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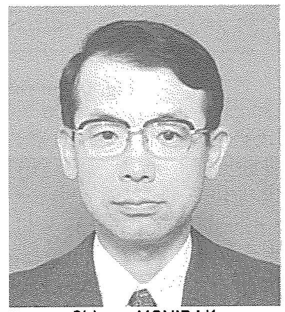
Characteristics of Hot Friction in Commercially Pure Titanium





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Abstract

It is said that in hot-rolling titanium, surface defects are apt to occur by seizures between rolls and products. The authors examined the effects of temperatures and lubricants on the tribological behavior of titanium strip surface contact with rolls using a hot rolling and sliding wear tester with commercially pure titanium disks and a high speed steel. Consequently, in cases of water spray without lubricating oil, fine cracks due to hard layers by oxidation decrease with lower temperature, but the coefficient of friction increases because oxide scales become thin and then metals come easily into contact. The coefficient of friction at 650℃ doubles in comparison with that of 850℃ and foil-like overlaps occur. Addition of lubricating oil reduces the coefficient of friction at 650℃ by half and smooth surfaces are obtained. The smooth surface is thought to be due to the lubrication effects of oxide-scales as well as the lubricating oil.

1. Introduction

Surface roughening, scratches, and scuffing are known as surface defects that occur in the hot rolling of titanium[1,2]. Titanium is more active than steel and is more likely to seize to rolls and guides during hot rolling. This is one cause for the occurrence of the surface defects[1,2]. To focus on the friction behavior of the titanium surface in contact with the roll surface as one of the seizure phenomena during hot rolling, this work studied the effects of the surface temperature and lubricating oil by hot rolling and sliding contact wear test.

2. Experimental Methods

The hot rolling and sliding contact wear test apparatus and conditions are shown in **Fig. 1**, and the general views of this apparatus are shown in **Photo 1**. First, disks of JIS Grade 1 commercially pure titanium and JIS SKH 51 high-speed tool steel were rotated with a peripheral speed difference equivalent to a slip ratio of 11% and were high-frequency induction heated so that the temperature near the contact surface of the commercially pure titanium disk reached 650, 750 and 850°C. The surface temperature of the high-speed tool steel disk was adjusted to 400-500°C by regulating the flow rate of cooling water or lubricating oil. After the temperature stabilized, the two disks were brought into contact under a constant load of 70 kgf, and the coefficient of friction in the contact surface was determined from the rotational torque. The temperature of each disk was measured with a radiation thermometer (Photo 1). At 650°C, another test was

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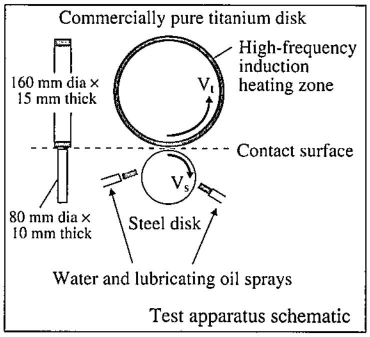

Test conditions

Type of disk	Test material conditions	Surface Ra (μm)	Speed (rpm)	Temperature (°C)
Commercially pure titanium	JIS Grade 1 commercially pure titanium, vacuum arc melting ⇒ hot working ⇒ machining	About 0.8	389	650, 750, 850
SKH51	JIS G 4403 SKH 51, quenching and tempering ⇒ machining	About 0.5	700	About 400-550

