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A Comparative Study on the Evaluation of the Wear Resistance in Zr-xNb-xSn Alloys

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Abstract: Sliding wear tests have been carried out in room temperature air and water in order to compare the wear resistance of Zr-xNb-xSn alloys of various alloying elements (Nb and Sn). The main focus was to quantitatively compare the wear properties of the recently developed Zr-xNb-xSn alloys with the commercial ones using the evaluation parameters of the wear resistance with the consideration of the worn area. As a result, the recently developed alloys had a similar wear resistance compared with the commercial ones. The dominant factor governing the wear resistance was the protruded volume of the wear debris that was formed on the worn area in the air condition, but the accommodation of the plastic deformation on the contact area in water. In addition, the worn area size appeared to be very different depending on the tested alloys. To evaluate the wear resistance of each test specimen, the ratio of the wear volume or the protruded volume to the worn area (D_e or D_p) is investigated and proposed as the evaluation parameters of the wear resistance.

Keywords: Sliding wear, Zr-xNb-xSn alloy, ratio of wear volume to worn area, alloying element

Introduction

Zircaloy-4 has been extensively used as cladding material for fuel rods in a nuclear reactor because of their low thermal neuron absorption cross-section, good corrosion resistance and mechanical properties in the pressurized water reactor (PWR) environment. However, it is necessary to develop advanced fuel cladding materials in order to satisfy the demands of the utilities for the economy and reliability of the nuclear fuel assembly because their demands such as a higher burn-up and a long term operation inevitably result in severe operating conditions such as an increased operation temperature, long-term flow-induced vibration (FIV) and a severe caustic environment. Recently, several new Zirconium (Zr) alloys such as Zirlo™ (Zr-1.0Nb-1.0Sn-0.1Fe) [1], M5 (Zr-1.0Nb-O) [2] and NDA (Zr-0.1Nb-1.0Sn-0.27Fe-0.16Cr) [3] have been developed and are being tested in-reactor. To sum up, the development trends of new Zr alloys are to evaluate the optimized content of the Nb and Sn element in the Zr matrix to obtain excellent corrosion resistance in the PWR environment.

Up to now, fretting-related degradations between the fuel rods and their supports (spring and dimple) due to the FIV have been frequently reported in the nuclear power plant where Zircaloy-4 materials are used as the fuel cladding materials. This means that new Zr alloys should be verified for their fretting wear properties even though they were developed to increase the corrosion resistance and mechanical properties in the operating conditions. Also, the effect of alloying elements of the Zr alloys on fretting wear has received little attention although a little amount of an alloying element in the Zr matrix can change its microstructure which is closely related to the corrosion and mechanical properties. Therefore, it is necessary to investigate the correlation between the alloying element and the wear behaviors of the new Zr alloys.

In this study, the sliding wear test was performed in room temperature air and water using five kinds of Zr-xNb-xSn alloys with different Nb and Sn contents and three kinds of commercial alloys. Research objective is to verify the wear properties of Zr-xNb-xSn alloys and compare the wear resistance of each Zr alloy by using the presently proposed evaluation parameters of wear resistance.

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Experimental Procedure

Specimen

The rod specimens used in this test were fabricated from five kinds of Zr-xNb-xSn alloys with different Nb and Sn contents and three kinds of commercial alloys. The chemical composition, yield stress and bulk hardness are summarized in Table 1 and their labels are designated as C1~C5. From this table, the mechanical properties can change with a small amount of the alloying elements in the Zr matrix. The rod specimen, 9.5 mm diameter, 0.6 mm thickness by 45 mm long, is cut from the straight rod. The spring specimen is fabricated by pressing and punching a strip (thickness 0.46 mm) of commercially used Zr alloys for the spacer grids in a PWR. Since this spring is designed to have a concave contour, it is expected to warp around the rod specimen in the transverse direction of the contact region. The schematic shape of the rod and spring specimen is shown in Fig. 1. For the comparison of the wear resistance in the Zr-xNb-xSn alloys, the commercial

