

SLIDING WEAR AND FRICTION BEHAVIOR OF ZIRCONIUM ALLOY WITH HEAT-TREATED INCONEL718

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ABSTRACT

In water cooled nuclear reactors, the sliding of fuel rod can lead to severe wear and it is an important issue to sustain the structural integrity of nuclear reactor. In the present study, sliding wear behavior of Zirconium alloy in dry and water environment using pin-on-disk sliding wear tester was investigated. Wear resistance of zirconium alloy against heat treated inconel718 pin was examined at room temperature. Sliding wear tests were carried out at different sliding distance, axial load and sliding speed based on ASTM G99-05. The results of these experiments were verified with specific wear rate and coefficient of friction. The micro-mechanisms responsible for wear in zirconium alloy were identified to be microcutting and microcracking in dry environment. Moreover, micropitting and delamination were observed in water environment.

INTRODUCTION

Spacer grids are the key components of a Light Water Reactor's (LWR) fuel assembly. The most important function of it is to hold the fuel rods and to maintain the distance between the fuel rods inside the fuel assembly. LWR fuel rods are composed of a thin tube in which uranium dioxide pellets are stacked. Its slenderness ratio is extremely high since its length is around 4m and its diameter is around 1 cm. Therefore, it can vibrate like a string as the coolant passes through the fuel assembly, which is termed as a flow-induced vibration (FIV). This vibration is restrained by its contact with the springs and dimples of a spacer grid.

The design requirements for the contact force between the supports and fuel rods should be sufficient enough to hold the fuel rods but it should be less than that allowing an axial slip of a fuel rod at the contacts during a thermal and irradiation growth. So, a slipping is inevitable on contacts as long as the fuel rods vibrate. This implies that a fuel fretting wear cannot be eliminated completely. The most severe case of a wear is a perforation of a thin (around 0.6mm) fuel rod tube. If it happens, radioactive fission gases, trapped inside the fuel rods during a reactor operation, are released into the coolant, which increases the radioactivity level of the coolant. Even when a perforation does not occur, a thickness reduction due to a wear can decrease the strength of the fuel rods. Therefore, it is required to minimize the wear damage to achieve a fuel with a higher reliability. Solutions to fuel fretting wear are not obtained by simply applying the ordinary tribological remedies such as a lubrication, hard coatings, material change, etc. due to the special requirements of a nuclear fuel. For instance, foreign lubricant should be strictly prohibited for a purity control of a reactor coolant, the heat transfer capability should not be deteriorated which could happen due to a coating. The neutron economy is one of the most important properties for the fuel rod tube material. Alternatively, improving of the support shape can provide a solution [1, 3]. Zirconium and Inconel alloys that are used for spacer grid materials are highly desirable in nuclear applications due to their transparency to thermal energy neutrons and due to their high corrosion resistance. Fretting wear mechanisms are initially dominated by adhesion and abrasion actions and then by delamination and surface fatigue [2].

From further research, most of all studies have been performed with zirconium to zirconium alloy where was mid-section of fuel assembly because the most severe wear occurred at mid-section of fuel assembly. In this study, the combination of contact materials chosen as upper and bottom section of fuel assembly. Also, the wear occurred on the upper grid section of fuel assembly can cause same problem. The zirconium alloy against heat treated Inconel alloy was investigated as to their abrasive wear behavior under various working conditions by the Pin-On-Disk tester. Because it is known that fretting wear initiated by adhesion, and when the particles (debris) are subsequently oxidized, abrasion becomes the primary mechanism. And the reason of using the Pin-On-Disk wear tester is the coolant behavior of upper section of fuel assembly was irregular than mid and bottom section by low

coolant speed and coexistence between different designs of fuel assemblies which installed in the reactor. Sliding distance and velocity, axial load were selected as parameters. From the results of each test, specific wear rate and friction coefficient were evaluated for identifying the relative wear losses. To verifying wear mechanism, worn surface of specimen was observed by Scanning Electron Microscope (henceforth termed SEM).

