Friction and Wear Properties of a Novel Copper-Titanium-Silicon-Carbon-Graphite Alloy Material: Postprint

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Abstract

Copper-titanium-silicon-carbon-graphite alloy materials were fabricated using a cold-pressing sintering powder metallurgy method. The wear properties and wear mechanisms of these alloy materials, as well as the effects of speed and load on the friction and wear performance of the slider, were investigated using a friction and wear testing machine and scanning electron microscope (SEM). The results indicate that under conditions of higher speed or lower load, wear volume increases linearly with sliding distance, and within the experimental parameter range, the overall curve of wear volume variation with sliding distance demonstrates certain regularity. Microscopic analysis reveals that the sporadic distribution of titanium-silicon-carbon and graphite on the worn surface significantly enhances the wear resistance of the copper-based material. The primary wear mechanisms are adhesive wear, abrasive wear, and oxidative wear.

Full Text

Preamble

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Friction and Wear Properties of a Novel Cu-Ti_3SiC_2-C Graphite Alloy Material

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Abstract
A new Cu-based composite Cu/Ti_3SiC_2/C was prepared by powder metallurgy using cold pressing and sintering. The tribological performance of the composite was examined under different sliding speeds and loads using a specially designed sliding apparatus, and the worn surfaces were characterized by scanning electron microscopy (SEM) equipped with energy-dispersive spectroscopy (EDS). The results show that under conditions of high speed or low load, wear loss increases linearly with sliding distance, and within the experimental parameter range, the overall wear loss curves exhibit consistent patterns with respect to sliding distance. Microscopic analysis reveals that the scattered distribution of Ti_3SiC_2 and graphite on the worn surface significantly enhances the wear resistance of the copper matrix material. The primary wear mechanisms are adhesive wear, abrasive wear, and oxidative wear.

Keywords metallic materials, Ti_3SiC_2, friction and wear, speed, load, wear mechanism
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Introduction

In the early 20th century, the former Soviet Union, Japan, Western Europe, and other countries conducted extensive research on the development and application of pantograph slider materials. China developed its first batch of powder metallurgy pantograph slider materials in 1965. Since the 1980s, copper-based powder metallurgy sliders have been widely used domestically; however, they cause severe wear on contact wires [1-4]. Subsequently, metal-impregnated carbon slider materials combined the advantages of both carbon and metallic materials, essentially solving the problem of low mechanical strength of carbon sliders while significantly improving wear resistance and reducing excessive wire wear. However, these materials suffer from insufficient impact resistance, susceptibility to chipping, and high cost [5]. Copper-graphite alloy materials exhibit excellent heat resistance, wear resistance, and stable friction coefficients, making them ideal for high-speed train braking applications.

The specific heat capacity of graphite is 1.648 J/(kg · K), substantially higher than that of copper (0.39 J/(kg · K)). Adding graphite to copper-based alloys can reduce the temperature at the material’ s friction surface. Additionally, graphite functions as a solid lubricant and provides anti-welding properties [6], making it widely used in conductive materials. Ti_3SiC_2 represents a novel multifunctional material system that combines structural, electrical conductive, and self-lubricating properties. It exhibits metallic characteristics such as electrical and thermal conductivity and easy machinability, along with ceramic-like features including light weight, oxidation resistance, and high-temperature stability. Ti_3SiC_2 can enhance the strength, hardness, and wear resistance of copper-graphite alloys without compromising their self-lubricating and conductive properties [7-8].

The room-temperature electrical conductivity of Ti_3SiC_2 is 9.6$×10^{-6}$ $\Omega^{-1}\cdot m^{-1}$, nearly two orders of magnitude higher than that of graphite. Its coefficient of thermal expansion between 25-1000°C is (10-11)$×10^{-6}$ $°C^{-1}$, close to that of copper (17$×10^{-6}$ $°C^{-1}$). The compressive strength, Young' s modulus, and hardness of Ti_3SiC_2 are 900 MPa, 326 GPa, and 4 GPa, respectively. More importantly, Ti_3SiC_2 exhibits excellent oxidation resistance at 1300°C, far superior to graphite. While numerous studies have investigated the preparation and wear properties of copper-graphite alloys [9-11], this work focuses on preparing a Cu-Ti_3SiC_2-C graphite alloy material via cold pressing and sintering powder metallurgy, studying its friction and wear performance, and exploring the underlying wear mechanisms.

