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Effect of Seawater on Fretting Wear*1

By
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Fretting tests of a steel ball (SUJ-2 bearing steel) vs glass (ordinary window glass) were carried out in air, deionized water, and natural seawater. The effect of seawater on fretting wear was investigated by mainly direct observation of the process of fretting. The following results were obtained. 1. The wear debris produced by fretting was strongly influenced by the environments and behaved itself like a lubricant differently in each environment. 2. In the aqueous environments, the fluid lubricating condition was observed and most of the wear debris removed itself easily from the contacting surfaces at the large amplitudes. 3. The wear rate was the highest in air, lower in deionized water and the lowest in seawater. 4. Green wear debris was observed in deionized water and seawater.

1. Introduction

Fretting is the wear phenomena occurring between two surfaces having oscillatory relative motion of small amplitude[1]. It is known that fretting occurs in bearings, flexible couplings, wire ropes, bolted flanges, keys and propeller bosses, etc[2]. When fretting occurs on components which have oscillatory relative motion, it reduces the accuracy of machines and breaks surfaces which are undergoing friction due to the increase of frictional resistance. On the other hand, when fretting occurs where the contacting surfaces are not designed to move relatively to each other, fatigue strength is reduced. Therefore, the damage caused by fretting on machines can be extensive.

Many studies on fretting have been done and the effect of the factors, e.g. load, amplitude, frequency, temperature, humidity, on fretting has been clarified considerably[3]. Concerning the effect of environments, fretting in gaseous environments (air, nitrogen, argon, etc.), vacuums, and lubricants has been investigated[4~9].

Fretting on ship and marine apparatus and offshore structures occurs in seawater, which is a corrosive environment. There are some investigations on ordinary continuous sliding wear in corrosive environments[10~13], but very few on fretting and also most of the experiments done have been carried out using NaCl solution as the corrosive environment[14,15]. In this paper, fretting tests of a steel ball (SUJ-2 bearing steel) vs glass (ordinary window glass) have been carried out in air, deionized water, and natural seawater.The effect of seawater on fretting wear has been investigated by mainly direct observation of the process of fretting.

2. Experimental details

The schematic illustration of fretting apparatus is shown in Fig. 1. One end of the beam ① is fixed,

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the other end is free. The rotational motion of a motor is converted to reciprocating motion through the belt ②, eccentric cam ③, and bar ④.The free end of the beam is oscillated horizontally. 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 eccentric cam. Therefore, very small amplitudes can be set accurately.

Fretting occurs between glass ⑤ fixed in the holder ⑥ and a steel ball ⑦ fixed on the beam ①. The friction force is measured using strain gauges attached to the strain ring ⑨. The relative amplitude between the steel ball and glass is detected using the eddy current pick-up ⑩ attached to the holder ⑥. The specimens are loaded with dead weight ⑪. The phenomena on the contacting surfaces during the process of fretting are observed through the upper specimen glass using an optical microscope.

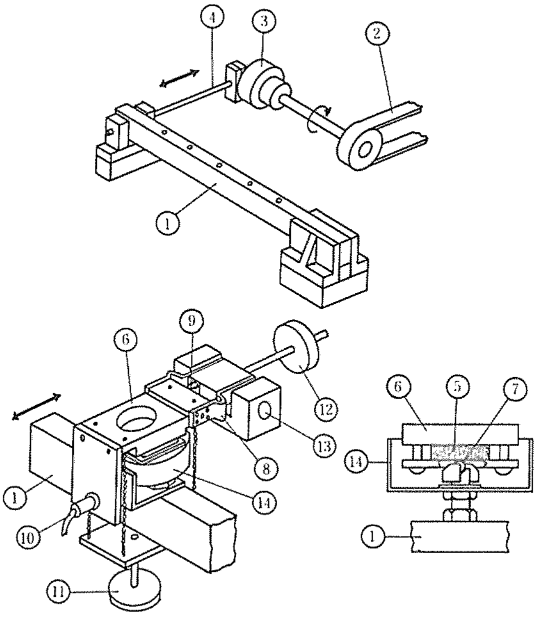


Fig. 1. The schematic illustration of fretting apparatus.

