The inherent properties of ceramic type of reinforcements such as high fracture toughness, high corrosive resistance, improved wear resistance make it suitable as reinforcements in Metal Matrix Composites (MMC). This review article summarizes the wear behavior of ceramic particulate reinforced Aluminium Metal Matrix Composites (Al-MMC). The influence of material factors such as type of ceramic reinforcement, size and volume fraction; mechanical parameters such as sliding velocity, sliding distance and applied load on the wear behavior of Al-MMC have been discussed. The reduction in wear rate due to formation of tribolayer between the contact surfaces has been reviewed in the current study. Literature revealed that uniform distribution of hard ceramic particles (B\textsubscript{4}C, SiC) and solid lubricants (Gr, MoS\textsubscript{2}, Boron Nitride) as hybrid reinforcements can adequately enhanced the wear behavior of mating surfaces. The study illustrates that Al-MMC exclusively hybrid MMC can be treated as preeminent material for design of brake discs, piston-cylinder arrangements which require high specific strength and wear resistance.

1. Introduction

Composite is combination of two or more constituent materials having dissimilar mechanical properties when combined to form a material having properties superior than individual constituents. Now a days Aluminium MMCs are widely used rather than Aluminium alloy because of their low weight, low density, improved dimensional stability and higher strength to weight ratio [1]. The properties of the composite material can be changed by varying size, volume fraction, type of reinforcement particles [2]. Aluminium MMCs are extensively used in manufacturing of reciprocating parts like piston in internal combustion engines [3]. Aluminium and its alloys processes poor Tribological and mechanical properties like high ductility, low wear resistance and seizure at elevated temperatures [4]. Hence it is necessary to develop new materials with better wear and mechanical properties. K.G Satyanarayana et al. [5] reported that Ceramic reinforcements like SiC, Al\textsubscript{2}O\textsubscript{3}, TiC in Aluminium MMCs shows superior properties than unreinforced Aluminium alloy. Aluminium matrix reinforced with self-lubricating materials such as graphite deteriorates the Tribological and mechanical properties of material, in such cases incorporation of hybrid reinforcements contains hard ceramic particles and self-lubricating particles enhances the wear properties of tribosystem [6]. The hard-ceramic particles provide sufficient strength to matrix material and self-lubricating particles provides sticky substance on wear track there by reducing wear rate of material. Therefore, selection of reinforcement type and operating parameters like applied load, sliding distance, sliding velocity...
are influences the wear rate of material. In this review article a wide spectrum of effect of mechanical parameters on the Tribological behavior of Aluminium MMCs are assessed.

2. Microstructural characteristics

The morphology and distribution of reinforcement particles have major effect on the tribological and mechanical properties of composite. Obtaining uniform distribution of reinforcement particles within the matrix is main criteria during fabrication of composite. Literature reveals that constituents of the composite at the microstructural level plays a vital role in its behavior. Mohammad rouhi et al. [7] examined the microstructural distribution of reinforcements in Al/SiC and Al/SiC/MoS₂ composites. Because of uniform sintering no boundaries were observed between Al and SiC particles. Investigator noticed some dark patches in Al/SiC which represents the porosities that are formed during manufacturing process or voids formed on the surface of specimen by detachment of SiC particles during polishing of specimen. The amount of porosities are found to be increased with volume fraction of SiC reinforcements. K.M Shorowordi et al. [8] analyzed the microstructure of Stir Casted Al/13%B₄C and Al/13% SiC composite. It has been revealed that both SiC and B₄C reinforcements are uniformly distributed within the Al matrix. SEM analysis clearly indicates that formation of good bonding at the interfaces between matrix and reinforcement particles. Optical microscopy of phenolic counter body pad material shows the existance of Phenolic particle, asbestos fiber, brass. A.Daoud et al. [9] fabricated Al359-20% SiC composite disc rotor by sand casting process. SEM analysis of composite specimen shows that SiC particles are fairly distributed within the Al359 matrix material. XRD pattern of commertially available brake pad counter body reveals that presence of C, Fe, Cu, CaCO₃, TiO₂, ZnO, M.Kok[10] reported similar results on microstructure of Al2024-Al₂O₃ composite fabricated through squeeze casting with different sizes (66 μm, 32 μm, 16 μm) of reinforcements. SEM analysis reveals that the corser size reinforcements (66μm) are distributed uniformly compared finer size particles with sizes 32 μm, 16 μm. This was associated with thermal mismatch between molten alloy and ceramic reinforcements during solidification which led to agglomeration of finer particle in the interdendritic region. A.Rehman et al. [11] have developed Al Alloy-SiC MMC by stir casting technique. SEM micrographs clearly represents the microstructural changes of SiC particles from needle shape to spherical shape during T6 heat treatment process. In addition with author identified the formation of some eutectic silicon around the SiC particles and good interfacing bonding between aluminium and SiC particles. These above literature reveals that composite can fabricated through various techniques like solid state pressing and casting method. For achieving perfect bonding between particles and uniform distribution of reinforcements the processing perameters must be optimized during fabricication process. However isotropic characteristic properties of the composite can be obtain by incorporation of uniform distribution of reinforcements.

