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The Effect of Hardness of Hardened Steel on Fretting Wear in Seawater*1

by

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The purpose of this work is to investigate the extent to which fretting damage in seawater is reduced by increasing the hardness of steel. Fretting tests of bearing steel balls (SUJ-2) on plates of the same material hardened from 267 to 801 Hv by heat treatment were carried out in seawater, deionized water and air through 10^5 cycles with a normal load of 9.8 N, slip amplitudes of 17−120 μm, frequency of 7.5 Hz. The effect of hardness was discussed from the electrochemical standpoint. The results showed that (1) increasing the hardness from 267 to 801 Hv decreased the wear volume by a factor of 5 in seawater but only 2.8 in deionized water and in air, (2) in the case of fretting wear in seawater, increasing the hardness by heat treatment reduced not only mechanical damage due to fretting, but also electrochemical damage.

1. Introduction

The variables which affect fretting damage can be divided into three main groups[1]: 1) mechanical variables; normal load, amplitude of slip, frequency and number of cycles, 2) physical variables; temperature, relative hardness of the surfaces and surface finish, 3) environments. Many studies on these variables have been made in the past and the effect of hardness on fretting wear has often been discussed. Hardness can affect fretting wear in the following two possible ways[2]. Firstly, in so far as fretting wear is caused by the breakdown of a surface under local high stress fatigue processes, a decrease in damage can be expected in higher hardness steel. Secondly, higher hardness steel seems to have a higher resistance against the abrasive action of the oxide debris between two surfaces.

With regard to the effect of hardness of steels on fretting wear in air, WRIGHT[3] and PITTOROFE[4] have shown that wear volume is in inverse proportion to hardness to 2.5−3 th power. ITO[5] and HATORI[6] *et al.* have shown that wear volume decreases linearly with hardness. On the other hand, ROLFE[7] and HOGMARK[8] *et al.* have shown that fretting damage is not related to hardness under certain conditions. ENDO[9] and KAYABA[10] *et al.* have shown that the effect of hardness is complicated, that the significant factor is the action of the oxide debris produced and that hardness has only a minor influence on fretting wear. Therefore, it can be understood, with regard to fretting wear in air, that the increase in hardness is effective in reducing the mechanical action of fretting, whereas the effect of hardness is changed by the behaviour of the oxide debris between two surfaces.

Fretting damage which occurs in seawater,

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such as on ships, marine apparatus and off shore structures, has been reported[11]. During the fretting of steel in air, mechanical and oxidational components are responsible for wear loss. In the case of fretting in seawater, an electrochemical component is additionaly responsible for wear loss. Most of the wear debris removes itself easily from the contacting surfaces in aqueous environments[12, 13]. PEARSON and WATERHOUSE[13, 14] have shown that fretting damage decreases drastically when the electrochemical and oxidational components are removed by applying cathodic protection. Their works suggest that fretting damage of steel hardened by heat treatment seems to be reduced because the corrosion resistance of the steel is improved. However, there have been very few investigations relating to the effect of hardness on fretting wear in seawater.

The present study aims to investigate the extent to which fretting damage in seawater is reduced by increasing the hardness of the steel. Fretting tests of bearing steel hardened from 267 to 801 Hv by heat treatment have been carried out in seawater. Fretting in seawater has been compared with fretting in deionized water and air. The effect of hardness has been discussed from the electrochemical standpoint.

2. Experimental

The schematic illustration of fretting apparatus[15] is shown in Fig. 1. One end of the beam is fixed, the other end is free . The free end of the beam is oscillated horizontally by reciprocating motion, to which the rotational motion of a motor is converted through an eccentric wheel. The frequency is adjusted by varying the rotational speed of the motor. The amplitude can be adjusted by changing the position of the specimen or the value of eccentricity of the wheel. Therefore, very small amplitudes can be set accurately. Fretting occurs between an upper specimen (plate) fixed in the holder and a lower specimen(ball) fixed on the beam. The relative amplitude between the upper and lower specimens is detected using the eddy current pick-up attached to the holder.