① : Beam,
② : Belt,
③ : Eccentric cam,
④ : Bar,
⑤ : Upper specimen,
⑥ : Holder,
⑦ : Lower specimen,
⑧ : Spring,
⑨ : Strain ring,
⑩ : Eddy current pick-up,
⑪ : Dead weight,
⑫ : Balance weight,
⑬ : Fulcrum,
⑭ : Container.

Details of the specimens are listed in Table 1. The upper specimen is ordinary window glass. The lower specimen is SUJ-2 bearing steel. All the specimens were cleaned with acetone and kept in a desiccator before being used for the tests.

Table 2 shows the experimental conditions. The relationship between the amplitudes and overlaps of the area of elastic contact is shown in Fig.2. Initial amplitude was adopted because relative amplitude varied with the varying friction force during the measurements of friction force. In order to keep the amplitude constant in the tests of wear volume, the holder without a spring for measuring friction force was used. The wear volume, as shown in Fig.3, can

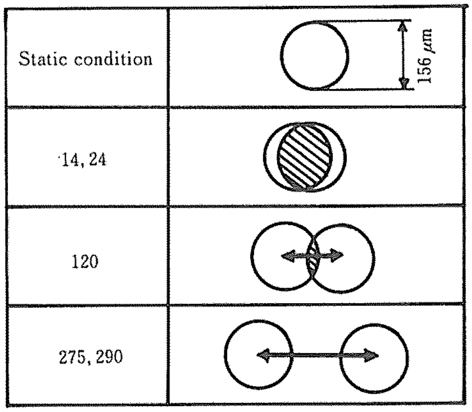


Fig. 2. The relationship between the amplitudes and overlaps of the area of elastic contact.

Table 1. Details of the specimens

Specimens	Materials	Hardness (Hv)	Size (mm)	Surface roughness Ra(μm)
Steel ball	(JIS)SUJ-2	857	6. 35(diameter)	0. 05
Glass plate	(JIS)R-3210	540	20×20×5	—

Table 2. Experimental conditions

		Measurement of friction	Measurement of wear volume
Load	kgf	1	1
Frequency	Hz	2	5
Amplitudes	μm	24, 120, 290	14, 50, 120, 170, 275
Room temperature	°C	10 ~ 17	10 ~ 14
Relative humidity	%	62 ~ 75	60 ~ 67
Environments		air, deionized water, seawater	air, deionized water, seawater

be geometrically calculated by equation (1)[16]. In the case of the tests in deionized water and seawater, the specimens were immersed in liquid which was made to overflow continuously during the tests. Natural seawater was filtered for the tests. The concentration of Cl^- ions in seawater is 18.31‰.

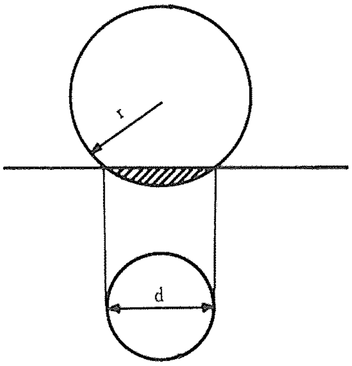


Fig. 3. The measurement of wear volume.

$$V=\frac{\pi}{64}\left(\frac{d^4}{r}-\frac{d^6}{24r^3}\right)\text{—(1)}$$

V : Wear volume mm
r : 3.175 mm (steel ball)
d : scar

3. Experimental results and discussion

3·1 Behaviour of the coefficient of friction

The behaviour of the coefficients of friction in each of the amplitudes and environments is shown in Fig. 4. When the amplitude is 24 μm, the variation of initial friction in each of the environments is great. The coefficients of friction rise with the number of cycles. They reach their peak at about 40 cycles, decrease between the hundred and thousand cycles, then increase again gradually and keep constant values. It can be understood that the increase of the coefficients of friction in the initial stage is mainly due to the destruction of stains and oxide films. These work as a lubricant during the initial period of friction. But the coefficients of friction rise with the increasing adhesion between the steel ball and glass because these films are destroyed by fretting. It is considered that the first decrease of the coefficients of friction after the peak occurs because the wear debris produced by friction works as a lubricant. Also, the coefficients of friction increase again with the number of cycles because new adhesion between the two surfaces increases with the removal of the wear debris from the contacting surfaces.Though the relationship of the coefficients of friction in each of the environments is variable before 500 cycles, it becomes constant after 500 cycles. The wear debris produced by fretting is strongly influenced by the environments and works as a lubricant differently in each environment. The coefficients of friction are in the order air, deionized water, seawater.

