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Fretting Wear Mechanisms of Zircaloy-4 and Inconel 600 Contact in Air

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The fretting wear behavior of the contact between Zircaloy-4 tube and Inconel 600, which are used as the fuel rod cladding and grid, respectively, in PWR nuclear power plants was investigated in air. In this study, number of cycles, slip amplitude and normal load were selected as the main factors of fretting wear. The results indicated that wear increased with load, slip amplitude and number of cycles but was affected mainly by the slip amplitude. SEM micrographs revealed the characteristics of fretting wear features on the surface of the specimens such as stick, partial slip and gross slip which depended on the slip amplitude. It was found that fretting wear was caused by the crack generation along the stick-slip boundaries due to the accumulation of plastic flow at small slip amplitudes and by abrasive wear in the entire contact area at high slip amplitudes.

Key Words: Fretting, Wear Volume, Specific Wear Rate, Partial Slip, Plastic Flow, Abrasive Wear

1. Introduction

Fretting is generally known as the wear phenomena generated between two surfaces with an oscillatory motion of small amplitude(Waterhouse, 1975). Since fretting damage is mostly due to incidental microscopic vibration, catastrophic failure of mechanical components and structures can be caused if such an unexpected fretting damage is accumulated.

Nuclear energy has been developed as a high-efficient and stable energy supply since the 1970's. However many problems have been found in nuclear power plants. In this country, commercial atomic power generation was first started in 1978, and since then 288 problems have been reported in 11 nuclear reactors till 1996. To solve these problems, a lot of intensive researches have been pursued including works on fretting(Ko, 1979). Steam generators, nuclear reactors and other heat exchangers in nuclear power plants have been designed to maintain their stability in operation, yet many examples have been reported where serious tube damage has occurred due to the friction and wear caused by flow-induced vibration between the tubes and the grids (Fisher et al., 1995, Ko, 1985 and Cha et al., 1987). Flow-induced vibration with high temperature and high pressure, which was not considered in the design, is generated in the tube systems of the nuclear reactor and heat exchangers, resulting in the failure of the tube systems. Even now, no general solution of fretting damage is found because it is very difficult to analyze the problem in spite of its importance.

The fuel rod claddings in nuclear reactors are supported by lattices, which are called spacer grids. These spacer grids support 11 points on the

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Table 1 Chemical composition and mechanical properties of Zircaloy-4 tube

Chemical elements (wt. %)					
Sn	Fe	Cr	C	O	Zr
1.25	0.21	0.11	0.0153	0.134	Balance
Mechanical Properties (Room temp.)		UTS (MPa)	0.2% YS (MPa)		Elongation (5.00 cm)
		696	517		24 %

Table 2 Chemical composition and mechanical properties of Inconel 600 tube

Chemical elements (wt. %)					
Cr	Fe	Mn	Al	Ti	Ni
15.45	8.3	0.2	0.14	0.3	75.4
Mechanical Properties (Room temp.)		UTS (MPa)	0.2% YS (MPa)		Elongation (5.00 cm)
		552	241		30 %

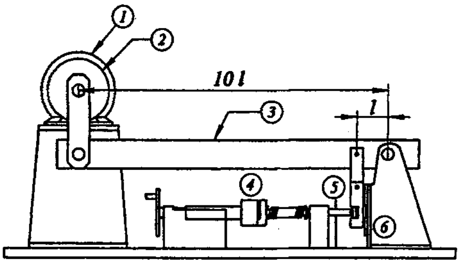


Fig. 1 Schematic diagram of fretting wear tester

(1) motor (2) eccentric plate
(3) vibrating beam (4) load cell
(5) specimens (6) LM guide

fuel rod claddings at uniform intervals longitudinally. The bottom of the spacer grids is composed of Inconel and the rest is Zircaloy-4. Studies on contact between Zircaloys has received a lot of focus (Vingsbo et al., 1996). However, research related to the Zircaloy-Inconel contact has been insignificant. Therefore, the purpose of this study was to perform a fretting wear experiment using Zircaloy-4 tubes as fuel rod claddings and Inconel 600 whose material is similar to that of the spacer grids and to find the transition point where the fretting behavior varies with the load, slip amplitude and number of cycles.

