

Wear Behavior and Mechanism of a Cr-Mo-V Cast Hot-Working Die Steel

M.X. WEI, S.Q. WANG, Y.T. ZHAO, K.M. CHEN, and X.H. CUI

The wear behavior and mechanisms of a Cr-Mo-V cast hot-working die steel with three microstructures (tempered martensite, troostite, and sorbite) were studied systematically through the dry-sliding wear tests within a normal load range of 50 to 300 N and an ambient temperature range of 298 K to 673 K (25 °C to 400 °C) by a pin-on-disk high-temperature wear machine. Five different mechanisms were observed in the experiments, namely adhesive, abrasive, mild oxidative, oxidative, and extrusive wear; one or more of those mechanisms would be dominant within particular ranges of load and temperature. The transition of wear mechanisms depended on the formation of tribo-oxides, which was related closely to load and temperature, and their delamination, which was mainly influenced by the matrix. By increasing the load and ambient temperature, the protective effect of tribo-oxides first strengthened, then decreased, and in some cases disappeared. Under a load ranging 50 to 300 N at 298 K (25 °C) and a load of 50 N at 473 K (200 °C), adhesive wear was the dominant wear mechanism, and abrasive wear appeared simultaneously. The wear was of mild oxidative type under a load ranging 100 to 300 N at 473 K (200 °C) and a load ranging 50 to 150 N at 673 K (400 °C) for tempered martensite and tempered troostite as well as under a load of 100 N at 473 K (200 °C) and a load ranging 50 to 100 N at 673 K (400 °C) for tempered sorbite. At the load of 200 N or greater, or the temperatures above 673 K (400 °C), oxidative wear (beyond mild oxidative wear) prevailed. When the highest load of 300 N at 673 K (400 °C) was applied, extrusive wear started to dominate for the tempered sorbite.

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I. INTRODUCTION

HOT-WORKING dies, as tools used for the hot shaping of metal, play an important role in many industries, such as automobile, autocycle, agricultural machinery, *etc.* AISI H11, H13, H20, H21, and H22 are commonly used hot-working die steels.^[1,2] Cast hot-working steels have been studied and used increasingly as an alternative for traditional hot-working dies since the 1940s, because of their advantages such as high use ratio of materials, low finish allowance, short process time, and the recyclability of obsolete dies.^[3-6]

Hot-working dies are subjected to high mechanical and thermal loadings, with the wear being the most important cause of failure.^[7-10] Therefore, increased wear resistance is an important reason for the development of a new Cr-Mo-V cast hot-working die steel.^[11-13]

Wang *et al.* and Cui *et al.* studied the effects of alloying elements,^[14,15] rare-earth modification,^[16] and second carbides^[17,18] on the elevated-temperature wear of this cast steel. Wei *et al.*^[19] studied the wear behavior of the cast steel at 673 K (400 °C) and discovered that the cast steel had a substantially higher wear resistance than H13 and H21 steels. No systematic investigation of the wear

of the newly developed Cr-Mo-V cast steel has been reported,^[13-19] and the wear behavior and wear mechanism are addressed in the current study.

II. EXPERIMENTAL DETAILS

The cast hot-working die steel (0.35C-3Cr-2Mo-1V) was melted in a 50 kg medium frequency induction furnace with a nonoxidation method. At 1823 K (1550 °C), the melt was deoxidized by aluminum and then poured. The modified agents containing the rare metal elements (RE) were put in a ladle for the modification of the melt. Finally, the standard wedge-shaped specimen was cast. The cast steel was austenitized at 1293 K (1020 °C) for 30 minutes, quenched in oil to attain martensite with a hardness of 53 HRC, and subsequently tempered at 473 K, 823 K, and 973 K (200 °C, 550 °C, and 700 °C) for 2 hours to produce tempered martensite (Tm), tempered troostite (Tt), and tempered sorbite (Ts), respectively, with the respective hardnesses of 51, 50, and 30 HRC.

The pin specimens were of 6 mm diameter and 12 mm length; the disks were of 70 mm diameter and 8 mm thickness. The cast steel was used for the pin specimens, whereas the disk specimens were made of a commercial D2 steel with a heat-treated hardness of 60 HRC. Prior to each test, the contact surfaces of the pin and disk specimens were prepared by grinding against a 400-grit silicon carbide paper to attain an R_a value of about 0.45 μm then cleansed with alcohol.

M.X. WEI, Ph.D. Student, S.Q. WANG, Professor, Y.T. ZHAO, Professor, K.M. CHEN, Associate Professor, and X.H. CUI, Associate Professor, are with the School of Materials Science & Engineering, Jiangsu University, Zhenjiang 212013, P.R. China. Contact e-mails: shuqi_wang@ujs.edu.cn; zhaoyt@ujs.edu.cn

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Dry-sliding wear tests were conducted using a pin-on-disk high temperature wear machine (MG-200 Type) (Hebei Xuanhua Testing Machine Factory, Zhangjiakou, China). The disk specimen was fixed on a rotating lower shaft; the pin specimen was installed in a holder attached on a static upper spindle by set screw and then pressed against the disk under a vertical load by a dead weight. The moment of friction force between the pin specimen and the disk during wear was measured by a sensor; these signals were input into a personal computer. The wear apparatus was equipped with a 2-kW resistance heater to obtain an ambient temperature up to 773 K (500 °C). The detailed description of the apparatus was given in Reference 19. The test parameters were selected as follows: the ambient temperature of 298 K, 473 K, and 673 K (25 °C, 200 °C, and 400 °C), the normal load of 50 to 300 N in steps of 50 N, the sliding velocity of 1 m seconds⁻¹ and the sliding distance of 1.2×10^3 m. The mass of each specimen was measured using an electronic balance with an accuracy of ± 0.01 mg before and after each wear test. The mass difference was divided by the sliding distance to calculate the wear rate. The mass-based wear rate was then converted to volumetric wear rate using the density of the steel (7.8 g cm^{-3}).

A HR-150A type Rockwell apparatus (Shanghai Materials Testing Machine Factory, Shanghai, China) was used to measure the hardness of the specimens. A D/Max-2500PC type X-ray diffractometer (Rigaku Corporation, Tokyo, Japan) and a JSM-7001F type scanning electron microscope (SEM) (JEOL, Tokyo, Japan) equipped with an Inca Energy 350 type energy dispersion spectrometer (EDS) (Oxford Instruments, Oxford, UK) were used to characterize the structure, morphology, and composition of the worn surface; the longitudinal cross section of the worn surface; and the wear debris.

III. RESULTS AND DISCUSSION

A. Wear Behavior

Figure 1 shows the variation of wear rate with load for the cast steel with three tempered microstructures at 298 K, 473 K, and 673 K (25 °C, 200 °C, and 400 °C), respectively. The results for 298 K (25 °C) are in Figure 1(a). The wear rates increased rapidly under a load ranging 50 to 100 N. With a subsequent increase of the load from 150 to 300 N, the wear rate of low-hardness tempered sorbite still increased rapidly. However, tempered martensite and tempered troostite with high hardnesses had a relatively slower increasing tendency and lower wear rates than tempered sorbite. In addition, the wear rates of tempered martensite and tempered troostite approached each other; under the loads of 50 to 150 N, tempered martensite possessed slightly higher wear rates than tempered troostite but vice versa under the loads of 200 to 300 N.