When the amplitude is 120 μm, the coefficient of friction in air rises as far as 20 cycles and de-

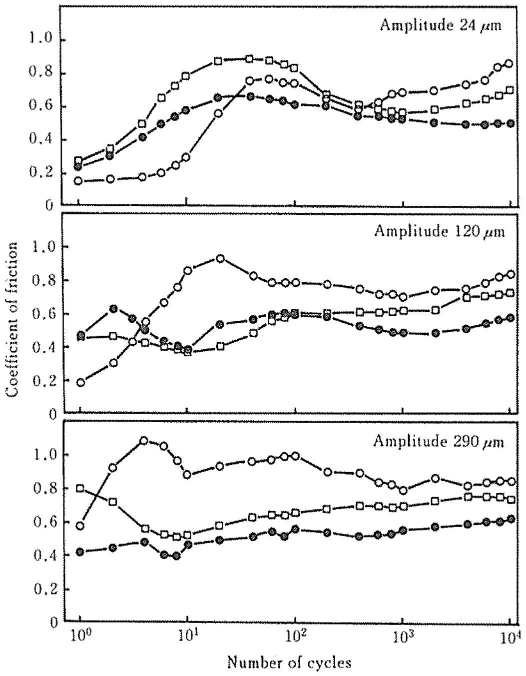


Fig. 4. The behaviour of the coefficients of friction in each of the amplitudes and environments.
○ : in air, □ : in deionized water, ● : in seawater.

creases a little, then becomes roughly constant. In deionized water and seawater, the effect of the lubrication caused by liquid is more apparent than that caused by the stains and oxide films from the initial stage of fretting. The coefficients of friction in these environments are rather lower than that in air. The relationship of all the coefficients of friction in each of the environments is variable until 200 cycles, but thereafter their relationship is the same as for amplitude 24 μm.

In the case of the large amplitude 290 μm, which does not have the overlap of a contacting surface, the stains and oxide films are removed in the first few cycles. This effect can be seen especially in air. The behaviour of the coefficients of friction in deionized water and seawater shows a similar tendency at amplitude 120 μm.

3·2 Direct observation of phenomena with optical microscope

When the static contact between the steel ball and glass under loaded condition is observed with an optical microscope, as shown in Fig. 5, Newton rings of concentric circles can be seen. The inner black area is contacting surface. The measured diameter of the contact area is 156 μm.Therefore, the calculated diameter 158.6 μm, from the Hertzian theory, agrees with the measured value .

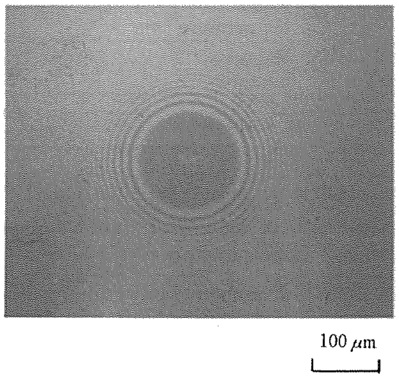
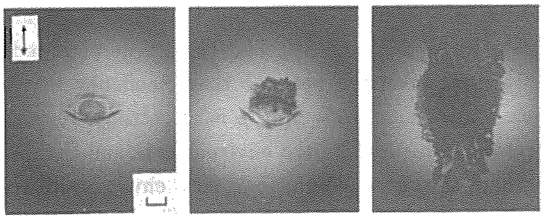


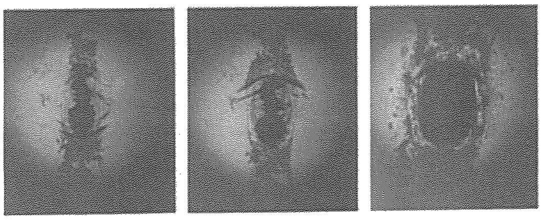
Fig. 5. The optical micrograph of the static contact between the steel ball and glass under loaded condition.

