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Sliding wear and friction behaviour of zircaloy-4 in water

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ABSTRACT

In water cooled nuclear reactors, the sliding of fuel bundles in fuel channel handling system can lead to severe wear and it is an important topic to study. In the present study, sliding wear behaviour of zircaloy-4 was investigated in water (pH ~ 10.5) using ball-on-plate sliding wear tester. Sliding wear resistance zircaloy-4 against SS 316 was examined at room temperature. Sliding wear tests were carried out at different load and sliding frequencies. The coefficient of friction of zircaloy-4 was also measured during each tests and it was found to decrease slightly with the increase in applied load. The micro-mechanisms responsible for wear in zircaloy-4 were identified to be microcutting, micropitting and microcracking of deformed subsurface zones in water.

1. Introduction

Zirconium based alloys are most widely used as structural materials for nuclear fuel channels in water cooled reactors because of their low thermal neutron absorption cross section, resistance to high temperature aqueous environment, optimum mechanical properties and resistance to radiation damage [1]. The mechanical properties and tribological behaviour of these materials must possess the ability to withstand severe operating conditions with higher reliability and excellent performance during service [2–10]. Zircaloy is the main construction material in the core of Indian PHWR's. Calendria tube, pressure tube, garter springs, fuel cladding and spacer are the main components where this alloy is used. Fuel bundle travels from fresh fuel storage bay to reprocessing plants through various assemblies and channels. Majority of these channels (outside calendria) are made out of SS 316, 17-4 PH and SS 420 steels. Spacer on the fuel bundle is provided to keep the necessary flow path around the bundle to ensure adequate cooling all the time. Reduction of its size due to sliding wear during its entire travel may hamper its cooling requirements. Friction coefficient of the zircaloy is also important to study as it can help in optimizing the force required to push the fuel bundles in the channels. It is well known that the wear resistance of zirconium alloys is much lower than other nuclear grade materials, e.g., superalloys and various grades of stainless steels. Therefore, the wear resistance of these alloys could pose a serious limitation during designing of various components and safe operation of nuclear reactors. However, to the best of our knowledge, there have been no reports on the abrasive/sliding wear behaviour of zircaloys. Some reports have been published on the fretting damage between pressure tubes and its supporting spring in operating power plants [11–15]. Therefore, dedicated research efforts are required to understand the reciprocating sliding wear mechanism in these alloys under different environmental conditions. The present paper is an attempt to study the sliding wear resistance of zircaloy-4 and also to delineate the wear mechanisms during wear under water as a medium.

2. Experimental

Wear tests were performed on a wear and friction machine (TE-70, Phoneix Tribology Ltd., UK) with reciprocating ball-on-plate configuration. Plates (as rolled) of zircaloy-4 were metallographically polished with an average surface roughness (Ra) value of 0.26 μm. The specimens were cleaned before and after the tests by immersing in acetone in an ultrasonic bath. Wear tests were carried out in demineralised water having 10.5 pH (as used in reactor systems) at room temperature using AISI SS 316 ball (12.7 mm dia. AFBMA Grade 25 having hardness of HV 160–180) as a mating material. In order to retain uniform test conditions, a new ball was used for each test. The mean contact pressure at 3 N was 0.22 GPa and at 7 N was 0.40 GPa which was well under the elastic limit of the material. The ball was made to slide on the plate sample with three frequencies (5, 10 and 15 Hz) keeping the sliding amplitude of 1 mm constant for different time durations. The tests were performed at different load conditions (3, 5, 7, 9 and 11 N). Each test was repeated three times to verify the repeatability of the results and wear volume was found to be within ±1%. Average values of the result are reported in the manuscript. Wear track profiles were formed on the plate due to ball

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sliding. 3-D profilometry using Hommelwerke make profilometer T2000 was carried out to calculate the dimensions of wear grooves. Wear rate was calculated by dividing the volume of the wear groove by the sliding distance. The micro-mechanisms responsible for sliding wear were studied in detail by SEM.