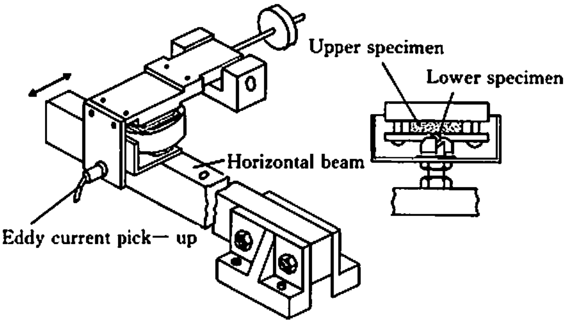

Fig. 1. Schematic illustration of the fretting apparatus.

Details of the specimens are listed in Table 1. The upper specimen is a bearing-steel plate. The upper specimen surfaces were abraded on # 1000 silicon paper. The lower specimen is a commercial bearing-steel ball. The conditions of heat treatment for the upper specimens are shown in Table 2. Table 3 shows the experimental conditions. Neither room temperature nor relative humidity was controlled for the tests. During the tests in aqueous environments, the specimens were immersed in liquid, which was made to overflow continuously. The seawater was natural seawater and its pH was 7.4. The concentration of Cl^- ions in seawater was 18.31‰. The wear volume after 10^5 cycles was measured in the tests. The wear scar can be assumed to be of the simplified form shown in Fig. 2. The wear volume was calculated by equation (1)[10]. The value of a was calculated as the mean value of the radius in the sliding direction and the radius perpendicular to this direction. The value of R was calculated from the mean value of the maximun depth measured using a optical microscope.

It was to be expected that the corrosion resistance of the specimens would be changed by

Table 1. Details of the specimens

Specimens	Materials	Hardness(Hv)	Size(mm)
Upper specimen	Steel plate (SUJ-2)	Table 2	ϕ 29×5
Lower specimen	Steel ball (SUJ-2)	857	6.35 (diameter)

Table 2. The conditions of heat treatment of the upper specimens

Upper specimens	Quenching	Tempering	Hardness(Hv)
A		700°C, 30 min, oil	267
B	840°C	550°C, 30 min, oil	412
C	40 min	400°C, 30 min, oil	568
D	water	300°C, 30 min, oil	637
E		180°C, 30 min, oil	801

Table 3. Experimental conditions

Load	N	9.8
Frequency	Hz	7.5
Amplitude	μm	17~120
Room temperature	°C	15~26
Relative humidity	%	57~67
Environments		seawater, deionized water, air

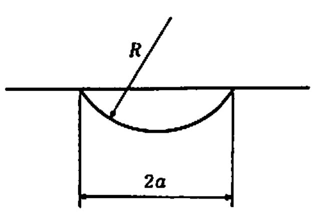

Fig. 2. Simplified wear scar for the calculation of wear volume.

$$V = \frac{\pi a^4}{4R} \quad (1)$$

V : Wear volume mm³

a : Radius of wear scar mm

R : Vertical radius of wear scar mm

the heat treatment of the materials. Therefore, electrochemical measurements were carried out to determine the corrosion current of the specimens under stationary conditions in the absence of fretting in seawater. The potentiostatic polarization measurement was made as follows; after admission of the seawater into the cell, potentiostatic control was imposed to maintain the potential of the specimen −400 mV s. c. e with respect to the standard reference electrode. The potential of the specimen was then made more negative in steps of 20 mV using the manual fine control of the potentiostat. Each current was recorded 2 min. after adjustment of the potential.