The progression of fretting damage in air is shown in Fig. 6. When the amplitude is 14 μm, cracks occur on the glass until 50 cycles. One or two cracks appear symmetrically around the edge of the contacting surface. The stains and oxide films on the surfaces are destroyed and wear debris is produced with the increasing adhesion between the surfaces in the early stage of fretting . The removal of the wear debris from the contacting surfaces begins at about 1000 cycles.As shown in the optical micrograph at 10000cycles, the contacting surfaces are completely covered with the wear debris, much of which is continuously removed after 1000 cycles. This progression of fretting damage can explain the behaviour of the friction force shown in Fig.4. In the case of amplitude 140 μm,many cracks occur simultaneously when the specimens are fretted.



50 cycles 100 μm 10^3 cycles 10^4 cycles

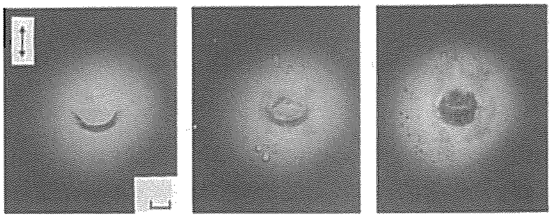
(a) Amplitude 14 μm



50 cycles 10^2 cycles 10^3 cycles

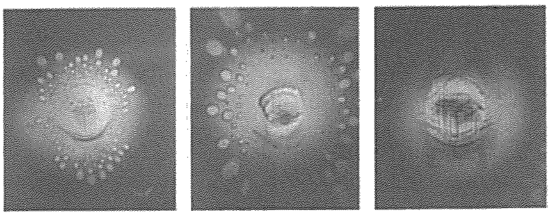
(b) Amplitude 140 μm

Fig. 6. The progression of fretting damage in air.



50 cycles 100 μm 10^3 cycles 10^4 cycles

(a) Amplitude 14 μm



50 cycles 10^3 cycles 10^4 cycles

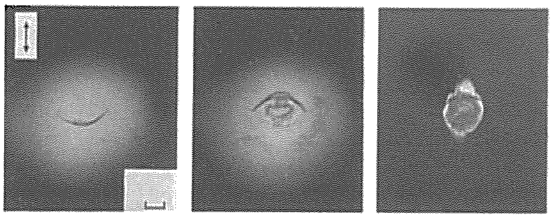
(b) Amplitude 140 μm

Fig. 7. The progression of fretting damage in deionized water.

This is because the maximum principal stress varies successively due to the slip[17]. The wear debris is produced and removed from the contacting surfaces within a few cycles. The fretting damage is much more extensive than at amplitude 14 μm. An optical micrograph of the cntacting surfaces after 1000 cycles could not be taken because they were covered with too much wear debris. The wear debris on the surfaces was mainly a reddish brown colour. That removed from the contacting surfaces was a brownish black colour.

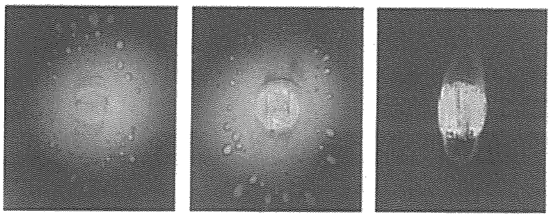
The progression of fretting in deionized water is shown in Fig.7. The cracks in deionized water at amplitude 14 μm occur earlier than the cracks in air at the same amplitude. It can be understood that this is because the coefficient of fricition in deionized water is bigger than that in air in the initial period of fretting , as shown in the diagram of amplitude 24 μm in Fig.4. The wear debris is produced more slowly than in air. Slight wear debris can be observed at 3000 cycles. Some of the wear debris diffuses to the water and also adheres to the steel ball. At amplitude 140 μm, many cracks occur in the first few cycles and many bubbles are produced at the same time. The amount of damage on the glass in deionized water is almost the same as the amount in air. Most of the wear debris removes itself easily from the contacting surfaces and diffuses to the water. The wear debris was generally a brown colour. But the wear debris stuck to both ends of the contacting surfaces, as shown in the optical micrograph at 10000 cycles, was a green colour. This green wear debris was also observed in seawater.

