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Exploring the Friction and Wear Properties of Silver Coatings on 718 Alloy

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Abstract

Fasteners of 718 alloys are used to set up connection between each support and other components for ITER system, metal-based Ag solid lubricant coating is widely used as an anti-seizure lubricant coating due to its strong low-temperature shear resistance. But the poor adhesion to the steel surfaces has been a critical restriction for applying the silver coatings to the practical machine elements. In this work, an 8-μm silver self-lubricating coating was deposited on the surface of 718 alloy by the method of magnetron sputtering. The coating was uniform, dense and consistent. The wear mechanism was investigated by analyzing the friction and wear properties of the coating. Stress is one of the important impacts on the friction coefficient, the results showed that it first increased and then decreased with the increase of pressure at room temperature and under vacuum. Temperature exerted an effect on the silver self-lubricating coating. A study was conducted under vacuum on the friction and wear performance of the coating at 300 K, 225 K, 155 K, and 77 K, respectively. The results showed that the wear mechanism and wear state varied under various low-temperature conditions, with the severity of wear reaching the maximum only at 225 K. Through the same silver coating process, the washer of superbolt was improved by silver coating treatment.

Keywords

ITER, Silver Coating, Friction and Wear Properties, Lubrication, Superbolt

1. Introduction

International Thermonuclear Experimental Reactor (ITER) is a full superconducting nuclear fusion reactor, the components of the ITER magnet support system operate in a complex environment characterized by high load, strong magnetic field, low temperature, and multiple-field coupling. In this environment, there are a variety of physical factors involved, fasteners of 718 alloys are used to set up connection between each support and other components [1]. At present, the metal-based Ag solid lubricant coating is widely used as an anti-seizure lubricant coating for the ITER magnet support bolts due to its strong low-temperature shear resistance and excellent vacuum friction properties [2]. The existing methods commonly used to deposit lubricating coatings on metal substrates include electroplating, chemical plating, etc. [3] [4].

Soft metallic such as silver coatings usually have very little mutual solubility with substrate alloys, so they generally show poor adhesion to the steel surfaces. This has been a critical restriction for applying the soft metallic coatings to the practical machine elements [5]. Seung and his colleagues focused on the tribological characteristics of silver transfer layers, and constructed the wear map of bearing steel lubricated by silver film, they delineated the wear transition behavior with the change in operating conditions [6]. It has been normally recognized that initial failure of coated layer is the definite end of service life. Miyake fabricated nanocomposite films composed of DLC and Ag or Au. The films have low friction coefficients as a result of increases in hardness and Young's modulus arising from the nanocomposite structure [7]. Okuda studied the internal friction peaks in silver and platinum at low temperature [8]. Shindo developed new solid lubricant films based on low friction multilayer model, nanoperiod Au and Ag multilayer films were deposited, the results indicated that multilayer films exhibit a higher elastic modulus, a higher hardness and a lower modulus of dissipation energy than single layer films [9]. Furthermore, the temperature plays an important role in sliding friction, particularly in the cryogenic regime [10]. However, for large-sized high-strength bolts, electroplated coatings perform poorly in bonding to substrates, and various problems tend to arise, such as "hydrogen embrittlement" that may occur during the electroplating process [11]. In the present work, the friction and wear properties of silver coatings prepared by magnetron sputtering are investigated.

2. Experiments and Characterization

Substrate of 718 alloy was prepared as a size of Φ25 mm × 7.8 mm, its chemical composition is detailed in **Table 1**. After quenching and tempering treatment, the microhardness (HRC) was 40, the yield strength ($6_{0.2}$) was 1110 MPa, and the tensile strength (6) was 1378 MPa. The surface roughness after precision grinding was lower than 0.8 μm. Before coating, the substrate was sonicated and anhydrous ethanol for 10 minutes each.

The silver coating was produced on the 718 substrate through magnetron sputtering, when the base vacuum reached 4.5×10^{-3} Pa, a uniform silver layer was deposited (target purity ≥ 99.5%) by applying a 300 V pulse bias voltage, an 80 V DC bias voltage, and a duty cycle of 15% during the sample deposition process.