3. Results and discussion

3.1 The effect of hardness

The relations between the wear volume and hardness in air are shown in Fig. 3. The wear volumes at both the amplitudes are almost constant in the region up to the hardness 568 Hv, then they decrease. The action of oxide debris formed between two surfaces seems to be an important factor on fretting wear in air. Oxide debris can be expected to behave in two different ways;wear is accelerated by oxide debris acting as abrasive particles[16], or oxide debris suppresses wear by working as a protective layer[17, 18]. According to the hardness of materials, the relative hardness of the debris and the surface may change the action of wear debris[10]. Therefore, it can be understood that the effect of hardness on fretting wear changed at about the hardness 568 Hv in this experiment because the hardness of oxides of steel (α-Fe_2O_3) is approximately 500 Hv[9].

Figure 4 shows the relations between the wear volume and hardness in seawater and deionized water. The wear volumes at both the amplitudes decrease almost linearly with the hardness in both the environments. Decreases in the wear volume in seawater are 5-fold at 120 μm and 2.4—fold at 23 μm respectively. Those in deionized water are 2.8-fold at 120 μm and 1.7-fold at 23 μm respectively. The decrease in seawater is greater than in deionized water. The wear debris in aqueous environments seems to affect fretting wear less than that in air. It is evident that linear decrease in wear volumes in aqueous environments is due to the reduction in mechanical damage of fretting by increasing the hardness of the material.

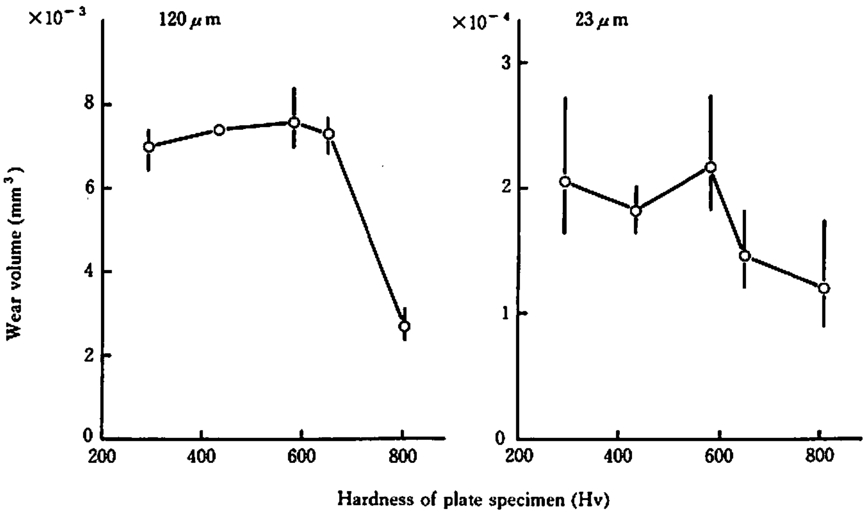

Fig. 3. The relations between the wear volume and the hardness of the plate specimen in air.

3.2 The effect of amplitude

Environments strongly affect fretting wear, but the amplitude of slip can be expected to change the degree of their influence. Figure 5 shows the relations between the specific wear rate and the amplitude in each environment. As the amplitude increases, the specific wear rate in air increases, but conversely the specific wear rates in aqueous environments decrease. Consequently, at larger amplitudes, the degree of fretting damage in air is the greatest and that in seawater is the least. At smaller amplitudes

