Dry Sliding Wear Behavior of 38CrNi3MoV Steel at Elevated Temperatures

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Friction and wear behavior of 38CrNi3MoV steel were investigated from 25–600°C using a pin-on-disc elevated temperature tester. Thereafter, the hot hardness of the pin and disc, tribo-oxides phase composition, worn surface and interface morphology were examined to understand the wear mechanisms. The results show that the 38CrNi3MoV steel presented different wear rates at various temperatures. The ambient temperature is the main factor affecting the formation of tribo-oxides. While, the final morphology of tribo-oxides remaining on the worn surface depended on the difference between the disc's hot hardness and the pin's hot hardness ($H_{disc} - H_{pin}$). Adhesive and abrasive wear, mild oxidative wear, severe oxidative wear, and mild oxidative wear prevailed at 25, 200, 400, and 600°C, respectively.

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1. Introduction

Wear at elevated temperature has become an important problem in the fields of energy, transport, materials processing, engines, and armaments.^{1–3)} In order to improve wear resistance at elevated temperature and prolong the service life of the materials, many studies have been carried out and conclude that the loss of mechanical strength and enhanced oxidation of materials surface are the two most important factors that affect the wear process.^{4–6)}

The oxidation of materials during the wear process has been systematically studied by many researchers. Fink⁷⁾ first identified the effect of oxidation on wear in 1930. Archard and Hirst⁸⁾ reported the relationship between tribo-oxides and wear and classified wear into the mild wear and severe wear categories. Wilson and Quinn^{9–11)} separately established the theory of oxidative wear of steel based on different experimental conditions in the 1980s. Their model suggested that tribo-oxides can hinder metal–metal contact to reduce wear and oxidation wear depends only on the tribo-oxides.

Researchers found that the matrix also played an important role in the wear test, especially under severe conditions, such as higher temperatures or heavier loads.^{12–16)} Wang^{17–19)} studied the transition of mild to severe wear in the oxidative and transition regions and analyzed the mechanisms surrounding how the matrix and tribo-oxides jointly affect the wear process. The influence of the variation of matrix property on wear behavior was considered and it was determined that tribo-oxides reduced wear if the matrix retained the necessary strength to support tribo-oxide layer.¹⁶⁾

The effect of the hardness of the material on the wear behavior was also studied, and it was found that the hardness ratio of the disc to the pin (H_{disc}/H_{pin}) was the key factor affecting the material wear characteristics.²⁰⁾ However, studies on the role of material matrix properties have been limited to the mechanical properties of materials at room

temperature. There is still little research on the relationship between material properties and wear behavior at elevated temperatures, which must be further investigated.

In this work, we examined the influence of the change of the properties of the sliding material and the counterface materials (the pin and disc) under elevated temperatures on the wear properties of gun-barrel used steel 38CrNi3MoV. The friction and wear behavior of 38CrNi3MoV steel under various ambient temperatures was investigated using the pin-on-disc type wear tester. The hot hardness of the disc and pin at various ambient temperatures and the worn surface and interface of the sample were presented. The influence of the hot hardness of the disc and pin under various ambient temperatures on the tribo-oxides and the wear behavior of the pin was also analyzed.

2. Experimental Procedure

38CrNi3MoV and AISI M2 steels were used as the pin and disc specimens, respectively. The chemical compositions of these two materials are shown in Table 1. The 38CrNi3MoV steel was supplied as a hot-forge bar with a diameter of 70 mm. Samples from this bar were heated to 870°C and cooled in air, austenitized at 870°C for 1 h followed water quenching and then tempered at 610°C for 2 hours to attain tempered sorbite (39–41 HRC). M2 steel was taken from a hot rolled bar of 80 mm in diameter. Samples of M2 steel were austenitized at 1180°C for 1 h, then water quenched and tempered three times at 540°C for 2 hours to attain tempered martensite with carbides (62–64 HRC).

The measurements of hot hardness were carried out up to 600°C using an AKASHI AVK-A type hot hardness tester with a Vickers indenter at a load of 500 g and a dwell time of 5 s. The specimens were heated to the test temperature and hold for 10 min in argon atmosphere. Each hardness value presented is the average of 5 measurements.

Wear tests were carried out on a pin-on-disc MG-2000 wear test apparatus equipped with a heater to obtain ambient temperatures up to 800°C. 38CrNi3MoV steel was selected

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Table 1 Chemical composition of material for experiment (mass%).

