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Effects of solid lubricants, load, and sliding speed on the tribological behavior of silica reinforced composites using design of experiments

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ABSTRACT

In the present study, the effects of solid lubricants, braking load and sliding speed on the tribological behavior of Cu/silica composites were investigated using design of experiments and statistical methods. Three types of composites were prepared using different types of solid lubricants (h-BN, graphite, and MoS_2) by powder metallurgy. The wear and friction behavior of the composites were evaluated for a range of braking loads (300, 600, and 900 N) and sliding speeds (3, 6, and 9 m/s) in a subscale dynamometer. The composites were characterized for density, hardness, microstructure, wear surface morphology and surface roughness properties. A statistical model was developed to identify the significant factors affecting the wear resistance of the composites. The key findings of our study are: (1) MoS_2 reinforced composites possess the highest density, densification, hardness, and lowest surface roughness among the composites, (2) MoS_2 is the most effective lubricant in improving the wear resistance of the composites for the selected experimental domain, (3) Amongst the solid lubricant, brake load and sliding speed, the solid lubricant is the most significant factor affecting the wear resistance of the composites, (4) graphite reinforced composites provide higher braking performance at 3 m/s for all loading conditions whereas both h-BN and MoS_2 reinforced composites provide better braking performance among composites at higher speed (>3 m/s) and load (>300 N) conditions.

1. Introduction

Brake friction composites demand diverse physical, mechanical and thermal properties because of the complex process of sliding. The essential requirements are high wear resistance, high friction, superior thermal stability and conductivity, low heat expansion coefficient, high stiffness, high fracture toughness and high strength [1–4]. Some of these properties are contradictory, and usually do not coexist in a homogenous material, for example, the wear resistance and the friction coefficient, and the strength and the toughness. Therefore, the brake materials need to be designed with the right amount of diverse constituents to optimize these properties.

Particle reinforced metal matrix composites (MMC_p) are suitable materials for brake friction materials applications [4–9]. These composite materials have the application in the low (<500 kJ) and medium energy (<5 MJ) brakes. They have the potential to replace the currently used low life polymer based brake pads in the automobiles and high cost carbon based brake discs in the military aircrafts. MMC_ps have the capability to provide incompatible properties by simply combining constituents of diverse properties. A typical MMC_p has two main constituents: the matrix and the reinforcement. The matrix is intended to provide toughness, corrosion resistance, high thermal conductivity and melting point properties. Among the metallic elements, copper appears to be a most suitable matrix material because of the benefits of high melting point (1080 °C), high thermal conductivity (400 W/m K), good machinability, high toughness, excellent corrosion resistance, and low thermal expansion properties. There were many wear studies reported on the Cu matrix composites [10,11]. Further, most of wear studies on Cu based MMC_ps and other matrix materials such as Fe and Al based MMC_ps were performed at low speed (0.5–5 m/s) and load (2–50 N) conditions [10–16]. Literature on the high sliding speed and load effects on the wear and friction properties of the Cu based MMCs is limited [5].

The ceramic particles are aimed at improving the thermal stability, hardness, strength, wear resistance, and friction properties. Among various ceramic particles, SiC, B_4C, and Al_2O_3 are widely used with the metal matrix owing to their compatibility with the common matrix materials (Fe, Cu and Al) and easy availability [17]. Silica is another potential ceramic particle that has not been explored widely so far [18]. Silica has many advantages over SiC and B_4C. It is the cheapest reinforcement [19]. It has relatively less

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abrasive effect on the die during compaction and tools during machining and hence provides longer die/tool life than other reinforcements. It has near zero thermal expansion (0.55×10^{-6}/°C) and lower density (2.1 g/cc) than other reinforcements[19]. It has got excellent corrosion, chemical and thermal shock resistance [20]. It is stable in the metallic matrix especially in copper and does not react with the matrix during sintering. Hence, the bonding between the matrix and particles is expected to be better than other reinforcements. In contrast, carbides react with matrix materials and dissociate at elevated temperature resulting in poor interface bonding quality [21–23]. Most of the studies on silica reinforced MMCs are based on mechanical properties evaluation [20,24–26]. There are relatively very few wear studies on the silica reinforced MMCs. For instance, Rohatgi et al. [18] have developed composites of Al alloy (A206 grade)/silica with different silica contents (0–13 wt%) for the tribological applications. They reported that the higher amount of silica deteriorates the wear rate and friction coefficient of composites due to an incompatibility between the Al matrix and silica. Probably, silica and Cu have better compatibility. However, there are no studies reported on the Cu/silica composites.