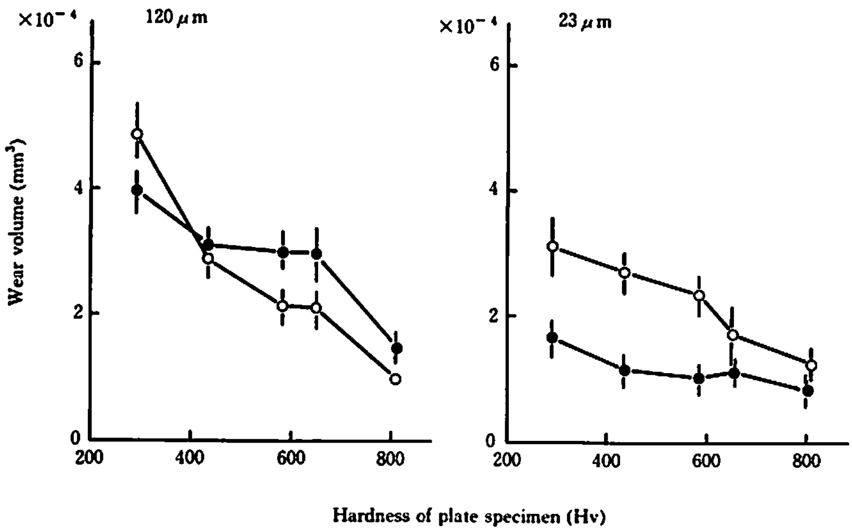

Fig. 4. The relations between the wear volume and the hardness of the plate specimen in seawater and deionized water; (○) in seawater, (●) deionized water.

the degree of fretting damage decreases in the order seawater, deionized water, air.

Fretting wear in air is caused by three possible processes[19]; 1) the disruption of oxide films on surfaces due to mechanical action, 2) the formation of local welds between contacting high spots and the removal of metal particles from surfaces by direct shearing or by a local fatiguing action, 3) the oxidation of metal particles and the abrasion of surfaces by these oxide particles. All the processes occur during fretting and their relative importance may be changed by experimental conditions, especially the amplitude of slip. At smaller amplitudes fretting wear is mainly due to oxidation, whereas at larger amplitudes fretting wear is due to oxidation, adhesion and abrasion[16]. The present results indicate that as the amplitude increases, the greater abrasive action of the oxide wear debris causes greater fretting damage.

Mechanical, oxidational and electrochemical

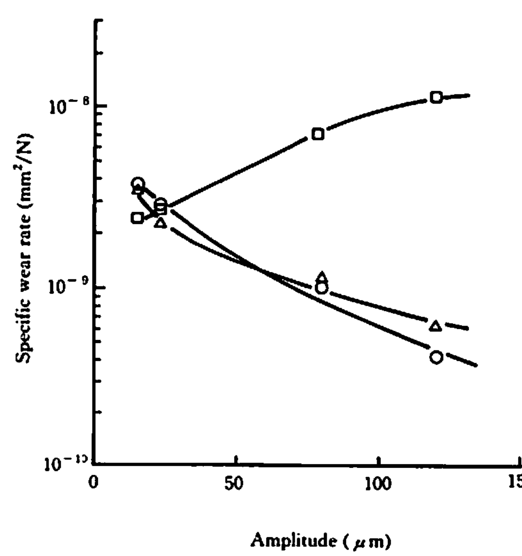

Fig. 5. The relations between the specific wear rate and the amplitude; (○) in seawater, (△) in deionized water, (□) in air.

components are responsible for fretting wear in seawater. PEARSON and WATERHOUS[14] have shown that fretting damage is greater in seawater that in air, and that fretting damage in seawater can be reduced drastically by cathodic protection. They have attributed the greater damage in seawater to great electrochemical corrosion. The present study produced the same results reported by PEARSON *et al.* at smaller amplitudes. However,at larger amplitudes, fretting damage in seawater was much less than that in air due to the increase of the lubricating action of liquid. Therefore, cathodic protection applied in order to reduce fretting damage in seawater seems to be more effective at smaller amplitudes.

Figure 6 shows the worn surfaces of the plate specimens at 10^5 cycles in each environment. The worn surfaces at amplitude 120 μm are quite different in each environment. Oxide wear particles and abrasive wear tracks are observed on the worn surface in air. Abrasive wear tracks and pits are observed on the worn surface in deionized water. Very smooth surfaces and fine abrasive wear tracks are observed in seawater. The worn surfaces at 16 μm are similar in each environment.

A typical wear scar of the plate specimens in seawater is shown in Fig. 7. Figure 8 shows the magnified regions of A and B in Fig. 7. The central area of the scar shows grooving which is parallel to the direction of fretting. No wear particles are visible because they removed themselves during fretting. Compacted debris and corroded debris are visible in the outer area. These observations of bearing steel are similar to OVERS' observations of weldable structural steels[11].