MATERIALS AND SPECIMENS

The disk specimen was prepared using a Zirconium alloy which applied for fuel rod and wear material with the dimensions of 56 mm diameter, and 0.65 mm thickness. The pin specimen was prepared with the dimensions of 83 mm length, 6 mm diameter. The pin made with Inconel alloy that applied for upper and protective grid material in fuel assembly and to realize the same hardness value like a upper-grid the pin was heat treated about 1200 °C over ten hours. In order to prevent a dislocation of thin specimens under long term testing, an attachment was designed and installed between disc specimen and test apparatus. The schematic views of the disk and pin specimen and jig are illustrated in Fig. 1. The hardness value of the pin and disk specimens are summarized in Table 1.

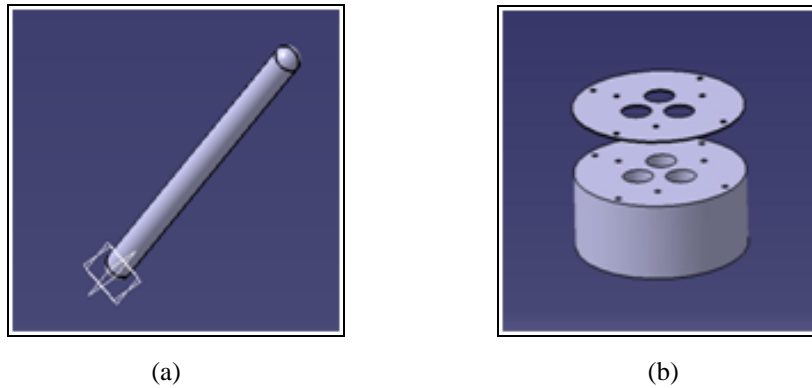


Fig. 1 Configuration of disc, pin specimen and jig
(a: pin specimen; b: disc specimen and jig)

Table 1 Vickers hardness of pin and disc specimens

| Vickers hardness(HV) | | |
|----------------------|-------------------------|-----------------|
| Pin specimen | | Disc specimen |
| Inconel718 | Heat treated Inconel718 | Zirconium alloy |
| 260~* | * ~400~* | 290~* |

EXPERIMENTAL PROCEDURES

In the Pin-On-Disk test, a stationary pin is loaded axially in contact with a rotating disc, as in the schematic sketch shown in Fig. 2. The friction force on the pin can be measured, thus making it easy to compute the friction coefficient. The Pin-On-Disk test machine used in these test is a Se-Jin Pin-On-Disk tester. The tests start at an ambient temperature, 25° C, and the equipment is gradually heated during the measurements. Before the test starts, the surfaces are run in with the dry state. The sliding distance that applies for this parameter was selected as 10,000 cycles for sliding speed variation test and 30,000 cycles for axial load variation test. The disc rotates at a speed of 50

to 550 revolutions per minute with 9.8 N axial load, corresponding to a sliding speed of 0.1047 to 1.1517 m/s. The axial load chosen as 5 to 15 N that range applied for real situation of contact force between rod and grid-spring in a activated reactor. The sliding distance variation test was carried with test conditions of 10,000 to 100,000 cycles, 9.8 N of axial load and 400rpm of sliding speed.

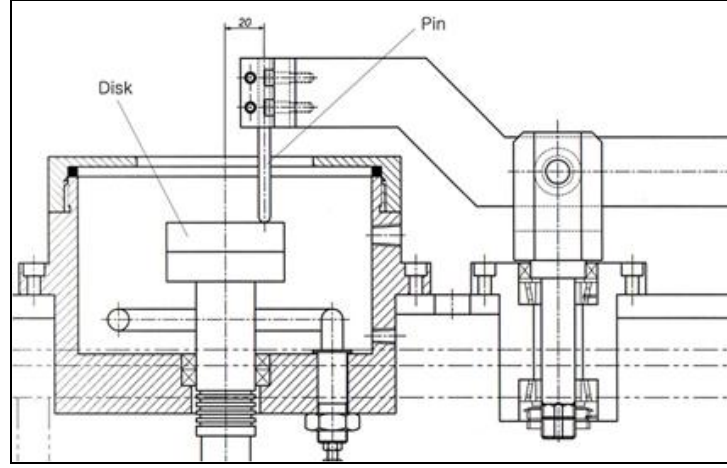


Fig. 2 Schematic diagram of pin-on-disc apparatus.