The results for 473 K (200 °C) are in Figure 1(b). The wear rates decreased abruptly about 50 pct and reached

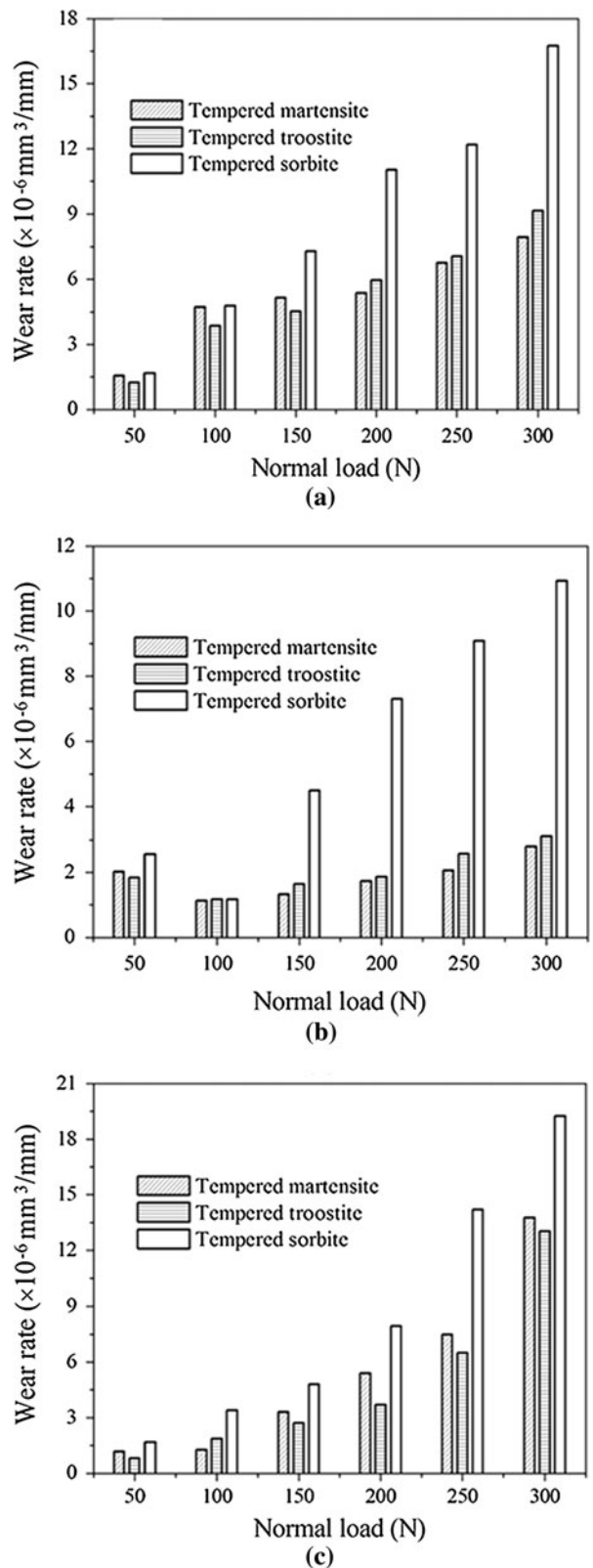


Fig. 1—Variation of wear rate with load for the cast steel with three tempered microstructures at 298 K (25 °C) (a), 473 K (200 °C) (b), and 673 K (400 °C) (c).

almost same value for three tempered microstructures within the load range of 50 to 100 N. With increasing the load from 100 to 300 N, the wear rates of tempered martensite and tempered troostite increased slightly, but the wear rate of tempered sorbite increased markedly and was significantly higher than those of the formers. More important, tempered martensite and tempered troostite presented almost the same wear resistance all the time.

The results for 673 K (400 °C) are in Figure 1(c). The wear rate increased slightly with an increase in the load from 50 to 100 N. The wear rate of three microstructures increased rapidly at the loads of 150 N and higher. Tempered troostite had a slightly lower wear rate than tempered martensite, and tempered sorbite had significantly higher wear rate than other two microstructures.

Interestingly, wear dropped when temperature increased from 298 K to 473 K (25 °C to 200 °C), and increased strongly when temperature was raised to 673 K (400 °C). These might be attributed to the fact that oxide is present at 473 K (200 °C) and attenuates adhesion, but delaminates aggravate at higher temperatures. The detailed reasons will be given in Sections III-B-2 and III-B-3.

B. Wear Mechanisms

To clarify the wear behavior and mechanism of the studied microstructures; the morphology, structure, and composition of worn surfaces; and wear debris were investigated thoroughly. Under various sliding conditions, five different wear mechanisms were identified to appear with increasing the load and ambient temperature; they were adhesive, abrasive, mild oxidative, oxidative wear, and extrusive wear. The detailed wear mechanisms will be discussed in the subsequent sections. The wear mechanisms under various sliding conditions for the different microstructures are summarized in Table I.

1. Adhesive wear and abrasive wear

Under a load ranging from 50 to 300 N at 298 K (25 °C) and a lower load of 50 N at 473 K (200 °C), there were signs of smearing, yielding, and ripping on the worn surfaces, as shown in Figure 2(a), which were the typical characteristics of adhesive wear. Moreover, rows of furrows were also found on the worn surfaces. A thin, metal flake-like wear debris is present in Figure 2(b). It is clear that the deformed wear debris was generated by the shear of adhesive junctions between asperities because of high local contact pressure during sliding.^[20]

The adhesive wear complied with Archard's law defined by the following relation^[21]:

$$W_v = k \frac{LS}{H} \quad [1]$$

where W_v is the volumetric wear loss, k is the coefficient of adhesive wear, L is the normal load, S is the sliding distance, and H is the metal hardness. The wear loss of a material is positively proportional to normal load and sliding distance but inversely proportional to hardness. In Figure 1(a), various microstructures presented approximately linearly increased wear rates; the wear rates of tempered martensite (51 HRC) and tempered troostite (50 HRC) were far lower than those of tempered sorbite (30 HRC). It is suggested that our results at 298 K (25 °C) are in agreement with Archard's law. However, at higher temperatures (473 K and 673 K [200 °C and 400 °C]), the relation between wear rate and load did not present linear increases, as shown in Figures 1(b) and (c). It is clear that Archard's law is valid mainly for adhesive and abrasive wear.

Except for those adhesive traces, a small amount of grooves and scratch marks appeared on the worn surfaces (Figure 2(c)), which were mostly parallel to the sliding direction. Such a feature was the characteristic of abrasive wear, in which hard asperities on the counterface and/or hard oxide particles in between the

Table I. Wear Mechanisms for Each Combination of Sliding Condition and Material Microstructure

Ambient Temperature, K (°C)	Load (N)	Microstructure	Wear Mechanism*				
			Adhesive Wear	Abrasive Wear	Mild Oxidative Wear	Oxidative Wear	Extrusive Wear
298 (25)	50-100	Tm, Tt, Ts	☆☆☆	☆			
	150-300	Tm, Tt	☆☆	☆	☆		
		Ts	☆☆	☆		☆	
473 (200)	50	Tm, Tt, Ts	☆☆☆	☆			
	100	Tm, Tt, Ts			☆☆☆		
	150-300	Tm, Tt			☆☆☆		
Ts				☆	☆☆☆		
673 (400)	50-100	Tm, Tt, Ts			☆☆☆		
		Tm, Tt			☆☆☆		
	150	Ts			☆☆	☆☆☆	
		Tm, Tt			☆☆	☆☆	
	200-250	Ts			☆☆	☆☆☆	☆
		Tm, Tt			☆☆	☆☆	☆☆
300	Tm, Tt			☆	☆☆	☆☆☆	
		Ts				☆☆☆	

*Relative extent of each wear mechanism: ☆—slight; ☆☆—moderate; and ☆☆☆—heavy.