Materials	C	Si	Mn	Cr	Ni	Mo	V	W	Fe
38CrNi3MoV	0.34–0.41	0.17–0.37	0.25–0.50	1.20–1.50	3.00–3.50	0.35–0.45	0.10–0.25	/	Bal.
AISI M2	0.80–0.90	0.20–0.45	0.15–0.40	3.80–4.40	/	4.4–5.5	1.75–2.20	5.50–6.75	Bal.

as the pin with dimensions of 6 mm in diameter and 12 mm in length and M2 steel was chosen as the discs with dimensions of 70 mm in diameter and 10 mm in thickness. The contact surfaces of the pins and discs were ground to reach a roughness (R_a) of about $0.2\ \mu\text{m}$ and cleaned with acetone before each test. Experiments were carried out at 25, 200, 400, and 600°C with a load of 200 N. The rotation speed was set as 400 r/min (sliding velocity of 1.26 m/s), and the total number of tests for each group was 4000 cycles (sliding distance of 753.6 m). The wear mass loss of the pin specimen was determined using a FA1004N type electronic balance with an accuracy of 0.1 mg. The wear rate was calculated through the volume loss divided by sliding distance, where the volume loss was defined as the mass loss of unit density of $7.83\ \text{g}/\text{cm}^3$. At least three tests were performed for each experimental point.

Morphology and composition of the worn surface, subsurface were examined by an FEI Quanta 250 scanning electron microscope (SEM). The morphology of the wear tracks was characterized using a KEYENCE VHX-2000 digital microscope with a depth-of-field imaging system. Phases on the worn surface were identified by a Smart Lab type X-ray diffractometer (XRD) with $\text{Cu K}\alpha$ radiation, the wavelength of $1.5406\ \text{\AA}$, the working voltage of 40 kV, the working current of 150 mA, the diffraction angle of $20\text{--}80^\circ$, and the scanning speed of $20^\circ/\text{min}$.

3. Results

3.1 Wear performance

The friction coefficients as a function of time for 38CrNi3MoV steel pin sliding at various ambient temperatures are shown in Fig. 1. The friction coefficients at various ambient temperatures presented the same trend of variation—they increased rapidly from zero to a certain value at around 30 s in the initial stage and then oscillated to a certain range (between 0.3–0.4) during the rest wear process.

The key factor that affects the friction coefficient is the contact between the sliding material and the counterface, which includes the deformation of asperities, the migration of wear particles, the plowing of hard asperities, and the formation of tribo-oxides.^{21,22)} In the initial stage of the process, which we termed the run-in or break-in period,²³⁾ the friction coefficient increased continuously due to the increased adhesion between the contact surfaces. After the run-in period, a dynamic equilibrium for the formation and migration of the tribo-oxides on the worn surface was reached, causing the wear process to enter a steady-state sliding period.

Fig. 1 The variation of friction coefficients in the wear process at various ambient temperatures.

Fig. 2 Wear rates of 38CrNi3MoV steel at various temperatures.

Figure 2 illustrates the wear rates of 38CrNi3MoV steel at various temperatures. 38CrNi3MoV presented a marked variation of the wear rate with increased temperature. The wear rate of 38CrNi3MoV steel first decreased at 200°C , then increased at 400°C , and decreased again at 600°C .

The wear rate results of both 38CrNi3MoV pins tested at 25 to 400°C are consistent with the results of H13 and H21 steel in Ref. 24), 25) for H13 and H21 steel. The variation in the wear rate of steels is related to the loss of mechanical strength and enhanced oxidation.^{4,26)} The wear rate of 38CrNi3MoV decreased at 200°C due to the formation of tribo-oxides on the worn surface, hindering the metal–metal

Fig. 3 The hot hardness of M2 steel disc and 38CrNi3MoV steel pin at various temperatures: (a) hot hardness; (b) the difference between the hot hardness of the disc and pin.

contact. When the ambient temperature rose to 400°C, the matrix softened and did not retain the necessary strength to support the tribo-oxide layer, leading to an increase in the wear rate. According to the former research,^{24,25} it may be speculated that the wear rate would increase further when the test ambient temperature rose to 600°C as the matrix would soften further for the increase in temperature. However, the wear rate of 38CrNi3MoV decreased instead at 600°C in this study. This phenomenon needed to be further analyzed by considering both the matrix properties and the tribo-oxides.