Slip ratio (titanium disk forward)	11.2%
Contact load (constant)	About 70 kgf

Fig. 1 Hot rolling and sliding contact wear test apparatus and conditions

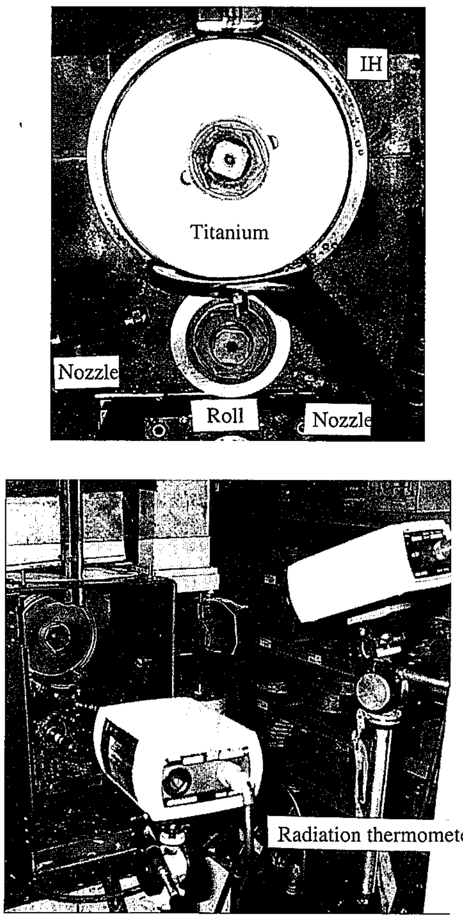

Photo 1 General views of hot rolling and sliding contact wear test apparatus

conducted using an emulsion-type lubricating oil. The above test conditions were set to provide a friction environment with such a severe slip ratio and load as to simulate the forward slip region at the roll exit side of hot finish rolling stands and to clarify the differences in friction characteristics.

After the test, the contact surface of the JIS Grade 1 commercially pure titanium disk was macroscopically observed, and the microscopic morphology was examined by scanning electron microscopy (SEM). The element concentrations in the surface and depth direction were investigated by energy-dispersive spectroscopy (EDS) and glow discharge optical emission spectroscopy (GDS), and the degree of reaction with oxygen and the mating steel was evaluated. The contact region metal flow was studied by observing the cross-sectional microstructures.

The JIS Grade 1 commercially pure titanium disk (hereinafter referred to as the titanium disk) was made from vacuum arc melted titanium that was then hot rolled. The JIS SKH 51 high-speed tool steel disk (hereinafter referred to as the steel disk) was made from a JIS G 4403 quenched and tempered steel. Each disk was machined to the specified shape. The contact surface roughness of the titanium and steel disks was about 0.8 μm and 0.5 μm, respectively (see Fig. 1).

3. Experimental Results

The coefficient of friction at each titanium disk temperature is shown in **Fig. 2**. The contact surfaces of the titanium disk and steel disk are shown in the upper and lower parts of **Photo 2**, respectively. **Photo 3** shows the SEM micrograph of the titanium disk contact surface without the lubricating oil at 650°C.

From Fig. 2, the coefficient of friction increases with decreasing temperature without the lubricating oil and is about 0.40 at 650°C or about twice larger than at 850°C. Use of the lubricating oil at 650°C halves the coefficient of friction to about 0.20 (as indicated by the solid circle in Fig. 2).

The morphology of the titanium disk contact surface is characterized as shown in Photo 2. Without the lubricating oil at high temperatures (850°C in Photo 2(a) and 750°C in Photo 2(b)), there are no macro cracks and overlaps, constant-pitch steps are formed by

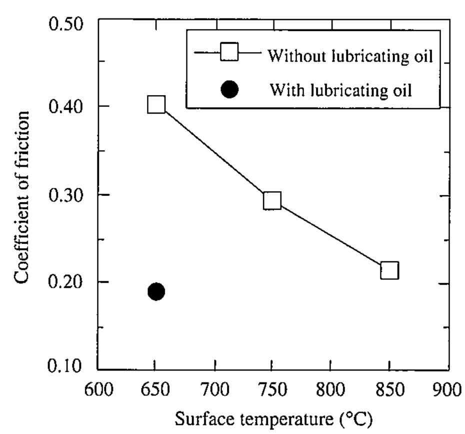

Fig. 2 Effects of titanium disk surface temperature and lubricating oil on coefficient of friction in hot condition