2. Descriptions and Experiment

2.1 Fretting wear tester

A fretting wear tester, as shown in Fig. 1, was designed and manufactured for this research. The adjusting plate attached to the motor shaft controlled the eccentricity. Because the distance from the motor shaft to the fixed shaft was exactly 10 times as long as that from the contact point of the specimens to the fixed shaft, the specimens actually moved only 1/10 of the eccentric amount. Further details of this fretting wear tester can be found elsewhere(Cho et al., 1998).

2.2 Specimens

The moving specimens in this study were Zircaloy-4 tubes for the fuel rod cladding material and the stationary specimens were Inconel 600 tubes as used in PWR-type nuclear power plants. The chemical elements and mechanical properties are shown in Tables 1 and 2, respectively. A cylinder-to-cylinder contact at a right angle was used for the wear rig, as shown in Fig. 2.

2.3 Experimental procedure

To examine the influence of the slip amplitude, load, and number of cycles, the slip amplitude was classified into six steps(40, 70, 100, 200, 300,

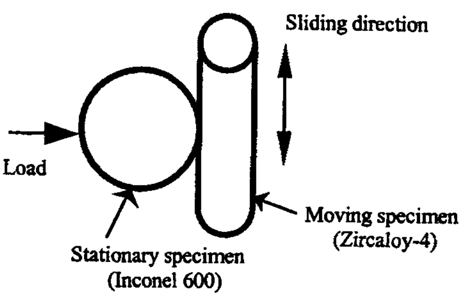


Fig. 2 Schematic illustration of contact geometry

400 µm) and the load into five steps(20, 40, 60, 80, 100 N). The experiments were carried out over three cycle lengths; 5×10^4, 1×10^5, and 3×10^5 cycles. The frequency of the specimen vibration was 10 Hz for all experiments.

3. Results and Discussions

3.1 Change of wear with increase in number of cycles

Figures 3 and 4 show the changes in the wear volume relative to the number of cycles with various slip amplitudes at the load of 40 N. It can be seen that the wear volume increases with increase in the slip amplitude for both Zircaloy-4 and Inconel 600. This is probably due to the increase in the total sliding distance as the number of cycles increases.

The wear from the initial stage of the experiment to 5×10^4 cycles changed much more abruptly than that from 5×10^4 cycles to 1×10^5 cycles or that from 1×10^5 cycles to 3×10^5 cycles.

Theoretically, point contact occurs at the initial stage of the test. But as the wear progressed, the contact area between the two specimens, Zircaloy-4 and Inconel 600, increases. As a result, the contact pressure decreases and the wear at the initial stage changes more rapidly than in the later stage.

It is shown in Figs. 3 and 4 that the wear at the slip amplitudes of 40, 70 and 100 µm were very small compared with those at other slip amplitudes, and the wear hardly increased at such small slip amplitudes even though the total sliding distance increased further. The slip amplitude(100 µm) showing this transition is defined as the critical slip amplitude.

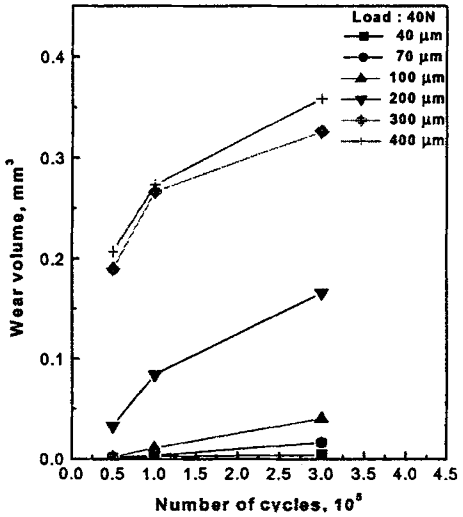


Fig. 3 Wear volume as a function of number of cycles for each slip amplitude at 40 N (Zircaloy-4)