The phenomena of fretting in seawater, as shown in Fig.8, are similar to the phenomena in deionized water. Though the amount of damage on the glass in seawater at amplitude 14 μm is the same as the amount in deionized water, the damage at amplitude 140 μm is less than that in deionized water. The wear debris was mainly a brownish black colour. Some of the wear debris removes itself to the seawater and some stays on the contacting surfaces at the small amplitudes. But in the case of large amplitudes, the wear debris removes itself completely and the slip region has a metallic lustre. The area of the steel ball not in contact with the glass is lit-



50 cycles 100 μm 10^3 cycles 10^4 cycles

(a) Amplitude 14 μm



50 cycles 10^3 cycles 10^4 cycles

(b) Amplitude 140 μm

Fig. 8. The progression of fretting damage in seawater.

tle corroded in deionized water, but greatly corroded in seawater.

When oscillatory motions are given, many bubbles are produced in deionized water and seawater. It can be understood that the bubbles are the dissolved air in the water. Detailed observation shows that the bubbles are caused by cracks produced on the glass. When many cracks occur on the opposite side to the direction in which the steel ball is moving, many bubbls (under 10 μm in diameter) are produced in the cracks. When the direction of slip turns the opposite way and the cracks close, the bubbles are pushed out by the steel ball in the direction of slip. While these bubbles are being exhausted, they grow bigger by joining the other small bubbles. Therefore, the bubbles distributed on the outside are larger and also smaller in number. Some bubbles are dissolved again in water and disappear. More bubbles are produced in deionized water than in seawater. This is because the damage on glass in deionized water is greater than that in seawater.

3·3 The effect of environments on fretting wear

The relationships between the wear volume and number of cycles at amplitudes 14 and 275 μm are shown in Figs. 9 and 10. The results at amplitude 120 μm are omitted because their tendency is the same as at amplitude 275 μm. Fretting wear is strongly influenced by the environments and the differences of the wear volume in each environment increase with the number of cycles. The wear volume in air is the greatest, followed decreasingly by that in deionized water and that in seawater. This result is the same as the relation of the coefficients of friction in Fig.4.

In the case of amplitude 14 μm, as seen in Fig.9, the initial wear rates in each environment are high until 10000 cycles and then the wear rates in air

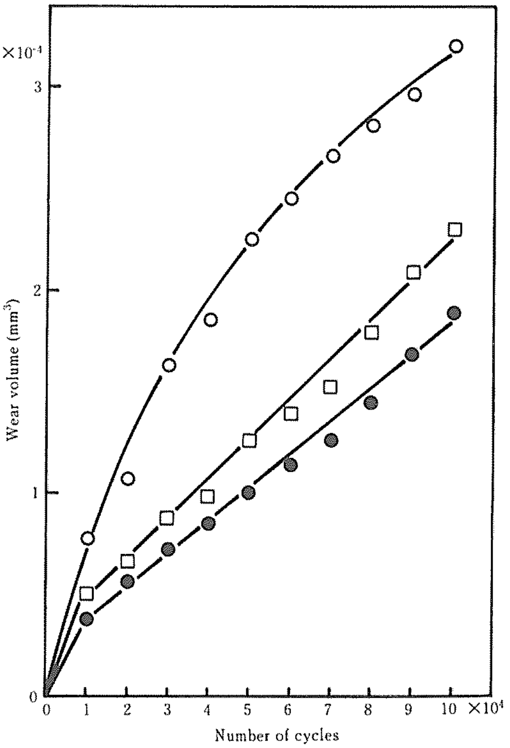


Fig. 9. The relationship between the wear volume and number of cycles at amplitude 14 μm.
○ : in air, □ : in deionized water, ● : in seawater.