Table 1. Chemical composition of 718 Alloy.

Material	Fe	Ni	Cr	Ti	Mn	Al	C	Si	P	S
718 Alloy	26.3	52.1	19.9	0.96	0.01	0.54	0.06	0.10	0.005	0.0001

X-ray diffraction analysis was conducted using a D/max-2500 X-ray diffractometer (X'Pert PRO) produced by Rigaku Corporation, Japan. The surface morphology of the coating and the worn samples was examined under a ΣIGMA field emission scanning electron microscope (SEM).

3. Results and Discussions

3.1. XRD Analysis and Morphology Characteristics

Figure 1 shows the phase structure of the magnetron sputtered silver coating. According to the figure, the samples show strong peaks of silver in the crystal planes of (111), (200), (220), (311), and (222) at 37.35˚, 43.5˚, 63.75˚, 76.65˚, and 81.66˚, respectively, but without clear orientation. The grain size of the Ag coating is close to 208nm, and the lattice strain is approximately 0.1168%.

The surface morphology of the magnetron-sputtered silver coating is illustrated in Figure 2a, revealing a homogeneous island growth mode with a dense surface, few defects, small grain size, and an island structure size of approximately 200 nm. An analysis of the coating cross-section was conducted, as shown in Figure 2b, to reveal a uniform coating thickness of about 8 microns with a distinct layered structure and strong adhesion to the substrate.

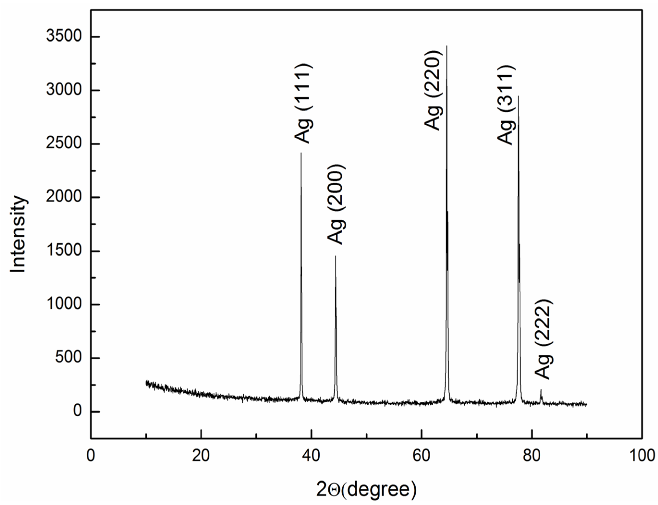

Figure 1. XRD characteristics of the coating.

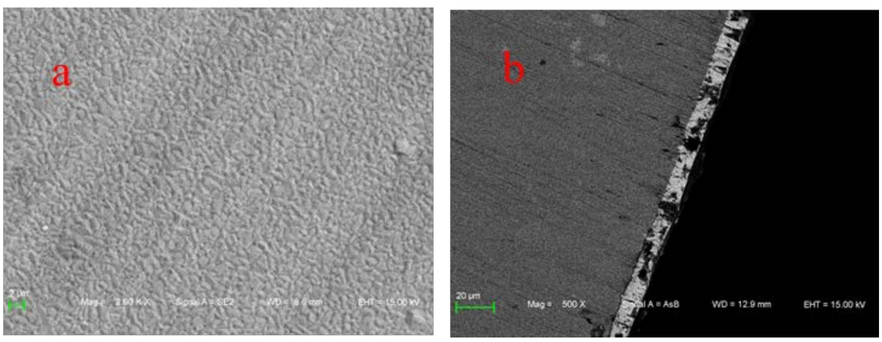

Figure 2. Silver coating (a) surface morphology; (b) cross-sectional backscattered electron pattern.