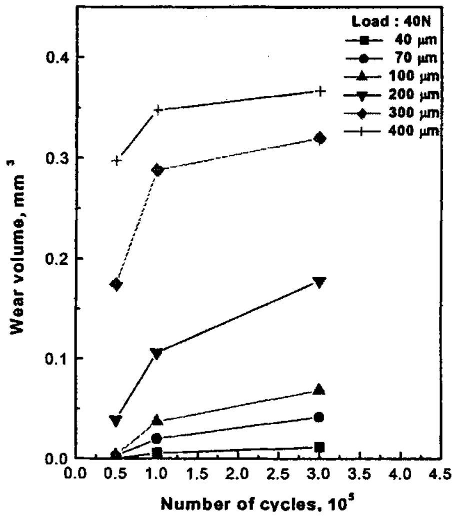
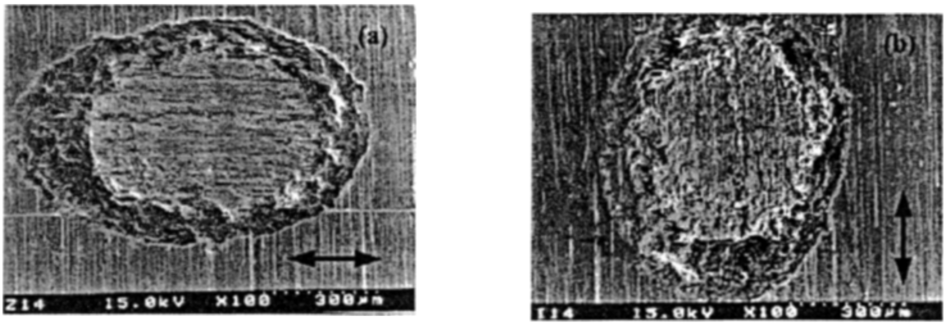


Fig. 4 Wear volume as a function of number of cycles for each slip amplitude at 40 N (Inconel 600)

Figure 5 (a) and (b) are the photographs of the worn surfaces of Zircaloy-4 and Inconel 600, respectively, after sliding for 3×10^5 cycles with a slip amplitude of 40 µm and a load of 100 N. These photographs show partial slip at relatively smaller slip amplitudes and larger normal loads. The central lightly shaded area, called the stick



(a) Zircaloy-4, 40 μm, 100 N, 3×10^5 cycles (b) Inconel 600, 40 μm, 100 N, 3×10^5 cycles

Fig. 5 SEM photograph showing the partial slip

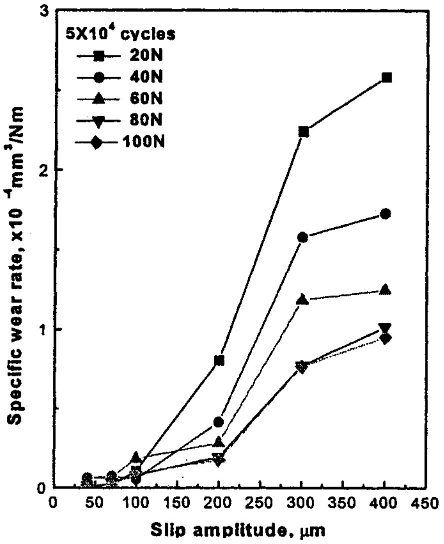


Fig. 6 Specific wear rate as a function of slip amplitude for each normal load at 5×10^4 cycles (Zircaloy-4)

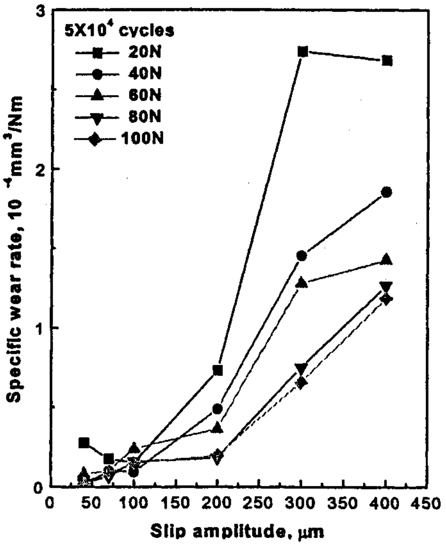


Fig. 7 Specific wear rate as a function of slip amplitude for each normal load at 5×10^4 cycles (Inconel 600)

region, in the middle of the contact area had almost the same surface feature as the non-contact region. This revealed that almost no wear occurred in the central region, even though the experiment was carried out for as long as 3×10^5 cycles.

