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Effects of environment on dry sliding wear behavior of silver−copper based composites containing tungsten disulfide

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Abstract: Silver based composites containing different amounts of WS_2 were prepared by hot-pressing method and their tribological behaviors were investigated against coin silver under humid air, dry nitrogen and vacuum on a ball-on-disk tester with normal load of 5 N. The components of composites, microstructure of debris and worn surface were characterized using XRD SEM, EDS and XPS. It is demonstrated that environmental conditions significantly affect the tribological behavior of silver based composites. The friction coefficient is the highest in humid air, and the lowest in dry nitrogen. It is found that the friction and wear behavior of the composites are strongly depended on the characteristics of the lubrication film forming in different operating environments, such as thickness and composition. In addition, it is indicated that the dominant wear mechanisms of silver based composites are abrasive wear and delamination under different conditions.

Key words: self-lubricating composites; tribological behaviors; atmosphere; wear mechanism

1 Introduction

Silver matrix composites containing solid lubricant are known as self-lubricating materials, which are widely used as precision electrical contact elements in automatic control systems and high performance motor of aerospace industry [1]. It is well known that silver possesses the highest electrical and thermal conductivity, which results in the superior current carrying capacity. However, the low mechanical property and high seizure tendency with its counterpart during dry sliding are the main obstacles for its application [2]. Transition metal disulfides (MS_2, where M is molybdenum or tungsten) are known as solid lubricant, which are featured as a laminar structure. The weak van der Waals force between layers but strong covalent bond within the layer gives rise to the easy shearing of basal plane of transition metal disulfides, which resulted in the decrease of friction [3]. Aimed at the problems appearing in the application of silver, the use of composites combining silver and transition metal disulfides is the most effective way to make full use of their advantages, and finally provides antiwear and antifriction properties to sliding electrical contacts [4]. In view of this, many research efforts have been put forth on the factors related to the operating performance of silver based self-lubricating materials, including composition [5], testing parameters [6] and rubbing conditions [7], and many valuable achievements have been obtained.

At present, with the increase of the machinery complexity as well as the broadening of operating range and serve life, the improvement of operational applicability of these materials in a wide range of testing conditions, especially the solution to avoid adverse impacts of friction on efficiency and reliability, remains an issue of high engineering and scientific interest [8]. It is common knowledge that the tribological behavior of metal based self-lubricant composite is highly related to the mechanical properties of the composites [9]. In addition, more and more dedicated investigators have realized that the enhancement of lubricating ability of solid lubricants in severe environments is likely to be a more effective way to control friction and wear-related mechanical failures. Therefore, the research of the wear mechanisms and the applicability of metal based self-lubricant composites in various testing conditions, such as elevated temperature, corrosive solution and atmosphere are gaining high momentum in order to extend the practical applications of such materials [10,11].

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The tribological properties of copper matrix composites containing MoS_2 and graphite were investigated with the environmental temperature ranging from −100 °C to 100 °C and the pressures ranging from ambient to as low as 10^{-4} Pa [12,13]. It has been found that the wear mode was transformed from oxidation and mild abrasive wear to severe adhesion as the testing condition changing from air at 25 °C to vacuum at −100 °C. What's more, the mechanically mixed layer on the worn surfaces, derived from work hardening, mechanical and chemical mixing of the wear debris, played a key role in reducing friction and wear. Operating atmosphere, such as inert gas as well as humid air, was also found to have significant impact on the tribological performance of metal based self-lubricant composites. The tribological test of powder metallurgical Ag−MoS_2−G composites was conducted in the mixture atmosphere of N_2 and O_2 [14]. It has been illustrated that the friction was exacerbated with the proportion of oxygen in O_2/N_2 atmosphere increasing due to the aggravated oxidation of MoS_2. Similar oxidation behavior was also detected on sputtered MoS_2 solid lubricant films [15−17], and the oxidation resistance and the wear life of such films will increase when it is deposited by sputtering with the addition of metal in a multilayer or composite structure [18−20].

In fact, WS_2 has a higher thermal stability withstanding temperatures (100 °C) compared with MoS_2 [21], which may provide a wider range of application as a solid lubricant. Unfortunately, the systematic study on the tribological properties of metal based composites containing WS_2 in different environments has been reported rarely. In addition, the connection between the tribological behavior of such materials and testing atmosphere has not been fully understood. In this work, the tribological behaviors of silver based composites containing different amounts of WS_2 fabricated by hot-pressing method against coin silver under humid air, dry nitrogen and vacuum were investigated on a ball-on-disk tribotester. Meanwhile, the composition and formation of tribolayer under different environments were studied in detail, and this investigation can provide some valuable information to utilize the silver based composites.

2 Experimental

2.1 Material preparation

Atomized silver−copper alloy powder (2.5% copper (mass fraction), 99.9% in purity, particle size <37 μm) and tungsten disulfide powder (99.8% in purity, particle size <1 μm) were homogeneously mixed in a ball milling jar for more than 24 h. The mixtures were then hot-pressed at 25 MPa under the protection of pure nitrogen atmosphere. The sintering process was carried out at 900 °C and maintained for 20 min. The content of tungsten disulfide in the prepared composites was varied from 8% to 24% (mass fraction).

For further investigation of the mechanical and tribological properties, the sintered materials were machined into 3 mm × 3 mm × 30 mm and 3 mm × 3 mm × 10 mm in size, respectively. The density of the composites was measured by the Archimedes principle. The hardness of the sintered material was measured using a Brinell hardness tester at a load of 625 N and ball indentation of 2.5 mm. And the bending strength was evaluated by a three-point bending tester. The components of composites were characterized using X-ray diffraction. Each test was repeated at least three times and the average value was reported.

2.2 Friction and wear tests

The friction and wear properties of the prepared composites were investigated using a pin-on-disc contact geometry on a CSM tribometer (see Fig. 1). The counterpart was coin silver with a Brinell hardness of HB 120. The equipment with a closed hood would be able to control atmosphere. When being tested in dry N_2, the hood was flushed with gas for about 20 min prior to the test and with a continuous flow during the whole tests to prevent any air to enter. Tests were performed in dry nitrogen (RH <5%), humid air (RH 70%) and vacuum (10^{-5} Pa), respectively. Prior to testing, the contacting surfaces of both the coin silver disc and pin specimens were lightly ground with 800, 1200, 1500 and 2000 grit SiC papers and then cleaned with acetone. Generally, high stability and reliability are main features for silver based self-lubricant materials used in precision instrument, thus the operating conditions are characterized as low load and speed. In this work, a certain amount of exfoliated tungsten disulfide which was proportional to the wear loss was necessary in order to gain insight into its reaction with atmospheres. Therefore, the sliding wear tests for AgCu−WS_2 composite were carried out under a comparatively high normal load of 5 N and sliding speed of 1 m/s. For each sliding condition, the coefficient of friction was continually recorded during the tests and the average value was calculated for each test within the distance of 10000 m, besides each sample was weighed before and after testing by a digital microbalance (0.1 mg in precision). The wear mass loss was calculated from the difference in the mass measured. The wear rate of the composites was calculated using the following formula: $w=m/(\rho Ps)$ [22], where w is the wear rate ($m^3/(N\cdot m)$); m is the wear mass loss (g); ρ is the density of specimens (g/cm^3); P is the normal load (N); s is the sliding distance (m). In order to obtain insight into the wear mechanisms involved, the microstructures of the worn surfaces and