Table 1. The chemical compositions (wt%), yield stress and bulk hardness of the Zr-xNb-xSn alloys

Label	Chemical composition	Yield stress (MPa)	Hardness (Hv)
C1	Zr-0.2Nb-1.1Sn-T.E	595	226
C2	Zr-1.5Nb-0.4Sn-T.E	588	212
C3	Zr-1.5Nb-0.4Sn-T.E	591	220
C4	Zr-0.4Nb-0.8Sn-T.E	554	215
C5	Zr-1.2Sn T.E	504	182

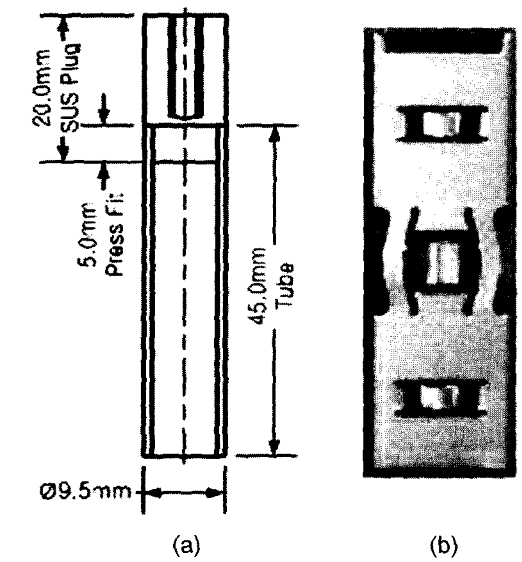

Fig. 1. The schematic view of the tested specimens; (a) Rod, (b) Spring.

alloys were tested also and designated as Z4, A and B alloys, respectively.

Test condition and wear tester

In this experiment, the main objective is to compare the difference of the wear resistance between the five developed Zr-xNb-xSn alloys and the commercial ones. So, the test conditions were fixed as a normal load of 10 N, slip amplitude of 80 μm, frequency of 30 Hz and 10^5 cycles in room temperature air and water. Each test at the same test condition was performed three times and the average values (wear volume and maximum wear depth) were used for the comparison of the wear resistance.

Fig. 2 shows the schematic view of the wear tester used for the present experiment. Reciprocating the sliding motion between the rod and the spring specimen is performed using a servomotor, an eccentric cylinder and the lever system. The sliding amplitude and frequency can be adjusted. In addition to the air condition test, the experiment can be done with the specimens in water below boiling temperature. Details of the wear tester have already been presented [4], so they are not reproduced in this paper.

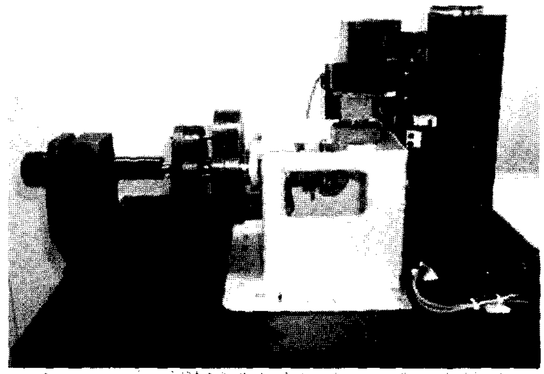

Fig. 2. The schematic view of the wear tester used for this experiment.