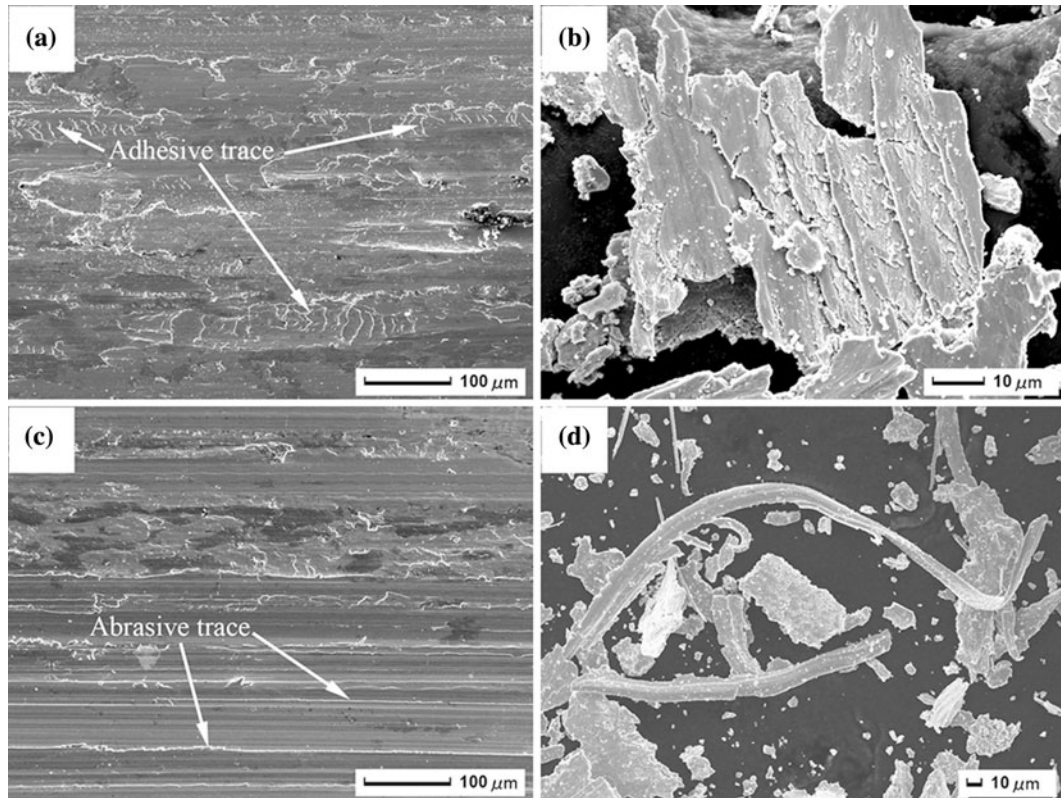


Fig. 2—SEM photographs of the worn surfaces and wear debris for the cast steel under a load of 100 N at 298 K (25 °C), showing the typical morphologies of (a) and (b) adhesive wear from Tt, (c) and (d) abrasive wear from Ts.

contacting surfaces ploughed the pin surface to result in wear by the removal of ribbon-like wear debris,^[22] as shown in Figure 2(d).

Under a higher load ranging 150 to 300 N at 298 K (25 °C), a small amount of discontinuous dark patches was found on the worn surfaces (Figures 3(a) and (b)). The EDS results illustrated that iron element was identified with almost no oxygen element in point 1 area (Figure 3(c)). However, a strong oxygen peak was recognized in point 2 area (Figure 3(d)). It is clear that these dark patches were tribo-oxides.

To observe the oxides and matrix after sliding, the longitudinal cross section of the worn surfaces was examined. Under a load ranging 50 to 100 N at 298 K (25 °C) and a lower load of 50 N at 473 K (200 °C), a plastically deformed region and an unaffected matrix without tribo-oxide layer appeared underneath the worn surfaces (Figure 3(e)). However, as a load of 150 N or greater was applied, a thin (approximately 3 μm) and discontinuous oxide patches formed on the worn surfaces (Figure 3(f)).

The presence of oxides can be verified by X-ray diffraction analysis in Figure 4. There was almost no oxide under a lower load of 50 N at 298 K and 473 K (25 °C and 200 °C) (Figures 4(a) and (d)). As the load reached 150 N or greater at 298 K (25 °C), trace FeO and a small amount of Fe₃O₄ started to appear on the worn surfaces, as shown in Figures 4(b) and (c).

When a pin slid on a disk at room temperature, the real contact area was only a small percentage of the

whole pin surface at the adhesive junctions between asperities. The normal pressure at the adhesive junction was sufficiently high to cause a plastic deformation of the underlying material and a high flash temperature, which was beneficial to the reaction of oxidation. Therefore, oxides formed preferentially at the contacting asperities, *i.e.*, the plastically deformed regions centered around the adhesive junctions between asperities.^[23]

We found that a small amount of FeO and Fe₃O₄ could reduce the wear to some extent for the tempered martensite and tempered troostite, resulting in a relatively slow increasing tendency of the wear rate (Figure 1(a)). However, for the tempered sorbite, the wear rate continued to increase rapidly; it is seemed that tribo-oxides offered no protection. This might be attributed to the fact that large plastic deformation in subsurface matrix undermined the protective effect of oxides. It is found that a harder matrix held an oxide layer more firmly compared with a softer one, which complied with the reported researches.^[23,24] The longitudinal cross-section observation of the worn surfaces identified that the extent of plastic deformation in subsurface matrix of the low-hardness-tempered sorbite was more severe than those of high-hardness-tempered martensite and tempered troostite. For example, within a load ranging from 150 to 300 N, the thickness of the plastically deformed region reached approximately 70 to 140 μm in the former but only 15 to 20 μm in the latter. As a result, tempered sorbite did not offer enough support for the oxides because of severe plastic

