

## Article

# Effects of Temperature on Wear Properties and Mechanisms of HVOF Sprayed CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> **Coatings and H13 Steel**

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Abstract: In this study, the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings were prepared by the high-velocity oxygen-fuel (HVOF) spraying. A series of ball-on-disk sliding wear tests were conducted to evaluate the tribological properties of the coatings at different temperatures (25 °C, 200 °C, 400 °C, and 600 °C). The results showed that the average coefficients of friction (COFs) of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings were lower than that of H13 steel at different temperatures. The average COFs of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings and H13 steel both decreased with increasing temperature. The wear rate of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings increased first and then decreased. The microhardness of worn surface of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings increased with increasing temperature, while the microhardness of worn surface of H13 steel at 25 °C and 200°C was higher than that at 400 °C and 600 °C. The wear mechanism of the two materials was mainly abrasive wear. The tribofilms were formed on the worn surface of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings, which had a good protective effect. Due to thermal softening and low binding strength of debris, it was difficult for H13 steel to form the tribofilms. The wear rate of H13 steel was much higher than that of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings at 400 °C and 600 °C, indicating that the high temperature wear resistance of the coatings was much better than that of H13 steel.

Keywords: CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub>; high temperature wear; H13 steel; wear mechanism; high-velocity oxygen-fuel spraying

### 1. Introduction

Improving the life of the hot extrusion dies and wear-resistant mechanical parts has crucial significance in the industrial application [1-7]. Reducing friction and wear is an important way to prolong the life of the hot extrusion dies and wear-resistant parts [8–10]. High temperature environment often results in significant loss of mechanical properties of the dies and wear-resistant parts in industrial production [8,11,12]. Commonly, changing the material composition or heat treatment of the material can improve the high temperature wear resistance [13–18]. However, this can still not meet some industrial application requirements. Preparing high-performance coatings on the hot extrusion dies and wear-resistant mechanical parts can also improve the mechanical performance and wear resistance of worn surface. In the production process, the wear-resistant parts not only need higher high temperature mechanical properties to prevent the deformation, but also have lower wear rate to maintain the working precision. The coatings often contain elements with outstanding high-temperature mechanical properties. Li et al. [19] used an atmospheric plasma spraying system depositing the NiCrAlY-Mo-Ag composite coatings, and found that the NiCrAlY-Mo-Ag composite coatings possessed an excellent



lubricating property and wear resistance at 500 °C. At the same time, adding hard phases (TaC,  $Al_2O_3$ , and TiC) is an important way to improve the high temperature mechanical properties of the coatings [6,20–25]. Hou et al. [26] added  $Al_2O_3$  to the CoCrAlYTaCSi coatings to increase the microhardness of the coatings from 573 HV<sub>0.1</sub> to 654 HV<sub>0.1</sub>. Meanwhile, it significantly increased the modulus, contact stiffness, and high temperature wear resistance. Amiriyan et al. [6,27] studied the effect of TiC content on the wear resistance of the coatings and noted that the coatings with 50 and 70 mol% TiC exhibited excellent sliding wear resistance.

Wear is not a simple process of material removed. Although, increasing the microhardness of the coatings can effectively improve the wear resistance of the material, the brittleness of the coatings would also be improved [28]. Nitesh et al. [29] found that high temperature heat treatment increased the brittleness of the WC-12Co and  $Cr_3C_2$ -25NiCr coatings. The fracture and spalling of carbide aggravated abrasive wear. A large number of hard phase particles spalled from the metal-ceramic coatings would influence the precision of the dies processing and damage the tribopair. During the wear process, not only deformation and oxidation would occur, but also new microstructures would appear. The tribofilms produced during wear process can improve the wear resistance of the coatings. Wimmer et al. [30] found that the dense tribofilms appeared on the worn surface of the CoCrMo alloy in a specific load range which made the alloy have excellent wear resistance. Although the preparation technology and high temperature wear behavior of the high temperature wear resistance and the wear mechanism of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings at different temperatures.

In this paper, the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings are prepared by high-velocity oxygen-fuel (HVOF) spraying. In order to approach industrial application, the heat treated H13 steel is used as the matrix and the contrast sample. The microhardness of H13 steel is similar to that of the coatings. The effects of high temperature resistance and tribofilms on the wear resistance of the coatings are mainly studied. The microstructures of the coatings are observed by scanning electron microscope (SEM) equipped with energy dispersive spectrometer (EDS). Comparing the surface morphologies, microhardness, and phase composition after the wear tests, the wear mechanisms of two kinds of materials at different temperatures are analyzed and the wear properties of the two kinds of materials at high temperatures are investigated. The data obtained can be used as a reference for the selection of high temperature wear coatings on hot-working dies and wear-resistant mechanical parts.