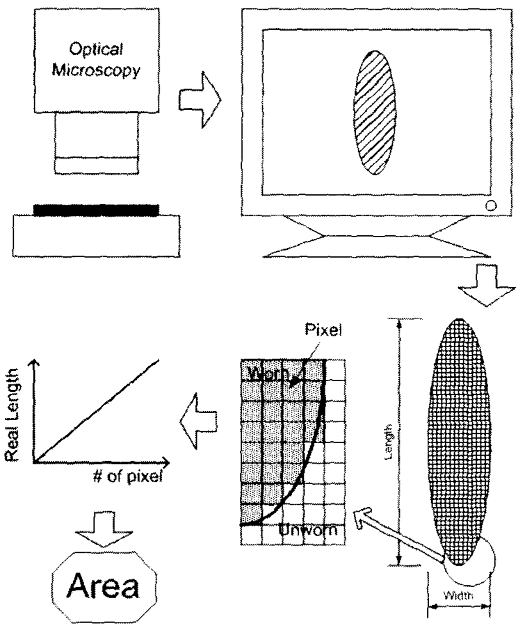

Fig. 3. The procedure of the worn area calculation after the wear test.

Evaluation of worn area

From the result of the worn surface observation using an optical microscopy, the size of the worn area was extensively varied with the rod specimens in air and water environment even though the test conditions such as the normal load, slip amplitude, spring shape, etc. were fixed. To analyze these variations of the worn area, it is necessary to calculate the exact worn area size at each test condition. To do this, the image of the worn area was obtained using an optical microscopy and the relationship between a pixel (picture element) size and a real size (length and width) of the worn area was calculated using a commercial program in the image analyzer [5]. Next, the boundary between the worn area and the unworn area was defined using the properties where the grey level of the image is rapidly changed at the boundary. Finally, the pixels that are included in the worn area are summed up and converted to the

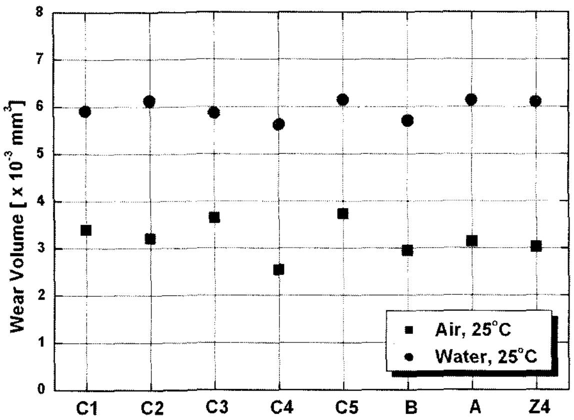

Fig. 4. The variation of the wear volume for each tested alloy.

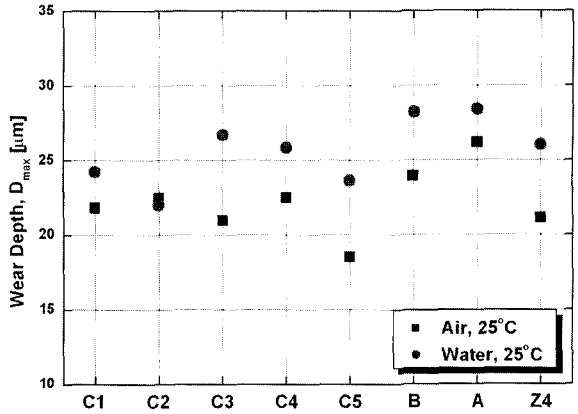

Fig. 5. Variation of the maximum wear depth. Note that this result is very different when compared with volume data as shown in Fig. 4.

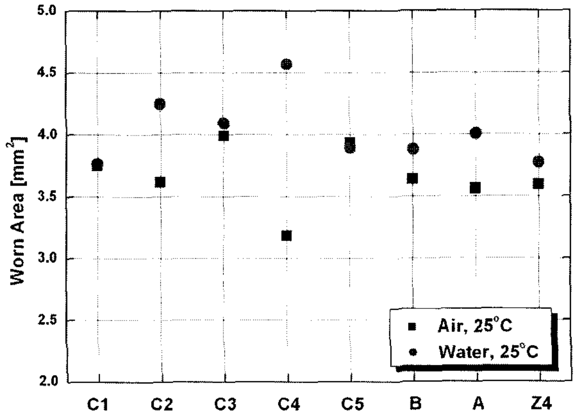

Fig. 6. Results of the worn area calculation after wear test using the procedure as shown in Fig. 3.

real size of the worn area. These procedures are summarized in Fig. 3.