The result of abrasive wear evaluated by specific wear rate, $\dot{\omega}$ is defined as

$$\dot{\omega} = \frac{\Delta m}{\Delta t} \frac{1}{v \rho F_N} \quad (1)$$

Where Δm is the volume loss by wear, F_N is the normal load applied on the wear surface and Δt is entire of the test time, v is the rotating speed of disc, ρ is density of the specimen. The meaning of specific wear rate is the rate of material removal or dimensional change due to wear, per unit of kinetic energy [4, 5].

$$\mu = \frac{F_f}{F_N} \quad (2)$$

Friction coefficient describes the ratio of the force of friction between two bodies and the force pressing them together [4]. The friction force between surface and pin specimen was measured by torque-load cell during the test. In dry friction, the Amonton-Coulomb's law was applied and the friction coefficient calculated like Eq. 2.

$$volumeloss, mm^3 = \frac{mass\ loss, g}{density, g/cm^3} \times 1000 \quad (3)$$

Eq.3 is equation for conversion of mass loss to volume loss. The disc specimen was cleaned by acetone in ultra-sonic one-hour before and after test to measure the precise mass of them.

RESULTS AND DISCUSSION

The sliding wear test carried out with three working conditions which were skidding distance, speed and axial load. The results of test in dry environment compared with in water condition. Fig. 3 shows the data plots of sliding speed variation test. Sliding speed were increased 50 rpm to 550. The specific wear rate and volume loss

shows same behavior. They shows most big values at 50 rpm because of the wear debris which generated by abrasion easily expulsed from contact surface.