3.2. Friction and Wear Properties of Coating

The low-temperature and vacuum friction and wear properties of the coating were characterized at Lanzhou Institute of Chemical Physics. The wear mode was explored through a ball-on-disk sliding friction and wear test, the vacuum degree was 1×10^{-5} Pa, and the friction pair was a 3 mm cylindrical ball made of alloy 718. The wear track width and depth have been further used in computing the wear volume (and subsequently wear rate), which is given by the following relationships [6]:

$$V_d\,(\text{mm}^3) = 2\pi \times \text{track radius} \times \text{track width} \times \text{track depth}$$

$$\text{Wear rate}\,(\text{mm}^3/\text{Nm}) = V_d/(\text{normal load} \times \text{sliding distance})$$

3.2.1. Different Pressure

Tests in room temperature and vacuum were performed at 5 N, 7 N, and 10 N as shown in **Figure 3**, according to Hertz contact theory, the maximum contact pressure was 1 GPa, 1.25 GPa, and 1.4 GPa respectively. The friction was very stable with a COF of 0.03 at 1.25 GPa, but in the other pressure, though the COF is still low for solid lubricants, but the curves is great fluctuation then stable under 0.2, and the average COF (**Figure 3b**) indicated with the pressure increased the COF first increased and then decreased. When the contact pressure was less than 1 GPa, no failure was found, as the silver coating film supported the applied load without the film failure, mild wear was observed. When the contact pressure increase, the silver coating failed and the wear coefficient rose abruptly. Oppositely, the COF decrease with the pressure increase continuously, which main due to the transfer layer formatted and which is the great contribution to decrease the COF. From **Figure 4a** and **Figure 4b**, it can be seen clearly that given a relatively low stress on the coating, stress concentration occurred only to the local micro-convex bodies. With a rise in the load applied (**Figure 4c** and **Figure 4d**), more of the micro-convex bodies between the friction pair and the coating came into contact, thus expanding the contact area. When a higher load was applied, the micro-convex bodies were more easily sheared, and it was more likely for the coating to crack, thus causing a progressive increase in the friction coefficient.

When the load was further increased (**Figure 4e** and **Figure 4f**), there was more debris generated as the critical stress was exceeded in most of the micro-convex bodies on the friction surface. The area occupied by the silver soft abrasive accumulated on the coating surface increased, thereby enhancing the lubrication effect. At the same time, the higher the load is, the greater the normal pressure is, and the higher the flash temperature during friction is. Therefore, it was more likely for adhesive wear to occur. With part of the silver coating adhering to the friction pair surface, the friction between the friction pair and the coating changed into the friction between silver and silver, thus further reducing the friction coefficient. Under the loads of 5 N and 10 N, the worn surface was found smooth and uniform, but no plow-shaped morphology was observed, with slight adhesive wear identified as the principal wear mechanism.

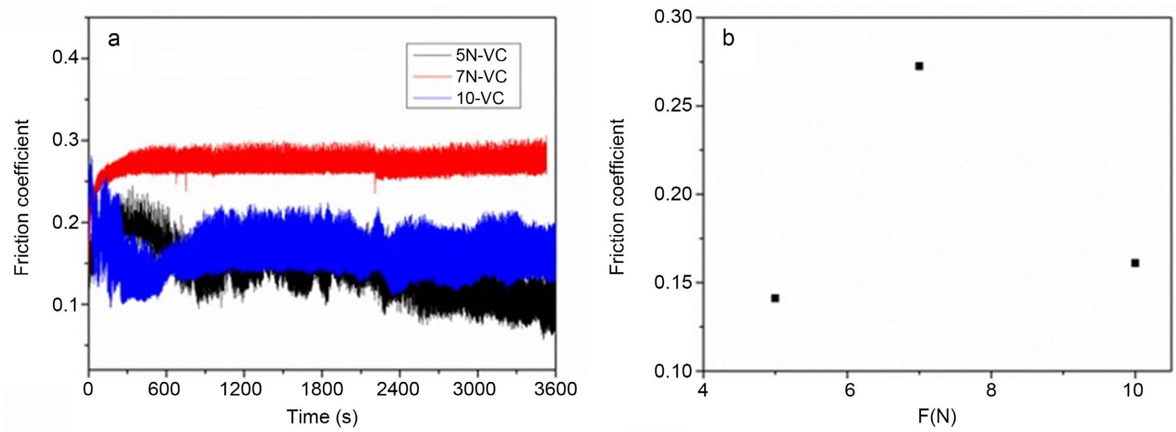

Figure 3. Silver coatings under different loads (a) friction and wear curves; (b) average coefficient of friction.