Apart from the matrix and ceramic particles, an additional constituent usually present in the friction material is the solid lubricant. The purpose of the lubricant addition is to stabilize the friction and wear during the braking process [27]. Graphite is the most common lubricant used in the friction material. The principal advantages of the graphite are that it has good lubricity, high thermal conductivity, high damping capacity, protection of counter surface against excessive wear by involving in forming tribofilm and excellent seizure resistance [17,28]. Besides graphite, other lubricants such as h-boron nitride (h-BN), MoS_2, Sb_2S_3, Cu_2S find widespread use in the friction materials. There are some studies focused on understanding the lubricant effects on the wear and friction properties of polymer based automobile friction materials [27,29]. These reports conclude that the lubricants help in forming a friction film at the pad-disc interface that improves the friction and wear resistance. The presence of many ingredients (filler, binder, fiber, abrasive, lubricants, friction modifiers and so on) in a polymer based friction material makes it difficult to understand the effect of solid lubricants on the wear and friction properties. To the best of our knowledge, similar studies on MMCs are not found in the literature. Therefore, there is a knowledge gap in understanding the effect of lubricants on the tribological behavior of MMC_p.

Models are generally developed to study the effects of mechanical (load, speed, and sliding distance) and constituent (particle size, shape, amount, and type, and abrasive grit size) factors on the tribological behavior of MMCs. Most of the wear models in the literature are finite element models combined with the Archard law and physical based models. The main limitations of these models are that (1) they do not provide information on the combined effects of factors, (2) they are also mostly qualitative in nature, and (3) the predictive capability of the models is usually limited [30,31]. On the other hand, models based on statistics are emerging recently. In statistical models, the techniques such as means and S/N ratio analysis, analysis of variance, artificial neural network and genetic algorithms are utilized to study the experimental data [32,33]. The advantages of these models are that (1) they explain the statistical and physical significance of the input factors, (2) they provide predictive equations of reasonable accuracy for the selected experimental domain, and (3) they help to understand the interaction between the input variables on the output. Numerous investigators have developed statistical models for Al/SiC, Zn (ZA 27) alloys and steels [12–16,34–36]. They used analysis of variance and linear regression techniques to study the interaction of various factors (load, speed, sliding distance, particle type and size, and abrasive grit size) on the wear resistance of composites.

In light of the above facts, the work is designed as follows: first, Cu/silica composites with various solid lubricants (graphite, h-BN, and MoS_2) were processed by powder metallurgy. These composites were tested for wear and braking behaviors under the spectrum of braking loads (300–900 N) and sliding speeds (3–9 m/s). The wear data were analyzed statistically to identify the significant factor influencing the wear resistance of the composites. Finally, the effects of solid lubricants, load and speed on the braking behavior of composites were also studied.

2. Experimental procedure

2.1. Materials and processing

The powders of copper, silica, MoS_2, graphite, h-BN were used to prepare the composites. The characteristics of the powders are presented in Table 1.

Initially, three batches of Cu/20 vol% silica mix were prepared in a double cone blender. These batches were mixed with different solid lubricant of 10 vol% (MoS_2 or graphite or h-BN) to form three separate mixtures. The composition of the mixtures is given in Table 2. These mixtures were cold compacted at a compaction load of 600 kN in a single uniaxial compaction press. The diameter and thickness of the compacts were 30 mm and 5 mm respectively. The green compacts were sintered in a bell furnace under the hydrogen gas reducing atmosphere. The sintering cycle is given in Fig. 1. In order to further improve the dimensional accuracy and to close the surface pores in the compacts, the sintered compacts were again pressed at a load of 800 kN.

2.2. Factorial experimental design

A factorial approach was used to study the factors affecting wear resistance of the composites. The experiments were designed using the Taguchi method. This method is simple, robust, efficient and systematic in designing experiments. Detailed information about the Taguchi method is given elsewhere [37,38]. In the present study, it is planned to study the influence of three factors (P) (braking load, braking speed, and type of solid lubricant labeled as L, S, and X respectively) on wear resistance of the composites. The solid lubricant was treated as a categorical variable whereas the speed and the load are considered as continuous variables. Three levels (n) (upper, base, and lower labeled as 1, 2, and 3 respectively) were considered in each factor, as shown in Table 3. A standard L_{27} orthogonal array was selected to plan our experiments. According to this scheme, there were 27 experiments and

Table 1
Properties of the powders.

Powder	Silica	Graphite	h-BN	MoS_2	Copper
Mean size (μm)	50–125	150–160	106–150	44–60	75–106
Purity (min)	99.5%	95%	99.8%	98.5%	99%
Apparent density (g/cc)	–	2.2	0.78	–	2–2.4
Grade	Fused silica	Natural (flaky)	Hexagonal type	–	Electrolytic