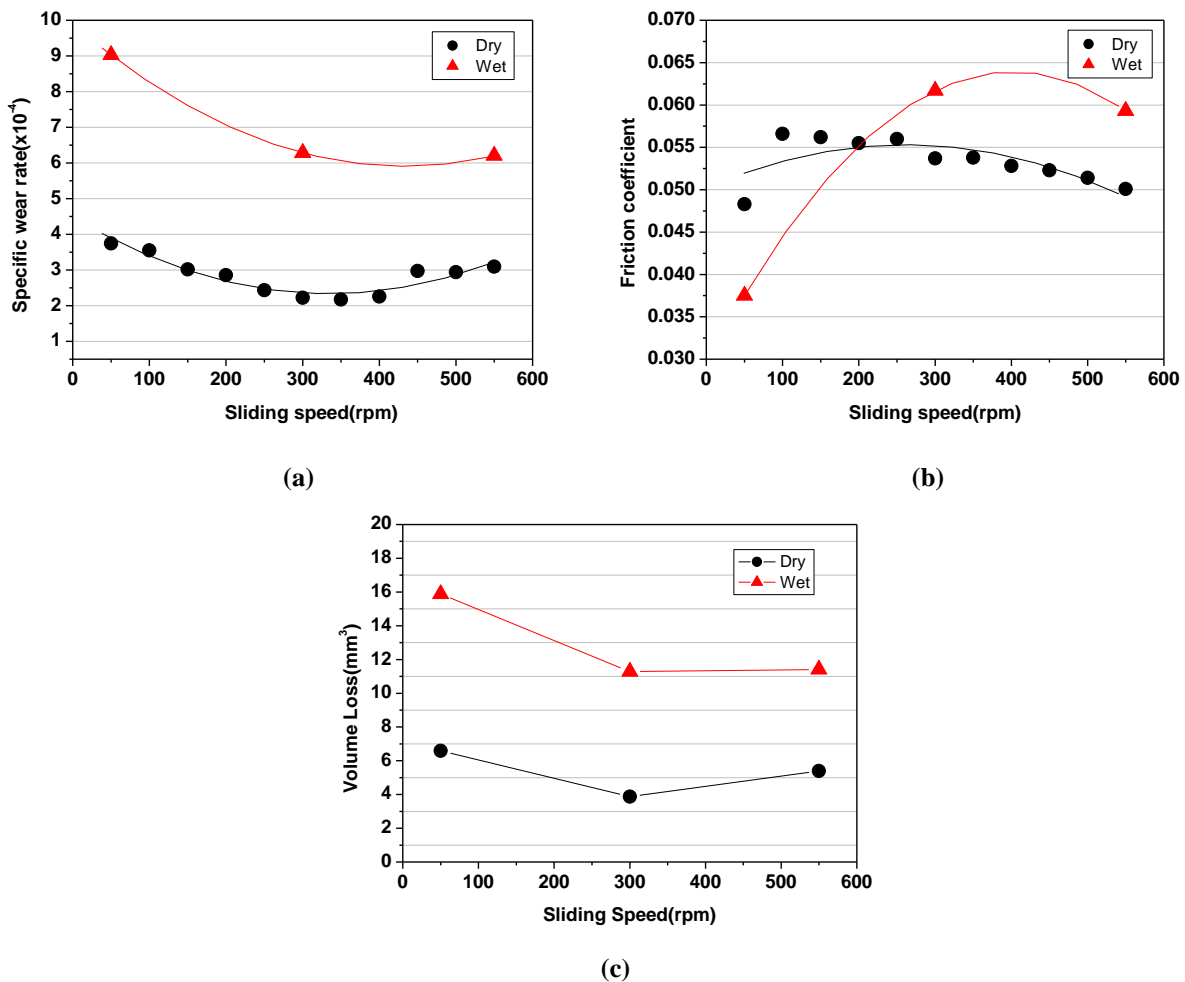


Fig. 3 Test results of sliding speed variation (a: specific wear rate; b: friction coefficient; c: volume loss)

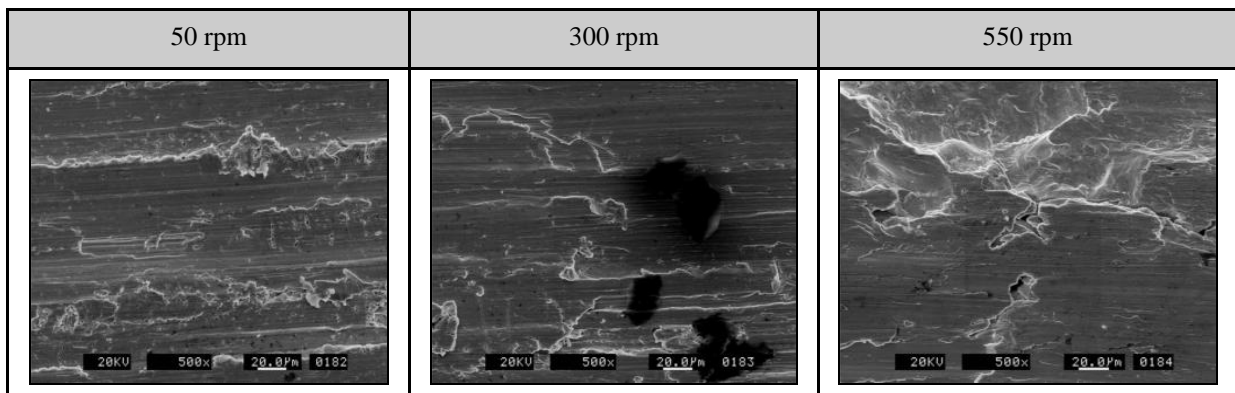


Fig. 4 SEM photographs of worn surfaces of the Zirconium alloys tested under variation of sliding speed in water

The volume loss was most small at the 300 rpm. This phenomenon can be explained by the change of wear mechanism which shows in fig. 4. At the SEM photograph, there was micro-pitting mechanism observed on the worn surface of disc specimen which tested with 300 rpm. These micro-pitting mechanisms can keep the wear debris and finally the volume loss was smaller than other test conditions. But, the friction coefficient was bigger than the other conditions by irregularity of contact surface. The micro-cutting mechanism was observed at 50 rpm and 300 rpm. But at 550 rpm in very high speed, the micro-cutting mechanisms were disappeared and the plastic deformation was observed only because the shear force can not be delivered to worn surface sufficiently from stationary pin