#### 2. Materials and Methods

#### 2.1. Material and Preparation

In this paper, commercially agglomerated and sintered powder of CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> (FUJIMI, Japan, having nominal composition as 24.7 wt.% Cr, 7.3 wt.% Al, 0.7 wt.% Y, 8.9 wt.% Ta, 1.8 wt.% C, and balance Co) had a particle size distribution of 15–45  $\mu$ m. The CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings were fabricated on H13 steel by HVOF spraying under parameters (i.e., oxygen flow 944 L·min<sup>-1</sup>, kerosene flow 0.41 L·h<sup>-1</sup>, argon carrier gas flow 10.86 L·min<sup>-1</sup>, spray distance 370 mm, powder feed 5 rpm, and relative traverse speed 280 mm·s<sup>-1</sup>). Our previous studies [31] had shown that the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings was prepared by HVOF spraying technology. The coating with a thickness of approximately 300  $\mu$ m was composed of Al<sub>2</sub>O<sub>3</sub>, Al<sub>5</sub>Co<sub>2</sub>, Co, Cr, Cr<sub>3</sub>C<sub>2</sub>, Cr<sub>7</sub>C<sub>3</sub>, Cr<sub>2</sub>O<sub>3</sub>, and TaC. The contrast samples were made of H13 steel and hardened to 595 ± 30 HV<sub>0.1</sub> (after heat treated by quenching and tempering), which was similar to that of hot working dies and slightly lower than that of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings (640 ± 50 HV<sub>0.1</sub>).

In order to study the effect of temperatures on the wear properties and mechanisms of the coatings and H13 steel, the microstructure and phase composition were determined with X-ray diffraction (XRD, Bruker D8-Advanced, Bruker Inc., Karlsruhe, Germany) and SEM (Hitachi S-3400N, Hitachi Inc., Tokyo, Japan) equipped with energy dispersive spectrometer. In order to study the effect of wear on the microhardness of wear surface, the microhardness was measured by a Vickers microhardness tester (HXD-1000TC, Taiming Optical Instrument Inc., Shanghai, China) and from the bottom of the worn surface to the inside along the cross section, as shown in Figure 1. The load and holding times were 0.98 N and 15 s, respectively. In order to ensure the data repeatability, at least 10 measurements were done for each specimen.



Figure 1. Schematic of microhardness test of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings and H13 steel.

#### 2.2. Sliding Wear Test

The high temperature fiction-wear tests were performed on a HT-1000 type ball-on-disk tribometer (ZhongKeKaiHua Technology Development Inc., Lanzhou, China). The tests were conducted at 25 °C, 200 °C, 400 °C, and 600 °C with a 6 mm Si<sub>3</sub>N<sub>4</sub> ball. The wear parameters: Time of 60 min, frequency of 15.9 Hz, rotation diameter of 10 mm, and load of 10 N. As the tests went on, a computer was connected with the tribometer and the coefficient of friction (COF) of the coatings and H13 steel was measured. The contour curves of worn tracks were measured on a Contour GK-K (AUTOMATED, Bruker Inc., Karlsruhe, Germany) three-dimension optical interferometry profiler (Bruker Inc., Karlsruhe, Germany), after the wear tests.

#### 3. Results and Discussion

#### 3.1. Sliding Wear Properties

The COF curves against time are shown in Figure 2. The two-stage trend could be distinguished from the COF curves of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings at different temperatures. At room temperature, the COF curve of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coating was similar to that of H13 steel testing at different temperatures. A rapid increase to a peak value in the COF curves could be seen within the initial running-in stage and then remained stable, as shown in Figure 2a,b. At the higher temperature, the COF first increased to a peak value within a short duration, then decreased and stabilized for the remainder of test, as shown in Figure 2a. It suggested that the wear mechanism might change, when the temperatures was higher than 200 °C.



**Figure 2.** The coefficient of friction (COF) curves of the two kinds of materials during sliding wear testing at different temperatures: (**a**) CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coating; (**b**) H13 steel.