Test Results

Wear volume

After the wear tests for each Zr alloy, the average wear volume was calculated and the results of the average wear volume are shown in Fig. 4. As a result, C4 alloy had a lower wear volume in both the air and water condition. But the specimen condition of a higher wear volume was hard to define due to the environmental effects, but the C5 and A alloys showed relatively higher wear volumes. Especially, the C3 alloy has a higher wear volume in the air condition compared with the Zr-xNb-xSn alloys except for the C5 alloy, but the C2 alloy had an opposite behavior for the environmental effects. From the above results, the Zr-xNb-xSn alloys, approximately, had a similar wear resistance compared with the commercial alloys. Because the operation condition of the in-reactor where the Zr alloys are applied is a water condition, it is reasonable to compare only the water data for the evaluation of the wear resistance. So, the C4 and B alloys have relatively higher wear resistance while the C2, C5 and A alloys have lower ones.

Maximum wear depth

Generally, the wear volume measured after the wear test was used to evaluate the fretting degradation. In the nuclear power plants, however, the fretting-related degradations have occurred in the relatively long structures such as the nuclear fuel rod, steam generator tube and control rod due to the FIV. The reliability and life time of these structures is evaluated and estimated by the extent of the thickness decrease. This means that a certain alloy which has a lower maximum wear depth could be expressed as a wear resistance alloy regardless of the larger wear volume. Fig. 5 shows the variation of the maximum wear depth for each Zr alloy. It is apparently shown that the variation of the maximum wear depth is very different from that of the wear volume. The lower depth in the air condition appears in the C5 alloy, but in the C2 alloy in the water condition. This is a confusing factor to determine the most wear-resistant alloy because the C4 alloy has a relatively lower wear volume in the air and water condition. This is because the abnormal wear in a specific region could generate a localized severe wear depth during the wear. Therefore, it is necessary to introduce a new parameter that could determine the wear resistance of the Zr alloys. To do this, the real size of the worn area for each Zr alloy was examined and calculated.

Worn area

After the wear test, the wear debris on the worn area was examined by an optical microscopy. At the same time, the image of the worn area was acquired and analyzed. Fig. 6 shows the results of the worn area variation for each tested Zr alloy. Contrary to the expectation, the worn area of the Zr alloys was more sensitive to their alloying element. It seems that while the wear debris was ejected from the worn surfaces after the deformation and fracture at the contact surface, the behavior of debris adhesion can be slightly changed by the material properties, which affect the behavior and ejection mechanism of the debris between the worn surfaces. However, it is difficult to closely examine the exact mechanism. In Fig. 6, the C4 alloy that had a lower wear volume in the air and water condition shows a relatively larger worn area in water, but a

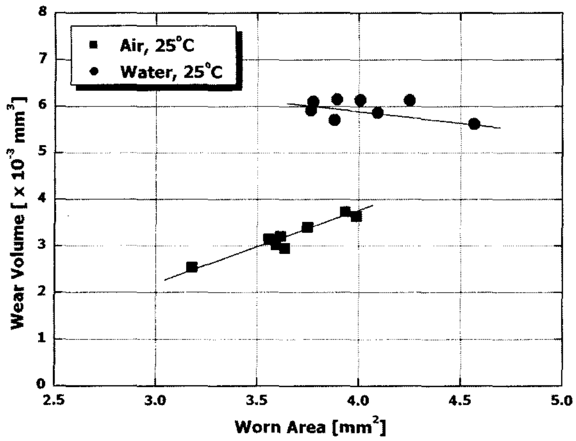

Fig. 7. The variation of the wear volume with worn area in the all tested conditions.