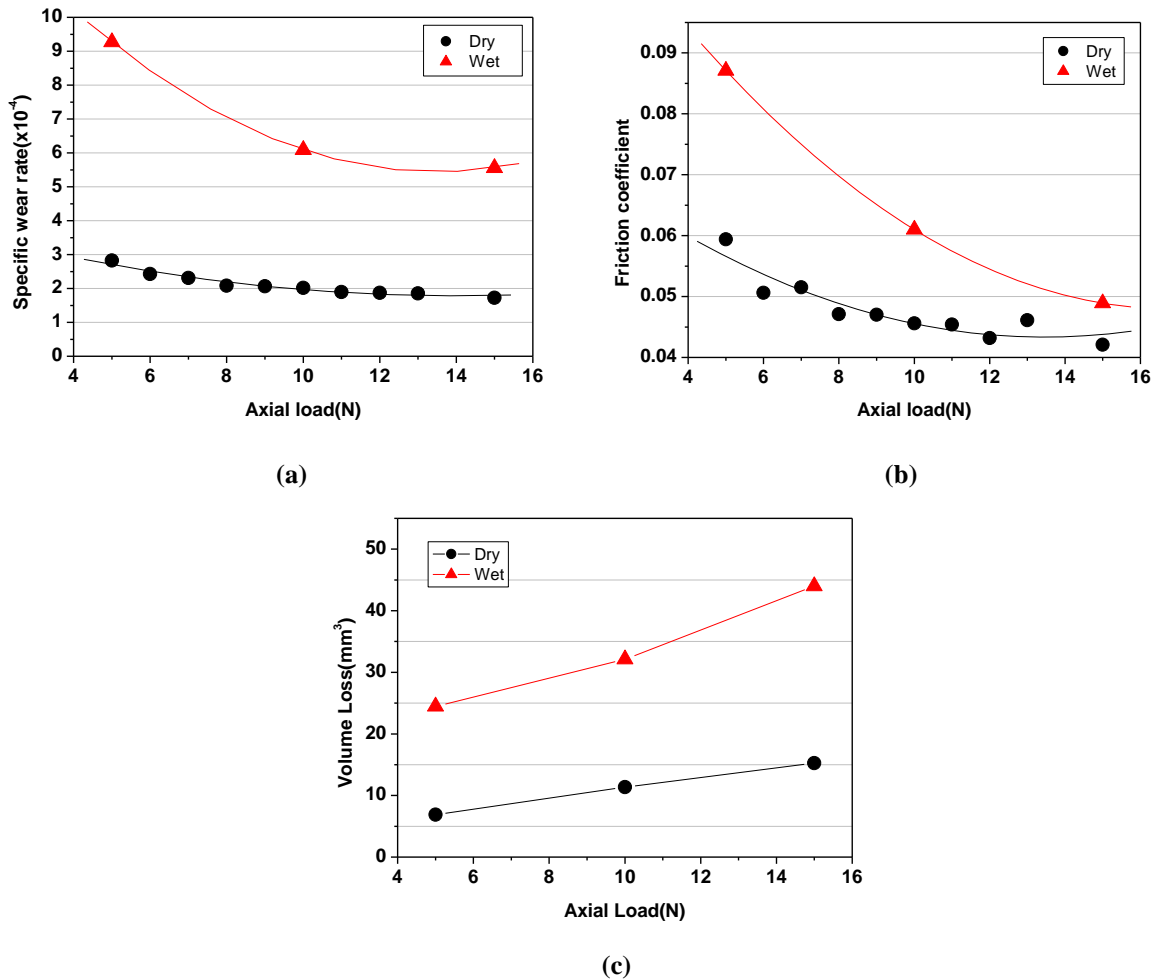


Fig. 5 Test results of axial load variation (a: specific wear rate; b: friction coefficient; c: volume loss)

Fig. 5 shows the data plots of axial load variation test. Axial load were increased 5 to 15 N and dry state tests were compared with in water condition. This parameter has been chosen for identifying the behavior of wear mechanism by the increase of surface fatigue. The volume loss was increased linearly with increase of axial load. But specific wear rate was decrease and stabilized after 10 N because of the wear debris which generated by abrasion easily expelled from contact surface at low axial load. Moreover, the micro-pitting mechanism observed at 5 N of SEM. The friction coefficient decreased from low axial load to high axial load. From Fig. 6, the plastic delamination was observed on the worn surface of disc specimen which tested at 15 N axial load. In this worn surface, there was no pitting mechanism and only observed plastic delamination and some of micro-cutting observed.