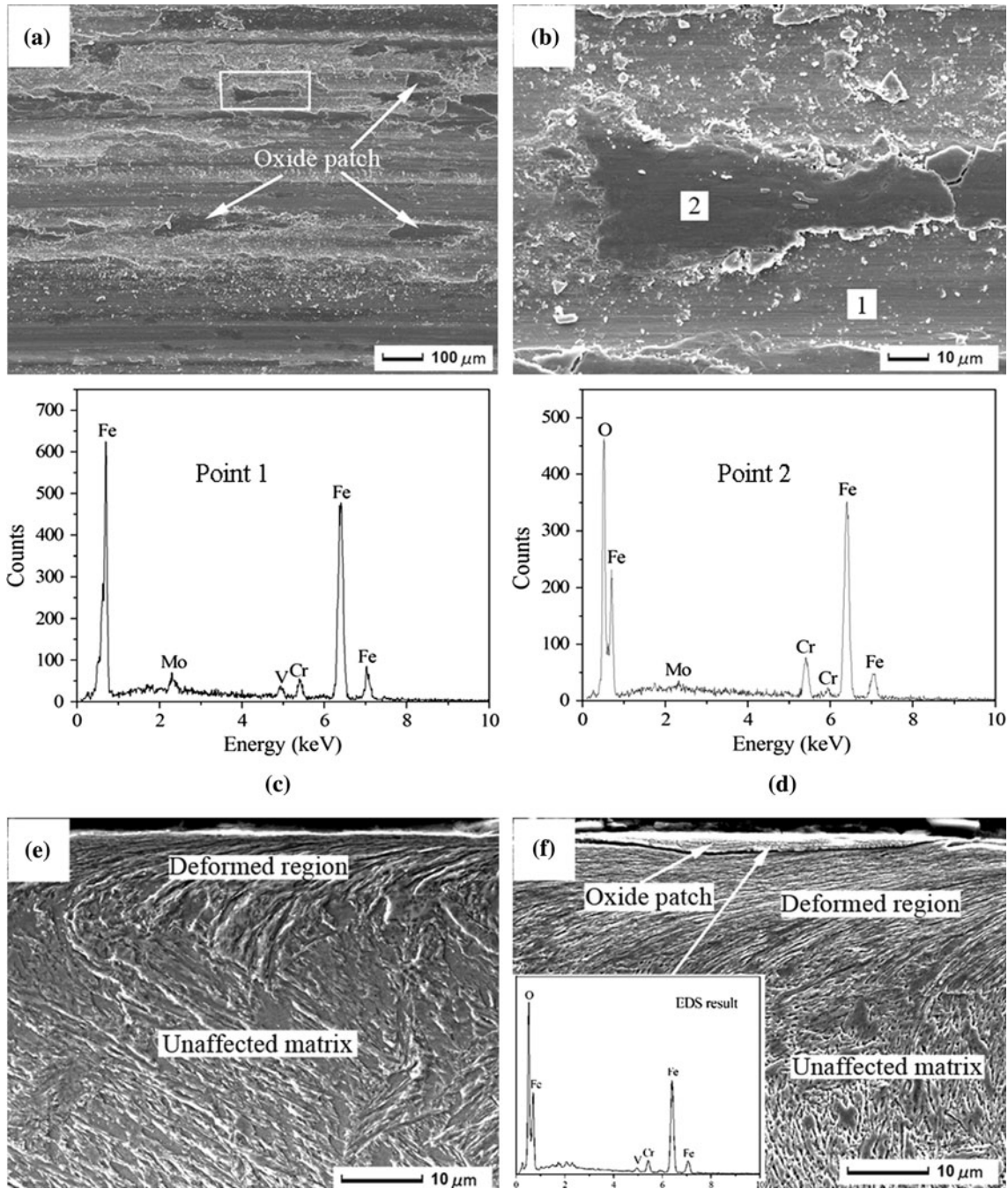


Fig. 3—Typical SEM photographs of the worn surfaces for the cast steel (from Tt): (a) and (b) under a load of 250 N at 298 K (25 °C) with the EDS analysis of point 1 (c) and 2 (d), as well as the longitudinal cross-section morphology (e) without oxide patch under a load of 50 N and (f) with oxide patch under a load of 250 N.

deformation; thus, its wear rate continued to increase rapidly.

Several mechanisms, such as adhesive, abrasive, and oxidative wear, would operate together in such a load range of 150 to 300 N at 298 K (25 °C), as suggested in Table I. Undoubtedly, the dominant mechanism was adhesive wear.

2. Mild oxidative wear

As the load reached 100 N at 473 K (200 °C) or the ambient temperature reached 673 K (400 °C), the worn

surface was dark without metallic shine. An examination of the longitudinal cross sections revealed that the single-layer oxides covered the worn surfaces (Figure 5(a) and (b)). Subjected to the sliding action, oxide layers might crack from the fatigue mechanism; cracks were perpendicular or normal to the sliding direction. The oxide layers were likely to spall off because of their brittleness, producing a plate-like wear debris (Figure 5(c)) and small, shallow delaminated craters on the worn surfaces (Figure 6(a) and (b)). The delamination would occur inside the oxide layer or at

the interface between the oxide layer and matrix. This was the typical mild oxidative wear proposed by Quinn and coworkers^[25–28] and Wilson *et al.*,^[29] in which the oxides were considered to play a decisive role in

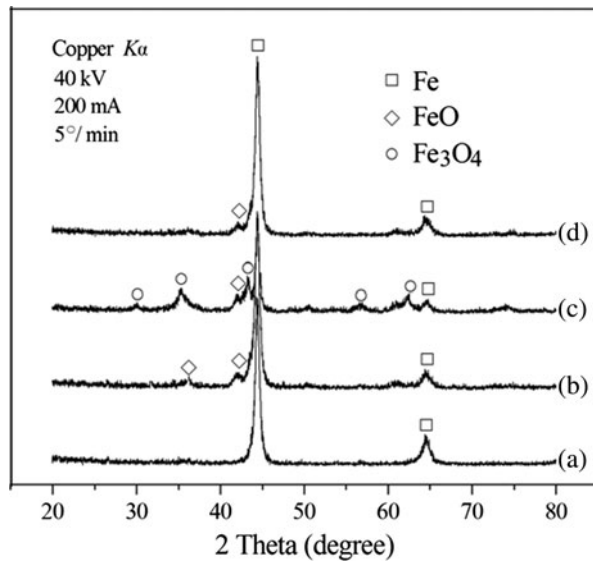


Fig. 4—X-ray diffraction patterns of the worn surfaces for the cast steel sliding under a load of (a) 50 N, (b) 150 N, (c) 300 N at 298 K (25 °C), and (d) 50 N at 473 K (200 °C) for Tt (almost the same as Tm and Ts).

determining wear rate, irrespectively of the matrix microstructures. This is why the wear rates dropped as the load increased from 50 to 100 N at 473 K (200 °C), and three tempered microstructures presented almost the same wear rate, as shown in Figure 1(b).

The X-ray diffraction patterns of the worn surfaces at 473 K and 673 K (200 °C and 400 °C) are shown in Figure 7. At 473 K (200 °C), the worn surface presented relatively less oxides; Fe₃O₄ was the dominant oxide with a small amount of FeO and a trace of Fe₂O₃ (Figure 7(a)). As the ambient temperature reached 673 K (400 °C), the amount of oxides on the worn surface increased markedly (Figure 7(b)). It is clear that there were much more tribo-oxides at 673 K (400 °C) than at 473 K (200 °C).

It can be observed that the mild oxidative wear prevailed for the different microstructures within certain sliding conditions: the load of 100 N at 473 K (200 °C) and the load range of 50 to 100 N at 673 K (400 °C) for tempered sorbite, and the load range of 100 to 300 N at 473 K (200 °C) and 50 to 150 N at 673 K (400 °C) for tempered martensite and tempered troostite, respectively. At 473 K (200 °C), a threshold load of 100 N was required for the formation of an oxide layer with a thickness of 10 μm on the worn surface. Although oxides formed only at the contacting asperites, they could totally prevent the adhesion between the metallic surfaces. At 673 K (400 °C), a great amount of oxides covered the whole worn surface and readily maintained a layer of oxides to prevent from metal–metal contact.