3.3 Electrochemical effect of hardness on fretting wear

A significant factor which can affect fretting damage in electrolytes such as seawater is the electrochemical component. Fretting damage can be greatly reduced when the electroche-

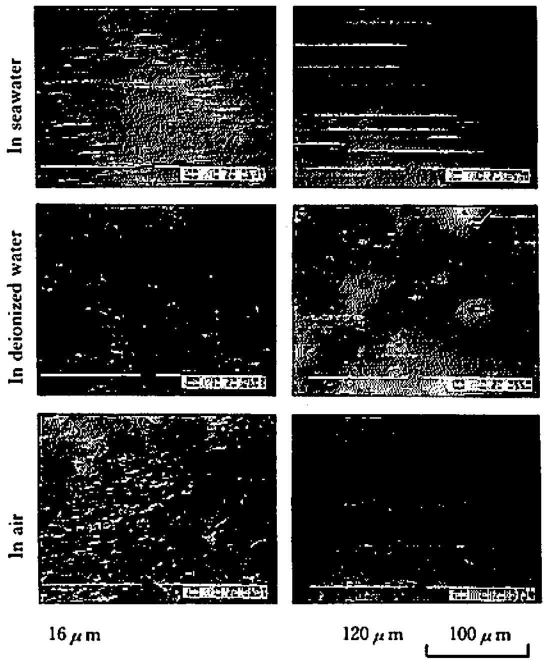

Fig. 6. Scanning electron micrographs of the plate specimens (801 Hv).

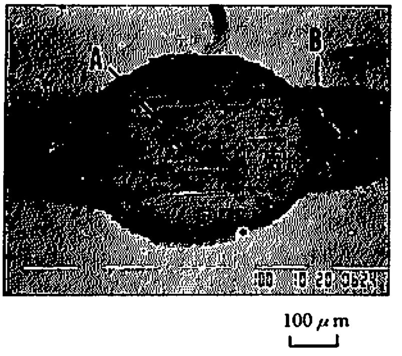

Fig. 7. A typical wear scar of the plate specimen (801 Hv) in seawater at an amplitude of 78 μm.

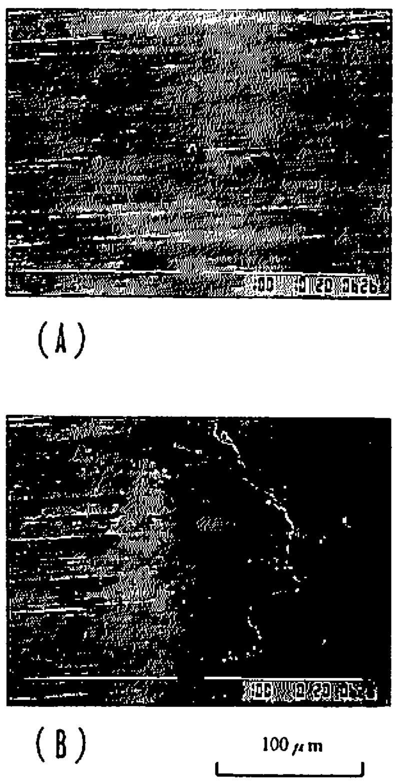

Fig. 8. The magnified regions of A and B in Fig. 7.

mical component is eliminated by the application of cathodic protection[11,14]. This suggests that when materials hardened by heat treatment were used, the damage due to the electrochemical component could be reduced.

In order to confirm that increasing the hardness of steels increases corrosion resistance, measurements of the corrosion current and corrosion potential of the specimens were made. A typical polarization curve for the specimen in seawater is shown in Fig. 9. The effects of hardness on the corrosion current and potential are shown in Fig. 10. Both the corrosion current and corrosion potential decrease almost linearly with increasing hardness. This increase in hardness improves the corrosion resistance. Also, as shown in Fig. 4, the decrease

linearly with increasing hardness. This increase in hardness improves the corrosion resistance. Also, as shown in Fig. 4, the decrease
of fretting damage was the greatest in seawater. Therefore, it can be surmised that in seawater increasing hardness reduces not only mechanical damage due to fretting, but also electrochemical damage.