Fig. 7 shows the data plots of sliding distance variation test. Sliding distance were increased 10,000 to 100,000 cycles and dry state tests were compared with in water condition. The specific wear rates of two environments show different behavior. But, both of them saturated after 50,000 cycles and deformation rate was

decreased. Also, the behavior of volume loss saturated similar like behavior of specific wear rate. The friction coefficient of dry state saturated near the 50,000 cycles but water environment shows different behavior. It increased like dry state to 50,000 cycles and decreased greatly to 100,000 cycles. The reason of this phenomenon was explained by SEM photographs as shown in Fig.8. In 100,000 cycles, the surface was smoother than the other conditions and micro-cutting mechanism was almost disappeared.

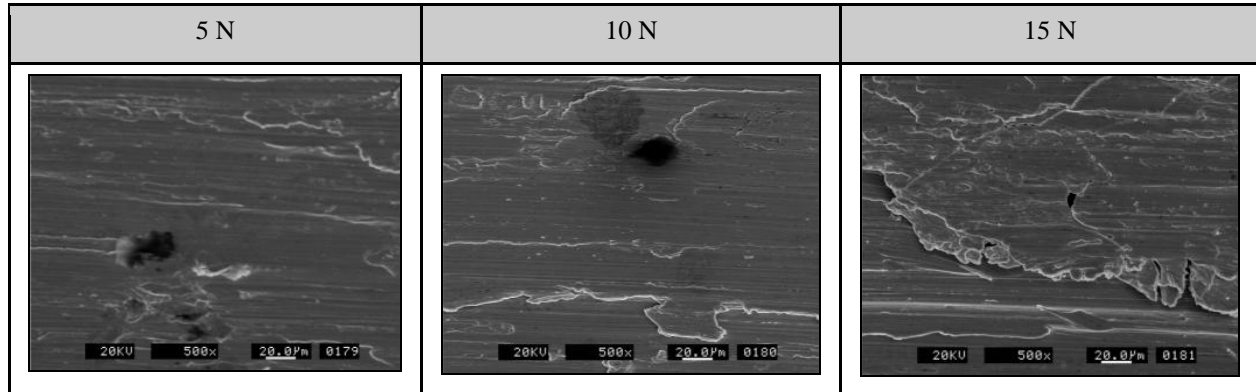


Fig. 6 SEM photographs of worn surfaces of the Zirconium alloys tested under variation of axial load in water