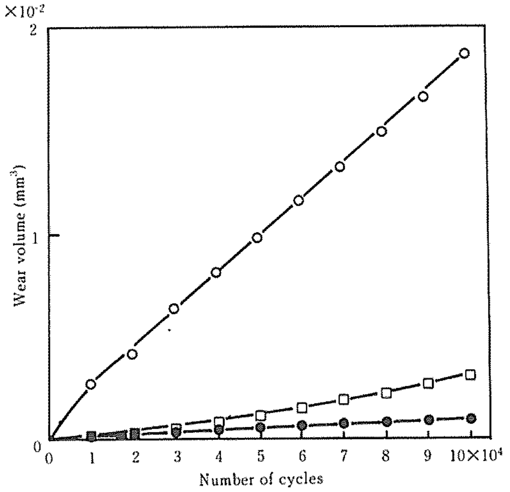


Fig. 10. The relationship beween the wear volume and number of cycles at amplitude 275 μm.
○ : in air, □ : in deionized water, ● : in seawater.

decrease, but those in deionized water and seawater are constant. The wear volumes at amplitude 275 μm increase linearly with the number of cycles in each environment.

Figure 11 shows the relationship between the wear volume and amplitude. The differences of the wear volumes in the different environments increase with the increasing amplitudes. Figure 12 shows the relationship between the specific wear rate and amplitude. The specific wear rate is the wear volume which is divided by the load and sliding distance. The specific wear rate in air increases linearly until amplitude 120 μm, then becomes saturated. The results in air suggest that there is a critical amplitude, as pointed out by Ohmae[18]. Namely, the oxide wear debris works as a protection against fretting action below the critical amplitude but works as an abrasion and accelerates the wear above the critical amplitude. The specific wear rates in deionized water and seawater are far less than that in air and decrease a little with the increasing amplitudes. The results in aqueous environments suggest that

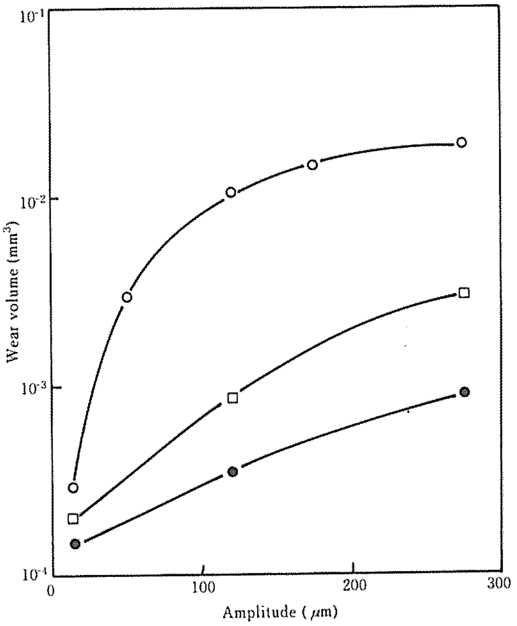


Fig. 11. The relationship between the wear volume and amplitude after 10^5 cycles.
○ : in air, □ : in deionized water, ● : in seawater.

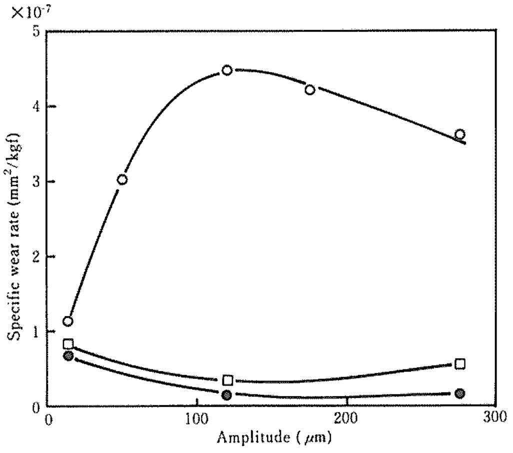


Fig. 12. The relationship between the specific wear rate and amplitude after 10^5 cycles.
○ : in air, □ : in deionized water, ● : in seawater.

the adhesion between the contacting surfaces decreases because of liquid, that the wear debris is especially corroded in seawater and that the corrosion products work as a lubricant. As shown in Fig. 13, the above mentioned observations can be seen from the SEM micrographs of the steel ball. However, the corrosion products have not been investigated in these tests. In the analysis on ordinary continuous sliding wear by Yahagi[12,13], β and γ-FeOOH, Fe_3O_4, $FeCl_2$-nH_2O, $FeCl_3$-nH_2O, etc. were detected. It was said that the concentration of Cl^- ions influenced these corrosion products. The corrosion products in our tests may consist of some of the corrosion products mentioned above.