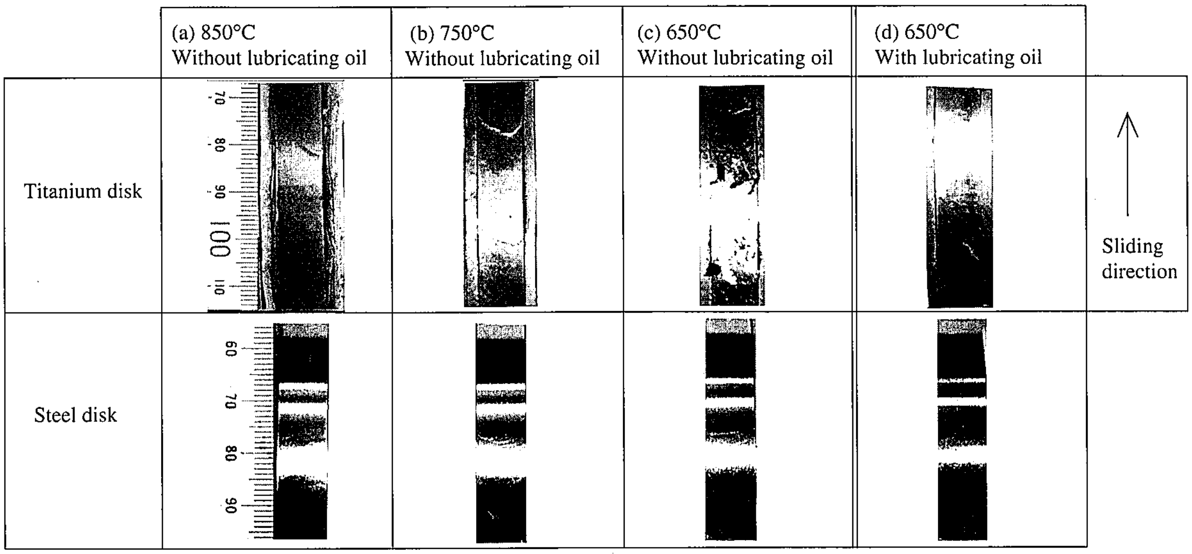

Photo 2 Appearance comparison of disk contact surface after hot wear test (titanium disk in top and steel disk in bottom)

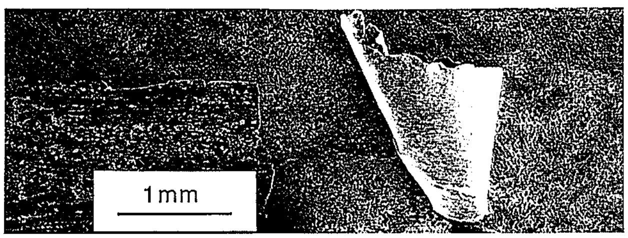

Photo 3 Enlarged view of overlap in titanium disk contact surface (test conditions: 650°C, without lubricating oil)

metal flow, and the surface is dark brown. At 650°C, macro foil-like overlaps occur as shown in Photo 2(c). The overlaps are formed in the direction opposed to the rolling direction (slip direction) of the forward titanium disk. With the lubricating oil at 650°C, the surface is smoothed as shown in Photo 2(d). The contact surface of the steel disk is free from macro defects under any test conditions and exhibits metallic luster in the same way as observed before the test (see the lower part of Photo 2).

The microscopically observed titanium disk contact surfaces are shown in **Photo 4**. Without the lubricating oil, fine cracks are conspicuous at high temperatures as shown in Photo 4(a) and (b), and diminish at 650°C as shown in Photo 4(c). Use of the lubricating oil remarkably reduces micro surface defects as shown in Photo 4(d).

4. Discussion

The hot friction characteristics of titanium greatly change with temperature and lubrication as described above, and can be clearly correlated with the differences in the coefficient of friction and the morphology of the contact surface. Here are discussed the effects of temperature and lubricating oil on the contact surface and mechan-