3.2 Hot hardness of the disc and pin

The wear of the pin is related to the hardness of not only the pin but also the disc.²⁷ Figure 3 shows both the hot hardness of the disc (M2 steel) and pin (38CrNi3MoV steel) and the difference between the hot hardness of the disc and pin ($H_{disc} - H_{pin}$) at various temperatures. The hot hardness of M2 steel was higher than 38CrNi3MoV steel at each temperature and the hot hardness of both the disc and pin decreased with the increase of the ambient temperature.

Studies have shown that (H_{disc}/H_{pin}) was the key factor that affected the material wear characteristics.^{20,28} However, the (H_{disc}/H_{pin}) value was always above 1 at any temperature for the presented M2-38CrNi3MoV steel tribo-system. Therefore, it was no longer suitable to explain the wear behavior of 38CrNi3MoV steel using the (H_{disc}/H_{pin}) value. We noted that the hot hardness of the disc dropped sharply and the ($H_{disc} - H_{pin}$) value for M2-38CrNi3MoV dropped below 300 HV at 600°C, which was in accordance with the decrease of the wear rate at this temperature.

3.3 Analysis of worn surfaces and cross section

Figure 4 shows the XRD patterns of the worn surface of 38CrNi3MoV steel at various temperatures. The diffraction peaks for the specimens after wear test at 25 and 200°C mainly belonged to α -Fe and cubic wüstite (FeO), which indicates that a certain amount of FeO appeared on the worn surface. Wüstite (FeO) has a hardness of ~ 317 HV and has good lubricity,²⁹ which decreases the wear and the friction coefficient. When the temperature reached 400°C, the intensity of the diffraction peak of cubic magnetite (Fe_3O_4) was higher than FeO, which indicated that a large amount of Fe_3O_4 oxide formed on the worn surface. Magnetite has an

Fig. 4 The XRD patterns of worn surfaces of 38CrNi3MoV steel after wear test at various temperatures.

intermediate hardness of ~ 450 HV and can also acts as a lubricant.³⁰ As the ambient temperature reached 600°C, the peaks corresponding to Fe disappeared, leaving only the diffraction peak of magnetite (Fe_3O_4) and hematite ($\alpha\text{-Fe}_2\text{O}_3$). It can be inferred that a large amount of tribo-oxides with a large thickness were formed at this temperature, which caused the X-ray diffraction analysis to be unable to detect the Fe matrix.

The macromorphologies of the worn surfaces of 38CrNi3MoV steel are shown in Fig. 5. It may be noticed that the worn surfaces at various ambient temperatures represented different oxidative colors in addition to the same furrows along the sliding direction. At 25°C, the worn surface was light gray overall with a small number of black marks along the sliding direction. The worn surface was yellow, blue and black at 200, 400 and 600°C, respectively. The color of the worn surface reflected the degree of tribo-oxidation, which was consistent with the XRD results shown in Fig. 4.

Figure 6 shows the morphologies of the worn surface of 38CrNi3MoV steel at various temperatures observed by a full-focus imaging digital microscope. At 25°C, a small amount of black oxide could be observed on the worn surface. At 200°C, the tribo-oxides essentially covered the

Fig. 5 Macromorphologies of worn surfaces of 38CrNi3MoV steel at various temperatures: (a) 25°C, (b) 200°C, (c) 400°C, (d) 600°C.

Fig. 6 Morphologies of worn surfaces of 38CrNi3MoV steel at various temperatures: (a) 25°C, (b) 200°C, (c) 400°C, (d) 600°C.

worn surface and some furrows were present. At 400°C, more furrows and signs of ripping appeared. When the temperature was 600°C, the worn surface was covered with thick tribo-oxides.

Figure 7 illustrates the micro-morphologies of the worn surfaces of 38CrNi3MoV steel at various temperatures. Rows of furrows and signs of smearing, yielding and ripping were found on the worn surface when the ambient temperature was 25°C. A little black area also appeared, indicating that a small amount of oxide had formed. At an ambient temperature of 200°C, the oxide layer covered the worn surface and little oxides spalled off from the worn surface. As the temperature reached 400°C, a smooth, glazed oxide layer predominated the worn surface with a large number of wear particles and some rows of furrows. When the ambient temperature reached 600°C, a thick oxide layer had formed on the worn surface, cracked and spalled.

