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Research Progress on the Tribological Properties of Tungsten and Tungsten Carbide Coatings

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Abstract: Tungsten and its compound, tungsten carbide, play significant roles in aerospace, aviation and friction welding fields. Through a systematic review and analysis of the literature, this paper summarizes the friction and wear characteristics of pure tungsten coatings from room temperature to high temperatures, the evolution of their microstructure, and the changes in tribological properties because of the formation of oxide films caused by alterations in the surrounding chemical environment at high temperatures. For tungsten carbide coatings, this paper summarizes their friction and wear processes, the formation of mechanically mixed layers, and their friction response in different environments (dry and lubricated)This research investigates the variation in the friction coefficient of pure tungsten across a temperature range from ambient conditions to over 1000℃, highlighting inconsistent trends between room temperature and 600℃. Additionally, the study addresses ongoing debates and outlines potential avenues for future research on pure tungsten and its composite coatings.

Keywords: Tungsten and Tungsten Carbide, Temperature, Friction and Wear Characteristics, Surrounding Chemical Environment

1. Introduction

Tungsten and its compounds are extensively utilized in aerospace, friction welding, and accelerator-driven systems (ADS) owing to their exceptional hardness, strength, superior wear resistance, and high melting point. In recent years, there has been a growing focus on studying the friction and wear characteristics of tungsten and its alloys or compounds. During friction, the temperature increases, potentially causing tungsten and its alloys or compounds to reach their ductile-to-brittle transition temperature (DBTT), which can significantly influence their friction and wear performance. Additionally, the formation of oxide films on the surface of tungsten or its compounds, or the influence of the surrounding chemical environment and lubricants (such as hexadecane), can also alter their friction and wear behavior. Therefore, this paper systematically reviews and analyzes the friction and wear processes through relevant literature and provides suggestions for environmental control in the preparation and production processes of tungsten and its compound coatings.

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2. Tribological Properties of Pure Tungsten

2.1. Effect of Temperature on the Tribological Properties of Tungsten

Temperature plays a critical role in influencing the ductile-to-brittle transition of materials. During the friction process of tungsten coatings, as temperatures rise, the material transitions from a brittle to a ductile state. At varying temperatures, the wear mechanisms of tungsten include adhesive wear, abrasive wear, fatigue wear, and corrosive wear. Xie Zhiming et al. performed ball-on-disk wear tests on polished rolled pure tungsten samples to eliminate surface roughness effects. Using a Rice MFT-5000 tribometer with an alumina ball as the counter material, tests were conducted from room temperature to 1000°C. The results revealed that the friction coefficient varied with both time and temperature. From room temperature to 750°C, the friction coefficient decreased with increasing temperature, but at 1000°C, the formation of an oxide film caused the friction coefficient to initially decrease and then rise. The wear rate was lowest at room temperature, peaked at 250°C, and then declined at 500°C and 750°C [1]. Due to challenges in measuring wear at 1000°C caused by the oxide layer, future experiments in an argon atmosphere are recommended to exclude oxygen interference.

In contrast, Ding Zhicheng et al. conducted rotational friction and wear tests on an MFT-5000 tribometer, also using an alumina ball, and evaluated tribological properties at four temperatures. Their findings diverged from Xie Zhiming et al.'s results. At room temperature, 200°C, and 400°C, the friction coefficient remained stable at approximately 0.45. However, at 600°C, the formation of a surface oxide film caused the friction coefficient to gradually decrease from 0.60 to 0.15 [2]. At lower temperatures, the friction coefficient trends differed from those in the previous study. Regarding wear rate, the maximum wear rate occurred at 200°C, after which it decreased with rising temperature. At 200°C, tungsten transitions from brittle to pseudo-plastic, resulting in severe adhesive wear and mass loss. The temperature corresponding to the maximum wear rate aligned with the earlier study [2]. In terms of wear mechanisms, abrasive wear and slight adhesive wear dominated at room temperature, while adhesive wear intensified at 200°C. At 400°C and 600°C, oxide film formation reduced the wear rate, and wear mechanisms shifted toward corrosive wear and fatigue wear, consistent with the previous literature.

Based on these two studies, future research should prioritize investigating the changes in the friction coefficient (COF) between room temperature (RT) and 600°C. Given tungsten's high melting point and its widespread use in friction welding, it is also recommended to explore friction coefficient variations, wear rates, and wear mechanisms at temperatures above 1000°C in an argon atmosphere.

2.2. Microstructural Evolution of Tungsten During Friction

Chen Zongtao et al. used molecular dynamics simulation methods with the Lammps software to study the effect of defects on the friction properties of single-crystal metals. They found that vacancy defects increase the interfacial potential barrier of single-crystal metals, thereby increasing the average friction force at the defect sites [3]. However, in the studies by Xie Zhiming and Ding Zhicheng et al., the influence of crystal structure, such as defects, on the friction coefficient and wear rate of tungsten was not discussed. Ding Zhicheng et al. pointed out that during the wear process, the subgrain size under the friction layer significantly decreased, especially at room temperature and 200°C. As the temperature increased, the subgrains gradually coarsened, and low-angle grain boundaries (LAGBs) gradually transformed into high-angle grain boundaries (HAGBs) [2]. Therefore, it is suggested that future experimental research should pay more attention to the influence of crystal structure on the tribological properties of tungsten.