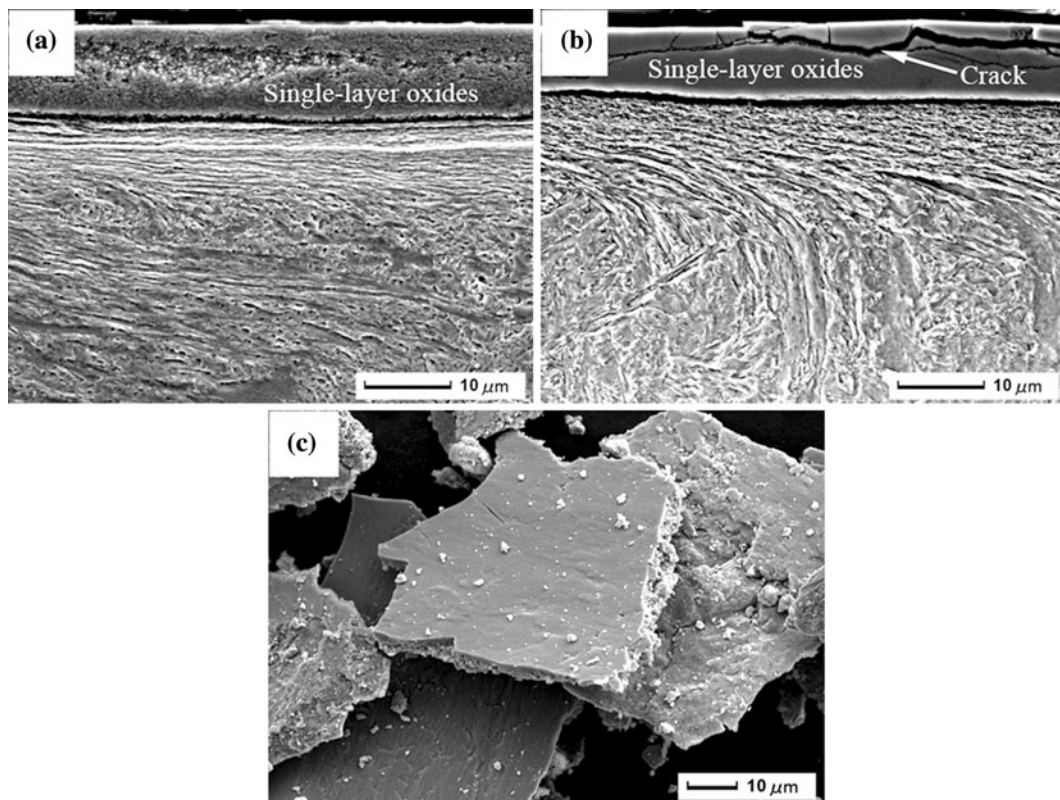


Fig. 5—SEM photographs of the longitudinal cross-sections showing the single-layer oxides: sliding at 298 K (200 °C) (a) and 673 K (400 °C) (b) under a load of 100 N and plate-like wear debris (c) for Tt (the same as Tm and Ts).

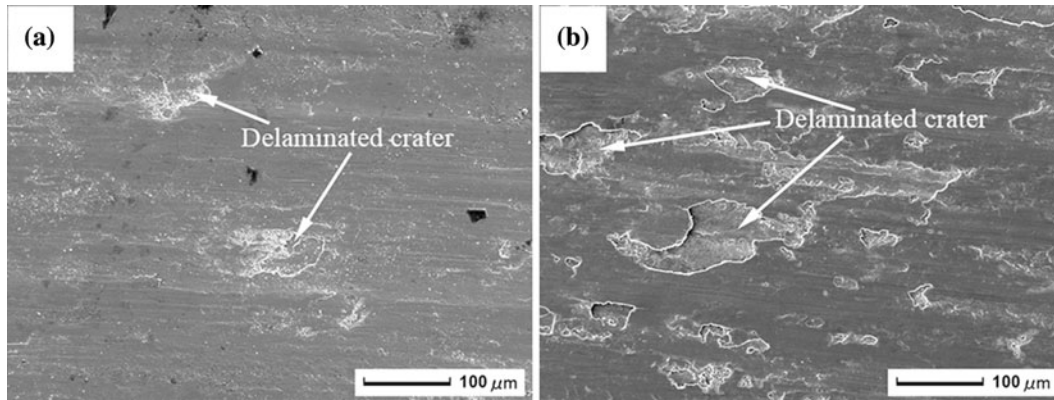


Fig. 6—SEM photographs of the worn surfaces showing some small and shallow delaminated craters, sliding at 473 K (200 °C) (a) and 673 K (400 °C) (b) under a load of 100 N for Tt (the same as Tm and Ts).

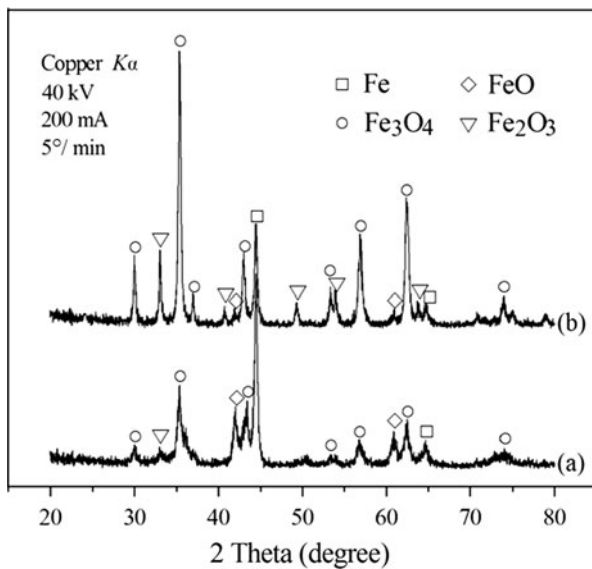


Fig. 7—X-ray diffraction patterns of worn surfaces under a load of 100 N at 473 K (200 °C) (a) and 673 K (400 °C) (b) for Tt (almost the same as Tm and Ts).

In the previously mentioned cases, the wear fell in mild oxidative wear. However, there was also a critical load above which the increasing load and frictional heating would cause a severe plastic deformation in the subsurface material; thus, a stable protective oxide layer could no longer be maintained. In such a condition, this wear was still oxidation-related wear, but the wear mechanism would be beyond the mild oxidative wear.^[23,30,31] It is understandable that the onset of the oxidative wear in tempered martensite and tempered troostite requires a higher load than in tempered sorbite.

3. Oxidative wear

As a higher load of approximately 200 N or greater was applied at 673 K (400 °C); the worn surfaces became rougher and the amount, area, and deepness of the delaminated craters increased substantially (Figure 8(a)) compared with those in the mild oxidative wear (Figures 6(a) and (b)). More important,

another type of oxide layer appeared, which was characterized by the appearance of oxides inside the matrix under an upper layer oxide, which could be called double-layer oxides (Figure 8(b)) or multiple-layer oxides (Figure 8(c)).