The COF curves of H13 steel at 400 °C was quite different from the COF curves at other temperatures, as shown in Figure 2b. The COF curves first increased to a peak value, then slowly decreased and finally stabilized. During the wear process, the flash temperature in the contact area of friction couple was much higher than testing temperature [32]. The temperature of worn surface increased with the wear testing. Meanwhile, the wear properties and COF of H13 steel changed with the increase of worn surface temperature. The peak value of 400 °C was similar to the value of the stable stage at 200 °C. In the final stage of wear testing, the COF curves of 400 °C and 600 °C was close. It might be indicated that the microstructure of the worn surface at the initial stage of 400 °C was similar to that at the stable stage of 200 °C and the microstructure of the worn surface at the final stage of 400 °C was similar to that at the stable stage of 600 °C.

The average COF curves and wear rate are shown in Figure 3. The average COF curves of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings were lower than that of H13 steel at different temperatures. The average COF curves of CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings and H13 steel decreased with increasing temperature. When the temperature was 600 °C, the wear rate of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coating was lower than that at 400 °C. At 400 °C, the wear rate of H13 steel was about four times to that of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coating. When the temperature increased to 600 °C, the wear rate of H13 steel was about five times to that of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coating. It indicated that the coatings had excellent wear resistance in the high temperature.



Figure 3. The average COF curves and wear rates of the two kinds of materials at different temperatures.

The profile curves of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings and H13 steel are shown in Figure 4. When the temperature was higher than 200 °C, the depth and width of wear surface of H13 steel were much larger than that of CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings. As shown in Figure 4a, the uneven curves showed that a large number of grooves existed on the worn surface. As shown in Figure 4b, with the increase of temperature, the volume loss of H13 steel increased. Especially, the volume loss of H13 steel increased dramatically when the temperature was higher than 200 °C.



Figure 4. The wear profiles of worn tracks: (a) CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coating; (b) H13 steel.

#### 3.2. Morphologies, Microstructures, and Microhardness of Worn Surface

The worn surface images of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings at different temperatures are shown in Figure 5. Some discontinuous strip-like tribofilms paralleling with the sliding direction were formed on the worn surface, as shown in Figure 5a. At higher magnification, some white particles (TaC) with a size of 1–2  $\mu$ m were uniformly distributed on the worn surface (Figure 5b), which made the coatings have excellent high temperature mechanical properties [23,26]. In addition, the number of TaC in the tribofilms was lower than that in the coatings, which indicated that the carbide was difficult to sinter into tribofilms. During the wear process, some debris was compacted and sintered on worn surface. But lower temperature and higher friction coefficient made debris difficult to sinter on the worn surface. The brittleness of the tribofilms made microcracks easy to form and propagate, then led to some spalled pits on the worn surface, as shown in Figure 5b.



**Figure 5.** The worn surfaces of CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coating at different temperatures: (**a**,**b**) 25 °C; (**c**,**d**) 200 °C; (**e**,**f**) 400 °C; and (**g**,**h**) 600 °C.

When the temperature increased from 25 °C to 200 °C, the morphologies of abrasive wear had changed obviously and a large number of grooves appeared on the wear surface, which indicated the abrasive wear was aggravating, as shown in Figure 5c. The continuous tribofilms were formed on the worn surface, which had a significant antifriction effect on the worn surface. The average COF of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings decreased from 0.83 to 0.65. As shown in Figure 5d, a large number of spalled pits appeared on the tribofilms, which was caused by the impact and cutting of abrasive particles and the rapid growth of microcracks in the tribofilms under the cyclic stress [33]. As temperature increased from 200 °C to 400 °C, due to the tribofilms were more compact with the increase of temperature, the number of spalled pits on the worn surface decreased rapidly, as shown in Figure 5e. Some TaC and spalled pits were observed on the worn surface, as shown in Figure 5f. It indicated that the spalled pits might be formed by carbide peeling off. Previous research showed that when the fine hard phase was distributed on the worn surface, plastic flow would slowly pull out the hard phase [34].

As shown in Figure 5g, the worn surface was smoother than that of 400 °C. The average COF of 600 °C was the lowest at different temperatures and the wear rate was smaller than that of 400 °C. It indicated that the smooth tribofilms had good protective effect on the coatings. As shown in Table 1, the results of the EDS analysis showed that all elements of tribofilms were similar at different temperatures, which suggested that the microstructure of worn surface was an important factor to high temperature wear resistance. The Y content was too low to be detected. Some finer debris were present in the worn surface, as shown in Figure 5h.