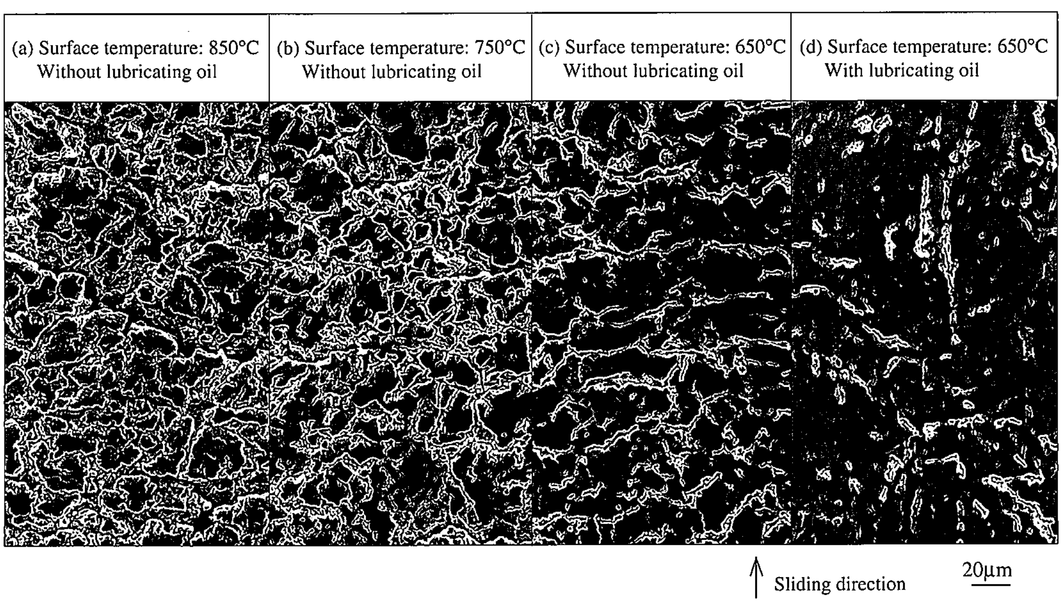

Photo 4 Titanium disk contact surfaces

isms for the occurrence of the above-mentioned phenomena. The relations with actual hot rolling operations are also inferred.

When the degree of oxidation in the contact surface of the titanium disk is compared by EDS, nonuse of the lubricating oil increases the peak intensity of oxygen for titanium with increasing temperature and the more oxidation of titanium as shown in **Fig. 3** (a) to (c). This corresponds with the increasing activity of reaction between titanium and oxygen with increasing temperature[3]. Use of the lubricating oil at the lower temperature of 650°C markedly increases the peak intensity of oxygen as compared with nonuse and strongly accelerates the oxidation of titanium as shown in Fig. 3(d). The lubricating oil is considered to act as a source of oxygen. The GDS multiple-element depth concentration profiles shown in **Fig. 4** are similar to the EDS results. The oxygen concentration near the surface increases with increasing temperature. The oxygen penetration depth is about 5 μm at 850 and 750°C and decreases to about 2.5

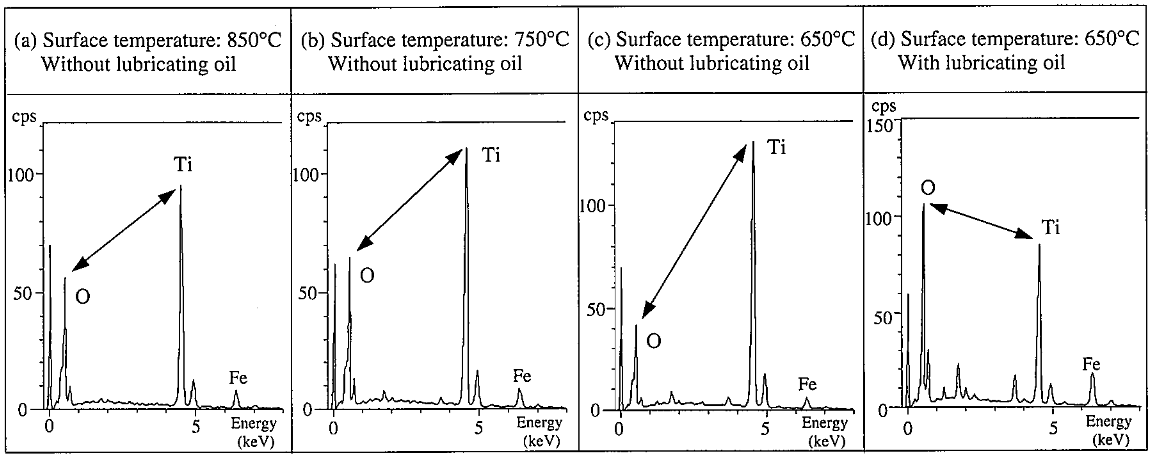

Fig. 3 Comparison of EDS spectrum of titanium disk contact surface after hot wear test (arrows inserted for peak intensity comparison of oxygen and titanium)