During the elevated-temperature wear, the plastic deformation occurred in the subsurface matrix because of the friction force and normal stress. With increasing the extent of plastic deformation, cracks would initiate and propagate at these positions, such as the pile-up dislocation, impurity, cavity, and second phase. Oxygen could come into these cracks easily and react with the steel matrix to form oxides inside the subsurface matrix under the upper layer oxides, which would accelerate the growth of cracks even more. As cracks propagated to a critical size, the matrix and its previously mentioned oxides totally spalled off to cause a higher wear rate. Therefore, the wear debris was included the oxide layers and some matrix, as shown in Figure 8(d). It can be deduced readily that both the oxides and deformed matrix would affect wear behavior. In such a condition, oxidation still operated during wear because oxide layer appeared and affected wear. But oxide layer was not a decisive factor, which is not the same as the mild oxidative wear proposed by Quinn and colleagues^[25–28] and Wilson *et al.*^[29] We referred to this type of wear as oxidative wear, namely the transition region of mild oxidative wear to severe wear, which was defined in the literature.^[30]

Some researchers addressed this kind of oxidative wear but did not distinguish between the mild oxidative and oxidative wear.^[23,31,32] Marui *et al.*^[31] pointed out that under a severe condition (a higher load), the wear behavior was affected strongly by the hardness reduction and microstructural variation of hypereutectoid steel; the oxide layer was not the main factor in determining the wear behavior. It is well known that the oxide layer is the main factor in determining the wear behavior in mild oxidative wear.^[25–29] Clearly, a transition region of mild oxidative wear to severe wear appeared in this case; actually, it was oxidative wear.^[30] So *et al.*^[23] studied the oxidative wear of steels systematically. They discovered that the wear fell under mild oxidative wear (it was called oxidation wear in the

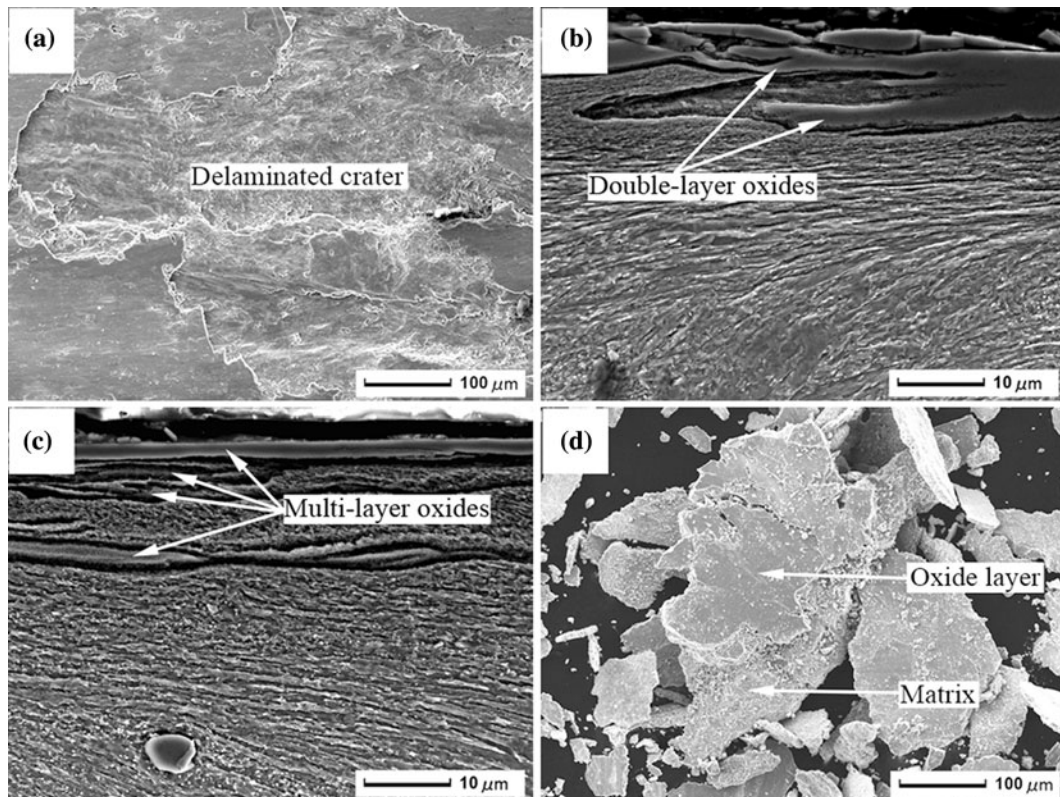


Fig. 8—Morphology (a) and longitudinal cross-sections images (b) (c) of worn surfaces and wear debris (d) under a load of 250 N at 673 K (400 °C) for Tt (the same as Tm).

original paper) only under conditions of 1.1 to 4.4 MPa and 2 to 4 m s⁻¹, beyond which extrusive wear prevailed totally or partly. However, they did not point out the difference between mild oxidative wear and oxidative wear, and the existence of oxidative wear. In practice, an oxidation partly affected region exists between mild oxidative wear and extrusive wear. Wang and Lei^[32] studied the wear behavior of steel 1080 with different microstructures during dry sliding, and considerable differences in wear volumes were observed under the condition of severe wear. This was the important feature of oxidative wear, *i.e.*, both oxides and matrix affected the wear rate.

4. Extrusive wear

Under the highest load of 300 N at 673 K (400 °C), the worn surface was comparatively smooth with some fine oxide particles for tempered sorbite (Figure 9(a)). A massive, plastically deformed region and thin oxide layers were found on the worn surface (Figure 9(b)). It can be observed that the worn surfaces were extruded sideways (Figure 9(c) and (d)). The extruded metal piled up on the periphery of the pin specimen to form a large mushroom shape. This was the typical extrusive wear, like the one reported by So *et al.*^[33]

When the pin specimen slid under the highest load of 300 N at 673 K (400 °C), a large temperature increase on the contact surface would occur because of the high ambient temperature and friction heat. Consequently,

the subsurface material was softened and its yield stress reduced substantially. In this case, a massively plastic deformation occurred; the plastically deformed region reached the depth of at least 140 μm for the tempered sorbite. A great amount of materials on worn surface would be extruded out because of such a plastically deformed region, thus resulting in a loss of the pin and the highest wear rate.

C. Summary of Wear Behavior and Wear Mechanism

The dominant wear mechanism dictates the characteristics of the worn surface and the subsurface matrix. The various wear mechanisms under different ambient temperatures and loads are illustrated in the schematic diagram shown in Figure 10.

At 298 K (25 °C), adhesive mechanism dominated with almost no oxide forming on the worn surfaces under a load below 100 N (Figures 10(a) and (b)). With increasing the load, a small amount of FeO and Fe₃O₄ subsequently started to appear under a load of 150 N or greater; thin and discontinuous oxide patches formed on the contacting asperities (Figures 10(c) and (d)). These oxide patches could reduce the wear to some extent for tempered martensite and tempered troostite because of their sufficient strength. However, the oxide patches presented no protection for tempered sorbite because the low-hardness microstructure did not offer enough support for the patches.