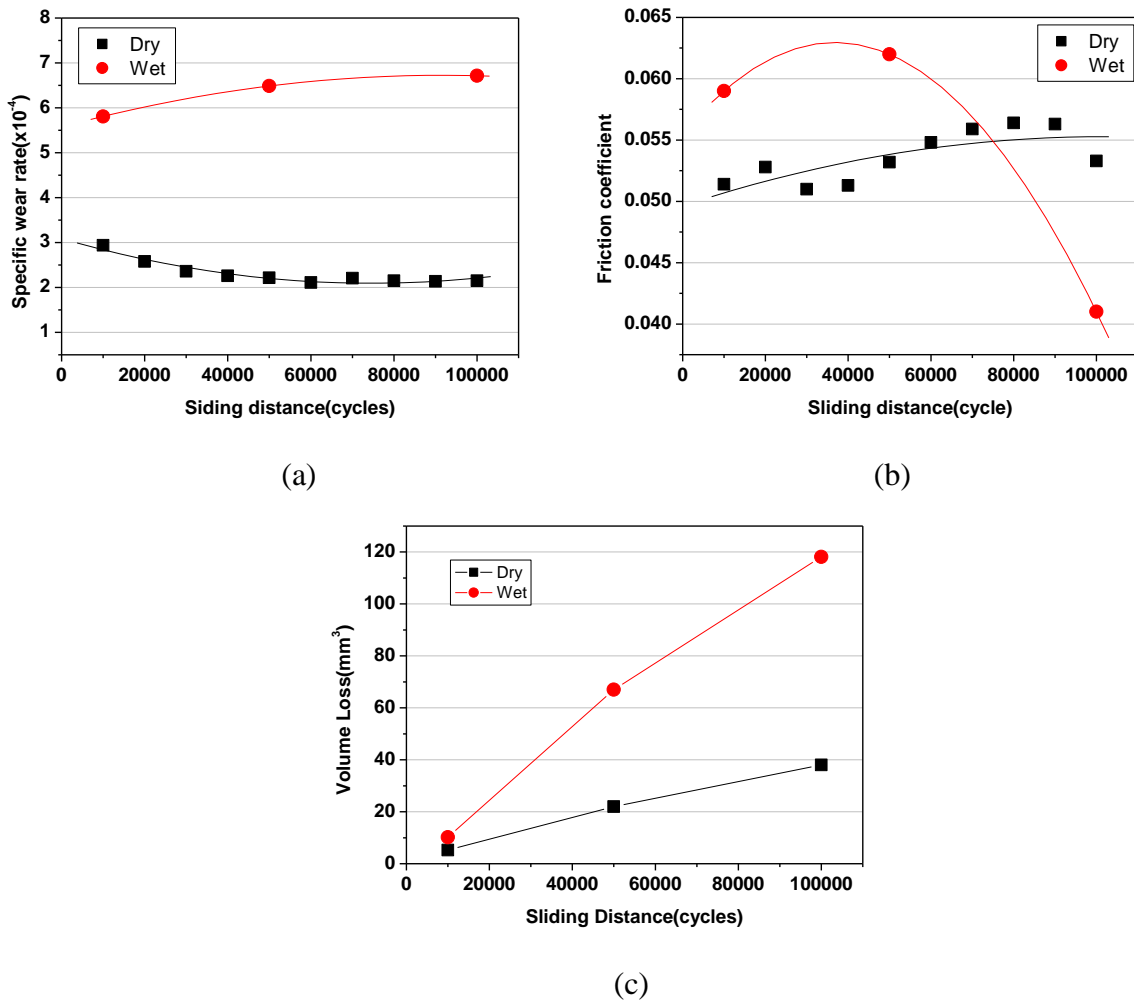


Fig. 7 Test results of sliding distance variation (a: specific wear rate; b: friction coefficient; c: volume loss)

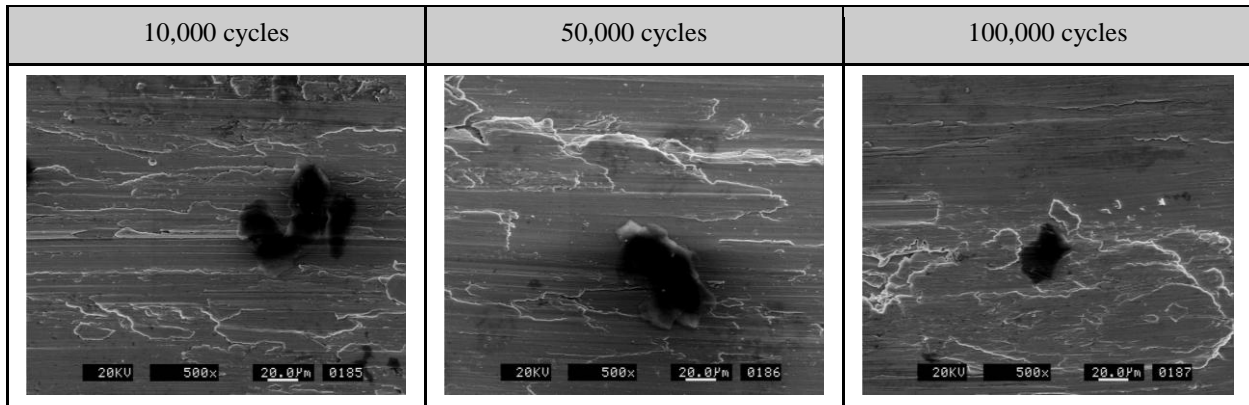


Fig. 8 SEM photographs of worn surfaces of the Zirconium alloys tested under variation of sliding distance in water