It would appear that for very small slip amplitudes the central region of the contact area only experienced elastic deformation and the plastic deformations caused by slip only occurred at the edge of the contact area. Accordingly, the wear hardly progressed when the slip amplitude was below 100 μm regardless of the load and number of cycles. This result suggested that fretting damage could be prevented if the slip amplitude is controlled to below 100 μm.

3.2 Observation of specific wear rate

Figures 6 and 7 show the change in the specific wear rate for various slip amplitudes after an experiment of 5×10^4 cycles. The specific wear rate can be calculated based on the value where the wear volume is divided by the load and total sliding distance. This is often used to understand the wear characteristics. In most cases for the experiments conducted in this work, the specific wear rate decreased with an increase in the normal load.

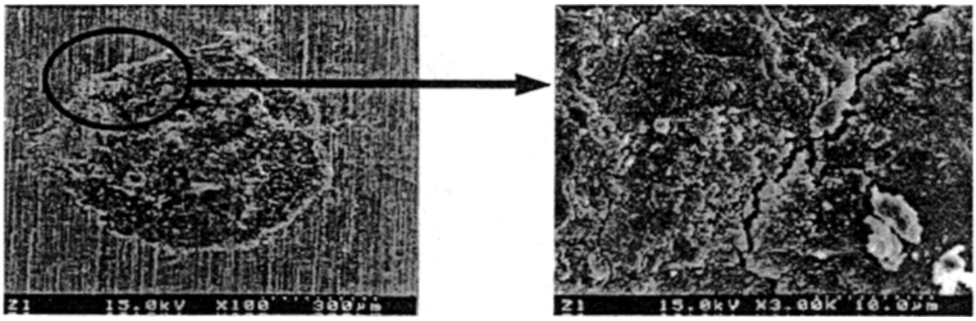


Fig. 8 SEM photograph showing crack generation (Zircaloy-4, 40 µm, 20 N, 1×10^5 cycles)

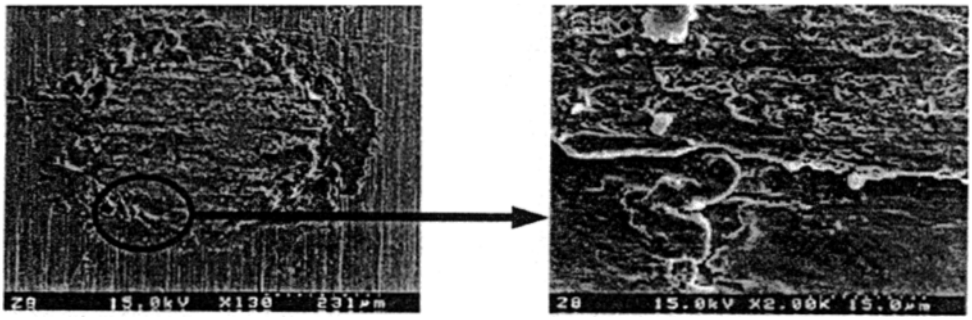


Fig. 9 SEM photograph showing debris generation by accumulation of plastic flow(Zircaloy-4, 40 µm, 60 N, 3×10^5 cycles)

In particular, it was found that for slip amplitudes above 100 µm the specific wear rate began to increase and the slope of the specific wear rate was the steepest between the amplitudes of 200 µm and 300 µm, as shown in Figs. 6 and 7. This remarkable increase in the specific wear rate corresponded to the gross slip stage when the change in the wear volume also increased abruptly and reached the maximum value. However, for slip amplitude above 300 µm the gross slip developed into sliding and the gradient of the specific wear rate became slow. Hence, in this experiment the slip amplitude of the fretting regime was confined to below 300 µm.

3.3 Microscopic observation of worn surface

In general there are three stages in fretting wear, such as stick, partial slip, and gross slip. Stick is the first stage of fretting and hardly any wear of the surface occurs at this stage(Vingsbo, 1988). Partial slip is the stage when no wear occurs in the contact area and stick and slip coexist on the contact surface. In this stage no wear occurs in the stick region but only in the slip region. Also, crack initiation is vigorous at the boundaries between the stick and the slip regions. In the stage of gross slip, the stick region disappears and slip occurs across all the contact area. In this stage the wear volume increases remarkably.