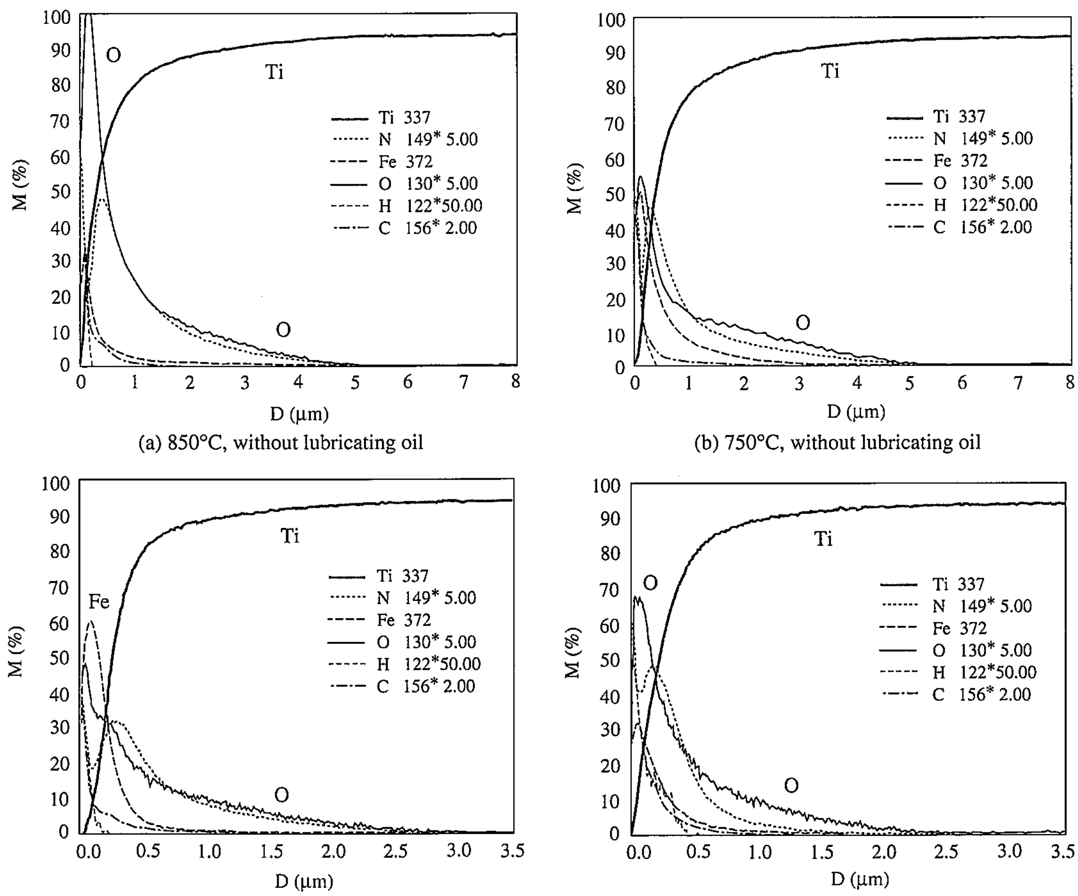

Fig. 4 GDS multiple-element depth concentration profiles in titanium disk contact surface after hot wear test

μm at 650°C as shown in Fig. 4(a) to (c). Since use of the lubricating oil raises the oxygen concentration and lowers the iron concentration near the surface (Fig. 4(d)), the titanium surface oxide layer and the lubricating oil film are considered to reduce the contact between the mating steel and titanium.