3. Results and discussion

The variation of coefficient of friction with distance at 5 Hz sliding frequency is shown in Fig. 1a. At the onset of sliding test, coefficient of friction (COF) was found to first increase instantaneously and then reduce to low value within few seconds of the start of the experiment. During the rest of the period COF remain more or less constant although with fluctuations in a narrow range. This initial high value is referred to as static COF while remaining portion of the graph shows dynamic COF. At low load COF increased marginally with increase in sliding distance whereas at higher loads it remained constant. This variation in COF was due to stick slip behaviour of the material pair resulting in transfer layer. Average of the values (excluding initial portion) are plotted against load at different sliding frequencies as shown in Fig. 1b. The average values of the coefficient of friction exhibit little dependence on the applied load, though the value at a lower load is slightly higher. Increase in sliding frequency to 10 and 15 Hz, showed a marginal decrease in average value of coefficient of friction at constant normal load. The average friction values were not found to be very high as the presence of water during sliding forms a partial hydrodynamic film between the ball and the sample thereby resulting in the reduction of the coefficient of friction for longer duration.

The 3-D profile and SEM image of wear groove formed on the sample at 3 N load is shown in Fig. 2a and b, respectively. Fig. 3a shows the variation of wear rate with sliding distance at different normal load conditions. The results showed that the wear rate increase with the increase in sliding distance and load. This is clearer in Fig. 3b, which showed the variation of wear rate with load at different sliding frequencies.

The micromechanism responsible for the wear in this alloy was studied in detail by SEM technique. Fig. 4a showed that dominant micro-mechanisms responsible for wear at 100 m sliding distance and 3 N load, were mainly microcutting and micropitting. The lose wear debris on the sides of the wear grooves showed irregular shapes and a large variation in sizes (Fig. 4b). With the increase in load to 5 N, worn surface showed severe microcutting and deeper pits as compared to 3 N load conditions for 100 m sliding distance (Fig. 4c). However, with the increase in sliding distance to 200 m, microcracking at deformed subsurface layers was also found to take place along with micropitting and microcutting (Fig. 4d). This was due to extensive damage occurring at surface at 7 N load. With the increase in load and sliding distance, the accumulated strains increase and this lead to formation of deformed subsurface zones. The continuous sliding of the SS 316 ball on the sample for longer duration led to cracking in these subsurface zones. Testing at 9 and 11 N loads showed extensive surface damage due to delamination of deformed platelets in subsurface zones as shown in Fig. 4e and f. Fig. 5 shows the wear of SS 316 ball tip against zircaloy-4 at different load. The ball tip showed mainly deep microcutting and microploughing as the main mechanisms at all the test conditions. As the hardness of SS 316 and zircaloy are comparable, there was mass transfer from both the counter surface i.e., ball to plate and plate to ball. These results showed that in zircaloy-4, during initial stages, micropitting and microcutting were found to be the dominant mechanisms. However, as the load increases, the surface suffers extensive damage and strains accumulate at the surface resulting in the formation of subsurface deformation zone. With the increase in stress, cracks developed in these subsurface layers and subsequent detachment of platelets occurred resulting in increase in wear rates. Thus, there was a change of mechanism in zircaloy-4 from microcutting and micro-

