Solid lubrication with MoS2-Ti-C films for high-vacuum applications in a nuclear fusion device

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Abstract

Purpose: EAST is a tokamak fusion device operating under ultra-high vacuum conditions. To prevent contamination of the inner vessel environment, solid lubrication has been applied to the surfaces of bearings and gears exposed to vacuum.

Design/methodology/approach: Anti-friction MoS coatings doped with different atoms have been developed using the multi-target magnetron sputtering deposition technique. This paper presents comparative testing of the tribological properties of three types of MoS -based coating layers.

Findings: Based on the test results, MoS -Ti-C coating films are recommended as the final selection due to their superior performance in friction coefficient and lubrication longevity.

Originality/value: Finally, detailed characterization of the hybrid coatings is provided, which can serve as a reference for applications of solid lubrication under similar high-vacuum and high-temperature conditions.

Full Text

Solid Lubrication with MoS -Ti-C Films for High-Vacuum Applications in a Nuclear Fusion Device

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Abstract

Purpose: EAST is a tokamak fusion device operating under ultra-high vacuum conditions. To avoid contaminating the inner vessel environment, solid lubrication has been applied to the surfaces of bearings and gears exposed to vacuum.

Design/methodology/approach: MoS -based antifriction coatings doped with different atoms were developed using a multi-target magnetron sputtering deposition technique. This paper presents comparative testing of the tribological properties of three kinds of MoS -based coating layers.

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Originality/value: Finally, detailed information has been characterized for the hybrid coatings, which can provide references for applications of solid lubrication under similar conditions of high vacuum and temperature.

Keywords: Solid lubrication; Adhesive wear; Coating; Vacuum; Lubrication performance

1. Introduction

The Experimental Advanced Superconducting Tokamak (EAST) is the first fully superconducting tokamak fusion device built in China [1-3]. Historical records from EAST physical experiments indicate that more than 30% of shutdowns and maintenance periods are caused by damage to small components inside the vacuum vessel (VV) due to enormous heat flux [4, 5]. [Figure 1: see original paper] shows the EAST tokamak device and its vacuum vessel, which maintains a pressure of 10 Pa.

To increase effective operational time, it would be far more efficient to repair damaged components without breaking the vacuum environment. The EAST Articulated Maintenance Arm (EAMA) is a serial robot system developed for remote maintenance within the EAST vacuum vessel during plasma pulses [6, 7]. The operational conditions for the EAMA robot can be summarized as high temperature (~80 °C), high vacuum (~10 Pa), and high loads (~1000 Nm), under which perfect lubrication for motion joints must be guaranteed.

[Figure 2: see original paper] illustrates the conceptual design of the EAMA robot arms and its end effector. For the entire robot mechanism, hundreds of bearings and gears are assembled inside the articulated joints to ensure smooth movement. All high-speed components (motors, gears, etc.), which require excellent lubrication, are sealed in boxes to prevent contamination of the vacuum environment, allowing high-temperature grease to be used. Meanwhile, some low-speed components (joint bearings and bushes) are considered for coating films as solid lubrication, as shown in [Figure 3: see original paper].

Regarding solid lubrication in the EAMA robot, the requirements can be summarized as follows: 1) Good reliability in vacuum (10 -10 Pa) and high temperature (~80 °C); 2) Ability to withstand compression forces up to 30 kN; 3) Low friction coefficient (~0.1) to enable smooth movement; 4) Thin film thickness to ensure the assembly accuracy of bearings.

Solid lubricant films based on MoS are widely used in vacuum conditions [8-10]. However, when exposed to atmospheric conditions with certain humidity, MoS is highly vulnerable to oxidation [11-13]. Moreover, for high-precision applications, thin films deposited by sputtering techniques exhibit poor adhesion and short lifetime due to process ionization limitations [14]. To improve solid lubrication performance, this paper presents a study on composite coating films based on MoS using a multi-target magnetron sputtering deposition technique. Scanning Electron Microscopy (SEM) images and X-ray Diffraction (XRD) patterns of different composite films have been obtained. MoS -Ti-C films are recommended as the final selection due to their superior tribological properties. Finally, detailed information has been characterized for the composite coating, which can provide references for applications of solid lubrication under similar conditions of high vacuum and temperature.

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2. Composite Coating Films Based on MoS

Sputtering deposition of composite coating films was performed on Bearing Steel GCr15 using a single-chamber magnetron sputtering system JGP-450, which can achieve a base pressure of 6.67 × 10 Pa after baking and degassing. The sputtering system contains three magnetron targets, with MoS , Ti, and C target plates respectively mounted on them, as shown in [Figure 4: see original paper].