The titanium disk surface is covered with an oxide (scale) layer of high oxygen concentration. As its thickness increases with increasing temperature, the oxidation-hardened layer[3] breaks down and produces fine cracks due to rolling. The coefficient of friction is reduced by what is called the scale lubrication effect of titanium oxide in precluding the contact between the metals. At lower temperatures, the resultant decrease in the scale thickness is considered to facilitate the contact between the metals and to increase the coefficient of friction. The lubricating oil presumably provides the lubrication effect due to its film and also the scale lubrication effect due to the promotion of oxidation. Since actual hot rolling exposes metallic titanium on the roll surface from time to time, however, it is necessary to consider the effects of the temperature and lubricating oil on scale regeneration.

The cross-sectional structures of the titanium disk contact portions are shown in **Photo 5**. The metal flow or worked and recrystallized microstructure depth is small at lower temperatures and is about 200 μm at 650°C. A foil-like overlap is observed for the titanium disk without the lubricating oil in Photo 5(c). From this condition, it is considered likely that the high-temperature region where the induction-heated contact portion can plastically flows is made shallower with decreasing temperature. At low temperatures without the lubricating oil, the titanium surface scale is thin, and the contact between the metals is facilitated (the coefficient of friction is large). The titanium eventually seizes to the steel and since the high-temperature region where the contact portion can plastically flow is made shallow due to induction heating, in consequence it is considered that the titanium surface suffers shear deformation and forms the foil-like overlap.

According to the above discussion, **Fig. 5** schematically illustrates the friction phenomena in the contact surface in this test in the following three cases: (a) high temperature and without lubricating oil; (b) low temperature and without lubricating oil; and (c) low temperature and with lubricating oil.

(a) High temperature and without lubricating oil: Since the titanium is oxidized at the high temperature, the coefficient of friction is reduced by scale lubrication, but the thick oxidation-hardened layer breaks down and produces micro cracks.

(b) Low temperature and without lubricating oil: At the low temperature, the scale is thin, the contact between the metals is promoted, and the coefficient of friction is increased. As a result, the titanium seizes to the steel and since the contact surface region where the titanium can plastically flow is shallow, a macro foil-