The existence of the tribo-oxide layer could be identified more clearly by observing the worn sub-surface morphology. The cross-section morphologies of the worn surfaces of 38CrNi3MoV steel at various temperatures are shown in Fig. 8. At 25°C, a thin oxide layer with a thickness of about

1–3 µm appeared in some areas of the worn surface of the 38CrNi3MoV steel and the oxide layer was observed to have spalled off. When the ambient temperature was 200°C, the worn surface was covered by a dense oxide layer with a thickness of 1–3 µm, which could effectively hinder the metal–metal contact between the disc and pin. When the ambient temperature was 400°C, the oxide layer began to delaminate. A very thick oxide layer with a thickness of 20–30 µm formed on the worn surface at 600°C, completely covering the worn surface.

4. Discussion

Combined with the results of Fig. 5–8, the variation of the tribo-oxide layer on the worn surface and the wear behavior of 38CrNi3MoV pin can be analyzed accurately. For the experimental tribo-system, as shown in Fig. 1, the friction coefficient increases significantly in the initial running-in period due to the adhesion between the two contact surfaces. Then Wear debris presented on the sliding surface and tribo-oxides the formed, the friction coefficient stabilize within a range of 0.3–0.4 and did not change

Fig. 7 Micromorphologies of worn surfaces of 38CrNi3MoV steel at various temperatures: (a) 25°C, (b) 200°C, (c) 400°C, (d) 600°C.

Fig. 8 Cross-section morphologies of worn surfaces of 38CrNi3MoV steel at various temperatures: (a) 25°C, (b) 200°C, (c) 400°C, (d) 600°C.

significantly with the test temperature. This can be explained on the basis of tribo-oxides. Due to the friction between the contact surfaces, oxidation of iron comes much easier. These

tribo-oxides hindered the direct contact between metals. It is true that the tribo-oxides formed may be different in thickness and integrity, the “generation-migration-generation” process occurred at different ambient temperatures. The tribo-components entered a stable process, the formation and migration of tribo-oxides and wear debris entered a state of dynamic balance.

Adhesive and abrasive wear prevailed in the M2-38CrNi3MoV steel tribo-system at ambient temperatures of 25°C. The pin and the disc were in metal-metal contact with only a small amount of oxide on the worn surface (Fig. 5, 6, 7(a)). These oxides spalled off in some areas and could not completely hinder the metal-metal contact. When the ambient temperature reached 200°C, mild oxidation wear prevailed, and the oxide layer already covered the entire worn surface. Although the surface of the oxide layer showed partial adhesion (Fig. 6(b)) and furrows (Fig. 7(b)), the tribo-oxides hindered the metal-metal contact between the pin and disc and reduced the wear rate of the pin (Fig. 2). When the temperature was not higher than 400°C, the $(H_{disc} - H_{pin})$ was always around 400 HV and the hardness of the disc remained much higher than the pin. Therefore, the variation in the performance of the disc could be ignored in this temperature range. Whether the tribo-oxides could remain on

the worn surface depended on the hot hardness of the pin. At a temperature of 25 and 200°C, the matrix could support the oxide layer because the hardness of the pin had changed very little.

Severe oxidation wear prevailed at a temperature of 400°C. Though the ($H_{disc} - H_{pin}$) value was stable at about 400 HV, the hardness of 38CrNi3MoV matrix decreased at a temperature of 400°C which retained a weak strength to support the tribo-oxide layer and leading to the spalling of the oxide layer. The subsurface matrix softened and underwent increasing shearing as the temperature increased, resulting in the delamination of the oxide layer.¹⁹⁾ The “generation-migration-generation” process in the oxide layer continued to occur and led to an increase in the wear rate.

