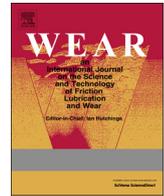




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Dynamic corrosion properties of impact–fretting wear in high-temperature pure water

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ABSTRACT

Dynamic corrosion is defined as the corrosion that occurs under mechanical actions such as sliding friction, which exposes fresh surfaces and accelerates wear. To estimate the corrosive wear properties of austenitic stainless steel in pure water, impact-fretting wear tests of Type 304 stainless steel disks against Al₂O₃ balls were performed, and polarization tests were carried out. A scanning electron microscope (SEM), electron-probe micro-analyzer (EPMA), atomic force microscope (AFM), and three-dimensional (3D)-profilometer were used for observation, analysis, and measurement of wear scars. The maximum wear depth of the disk increased with an increase in both water temperature and oxidation time for temperatures below 100 °C. However, the maximum wear depth decreased at 130 °C due to the intact oxide layer adhered to the wear scar of the Type 304 disk. We proposed a wear model for impact-fretting, which showed that dynamic corrosion agreed with the parabolic law of oxidation of metals and the thermal activation process. To specify the process of dynamic corrosion, the activation energy was obtained from the change in the electric current density at different water temperatures using the potential pulse method (PPM) in Na₂SO₄ solution. The activation energy was approximately the same as that obtained by impact-fretting wear tests in pure water. As a result, the oxide removal efficiency from the fresh surface was less than 10%, and the corrosion of the fresh surface in pure water was caused by electrochemical dissolution according to the micro-cell formation.

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1. Introduction

The surfaces of austenitic stainless steels are usually covered with a thin oxide film, which improves the corrosion resistance of the surface in static conditions. These films are typically well-known passive films. Passive film inhibits corrosion, prohibiting the dissolution of metallic ions or the diffusion of oxygen ions through the film. However, the formation of passive films (passivation) also follows the same reaction process. Thus, the formation of passive layer depends on the electro-chemical reactions in solution.

Corrosion-resistance materials, including austenitic stainless steels, were used to expand the reactor components life-time in nuclear power plants. Also, these reactor components have been generally used in low electrical conductivity solutions such as pure water. However, corrosion certainly occurs in those environments. For example, serious corrosion is identified at the contact points between the control rod and guide card under water surging [1],

at the fixed components of heat transfer tubes [2] and cooling pipes under vibration in many power stations [3–10].

In addition, passive films are easily broken due to mechanical stresses such as contacting, sliding, or impinging [11,12]. The fresh surfaces exposed by such mechanical factors have very high chemical activity, and severe corrosion occurs there. Thus, even though austenitic stainless steels are employed, the steel suffers from severe wear, reducing the life-time of machine components under specific conditions.

The corrosion of the fresh surface is called “dynamic corrosion” [13,14] because of the synergy between mechanical wear (delamination or abrasion with friction) and corrosion. The synergistic effects of corrosive wear are known to play an important role in the wear of materials. The corrosive wear volume W is normally defined by the following equation [14]:

$$W = M_0 + C_0 + \Delta W \quad (1)$$

where M_0 is the pure mechanical wear volume, C_0 is the pure (static) corrosion volume, and ΔW is the synergistic factor. The dynamic corrosion factor W_d on a fresh surface is written as

$$W_d = C_0 + \Delta W \quad (2)$$

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The synergistic factor ΔW involves both ΔC_M and ΔM_C . Here, ΔC_M is the mechanical-assisted corrosion factor, indicating the corrosion volume on the fresh surface exposed by mechanical factors. Moreover, ΔM_C is the corrosion-assisted mechanical wear, describing the effect of oxide film removal on the wear scar. Depending on the condition, these oxide films could either reduce wear by lubricating or accelerate wear by abrasion. Therefore, the corrosive wear volume is expressed as follows [14–17]:

$$W = M_0 + W_d = M_0 + C_0 + \Delta C_M + \Delta M_C \quad (3)$$

Schematic diagrams of these wear factors are shown Fig. 1.

We have previously studied this phenomenon by focusing on the removal and formation of the oxide film on a steel surface using an impact-fretting tribometer [18,19]. Impact fretting is the impact motion added to the small sliding motion, fretting, as illustrated in Fig. 2. Oxidation is expected to easily occur on the fresh surface due to mutual separation between specimens.

In this study, we plan to clarify the synergistic effects of corrosive wear in more detail. This study describes the significant differences in impact-fretting wear by comparing impact-fretting wear with pure impact or with fretting. We then perform experiments on the effects of water temperature and oxidation time on impact-fretting wear in pure water. Finally, from the electrochemical behavior of the specimen in corrosive solution, the relationship to impact-fretting is considered. The potential pulse method (PPM) is used to evaluate the polarization measurements in this work.