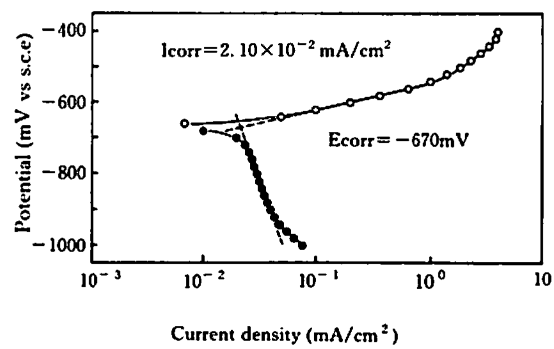

Fig. 9. A typical polarization curve for the plate specimen (267 Hv) in seawater; pH 7.4, 12.5℃.

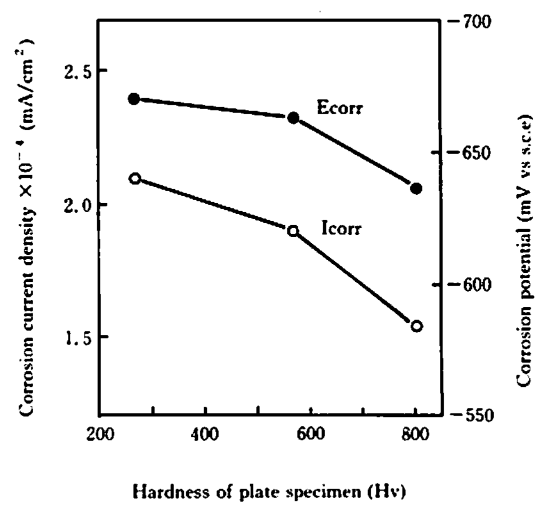

Fig. 10. The effects of hardness on the corrosion current and corrosion potential.

4. Conclusions

Fretting tests on combinations of bearing steel balls (857Hv) and plates of the same material (267—801Hv) hardened by heat teatment were carried out to investigate the effect of hardness on fretting wear in seawater. The following results were obtained.

(1) Fretting damage decreased linearly with increasing hardness in seawater and deionized water but decreased after the hardness 568 Hv in air.

(2) The effect of hardness was greater at larger amplitudes in all the environments. Increasing the hardness from 267 to 801 Hv decreased the wear volume by a factor of 5 in seawater but only 2. 8 in deionized water and air.

(3) In the case of fretting wear in seawater, increasing the hardness by heat treatment reduced not only mechanical damage due to fretting, but also electrochemical damage.

(4) As the amplitude increased, the fretting wear in air increased but the fretting wear in seawater and deionized water decreased.

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海水中のフレッチング摩耗に及ぼす焼入れ鋼の硬さの影響

竹内正明・佐藤準一

本報では，鋼の硬さを増すことによって，海水中のフレッチング損傷をどの程度軽減できるかを調べたものである。軸受鋼球（SUJ－2）と熱処理によって硬さを変えた同種板材を用い，海水中，清水中，大気中でフレッチング試験を行なった。実験条件は，荷重9.8 N，すべり振幅17—120 μm，振動数7.5 Hz，くり返し回数10^5サイクルである。海水中のフレッチング摩耗に及ぼす硬さの影響を電気化学的観点から考察した。その結果，硬さを267から801 Hv まで増すことにより，摩耗量は，海水中では5倍，清水中，大気中では2.8倍減少した。特に，海水中のフレッチング摩耗では，熱処理による硬さの増大は，フレッチングによる機械的損傷ばかりでなく，電気化学的損傷をも軽減することがわかった。