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3. Tribological Properties of Tungsten Carbide Coatings

Tungsten carbide (WC) exhibits excellent tribological properties, mainly due to its high hardness and wear resistance. In WC/C coatings, tungsten carbide particles provide the necessary hardness and wear resistance, thereby enhancing the tribological durability of the coating. Additionally, tungsten carbide can reduce adhesive wear. By doping tungsten carbide, the brittleness of DLC (diamond-like carbon) coatings can be improved, enhancing their durability under extreme conditions. The following sections summarize the research progress on the tribological properties of WC/C and WC/Co coatings.

3.1. Tribological Properties of WC/C Coatings

He Dongqing et al. investigated the low-friction mechanism of WC/C coatings under low-humidity conditions and discovered that WC/a-C films can achieve low friction in such environments, a feat not possible with traditional hydrogen-free carbon-based films. They identified two critical factors contributing to this low-friction mechanism: the graphitization of the sliding interface induced by friction and the passivation of dangling carbon bonds in the presence of environmental humidity. Furthermore, in an oxygen-rich environment, the WC phase oxidizes during friction, forming a WO3 transfer film, which leads to a low friction coefficient, resembling the tribological behavior of pure tungsten [4]. However, this study did not examine the impact of temperature on the friction performance of WC/C coatings. It is recommended that future research explore the tribological properties of WC/C coatings under ultra-high temperature conditions.

3.2. Tribological Properties of WC/Co Alloys

Wang Haibin et al. employed molecular dynamics simulations to uncover the tribological behavior of WC/Co alloys at the atomic scale. By modeling the friction process of WC-Co cemented carbides, they analyzed the movement of dislocations, the formation of stacking faults, and the initiation and propagation of microcracks. Their findings revealed that during friction, the interaction of stacking faults within WC grains leads to microcrack formation, and the growth and merging of these microcracks ultimately cause the fracture and fragmentation of WC grains. The Co binder phase was found to mitigate the risk of cracking along phase boundaries [5].

Deng Jianxin et al. investigated the friction and wear characteristics of WC/Co cemented carbides with varying WC grain sizes at different temperatures. Their results demonstrated that as the temperature increased, the wear rate of WC/Co cemented carbides also increased. The alloy with the smallest WC grain size exhibited superior wear resistance at temperatures up to 600℃, correlating with its higher hardness [6]. Furthermore, smaller WC grain sizes in WC/Co were associated with increased hardness and significantly improved wear resistance. Ultra-fine WC particles (less than 0.1μm) were shown to markedly enhance the wear resistance of cemented carbides [6].

For WC/Co alloys, both the microscopic mechanisms and their tribological properties at different temperatures have been extensively studied, providing valuable insights for research and industrial applications. It is recommended to reduce the WC grain size in WC/Co to further enhance its wear resistance.

3.3. Tribological Characteristics of WC in Dry and Lubricated Conditions

Stoyanov et al. conducted reciprocating sliding tests under dry and lubricated (hexadecane) conditions, monitoring the friction coefficient, wear rate, and surface morphology changes. They found that under dry conditions, the friction coefficient significantly increased after the initial running-in period and eventually stabilized at a higher level. Surface roughness increased with the number of sliding cycles,

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and obvious grooves and scratches formed within the wear track. A mechanically mixed layer (third body) formed on the WC surface, mainly composed of amorphous and nanocrystalline materials. In contrast, under lubricated conditions, the friction coefficient was significantly lower than under dry conditions and remained at a low level throughout the sliding process. Surface roughness increased more slowly, and fewer grooves formed within the wear track. The lubricant (hexadecane) limited direct contact between surfaces, reducing the formation of the third body and plastic deformation [7].

4. Conclusion

This paper analyzes a portion of the literature from 2019 to 2025 on the tribological properties of tungsten (W), tungsten carbide (WC), and their alloys, ranging from microscopic mechanisms to macroscopic tribological performance, and identifies future research directions. For WC and its alloys, the reviewed literature indicates that smaller WC grains and lubricated conditions result in lower friction coefficients and wear rates. This study pays less attention to the microscopic behavior of pure tungsten and tungsten alloys during friction processes, although relevant literature extensively explores changes in their microscopic behavior. For future research directions, due to the high affinity of pure tungsten for oxygen at elevated temperatures, it is recommended to investigate the tribological properties of pure tungsten under high-temperature conditions in an argon atmosphere and to explore its behavior under ultra-high-temperature conditions.

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