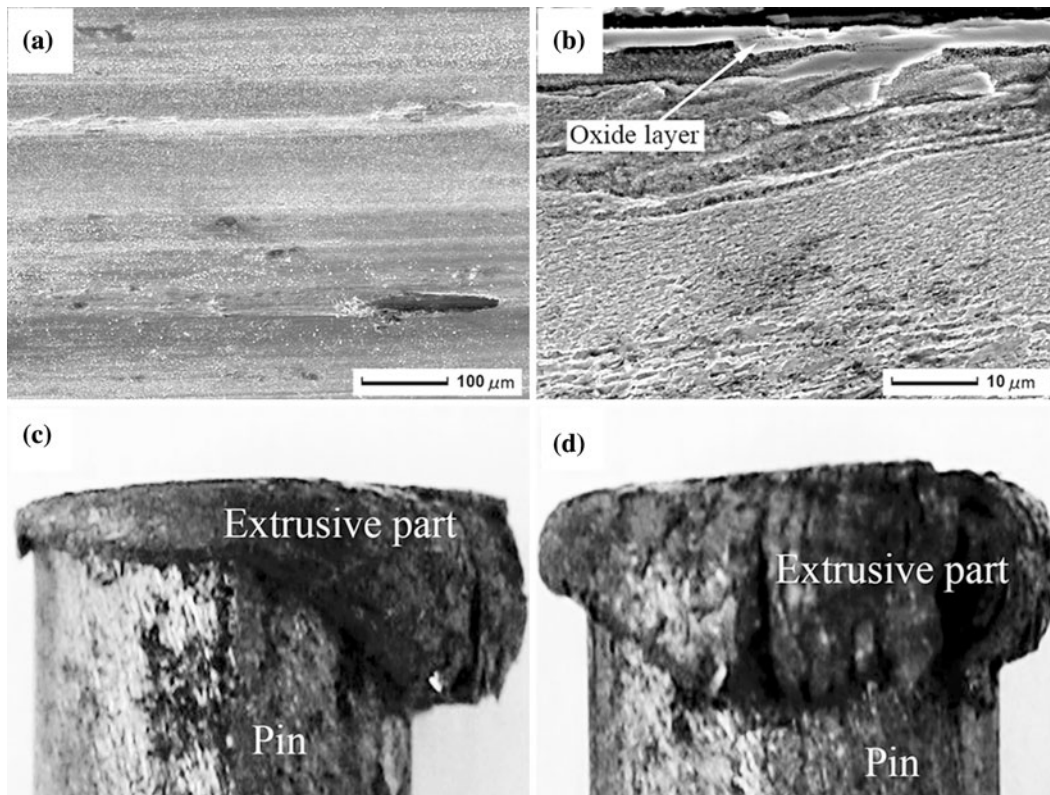


Fig. 9—SEM photographs of the worn surface (a) and longitudinal cross section (b), as well as macromorphology of perpendicular to sliding direction (c) and (d) facing to sliding direction of extrusive wear under a load of 300 N at 673 K (400 °C) for Ts.

When the load increased to 100 N at 473 K (200 °C), an oxide layer approximately 10 μm thick formed merely on the contacting asperities (Figures 10(e) and (f)). Although the amount of oxides was small, the metal-metal adhesion could be avoided; the wear strictly fell within mild oxidative wear. As the load increased, the wear rates of various microstructures presented obviously different trends. For tempered martensite and tempered troostite, the subsurface matrix possessed enough strength to support the oxide layer on the worn surface; the mild oxidative wear prevailed all the time. However, for low-hardness-tempered sorbite, a higher load caused an obvious plastic deformation of the subsurface matrix, thus accelerating the delamination of oxides and resulting in a substantially elevated wear rate. This finding was in good agreement with the results obtained by Pellizzari *et al.*^[34]

At 673 K (400 °C), the amount of oxides increased markedly to cover the worn surfaces wholly. Under a smaller load, the subsurface matrix had enough strength to inhibit the severe plastic deformation; a dense and continuous single-layer oxide formed on the worn surface with a spot of small delaminated craters (Figures 10(g) and (h)). Mild oxidative wear prevailed, thus resulting in a lower wear rate.

As the load increased, the subsurface matrix softened and underwent an increasing shearing action. When the matrix would not provide a solid support for the oxide layer, a severe plastic deformation

occurred to accelerate the delamination of oxide layer; thus, more and larger delaminated craters presented on the worn surface (Figure 10(i)). Meanwhile, the severe plastic deformation would cause the appearance of cracks in the subsurface matrix; oxygen could be in contact directly with the matrix underneath the worn surface. Hence, oxidation would occur not only on the worn surface by the diffusion but also inside the matrix by the direct ingress of oxygen through the cracks; thus, double-layer, even multiple-layer oxides would form on the worn surface (Figure 10(j)). The delamination would occur at the interface of the matrix and the underlying-layer oxide. The delaminated materials should include these oxide layers and some matrix, resulting in a higher wear rate. In this case, both the oxides and deformed matrix would affect wear behavior; the wear was beyond mild oxidative wear proposed by Quinn and colleagues^[25–28] and Wilson *et al.*^[29]

As the highest load of 300 N at 673 K (400 °C) was applied for the low-hardness-tempered sorbite, extrusive wear prevailed. In this case, the subsurface material would be softened substantially because of the high temperature on the contacting surface offered by the high ambient temperature and friction heat. The worn surface presented a comparatively smooth with some fine oxide particles (Figure 10(k)); a massive, plastically deformed region and thin oxide layer were found on the worn surface (Figure 10(l)). A great amount of wear loss