3. Wear behaviour

3.1 Influence of normal load

The identification of safe range of applied load for minimum wear of the composite material and unreinforced counter part is required to improve the life of the compoent. The effect of normal load on the coefficient of friction and tribolayer formation is discussed by Rajeev et al.[12] In the study investigator found that the wear and frictional behaviour of Al-SiC composite. It was noticed that the wear of the composite increases with increasing load from 60N to 120N. This is attributed to improved metallic intimacy
with increment in applied load. At initial stages direct rubbing between softer Al matrix and C.I counter part, which removes the outer surface of Al alloy which causes harder SiC particles to project out to rubbing surface which increases the wear. The coefficient of friction ($\mu$) value follows quadratic relationship and is found to be minimum at 100N applied load due to formation of stable transfer layer at lower loads in the range 60N to 100N, where as $\mu$ value is found to be increased at higher loads (90N to 120N) due to breaking of the transfer film. A. Baradeswaran et al. [13] reported the wear behaviour of Al-$x$%Al$_2$O$_3$ ($x=$2,4,6,8) composite at a sliding distance of 1200 m for an load range of 10N-40N. It was noticed that the wear rate of all composite samples is lesser than unreinforced alloy and minimum wear rate of 0.01 mg/m is obtained at 6% reinforcement for all composite samples. This wear rate increases with applied load due to no longer formation of Mechanically Mixed Layer (MML) at higher loads. N. Radhika et al. [14] used analysis of variance (ANOVA) technique to study the wear behavior of Al-9%Alumina-3%Gr hybrid composite under the effect of controllable parameters. It has been stated that the mechanism of wear changed from pure adhesion to abrasion with increasing the applied load value. Summarizing the effect of applied load on the wear characteristics of Aluminium MMC’s, the wear rate of the composites is controlled by distinct load dependent vicinities.

3.2 Influence of sliding distance

The softening of asperities due to temperature raise between the surfaces of composite specimen and counter body is depends on the sliding distance. A brief summary on phenomenon of wear due to different sliding distances are reviewed as follows. V.R Rajeev et al. [15] studied the wear and frictional behaviour of Al-15%SiC composite at different sliding distances an applied load of 90N with speed of 0.3 m/s. Author found that with increasing sliding distance from 250m to 750m the wear rate of composite increases. It happens due to raise in temperature which causes softening of material with more contact time between the surfaces. The Coefficient of friction ($\mu$) has been found to be increased slightly due to the three body abrasive wear which is caused by the entrapment of wear debris between the mating surfaces causing higher frictional forces. Similar results are observed by R. Kumar et al. [16] who have analyzed specific wear rate variation of pure Aluminium, Al-7075-7%SiC-3% Gr composite with sliding distance of 2000m to 4000m. At low load (20N -40N), low speed (2-4 m/s) combination the wear of both composite and alloy material follows decreasing trend. This phenomenon is attributed because at initial stages the sharp asperities come in contact between two contact surfaces. These asperities are deformed plastically and occupies the valleys present on the composite pin and counter surface. There is a feasibility of some of these asperities are fractured and enter into matrix material which causes the work hardening of pin which improves the wear resistance of composite. However, at high load (40 N-60N) and high speed(4-6 m/s) combination the composite material plastically deforms which increases the wear rate. Sandeep Sharma et al. [17] reported tribological behavior of the stir casted sillimanite reinforced Al MMC under varying pressure conditions(0.2 MPa-1.0 MPa) with respect to sliding distance of 0-3000m. Up to the sliding distance of 500m the interface temperature between the contact surfaces are increased because of existence of continuous contact of sharp asperities causing softening of material, which increases the wear rate. Whereas at high sliding distances as a result of formation of the mechanically mixed layer on the worn surface wear rate of the composite decreases. According to literature reported by [15,16,17], specific range of sliding distances are evaluated which causes minor wear rate of composite samples.