When the ambient temperature reached 600°C, even though the hardness of the pin was greatly reduced, the wear rate of 38CrNi3MoV steel decreased and the phenomenon of extrusive wear involved in Refs. 19), 30), 31) did not occur. The main reason for this was that the worn surface of 38CrNi3MoV steel was covered with a large amount of oxides (Fig. 8(d)). Compared with 400°C, the hardness of the pin experienced little change at 600°C. The main change in the tribo-system was the drastic decrease in the disc's hardness. The hot hardness of the disc dropped below 600 HV and the ($H_{disc} - H_{pin}$) dropped below 300 HV at this time, which caused the disc to be unable to effectively plow the oxide on the worn surface of 38CrNi3MoV. The thickness of the retained oxide layer not only prevented the metal-metal contact between the pin and disc but also coordinated the plastic deformation of the matrix.³²⁾ As such, mild oxidation wear prevailed again at this temperature.

The wear rate data of 30SiMn2MoV steel under the same experimental conditions reported in our previous work³³⁾ were also provided in Fig. 9 for discussion. Like 38CrNi3MoV steel, the wear rate changed very little when the ambient temperature rose from 25°C to 200°C, and increased at the temperature of 400°C. Figure 10 shows both the hot hardness of the disc (M2 steel) and pin (38CrNi3MoV and 30SiMn2MoV steel) and the difference between the hot hardness of the disc and pin ($H_{disc} - H_{pin}$) at various temperatures. The variation of ($H_{disc} - H_{pin}$) value at various temperatures for M2-38CrNi3MoV pairs was different from M2-30SiMn2MoV pairs as shown in Fig. 10(b). The ($H_{disc} -$

Fig. 9 Wear rates at various temperatures for 38CrNi3MoV steel in this work and 30SiMn2MoV steel presented in Ref. 33).

H_{pin}) value of M2-30SiMn2MoV pairs increased at 400°C and stable at about 470 HV when the temperature reaches 600°C. For M2-30SiMn2MoV pairs, the ($H_{disc} - H_{pin}$) value of increased at 400°C and stable at about 470 HV when the temperature reaches 600°C. The hot hardness of the disc dropped to about 100 HV, which indicated that the pin specimen is seriously softened and processes a low resistance to plastic deformation. The matrix softened did not retain the necessary strength to support the tribo-oxide layer. Plastic extrusion happened, the oxide film ruptured and peeled off with the matrix, leaving a small amount oxide film which cannot effectively prevented the metal-metal contact. As a result, the wear rate of 30SiMn2MoV pin keep increasing when the test temperature increased to 600°C.

The ambient temperature is a main factor determining the tribo-oxides as the hot hardness of the disc and pin changed with the test temperature. There is a correlation between the formation of tribo-oxides and the hardness of the pin/disc. The tribo-oxides exhibited different colors (as shown in Fig. 5) and phase compositions (as shown in Fig. 4) at various temperatures. However, the amount and final morphology of the oxide remaining on the worn surface depended on the ($H_{disc} - H_{pin}$) and the hot hardness of the pin and disc. For the presented M2-38CrNi3MoV steel tribo-

Fig. 10 The hot hardness of disc (M2 steel) and pin (38CrNi3MoV steel, 30SiMn2MoV³³⁾) at various temperatures: (a) hot hardness; (b) the difference between the hot hardness of the disc and pin.

system, when the $(H_{disc} - H_{pin})$ was high (approximately 400 HV at 25, 200 and 400°C), the disc could effectively plow the oxide layer produced on the worn surface of the pin and the oxide layer mainly depended on the pin's hardness. When the ambient temperature rose to 600°C, the oxide layer became mainly depended on the hardness of the disc. The hardness difference between the disc and pin ($H_{disc} - H_{pin}$) decreased to lower than 300 HV. The drastic decrease of the disc's hardness indicated that the disc became not effective in plowing the oxide layer formed on the worn surface of the pin. The retained oxide layer not only prevented the metal-metal contact between the pin and disc but also coordinated the plastic deformation of the matrix.

5. Conclusion

- (1) 38CrNi3MoV steel presented different wear rates at various temperatures due to the change in the amount and final morphology of the tribo-oxides on the worn surface.
- (2) The main factor determining the formation of tribo-oxides on the worn surface of 38CrNi3MoV steel was the ambient temperature. The amount and final morphology of the oxide remaining on the worn surface depended on the $(H_{disc} - H_{pin})$ and the hot hardness of the pin and disc.
- (3) For 38CrNi3MoV steel, adhesive and abrasive wear prevailed at 25°C while mild oxidative wear prevailed at 200°C. Severe oxidative wear was the dominant wear mechanism at 400°C and mild oxidative wear prevailed again at 600°C.

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