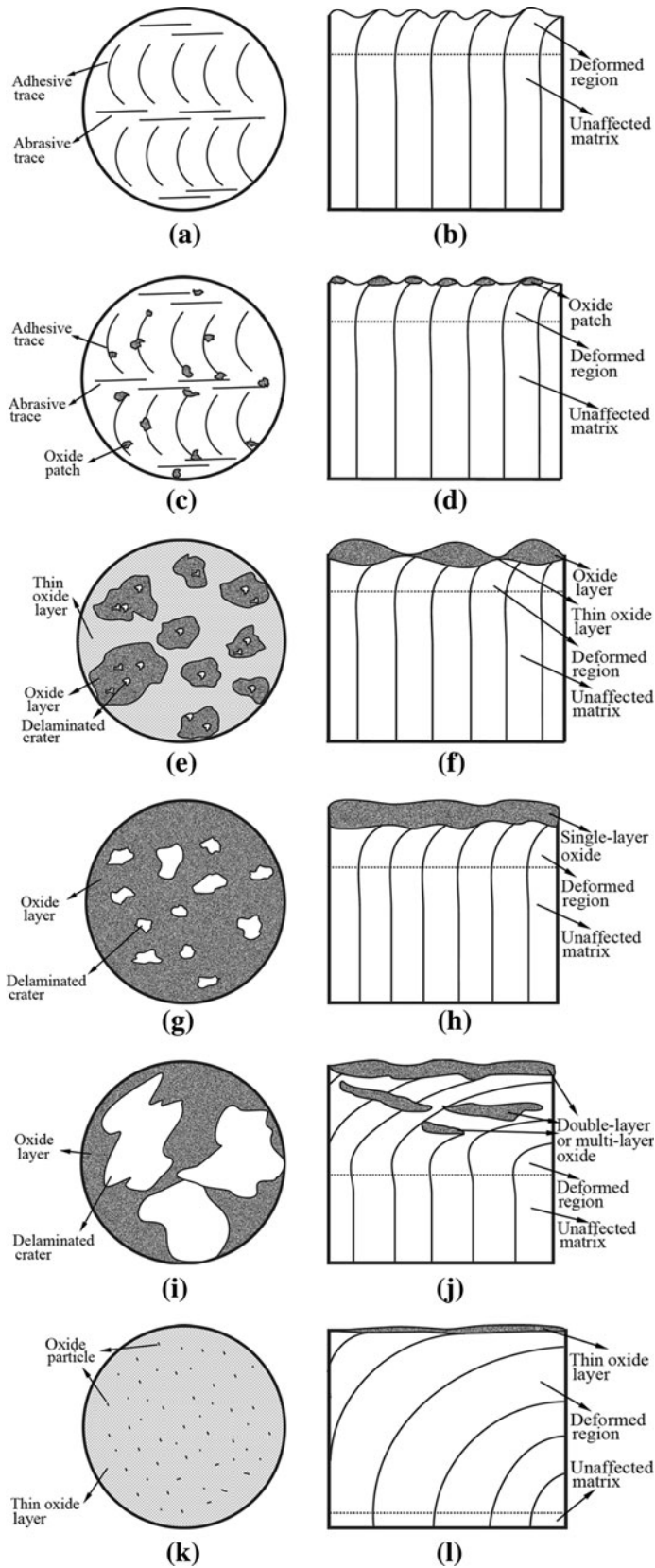


Fig. 10—Schematic diagram of wear characteristics—worn surface appearance in the left column and the cross-section morphology in the right-hand column: (a) and (b) a load range of 50 to 100 N at 298 K (25 °C) and a load of 50 N at 473 K (200 °C) for Tm, Tt, and Ts; (c) and (d) 150 to 300 N at 298 K (25 °C) for Tm, Tt, and Ts; (e) and (f) 100 to 300 N at 473 K (200 °C) for Tm and Tt, 100 N at 473 K (200 °C) for Ts; (g) and (h) 50 to 150 N at 673 K (400 °C) for Tm and Tt, 50 to 100 N at 673 K (400 °C) for Ts; (i) and (j) 250 to 300 N at 673 K (400 °C) for Tm and Tt, 200 to 250 N at 673 K (400 °C) for Ts; (k) and (l) 300 N at 673 K (400 °C) for Ts.

was resulted from the extrusion of the pin material, and the wear rate was very high.

IV. CONCLUSIONS

Five different mechanisms were observed in the experiments, namely adhesive, abrasive, mild oxidative, oxidative, and extrusive wear; one or more of these mechanisms would be dominant within particular ranges of load and temperature. The transition of wear mechanisms depended on the formation of tribo-oxides, which was related closely to load and temperature, and their delamination, which was mainly influenced by the matrix.

Adhesive wear prevailed with simultaneous abrasive wear for various microstructures under a load ranging from 50 to 300 N at 298 K (25 °C) and a lower load of 50 N at 473 K (200 °C). Oxidation occurred first at contacting asperities during sliding. Under a load greater than 150 N at 298 K (25 °C), a small amount of oxide patches could already reduce wear to some extent. Once a threshold of the load of 100 N at 473 K (200 °C) was reached, the oxide layers avoided the metal-metal adhesion completely and achieved a low wear rate. The wear fell in mild oxidative wear under a load ranging from 100 to 300 N at 473 K (200 °C) or a load ranging from 50 to 150 N at 673 K (400 °C) for tempered martensite and tempered troostite, and under a load of 100 N at 473 K (200 °C) or a load ranging from 50 to 100 N at 673 K (400 °C) for tempered sorbite.

With a subsequent increase of load and ambient temperature, the protective effect of oxide layer decreased gradually, and in some cases, it disappeared. At the load of 200 N or greater or at temperatures above 673 K (400 °C), oxidative wear (beyond mild oxidative wear) prevailed. When the highest load of 300 N at 673 K (400 °C) was applied, extrusive wear started to dominate for the tempered sorbite.

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REFERENCES

1. G.B. Li, J.J. Wu, X.Z. Li, and G.Y. Li: *J. Mater. Process. Tech.*, 1998, vol. 75, pp. 152–56.
2. G. Castro, A. Fernandez-Vicente, and J. Cid: *Wear*, 2007, vol. 263, pp. 1375–85.
3. P.R. Beeley and A. Blackmore: *Met. Tech.*, 1981, vols. 17–18, pp. 268–73.
4. P.M. Bralower: *Modern Cast*, 1988, vol. 78, pp. 3–8.
5. P.R. Beeley: *The British Foundryman*, 1983, vol. 76, pp. 15–19.
6. P.R. Beeley: *The British Foundryman*, 1986, vol. 79, pp. 441–45.
7. O. Barrau, C. Boher, R. Gras, and F. Rezai-Aria: *Wear*, 2003, vol. 255, pp. 1444–54.
8. L.H.S. Luong and T. Heijkoop: *Wear*, 1981, vol. 71, pp. 93–102.
9. Z.Y. Zhu: *Mech. Eng. Mater.*, 2001, vol. 25, pp. 39–42.
10. P.H. Hansen: Ph.D. Dissertation, Technical University of Denmark, Copenhagen, 1990.
11. Z.H. Zhang, H. Zhou, L.Q. Ren, X. Tong, H.Y. Shan, and L. Liu: *Int. J. Fatigue*, 2009, vol. 31, pp. 468–72.
12. S. Huth, N. Krasokha, and W. Theisen: *Wear*, 2009, vol. 267, pp. 449–57.
13. X.H. Cui, Ph.D. Dissertation, Jilin University, Changchun, China, 2006.
14. S.Q. Wang, K.M. Chen, X.H. Cui, Q.C. Jiang, and B. Hong: *J. Iron Steel Res. Int.*, 2006, vol. 13, pp. 53–59.
15. X.H. Cui, J. Shan, Z.R. Yang, M.X. Wei, S.Q. Wang, and C. Dong: *J. Iron Steel Res. Int.*, 2008, vol. 15, pp. 67–72.
16. X.H. Cui, S.Q. Wang, Q.C. Jiang, and K.M. Chen: *J. Rare Earths*, 2007, vol. 25, pp. 88–92.
17. X.H. Cui, S.Q. Wang, F. Wang, and K.M. Chen: *Wear*, 2008, vol. 265, pp. 468–76.
18. S.Q. Wang, F. Wang, X.H. Cui, and K.M. Chen: *Mater. Lett.*, 2008, vol. 62, pp. 279–81.
19. M.X. Wei, F. Wang, S.Q. Wang, and X.H. Cui: *Mater. Des.*, 2009, vol. 30, pp. 3608–14.
20. Y. Wang, T.Q. Lei, and J.J. Liu: *Wear*, 1999, vol. 231, pp. 1–11.
21. J.F. Archard: *J. Appl. Phys.*, 1953, vol. 24, pp. 981–88.
22. C.Y.H. Lim, S.C. Lim, and M. Gupta: *Wear*, 2003, vol. 255, pp. 629–37.
23. H. So, D.S. Yu, and C.Y. Chuang: *Wear*, 2002, vol. 253, pp. 1004–15.
24. V. Abouei, H. Saghafian, and S. Kheirandish: *Wear*, 2007, vol. 262, pp. 1225–31.
25. T.F.J. Quinn, J.L. Sullivan, and D.M. Rowson: *Tribol. Int.*, 1980, vol. 13, pp. 153–58.
26. T.F.J. Quinn: *Tribol. Int.*, 1983, vol. 16, pp. 257–71.
27. T.F.J. Quinn: *Tribol. Int.*, 1983, vol. 16, pp. 305–15.
28. T.F.J. Quinn: *Wear*, 1998, vol. 216, pp. 262–75.
29. J.E. Wilson, F.H. Stott, and G.C. Wood: *Proc. R. Soc.*, 1980, vol. A369, pp. 557–74.
30. S.Q. Wang, M.X. Wei, F. Wang, X.H. Cui, and C. Dong: *Tribol. Lett.*, 2008, vol. 32, pp. 67–72.
31. E. Marui, N. Hasegawa, H. Endo, K. Tanaka, and T. Hattori: *Wear*, 1997, vol. 205, pp. 186–99.
32. Y. Wang and T.Q. Lei: *Wear*, 1996, vol. 194, pp. 44–53.
33. H. So, H.M. Chen, and L.W. Chen: *Wear*, 2008, vol. 265, pp. 1142–48.
34. M. Pellizzari, A. Molinari, and G. Straffellini: *Wear*, 2005, vol. 259, pp. 1281–89.