If the wear particle accumulation in the clearance region causes the third body abrasion, it may be supposed that the abrasion is less under the water environment since it is thought that the particles would not be accumulated so that they can be removed easily due to water. However, in comparison with dry and water state, volume loss, specific wear rate and friction coefficient of water state were bigger than dry state. This implies that the wear particles can be accumulated in the clearance region and stay also under the water for some period, and can cause the third body abrasion even in the condition of easy particle dispersion by the water. It also means that the water environment did not remove the particles from the clearances as soon as they were generated. So the role of water in the present wear phenomenon is to accelerate the particle dispersion from the contact surface rather than lubricate the surface, which results in a faster repetition of the adhesion to abrasion cycle. It must be one of the reasons that, in general, a severer wear occurs in the water environment. In other words, it also implies that the wear particle bed forms a load bearing layer that can restrain wear as show in Fig. 9[6, 7].

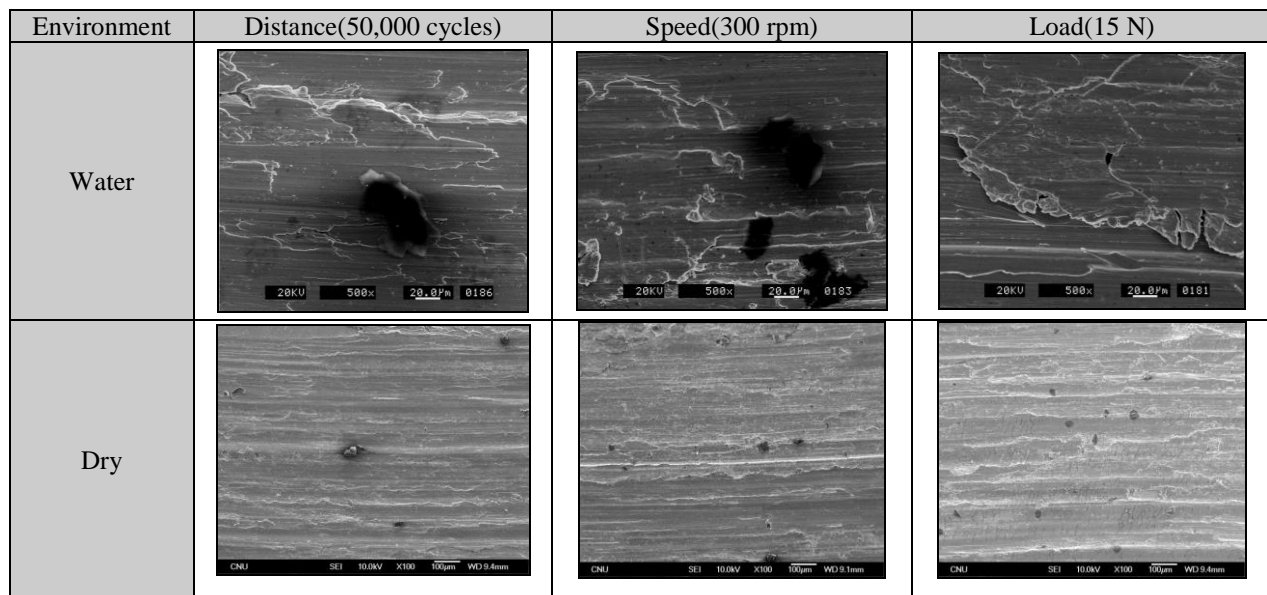


Fig. 9 SEM photographs of worn surfaces of the Zirconium alloys tested in water and dry environment

CONCLUSIONS

The wear behavior of fuel rod material against upper grid material was experimentally investigated by abrasive wear test. The parameters were chosen as sliding speed and axial load and environments. The conclusions obtained from this study

are as follows:

1. In variation of the sliding speed, the wear resistance shows good performance around 300 rpm of sliding speed by the micro-pitting mechanism. These pittings can keep the wear debris and finally the volume loss was smaller than other tests.
2. The increase of axial load causes the delamination on the worn surface by accumulation of surface fatigue.
3. The specific wear rate and volume loss are saturated with increase of the sliding distance by decrease of the micro-cutting mechanism
4. The wear mechanism shows different aspects by parameters even though the material combination in contact is the same.
5. The wear resistance in water environment is not better than that in air because the repetition of the adhesion to abrasion cycle is accelerated.

ACKNOWLEDGMENTS

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