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1. Experimental Procedure

1.1 Materials and Preparation

Table 1 lists the particle size and mass fraction of each powder used in the experiments. The preparation process flow is shown in [Figure 1: see original paper]. Raw powders were mixed mechanically for 12 hours, then pressed at 300 MPa using a side-acting powder compacting hydraulic press. The compacts were sintered at 920°C for 3 hours under hydrogen protective atmosphere, furnace-cooled to room temperature in the same atmosphere, and finally re-pressed at 300 MPa.

Table 1 Granularity and mass fraction of powders

Material	Granularity (mesh)	Mass Fraction
Ti_3SiC_2		
Graphite		

Figure 1 Preparation process flow diagram of copper-graphite alloy

1.2 Wear Testing

Wear tests were conducted on a custom-built friction and wear tester shown in [Figure 2: see original paper]. The apparatus features a 405 mm diameter cast iron rotating disc with copper strip material fixed along its outer edge. The linear speed at the disc periphery is adjustable from 0-100 km/h, providing stable motion. Pin specimens measured 10 mm × 10 mm × 35 mm, with a 10 mm × 10 mm friction surface. Tests were performed at contact pressures of 20 N and 40 N, with relative sliding distances of 25, 50, 75, and 100 km. Prior to testing, all specimens were polished with 800-grit sandpaper. Wear mass loss was measured using an electronic balance with 1 mg precision. All experiments were completed under laboratory ambient conditions.

Worn surface morphology and wear mechanisms were analyzed using a HITACHI S-2360N scanning electron microscope (SEM) and a Quanta 200 FEG field-emission environmental scanning electron microscope (ESEM) equipped with energy-dispersive spectroscopy (EDS).

2. Results and Discussion

2.1 Effects of Speed and Load on Friction and Wear Performance

Figure 3 [Figure 3: see original paper] shows the relationship between wear loss and sliding speed at a contact pressure of 20 N. Overall, wear loss increases substantially with increasing speed, exhibiting nearly linear growth after 50 km of sliding. At lower speeds ($V < 50$ km/h), wear loss initially increases with sliding distance before stabilizing. At higher speeds ($V \geq 50$ km/h), wear loss shows stable linear growth with sliding distance. This behavior occurs because increased speed leads to greater tangential impact forces on the surface, causing particles with weak interfacial bonding to detach from the matrix under large impact forces [12].

Figure 4 [Figure 4: see original paper] illustrates the relationship between wear loss and applied load at a sliding speed of 50 km/h. Wear loss increases with sliding distance. Under low loads, wear loss exhibits near-linear growth with sliding distance, while under high loads, it initially grows linearly then shows an upward trend. At sliding distances of 25 km and 50 km, wear loss differs by nearly a factor of two between the two load conditions; at 100 km, the difference approaches a factor of four. This is because higher applied loads increase contact pressure, resulting in greater weight loss [13-14]. During friction, plastic deformation of the subsurface layer under load causes dislocation slip and accumulation, generating numerous vacancies and microcracks that severely degrade alloy performance and wear resistance [15].

2.2 Wear Surface Morphology

Figure 5 [Figure 5: see original paper] presents SEM surface morphology and EDS analysis of the alloy after sliding 100 km under a 20 N load at 50 km/h. As shown in Figure 5a, the wear tracks are generally aligned in the same direction. The alloy surface exhibits numerous pits and some larger flake-like layers, with plowed grooves visible in some regions. Localized oxide films are present on the worn surface, and many particulate substances and large dark black residues are uniformly distributed across the friction surface. EDS analysis of points A and B in Figure 5a is shown in Figures 5b and 5c. Point A contains primarily carbon, originating from graphite in the material that fractured during friction and served a self-lubricating function. Analysis of point B reveals the presence of Ti, C, Si, O, and Cu, indicating the formation of hard TiC crystalline phases on the surface [16]. The detection of oxygen atoms suggests possible oxide formation during the friction process.