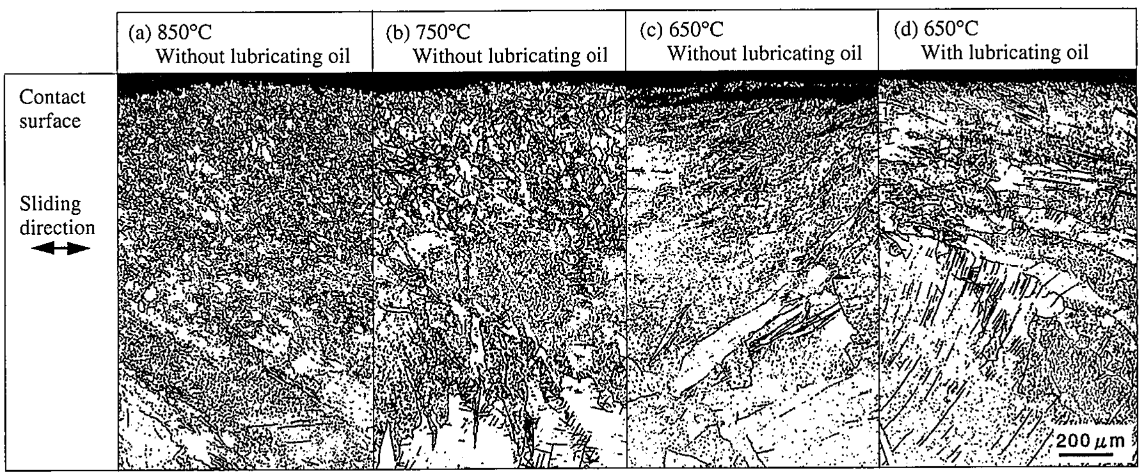

Photo 5 Cross-sectional microstructures beneath titanium disk contact surface

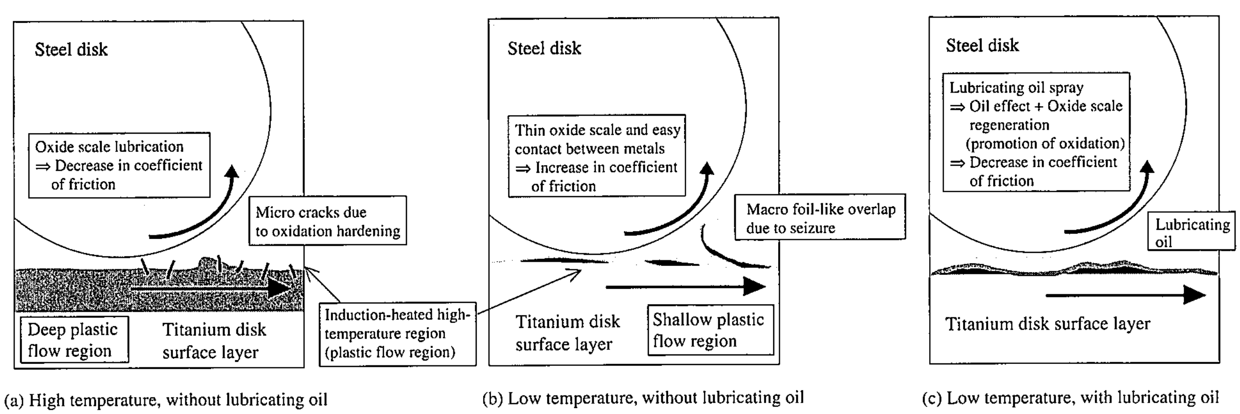

Fig. 5 Schematic illustrations of friction phenomena in titanium disk contact surface in hot wear test (effects of surface temperature and lubricating oil)

like overlap occurs.

(c) Low temperature and with lubricating oil: The oil provides the oil lubrication effect as well as the scale lubrication effect because the oil acts as a source of oxygen, which in turn promotes the oxidation of the titanium. As a result, the coefficient of friction is reduced, and the seizure of the titanium is prevented, and the titanium surface defects are diminished.

The friction phenomena during actual hot rolling are considered here according to the above-mentioned hot friction characteristics. When the temperature of titanium to be rolled is high, the scale lubrication effect can be expected. When its temperature is low, the oil film breaks, the lubrication condition worsens, the scale lubrication makes no contribution, and the coefficient of friction increases. Since the deformation resistance is also increased (the deformation resistance is approximately doubled for each temperature drop of 100°C)[2], the friction force itself increases thereby increasing the severity of the friction environment. Consequently, the seizure of the titanium is presumed to occur more frequently.

5. Conclusions

Concerning the effects of the surface temperature and lubricating oil on the hot friction characteristics of commercially pure titanium, a study was mainly made of the coefficient of friction and the morphology of the contact surface by hot rolling and sliding contact surface wear test. The following conclusions were obtained:

(1) When the lubricating oil is not used, the coefficient of friction in the temperature region of 650 to 850°C increases with decreasing temperature and approximately doubles at 650°C as compared with 850°C.

(2) Fine cracks occur in the contact surface due to oxidation hardening at high temperatures, and macro foil-like overlaps occur at the low temperature of 650°C. Use of the lubricating oil at 650°C halves the coefficient of friction, reduces the frequency of these defects, and smoothes the contact surface.

(3) At high temperatures, the titanium surface is readily oxidized and is covered with an oxide (scale) layer. This layer is considered to reduce the contact between the metals and to provide scale lubrication between the metals. The lubricating oil not only provides the oil film lubrication effect, but also accelerates the oxidation of the titanium surface. It is thus considered to contribute to scale lubrication.

(4) At the low temperature of 650°C and without the lubricating oil, the scale is thin, the contact between the metals is facilitated, and the coefficient of friction is increased. As a result, the titanium seizes to the steel. In addition, the high-temperature region where the titanium surface layer can plastically flow is made shallow due to induction heating, and the macro foil-like overlap described in (2) above occurs due to shear deformation.

References

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