Region	Composition (at.%)					
	0	Со	Cr	Al	Ta	С
А	58.67	11.53	11.15	8.69	0.04	6.61
В	61.35	11.26	11.12	9.22	0.97	6.09
С	60.86	11.75	9.93	8.75	0.83	7.88
D	60.01	12.19	11.02	8.58	0.95	7.25

Table 1. Chemical composition of the worn regions of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings.

The morphologies of worn surface of the H13 steel at different temperatures are shown in Figure 6. At 25 °C, some pits appeared on the worn surface (Figure 6a), which might be resulted from fatigue wear [13]. At high magnification, a few chip wear debris and micro-ploughing formed on the worn surface, which were caused by the extrusion and cutting action of the micro-convex of Si<sub>3</sub>N<sub>4</sub>, as shown in Figure 6b. With the increase of the temperature, the increasing volume loss of H13 steel resulted in a rapid increase of the wear debris on the worn surface, a large number of wear debris appeared on the worn surface and some debris agglomerated into the lump particles, as shown in Figure 6c. Under high magnification, it could be found that the large particles were poorly bonded to the worn surface as shown in Figure 6d. At elevated temperature of 400 °C, severe micro-cutting and grooves were observed on worn surface (Figure 6e), which were caused by abrasive wear and thermal softening. In addition, the debris accumulated in the grooves (Figure 6f). At elevated temperature up to 600 °C, some discontinuous tribofilms formed on the worn surface, which reduced abrasive wear and friction coefficient, as shown in Figures 6g and 3. At high magnification, the worn surface at 600 °C was smoother than that at 400 °C. Micro-cutting and plastic deformation decreased. A number of discontinuous tribofilms appeared in the grooves and some interlaced microcracks were distributed on the tribofilms, as shown in and Figure 6h. Because of the low binding force between debris, it was difficult to form the dense and continuous tribofilms.



**Figure 6.** The worn surfaces of H13 steel at different temperatures: (**a**,**b**) 25 °C; (**c**,**d**) 200 °C; (**e**,**f**) 400 °C; and (**g**,**h**) 600 °C.

The XRD patterns of the worn surface of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings and H13 steel after wear testing were shown in Figure 7. The unworn CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coating consisted mainly of Al<sub>2</sub>O<sub>3</sub>, Al<sub>5</sub>Co<sub>2</sub>, Co, Cr, Cr<sub>3</sub>C<sub>2</sub>, Cr<sub>7</sub>C<sub>3</sub>, Cr<sub>2</sub>O<sub>3</sub>, and TaC at room temperature, as shown in Figure 7a. The phases of the all worn tracks were basically same. With the increase of temperature, the diffraction peak of Al<sub>5</sub>Co<sub>2</sub> gradually weakened and finally disappeared in the XRD patterns. It indicated that the  $Al_5Co_2$  of the coatings might be oxidized to form the  $Al_2O_3$  and CoO. The H13 steel mainly consisted of Fe and Fe<sub>2</sub>O<sub>3</sub>, as shown in Figure 7b. At 600 °C, the obvious diffraction peaks of Fe<sub>3</sub>O<sub>4</sub> and Fe<sub>2</sub>O<sub>3</sub> were found in the XRD pattern, which indicated that worn surface and debris were both oxidized during the wear process.



**Figure 7.** The unworn and worn surface at different temperatures: (**a**) CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coating; (**b**) H13 steel.

The microhardness profiles along the cross-section of the bottom of worn surface are shown in Figure 8. For the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings, the microhardness of worn surface increased with increasing temperature, as shown in Figure 8a. When the distance from the bottom of worn surface was higher than 50 µm, the microhardness was similar at different temperatures. It suggested that work hardening and the tribofilms formed on the worn surface [35,36]. The tribofilms were found in the Figure 5d,f,h. At the same time, some studies showed that when the temperature was from 200 °C to 800 °C, the microhardness of the Cr<sub>3</sub>C<sub>2</sub>-NiCr and WC-Co coatings increased with the increase of heat treatment temperature. The decarburization and dissolution of carbide phases in cobalt and NiCr matrix increased the microhardness of the coatings [29,37]. Carbide decarburization might also occur on the surface of worn surface, resulting in the increase of the microhardness of worn surface. As shown in Figure 8b, the results showed the microhardness of H13 steel possessed different rules. At 25 °C and 200 °C, the microhardness of worn surface was almost the same and the microhardness of worn surfaces was higher than that at 400 °C and 600 °C, which might result from work hardening. At 400 °C and 600 °C, the friction heat made the temperature of worn surface higher than testing temperature. The dynamic recovery and recrystallization of the worn surface generated during the wear testing, which prevented work hardening [38]. Meanwhile, it indicated the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings exhibited higher high-temperature mechanical property than that of H13 steel.