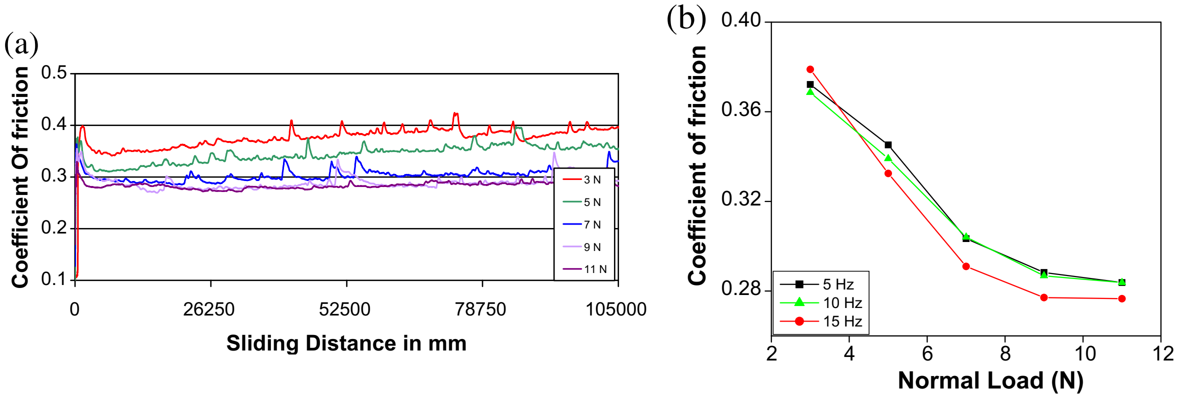

Fig. 1. Variation of coefficient of friction of zircaloy-4 alloy with (a) sliding distance at 5 Hz; error bars ±2% and (b) normal load at different sliding frequencies.

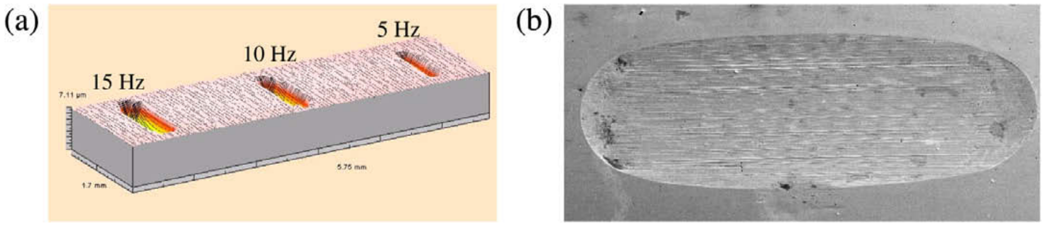

Fig. 2. Profiles of wear groove after testing (a) 3-D profile of wear tests at 3 N load for 5, 10 and 15 Hz and (b) SEM image of the wear groove at 3 N and 5 Hz condition.

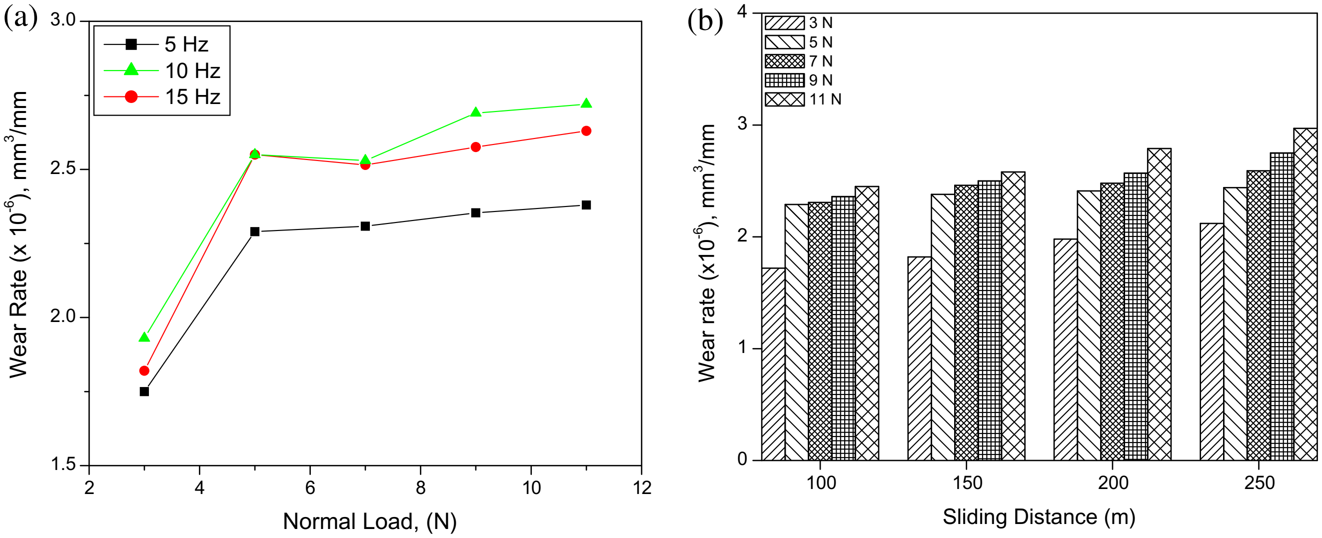

Fig. 3. Variation of wear rate with (a) normal load for different sliding frequency and (b) sliding distance for different loads.