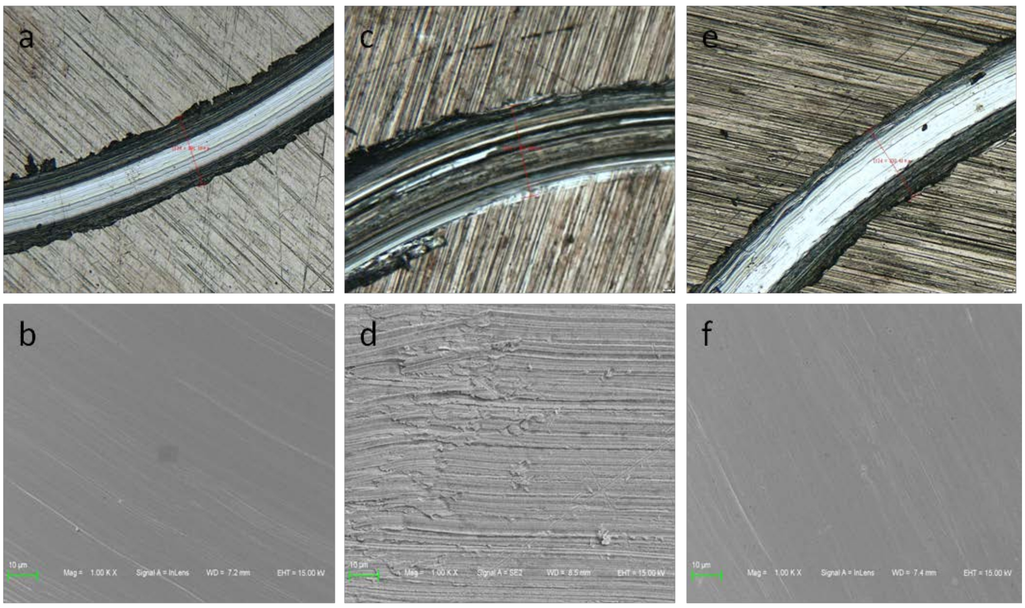

Figure 4. Optical mirror and surface morphology of silver coating under different loads.

3.2.2. Different Temperatures

To reveal the impact of temperature on the friction and wear properties of silver coatings, all the experiments were conducted under vacuum, with the vacuum degree set to 1×10^{-5} Pa and the tangential load set to 1.25 GPa (7 N). The average coefficient of friction (COF) and wear rate were shown in Figure 5. The average COF at 300 K was 0.27, and the wear rate was the highest accordingly. Figure 6a shows the morphology of the wear scar, revealing a plowing pattern. The wear mechanism is characterized by abrasive and adhesive wear.

The temperature was lowered to 225 K, the average COF approached 0.26, and the wear rate declined slightly. Although the surface of the wear scar still showed a plowing pattern, the abrasive wear was reduced. With the decrease of temperature, the adhesion between the coating and the substrate reached a level that was unsatisfactory. As shear plastic deformation and dislocations occurred continuously in the surface layer of the coating, cumulative dislocation caused cracks or voids in parallel to the surface at a certain depth. Finally, severe wear occurred in these areas where holes developed.

After the temperature dropped to 155 K, the average COF decreased to 0.16 and the wear was reduced to the minimum. As shown in Figure 6c, the wear surface was smooth and uniform, without grooves observed. Also, slight adhesive wear was dominant. After wear, a smooth and soft silver-based lubricating film developed on the surface. By adhering to the surface of the hard friction pair, it increased the lubrication effect.