The alloy wear surface contains substantial graphite. As a non-metallic, low-strength brittle material, graphite' s strength is far lower than that of metallic copper. Consequently, graphite easily fractures and flows under surface frictional shear stresses, resulting in numerous graphite particles on the friction surface [17]. Graphite has a hexagonal close-packed structure with excellent lubricity. The extensive distribution of graphite particles on the surface enhances lubrication, reduces plowing forces between asperities, mitigates surface grooving, and thereby decreases material wear.

Wear debris on the worn surface originates primarily from three sources: (1) work-hardened or oxidized matrix material and a few hard particles from sintered Ti_3SiC_2 agglomerates or friction-generated TiC crystalline phases [18]; (2) crack initiation in localized surface regions, with crack propagation leading to brittle fracture and spalling, where the detached debris acts as abrasive particles; and (3) fracture and detachment of oxide films formed on the wear surface, which become abrasive particles causing abrasive and oxidative wear. Under normal load, abrasive particles embed into the alloy surface and move along the sliding direction under compressive and shear stresses, creating plowed grooves or micro-cutting actions on the worn surface and raising ridges along groove sides or fronts. These ridges undergo deformation during subsequent friction, forming plastic deformation zones. Repeated plastic deformation leads to work hardening and smoothens the wear surface [19].

Additionally, delamination pits are observed on the alloy surface in Figure 5a. This occurs because low-strength graphite preferentially fractures, creating surface pits. Due to poor bonding between graphite and the copper matrix, graphite readily detaches into the friction interface during sliding, forming pits. These pits become accumulation sites for particulate matter, and when frictional stresses reach sufficient levels, the metal matrix at pit edges deforms and damages, allowing graphite and accumulated particles to be completely expelled. The substantial graphite particles expelled from the friction surface provide lubrication.

Figure 6 [Figure 6: see original paper] shows the worn surface morphology of the alloy under different loads. At low loads (Figure 6a), the wear surface is relatively smooth with consistent wear track directions and fewer hard particles generated by friction. Higher loads produce greater normal pressure and consequently larger shear stresses, which more readily generate adhesive wear, causing material transfer and spalling that produces more hard particles. Figure 6b shows the wear surface under high load containing more hard particles, though the wear tracks are less distinct and the surface is not smooth. Furthermore, frictional heating raises the specimen surface temperature, softening the material and reducing surface plasticity [20-21]. Increased temperature also intensifies surface oxidation [22], resulting in a relatively rough wear surface.

For the studied copper-graphite alloy, adhesive wear occurs during the initial wear stage. As wear progresses, accumulated abrasive particles increase, causing abrasive wear. Under cutting action from abrasive particles, material is stripped from the alloy surface to form wear debris, while plowed grooves form along the sliding direction on the alloy surface. Over time, cutting by abrasive particles intensifies, causing obvious plastic deformation on the alloy wear surface and increasing wear loss. As friction continues, rising surface temperature exacerbates oxidative wear.

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3. Conclusions

1. **Effect of speed on wear**: The wear loss of Cu-Ti_3SiC_2-C graphite alloy material shows consistent patterns, increasing linearly with speed. Under low loads, wear loss increases linearly with sliding distance, while under high loads, it initially increases linearly then shows an upward trend.
2. **Microstructure benefits**: During the wear process of Cu-Ti_3SiC_2-C graphite alloy material, Ti_3SiC_2 and graphite are uniformly distributed on the wear surface, significantly enhancing the wear resistance of the copper matrix material.
3. **Wear mechanisms**: The wear mechanism of copper-graphite alloy is primarily adhesive wear in the initial stage. With increasing wear, the mechanism becomes dominated by adhesive wear and abrasive wear, accompanied by oxidative wear.

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