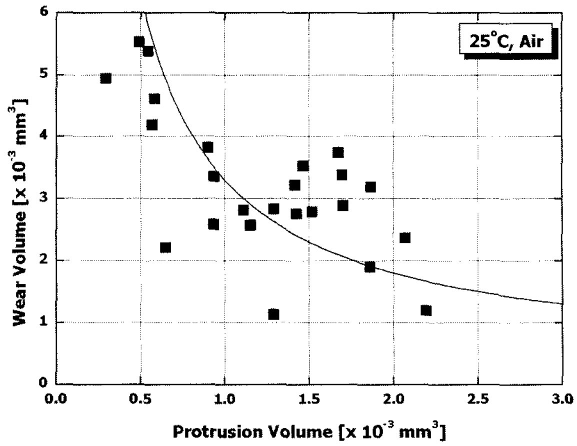

Fig. 9. The variation of the wear volume to the protruded volume in the air condition.

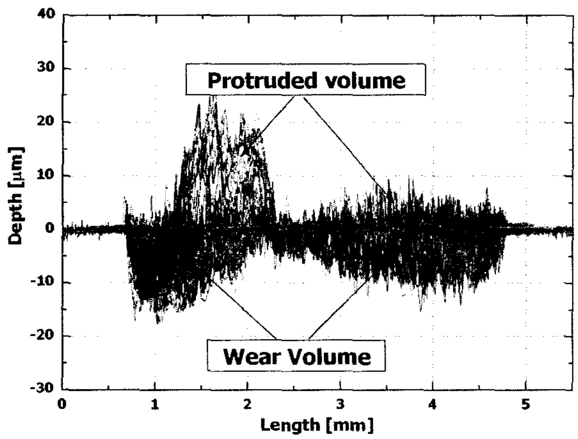

Fig. 8. Example of the surface profile data in the air condition (C5 alloy).

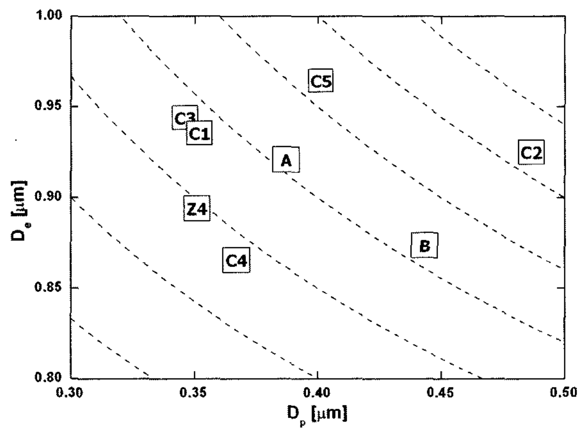

Fig. 10. The evaluation of the wear-resistant alloys (C4 and Z4) in the air condition.

smaller in the air condition.

Discussion

In order to determine the wear resistance of each Zr alloy, the variations of the wear volume with an increasing worn area are evaluated and their results are shown in Fig. 7. As a result, the effect of the size of the worn area on the wear volume depends on the test environment. Namely, the wear volume increased with an increasing worn area in the air condition, but was reversed in the water condition. This means that the wear mechanism could be changed by the environmental effects. Therefore, the evaluation of the wear resistance should be performed by separating the environment conditions.

Generally, in the air condition, the wear mechanism is closely related to the debris or wear particle layer on the worn surface [6]. If the worn surface was consisted of wear debris, further wear process was prohibited by the formation of the load bearing layer. Fig. 8 shows a typical example of the worn surface profile tested in the air condition. From this figure, it is expected that the formation of the protrusion on the worn surface is closely related to the wear resistance of each Zr alloy. In order to verify this assumption, the variation of the wear volume to the protruded volume is shown in Fig. 9. It is clearly shown that the wear volume is in an inverse proportion to the protruded volume in the air condition. Therefore, the wear resistance in the air condition was determined by the protruded volume or the average thickness of the wear particle layer. Thus, the most wear-resistant alloy has a relatively smaller wear volume and protruded volume per unit worn area (D_e and D_p) because the thickness of the protrusion does not continuously increase and the protruded volume is formed by the agglomeration of the wear debris. Therefore, the C4 and Z4 alloys that have smaller values for both D_e and D_p can be expressed as a wear-resistant alloy in the air condition as shown in Fig. 10.