When the temperature dropped to 77 K, the average COF rose to 0.36, and the wear amount increased as well. At this temperature, there was an increase in the Young's modulus of both the friction pair and the coating material, while the actual contact area was reduced under the same load, which enhanced hardening

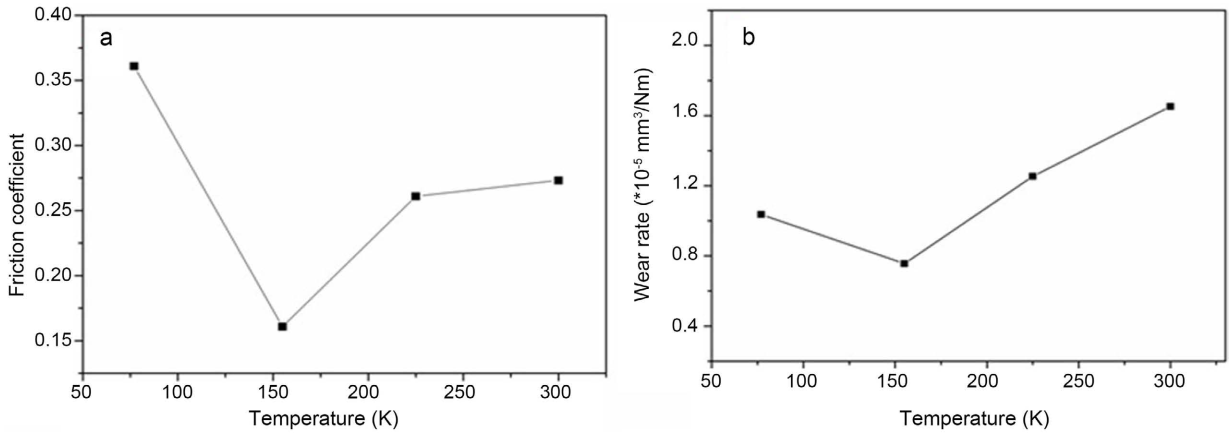

Figure 5. (a) Average coefficient of friction; (b) wear rate of the coating at different temperatures.

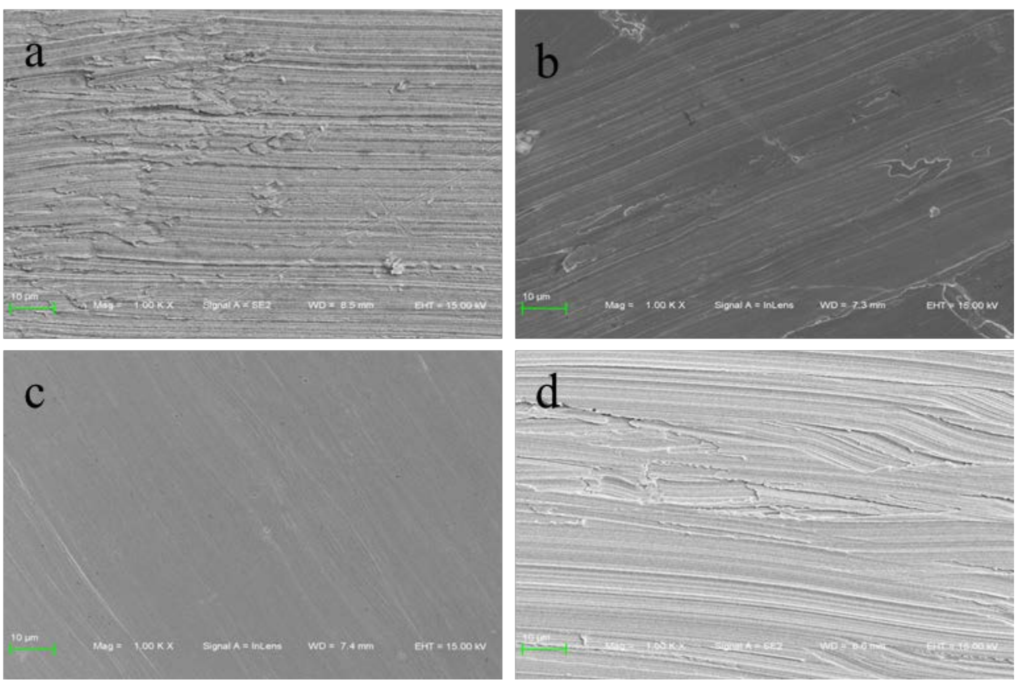

Figure 6. Morphology of wear scars at different temperatures (a) 300 K; (b) 225 K; (c) 155 K; (d) 77 K.