To observe the fretting wear stages and microscopic characteristics of the worn surfaces, a scanning electron microscope (SEM) was used. Figure 8 shows the crack generation and propagation on the contact area at relatively low slip amplitudes and loads. Cracks were generated near the boundaries between the contact and the non-contact area, however the position of crack generation moved into the boundaries of mixed stick-slip region as the normal load increased as shown in Figs 9 and 10.

Figures 9 and 10 also showed that the cracks were generated by accumulation of plastic flow at lower slip amplitudes. However, at higher slip amplitudes wavy surfaces were observed in Fig.

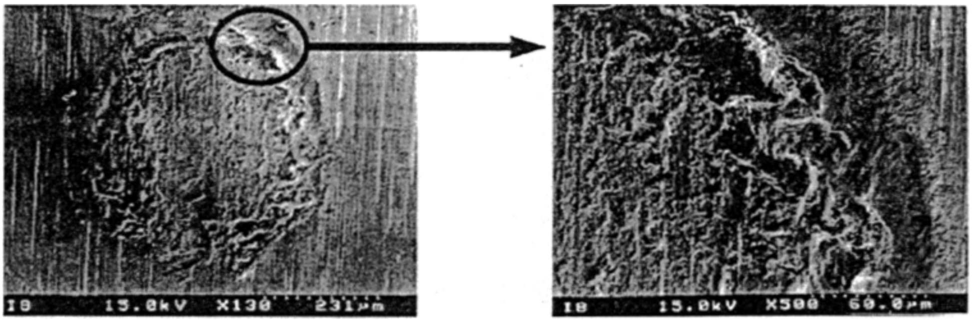
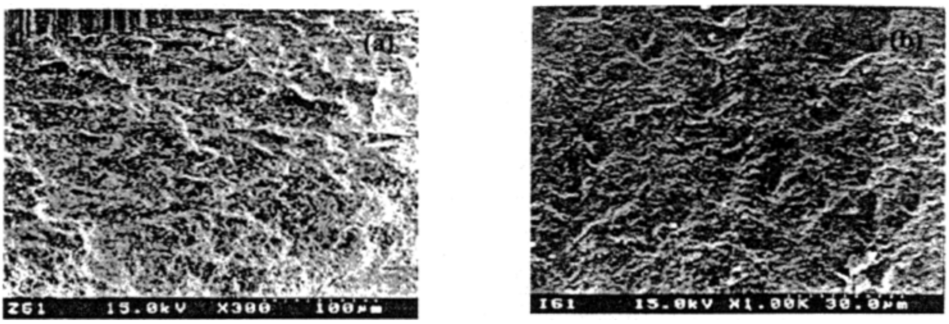


Fig. 10 SEM photograph of accumulation of plastic flow(Inconel 600, 40 μm, 60 N, 3×10^5 cycles)



(a) Zircaloy-4, 300 μm, 20 N, 1×10^5 cycles (b) Inconel 600, 300 μm, 20 N, 1×10^5 cycles

Fig. 11 Wavy surfaces by abrasive wear at higher slip amplitude

11, suggesting that the surface was mainly worn by abrasive wear.

Therefore, the fretting wear mechanisms of this study can be described by two phenomena: crack generation and propagation along the boundaries due to accumulation of plastic flow at smaller slip amplitude (i. e. below 100 μm) and the abrasive wear on the whole contact area at higher slip amplitude.

4. Conclusions

The main results from the fretting wear investigation with Zircaloy-Inconel contact in air were as follows:

(1) The gradient of the wear volume becomes less steep with an increase in the number of cycles because the contact pressure decreases due to growth in the contact area.

(2) The transition slip amplitude was investigated above which the wear increased abruptly. The transition slip amplitude of this study was about 100 μm.

(3) The crack generation and propagation along the boundaries due to accumulation of plastic flow dominated the fretting wear mechanism when the slip amplitude is small (i. e. below 100 μm).

However the fretting wear mechanism was mainly governed by the abrasive wear on the whole contact area when the slip amplitude was high.

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