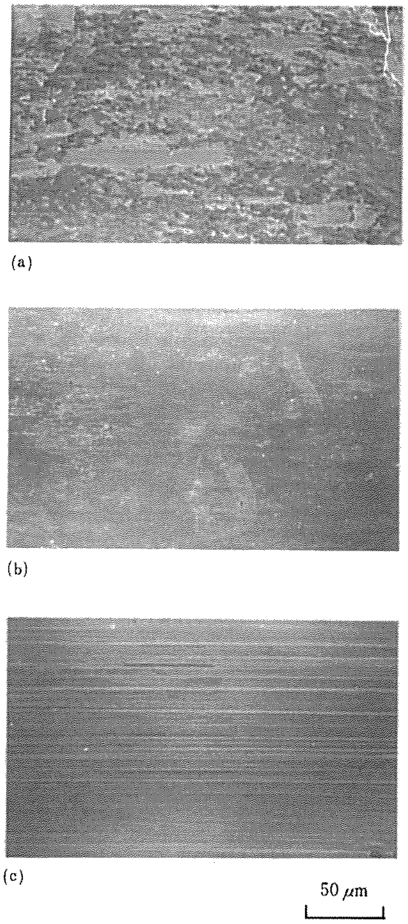


Fig. 13. SEM micrographs of the steel ball in various environments.
Amplitude 140 μm, frequency 5 Hz, 10^5 cycles.
(a) in air, (b) in deionized water,
(c) in seawater.

In the past, Wharton[15] reported that the corrosion wear products formed in 1% NaCl solution conferred some protection against fretting action. Pearson[14] found that the fretting damage in synthetic seawater was greater than that in air. On the other hand, according to the tests on ordinary continuous sliding wear, Endo[10] showed that the wear in 1% NaCl solution was greater than that in deionized water. It was reported by Iwai[11] that the wear rate in aqueous environments was greatly influenced by the load. Namely, under high load the wear rate in deionized water was greater than that in NaCl solution, but opposite results were obtained under low load. Yahagi[12, 13] carried out the tests in deionized water and NaCl solution (from 0.01 wt% to 25 wt%) and reported that the wear rate on SUJ-2 steel in 3 wt% NaCl solution was the greatest. The wear rate of SUS316 reached the peak in 0.1wt% NaCl solution. As mentioned above, it can be understood that the effect of the environments on fretting wear and ordinary continuous sliding wear is greatly changed by various factors; the conditions of friction, the configuration of wear, materials, etc. Therefore, the effect of these environments can not be used to clearly distinguish the fretting wear from the ordinary continuous sliding wear.

4. Conclusions

Fretting tests of a steel ball vs glass were carried out in various environments. The following results were obtained.

(1) The wear debris produced by fretting was strongly influenced by the environments and behaved itself like a lubricant differently in each environment. The coefficients of friction decreased in the order air, deionized water, seawater.

(2) In the aqueous environments, the fluid lubricating condition was observed and most of the wear

debris removed itself easily from the contacting surfaces at the large amplitudes.

(3) Green wear debris was observed in deionized water and seawater.

(4) The wear rate was the highest in air, lower in deionized water and the lowest in seawater.

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フレッチング摩耗に及ぼす海水の影響

竹内正明・井上進夫・佐藤準一

船舶や海洋機器等では，海水による腐食性環境下でフレッチング損傷が生じる。しかし，一般のすべり摩耗については食塩水による腐食の影響を調べた報告はいくらかあるが，環境の影響を強く受けるフレッチングについての報告は非常に少ない。本研究では，鋼球（SUJ-2軸受鋼）とガラス（JIS3210窓用ガラス）のフレッチング試験を大気中，純水中，海水中で行ない，フレッチング摩耗に及ぼす海水の影響を調べた。その結果，摩耗粉は環境の影響を強く受け，各環境によって異なった潤滑効果を示すこと，比摩耗量は大気中が最も高く，続いて純水中，海水中の順となることなど明らかとなった。