3.3 Influence of sliding velocity
The contact time between the composite specimen and counter body plays a predominant role in wear of the mating surfaces. The type of wear occurred on the worn surface like abrasion, adhesion, and delamination mostly depends on the magnitude of velocity for which the two contact surfaces are undergone rubbing action. The certain ranges of velocities at which the composite specimen is attaining maximum wear resistance are reported in the following literature. S. Basavarajappa et al. [18] studied the wear behaviour of Al 2219, Al 2219/15%SiC and Al/15%SiC/3%graphite by varying sliding velocities at an applied load of 40N. It has been reported that wear rate of all specimens remains unchanged up to 3 m/s. Beyond 3 m/s delamination wear is evoked in the unreinforced alloy due to the formation of large fragments in the interface of pin to the disc surface tending to higher wear rate. However, with increasing the speed up to 4.6 m/s the wear rates of SiC and SiC/Gr reinforced composites follow the same trend because of the higher wear resistance of SiC particles and the formation of mechanically mixed layer at the contact surface between disc and composite pin. P.J. Balu et al. [19] reported the frictional behaviour of phenolic brake pad material against the Gray cast iron disc in dry and wet conditions. In dry condition the interface material is softened which declines the shear strength of pad material causing reduction of the μ value linearly with increasing the sliding speed from 2 m/s to 10 m/s. This is also attributed to the higher sliding speeds the contact surface temperaturerises which leads to formation of metallic oxides as well, and some of these oxides contain self-lubricating properties thereby reducing μ value. Drastical decrease in coefficient of friction is observed in wet conditions up to sliding speed of 4 m/s due to the formation of hydrodynamic boundary layer between the two contact surfaces. K.M Shorowordi et al. [20] examined the wear behaviour of Al-SiC, Al-B4C composite disc material at two different velocities of 1.62 m/s and 4.17 m/s. The wear rates found to be decreases with increasing the velocities from 1.62 m/s to 4.17 m/s. Al-SiC attains higher wear resistance at low velocities, while at higher velocities Al-B4C exhibits better wear resistance. At initial stages the soft aluminium matrix wear out rapidly than hard ceramic particles, after some distance the reinforcement particles acted as micro cutters which removes the metallic chips from the phenolic resin counter body. These chips are penetrated into the softer Aluminium matrix at higher velocities which leads to lesser wear rate [21].

4. Morphology of worn surface

After the composite samples are subjected to wear test, the surface and wear debris are collected for worn surface characterization. Optical microscopy, SEM and EDS analysis are conducted on the wear surfaces to identify the mechanism of wear and some of the results are briefly discussed in subsequent section. Yezhe Lyu et al. [21] summarized the worn surface morphology of C.I, sintered and composite brake pad materials against the steel disc at low temperatures (-10°C to -30°C). At -20°C, SEM images reveal the existence of delamination wear for C.I pin material and large wear debris is identified on the worn surfaces. This is attributed to ductile to brittle transition at -10°C to -20°C. At these temperatures propagation of crack between graphite-ferrite, ferrite-pearlite phase boundaries is observed. Similar results were reported by K.M Shorowordi et al. [18] authors investigated the worn surface of Al-B4C, Al-SiC pin materials at an velocity of 1.62 m/s and 4.17 m/s. At low velocities SEM micrographs exhibits rough and deep sliding marks with hundred microns width, and also smooth worn surfaces are identified at higher velocities. M. Djafri et al. [22] studied the morphology of worn surface for Chromium steel, C.I, Al 359-SiC composite at an applied loads of 10N and 200 N. At low applied loads deep and rough sliding marks are distinguished on the worn surfaces of all three specimens. At higher loads (200N) parallel grooves are observed in the sliding direction.
with some fragments left on the Chromium steel disc. In case of composite discs some dark areas are observed due to the existence of continuous contact between contact surfaces are noticed at low applied loads.

Conclusions

From the detailed summary of literature presented, the following conclusions can be drawn:

- The effect of various controllable parameters on the wear characteristics of Aluminium MMC’S have been studied.
- At lower loads the ceramic reinforced Al composites exhibits superior wear properties than the unreinforced alloy. This phenomenon is because of hard reinforcements which prevents the sliding motion of counter face.
- As load increases to higher levels hard reinforced particles detached from matrix leads to three body abrasive wear. In this circumstances the wear of unreinforced alloy is almost similar to composite material.
- It has been found that because of transfer of material from composite to counter surface or vice versa Tribolayer is formed which decreases the wear rate of composite and enhances the wear resistance of tribo system.
- Different wear mechanisms like abrasive, adhesive, fretting and Delamination wears are observed on worn surfaces. Abrasive wear is predominant in composites at lower load conditions.
- Higher wear resistance of composite associated with stable tribo layer on worn surface and equiaxed wear debris. Stable tribolayer on worn surface and equiaxed wear debris incorporate high wear resistance property to aluminium metal matrix composites.

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