**Figure 8.** The microhardness profiles along the cross-section of the bottom of worn surface: (a) CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coating; (b) H13 steel.

Based on the previous analysis, the schematic diagrams of the evolution of wear characteristics of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings and H13 steel are shown in Figure 9.



Figure 9. Schematic of wear mechanism of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings and H13 steel.

At the low temperature (or in the initial running-in stage), the volume loss of the coatings and H13 steel was low, which resulted in some debris and grooves appearing on the worn surface, as shown in Figure 9a. With the increase of temperature, sliding wear increased the temperature of the worn surface. Thermal softening (the contact areas between the micro-convex) and adhesive wear led to the increase of wear debris. Subsequently, the abrasive wear gradually increased and the adhesive wear was inhibited. Some debris accumulated in the grooves. If the debris was compacted and sintered on the worn surface, the tribofilms would form on the grooves. If the binding force between the debris was poor, some spalled pits were obvious on the tribofilms, as shown in Figure 9b. With the increase of temperature and wear debris, the continuous tribofilms were formed on the worn surface like the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings, as shown in Figure 9c. During the wear process, the Al, Co elements in the coatings would form a compact and continues oxide layer under high temperature and block the diffusion of oxygen from the surface to the inside [39]. The wear debris without serious oxidation had good plasticity, so that the wear debris could be sintered together to form tribofilms. When the temperature increased to 200 °C, the tribofilms appeared on the worn surface, as shown in Figure 5d. In addition, the work hardening caused by the plastic deformation and the oxide produced in the wear process effectively improved the microhardness of the worn surface. The tribofilms reduced the cutting effect of abrasive wear on the worn surface. With the increase of temperature, the tribofilms became more and more compact and smooth, which made the average COF of the coatings decreased (Figure 3). At 600 °C, the worn surface had the highest microhardness and the lowest COF, which resulted in the wear rate of the coating at 600 °C was lower than that at 400 °C, as shown in Figure 3.

At 25 °C and 200 °C, the woke hardening improved the wear resistance of H13 steel. When the temperature increased to 400 °C, the microhardness of worn surface decreased and the wear debris did not form the tribofilms. It was difficult to resist the cutting effect of abrasive wear on the worn surface, which caused a sharp increase of wear rate (Figure 3). Even at 600 °C, only some discontinuous tribofilms with a number of microcracks appeared on the worn surface (Figures 9d and 5h). It was mainly formed by debris accumulation rather than sintering. With the increase of temperature, the amount of wear debris increased, which restrained the adhesive wear and reduced the wear. Therefore, the average COF decreased with the increase of temperature, as shown in Figure 3. The wear mechanism of the two materials was mainly abrasive wear. However, due to the influence of tribofilms

and high temperature resistance, the high temperature wear resistance of the coatings was much better than that of H13 steel.

#### 4. Conclusions

The CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings were prepared by HVOF spraying. The influence of temperatures (25 °C, 200 °C, 400 °C, and 600 °C) on the sliding wear behaviors of the coatings and H13 steel against  $Si_3N_4$  ball were investigated. The results could be summarized as follows:

(1) The wear mechanism of the two kinds of materials was mainly abrasive wear. Tribofilms were formed on the surface of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings. The tribofilms had a good protective effect. Due to thermal softening and low binding strength of debris, it was difficult for H13 steel to form tribofilms. The wear rate of H13 steel was much higher than that of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings at 400 °C and 600 °C. The results show that the high temperature wear resistance of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings was infinitely superior to that of H13 steel.

(2) The average COF values of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings were lower than that of H13 steel at different temperatures. The average COF values of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings and H13 steel decreased with increasing temperature. On the contrary, the wear rate of H13 steel increased with increasing temperature. With increasing of the temperature, the wear rate of the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coating first increased and then decreased as the temperature was higher than 400 °C.

(3) At 25 °C and 200 °C, the work hardening occurred on the worn surface of H13 steel. With the increase of temperature, the dynamic recovery, and recrystallization of the worn surface generated with the wear testing, which prevented work hardening. For the CoCrAlYTa-10%Al<sub>2</sub>O<sub>3</sub> coatings, the microhardness of worn surface increased with increasing temperature.

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