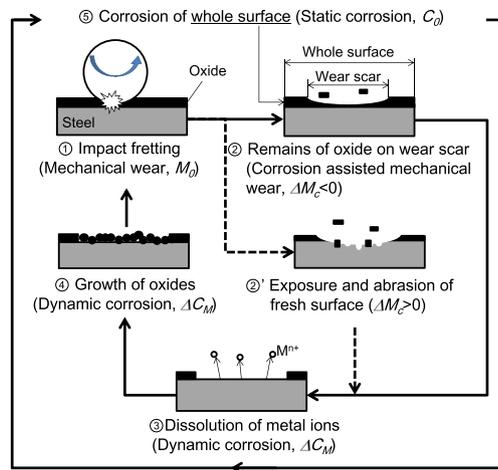


Fig. 1. Schematic diagram showing the corrosive wear process on impact-fretting wear.

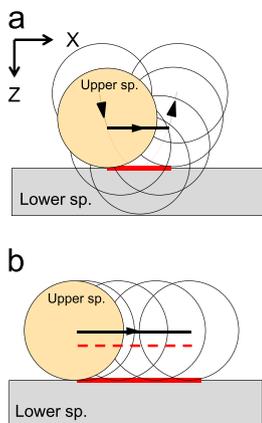


Fig. 2. Schematic diagram showing the motion of impact fretting and fretting. (a) Impact fretting. (b) Fretting.

2. Corrosive wear model

In oxide film growth on a steel surface, the film thickness d [m] is given by the oxidation law of metals [20] as

$$d = k\tau^\alpha \quad (4)$$

where k [m/s $^\alpha$] is the chemical reaction constant of specimen materials that is dependent on environmental conditions, τ [s] is the oxidation time, and the exponential index α represents the degree of oxidation rate. In this work, if the corrosive wear volume (Eq. (3)) can be applied as the wear parameter to the maximum wear depth of impact-fretting, Eq. (4) governs the values of ΔC_M and C_0 . Furthermore, the parameter k follows the Arrhenius equation [20] as

$$k = A_0 \exp\left(\frac{-Q}{RT}\right) \quad (5)$$

where A_0 [m] is the frequency factor, Q [J/mol] is the activation energy, R is the gas constant (8.31 J/mol K), and T [K] is the absolute temperature. Then, Eq. (4) becomes

$$k = A_0 \exp\left(\frac{-Q}{RT_0}\right) \quad (6)$$

If the surface oxide is removed by repeated friction, then, the corrosive wear depth can be expressed as the depth d multiplied by the number of cycles N . If it is assumed that the surface depassivates with each cycle of impact-fretting wear, then ΔC_M and C_0 in Eq. (3) can be written as

$$C_0 + \Delta C_M = dN = k\tau^\alpha N = A_0 \exp\left(\frac{-Q}{RT}\right) \tau^\alpha N \quad (7)$$

where τ represents the period between impacts. However, if there is inefficient depassivation due to a particularly thick oxides or low contact pressure, then Eq. (7) will be difficult to apply.

The effect of the corrosion products on wear is represented by ΔM_C , and can potentially inhibit the effect of ΔC_M . However, ΔM_C cannot be obtained directly. Therefore, in this work, ΔM_C is included as follows:

$$\Delta W = \Delta C_M + \Delta M_C = \Delta C_M + (\eta - 1)\Delta C_M = \eta \Delta C_M \quad (8)$$

where η is the removal efficiency of oxides, indicating the removal fraction of oxides per impact. When the oxide layer was completely removed from the wear scar by an impact, η takes the value of unity. On the other hand, when some amount of oxide remains on the wear scar, η has a value less than unity.

Although C_0 depends on Eqs. (4) and (5), the oxide thickness is expressed by the following equation:

$$C_0 = kt^\alpha \quad (9)$$

where t [s] is the total test time. Because the effect of the static corrosion factor C_0 is generally negligibly small for corrosive wear in pure water [11,14,17], the wear depth of dynamic corrosion W_d is related only to ηC_M in Eq. (2).

Here, the pure mechanical wear M_0 is defined as

$$M_0 = aN \quad (10)$$

where a is the mechanical wear depth per impact on impact fretting. This mechanical wear depth is not affected by chemical factors and depends on only the number of impacts N under constant load, constant sliding amplitude, and constant sliding velocity. As a result, we propose the following corrosive impact-fretting wear model:

$$W_{depth} = M_0 + C_0 + \eta \Delta C_M = aN + \eta k\tau^\alpha N = aN + \eta A_0 \exp\left(\frac{-Q}{RT}\right) \tau^\alpha N \quad (11)$$

where W_{depth} is the corrosive wear depth.

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