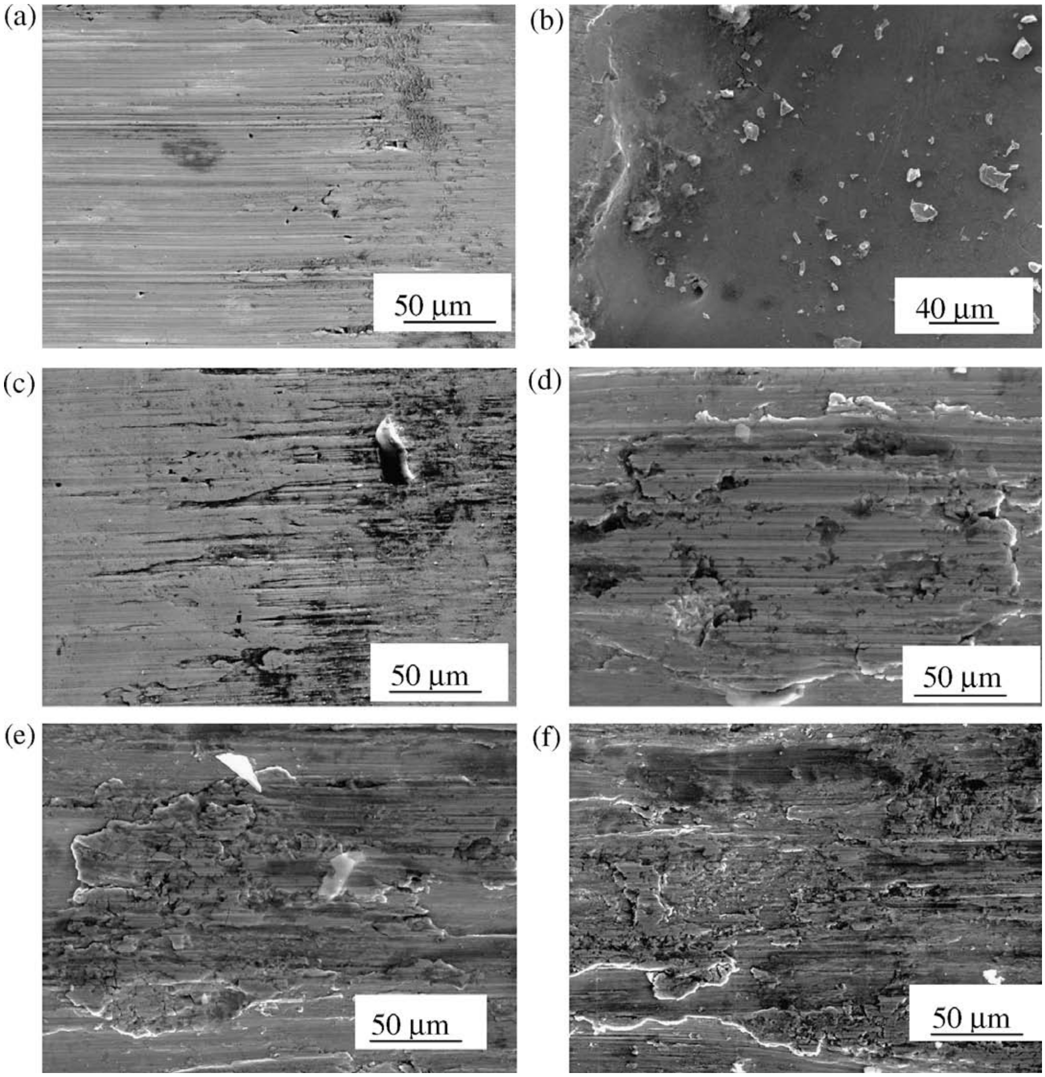

Fig. 4. SEM micrograph showing (a) micropitting and microcutting after a sliding distance of 100 m at 3 N, (b) loose wear debris at the sides of the wear groove, (c) micropitting and microcutting after a sliding distance of 100 m at 5 N normal load, (d) increased micropitting and microcutting after a sliding distance of 200 m at 7 N normal load, (e) severe surface damage and delamination of deformed subsurface zones 9 N and (f) delamination of deformed subsurface zones at 11 N normal load.