Three different coating films (MoS , MoS -Ti, MoS -Ti-C) were deposited to identify the optimal solution for bearing lubrication in the EAMA robot. The detailed deposition parameters are provided in .

3.1 Morphology of MoS -Based Films

The surface and cross-section SEM images of pure MoS and composite films are illustrated in [Figure 5: see original paper], where 1 m is used as the standard film thickness for comparison. Similar to images in other related work [13, 14], the pure MoS films exhibited a worm-like surface structure with aggregates of different sizes. When combined with Ti atoms, the nanocrystals of composite films were obviously refined. However, some small gaps could still be observed. After further doping with C atoms, the mound-like protrusions and film particles became finer, smoother, and more compact, indicating better hardness and wear resistance.

3.2 Microstructure Analysis

[Figure 6: see original paper] shows the X-ray diffraction (XRD) patterns of the three different films obtained using a RINT2400 X-ray diffractometer. By comparing the XRD patterns, several facts can be summarized as follows:

1) For pure films, MoS (002) and MoS (100) diffraction peaks appeared at Bragg angles 2 = 14.38° and 32.7°, indicating that preferential growth of films occurs on both lubricating and non-lubricated surfaces simultaneously. The MoS peak intensity ratio I(100) / (I(002) + I(100)) was 0.24.

2) For MoS +Ti composite films, the intensities of both MoS (002) and MoS (100) diffraction peaks decreased; however, the (100) peak intensity decreased even more significantly. The peak intensity ratio I(100) / (I(002) + I(100)) dropped to 0.21, demonstrating that Ti atoms have a greater inhibitory effect on the preferential growth of MoS (100) on non-lubricated surfaces.

3) For MoS +Ti+C composite films, the preferential growth of MoS (100) on non-lubricated surfaces was almost completely inhibited.

4) Based on the Scherrer equation [15-17], the average crystallite sizes of the three film types can be determined: MoS -Ti-C ~ 5 nm, MoS -Ti ~ 12 nm, MoS ~ 23 nm. The reduction in crystallite size is conducive to increasing film hardness.

4.1 Friction and Wear Tests

To evaluate the lubrication performance and longevity of different films, friction tests were performed using a pin-on-disk device under EAST-like high-vacuum and temperature conditions. The friction coefficient curves were obtained and are shown in [Figure 7: see original paper]. All films exhibited low friction coefficients at the beginning of the tests, particularly the MoS -Ti-C composite films (below 0.05). However, as the tests continued, fluctuations increased. Finally, the pure MoS films and composite MoS -Ti films sharply increased to more than 0.2 at 150 min and 240 min, respectively, indicating coating failure. The MoS -Ti-C composite films maintained relatively stable friction performance throughout the entire 300 min test. Considering the testing parameters (rotation radius: 3 mm, velocity: 1000 rpm), this corresponds to approximately 5600 meters of sliding distance.

4.2 Scratch Test

Scratch testing is primarily used to investigate the mechanical properties of thin coating films [18, 19]. As shown in [Figure 8: see original paper], the wear scar profiles for the three MoS -based films were measured from scratch tests. The pure MoS films were severely worn, with scars 500 m wide and 4.1 m deep. The MoS +Ti films showed scars 480 m wide and 2.8 m deep, representing only modest improvement. For MoS +Ti+C films, both the width and depth of wear scars were significantly reduced to 250 m and 0.8 m, respectively, decreasing the cross-sectional area by an order of magnitude. This demonstrates that MoS +Ti+C composite films possess the highest surface hardness and wear resistance.

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5. Summary

In this paper, three kinds of MoS -based films were developed using a multi-target magnetron sputtering deposition technique to identify a suitable solid lubrication solution for the EAMA robot. First, SEM images and XRD patterns showed that the crystallites of composite thin films have finer size and more compact microstructure than pure MoS . The average crystallite size of MoS +Ti+C is approximately 5 nm, much smaller than the 23 nm for pure MoS . Second, pin-on-disk tests directly demonstrated the superior performance of MoS +Ti+C composite films in both friction coefficient (below 0.05) and longevity (more than 300,000 cycles). Third, scratch tests also confirmed that MoS +Ti+C films possess the highest surface hardness and wear resistance.

Finally, MoS +Ti+C composite films have been identified as the most suitable selection for lubricating the EAMA robot under high vacuum and temperature conditions. The coatings have been applied to bearings and gears exposed to vacuum (shown in [Figure 9: see original paper]). Implementation inside the EAST tokamak ([Figure 10: see original paper]) demonstrated good performance in solid lubrication while protecting the vacuum environment. Further tests have been completed to characterize detailed information (listed in) for the solid lubricating products, which can provide references for similar applications.

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Note: Figure translations are in progress. See original paper for figures.