and weakened the adhesive force. The wear amount was reduced at room temperature. During the process of sliding, brittle contact occurred to the soft surface under cyclic load, which caused the bonding strength between the coating and the substrate to decline. The local weak areas on the surface resulted in extensive peeling and intensified friction, as shown in **Figure 6d**. There were grooves observed on the wear surface, and the wear was characterized by brittle fracture and delamination.

3.3. Superbolt Test after Washer Silver Coating

By following the aforementioned silver coating process, a layer of Ag lubricating coating was sprayed onto the washer of 718 alloy, as shown in **Figure 7**. The washer with or without silver coating were installed and tested.

During the experiment, the elongation ΔL of the bolts with different torques was measured using a dial indicator, with the linearity between ΔL and torque used to evaluate the efficiency of installation and anti-loosening effect of the super bolts as shown in **Figure 8**, the linear fitting curve without coating is $y = 0.00508x + 0.015$, with a linearity of $r^2 = 0.9632$. In contrast, the linearity of the silver-coated curve is $y = 0.00776x - 0.0085$, with a linearity of $r^2 = 0.9800$. A larger value of r^2 indicates the more consistent performance after coating.

Figure 7. Super-bolt nut.

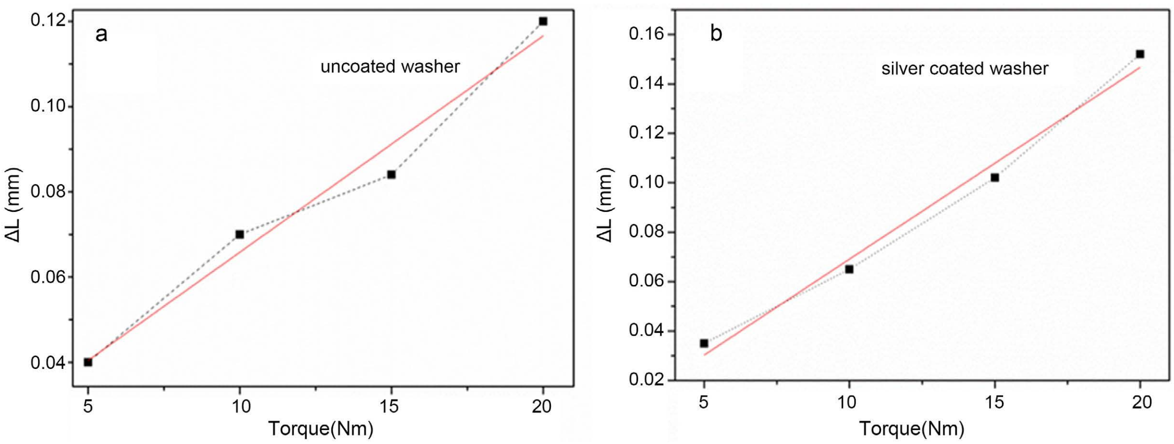

Figure 8. Linearity curve of torque and elongation.

4. Conclusions

1) The silver self-lubricating coating produced through magnetron sputtering has a good crystal structure and dense surface, with good adhesion to the substrate.

2) At ambient temperature and under vacuum, the load has an effect on the coating to some extent. With the increase of load, the friction coefficient first increases and then decreases. Temperature has a significant impact on the coating. At 155 K, the wear marks exhibit a smooth surface, the friction coefficient reaches its minimum, as does the wear amount.

3) Based on the results from friction studies and worn characterization of silver coating, the process is conducted to manufacture the washer of the super bolt, the anti-loosening of it coated with silver-coating has the better performance, which can be referenced for the super bolt manufacturing and application.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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