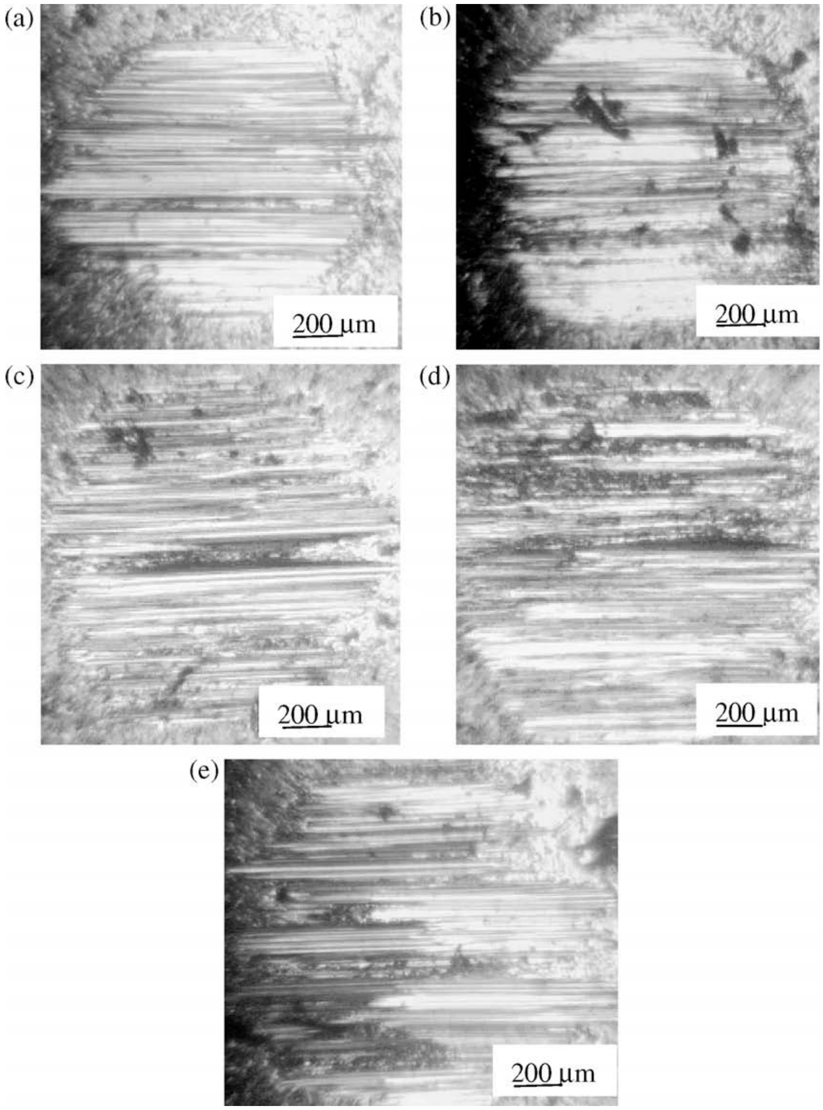

Fig. 5. Optical micrographs showing sliding wear in SS 316 ball tip against zircaloy-4 at 10 Hz sliding frequency for (a) 3 N, (b) 5 N, (c) 7 N, (d) 9 N and (e) 11 N.

pitting at lower applied load to delamination of deformed subsurface layers at higher load during sliding wear.

4. Conclusion

The sliding wear and friction behaviour of zircaloy-4 as a function of load and sliding frequency had been investigated in this study. The wear rate of zircaloy-4 was quantitatively measured and was found to follow the expected trend of increase in wear rate with increase in load and sliding frequency. The coefficient of friction of zircaloy-4 was found to decrease slightly with the increase in normal load. SEM examinations of the abraded surfaces showed a change in dominant wear mechanism from micropitting, microcutting under low load condition to delamination of deformed subsurface zones at higher load.

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