However, it is easy to remove the wear debris between the contact surfaces in the water condition compared with air condition. This behavior could be confirmed by the results of the worn area observation as shown in Fig. 11. So, it is expected that the most wear-resistant alloy in the water condition has a relatively lower ejection rate of the wear debris that is formed by the continuous plastic deformation and fracture during the wear [7]. Although the contact area

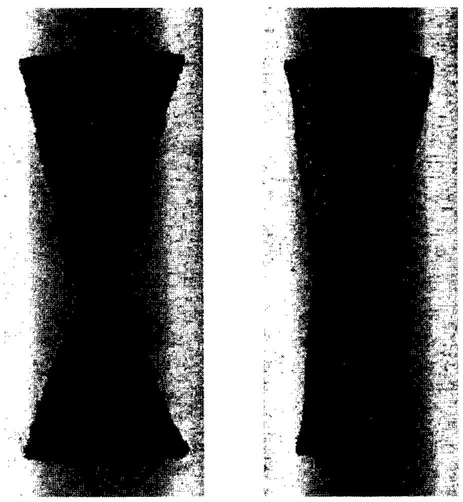

Fig. 11. The result of the worm area observation in the air and water conditions.

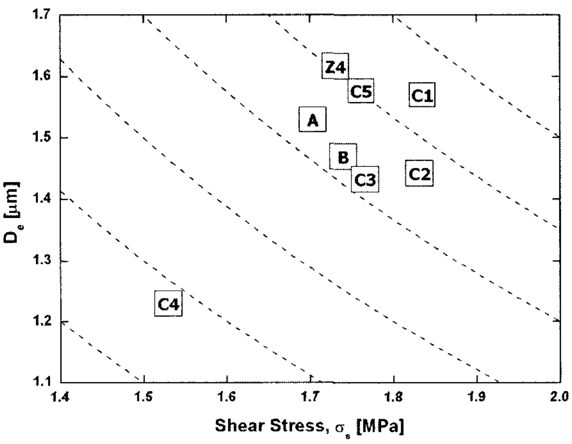

Fig. 12. The evaluation of the wear-resistant alloy (C4) in the water condition.

between the rod and spring is similar in the initial wear testing, the worn area can be varied with the change of the mechanical properties (the work hardening, the variation of hardness, the transformation of subsurface structure, etc.) due to the difference of the alloying contents. So, it is thought that the major factor governing the wear resistance is the accommodation of the plastic deformation between the contact surfaces because the deformation mainly occurs from the shear stress. As the normal load (10 N) is constantly applied in this test, the shear force can be calculated using the friction coefficient during the wear test. This result is shown in Fig. 12 and the C4 alloy had a relatively smaller shear stress and D_e value. Therefore, it is possible to apply D_e and D_p using the worn area for the evaluation of the wear resistance in the Zr alloys.

Conclusions

In the present work, the sliding wear test was performed with five kinds of Zr-xNb-xSn alloys and three kinds of commercial alloys for a concave spring in room temperature air and water. From these experimental results, the following conclusions were obtained;

(1) The Zr-xNb-xSn alloys have a similar wear resistance to the commercial alloys. Especially, the C4 alloy had a relatively higher wear resistance in the room temperature air and water.

(2) In the air condition, the wear resistance is closely related to the protruded volume on the worn surface, but to the variation of the friction coefficient in the water condition. This means that an evaluation of the wear resistance could be varied with the wear mechanism.

(3) It is possible to apply the ratio of the wear volume and the protrude volume to the worn area (D_e and D_p) to compare the wear resistance in the Zr alloys.

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