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Subsurface Deformation Behaviors of a Nuclear Fuel Rod under Elastically Deformable Contacts

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1. Introduction

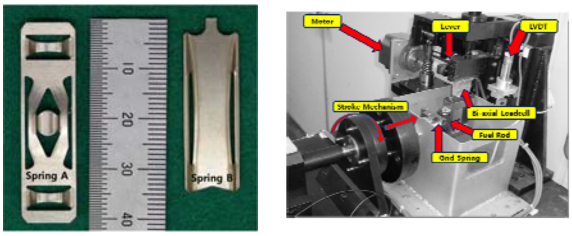
The formation of wear debris layers and the surface/ subsurface deformation are frequently observed phenomena under sliding or fretting contact of structural materials. Generally, the fretting wear behavior is strongly influenced by those two phenomena in various test conditions. If wear particles are easily oxidized and compacted on the contact surfaces, they act as a wear protective layer, which decreases the total wear rate. Otherwise, they may act as abrasives (i.e. third body abrasion) which accelerate wear damage. However, as the metal-to-metal contact is more dominant especially at high flow rate condition such as the nuclear core, it is expected that the wear behavior is controlled by the variation of mechanical properties in surface or in subsurface because wear particles are released after plastic deformation and fracture.

It is found that the wear scar formation and the wear debris behavior between nuclear fuel rod and spacer grid spring/dimple were dominantly changed with the contact spring shapes rather than test environments. Those works [1-3] have demonstrated that, with increasing number of cycles, the contact force between a fuel rod and an elastically deformable grid spring was gradually decreased due to a depth increase. This result indicates the variation of the fretting wear mechanism during the wear tests. Therefore, the objectives are to examine the variation of the surface or subsurface deformation mechanism with increasing fretting cycles and to evaluate the difference of the wear debris detachment mechanism at each test environment.

2. Experimental Procedure

2.1 Specimen, Tester and Test Conditions

In this study, a commercial Zirconium alloy used as a nuclear fuel rod material was prepared. Two kinds of grid spring specimens with the same Zirconium alloy were also prepared by using a plate with 0.46 mm thickness. Spring A has a concave contour, which was intended to have an area contact with a wrapping around the fuel rod in a circumferential direction of the contact region. As spring B has a convex contour, however, this spring was intended to have a line contact with a fuel rod in an axial direction of the contact region. A fretting wear tester for a nuclear fuel fretting has been specially designed and its detailed characteristics could be found in a previous study [4]. Fig. 1 shows the schematic views of the spring specimens and fretting wear tester used in this study. Also, test condition is given in Table 1.



(a) (b)

Fig. 1. (a) Schematic view of the spring specimen; (b) a fretting wear tester for room temperature conditions.

Table 1. Summary of test condition

Force	10 N
Amplitude	50, 80 and 100 μm
Frequency	30 Hz
Cycles	upto 10^7
Environment	RT air & distilled water

2.2 Worn Surface Observation

The worn surface was observed by using OM and SEM to examine the variation of the fretting wear mechanism with increasing number of cycles. To investigate the subsurface deformation mechanism, the wear scar of the fuel rod specimens were sectioned perpendicular to the worn surface and parallel to the slip direction. To minimize the sectioned surface damages during specimen preparation, the cutting speed of a low speed cutter was strictly maintained below 30 rpm/min. The sectioned surface was carefully polished by using SiC powder (1000 grit) and diamond discs (0.5~3 μm) before SEM observation was performed.

3. Results and Discussion

Fig. 2 shows the cross-section of the worn surfaces in axial direction of the fuel rod specimen after the fretting cycles of 10^7. Both springs in the dry condition show that hardened wear debris layers are well developed on the worn surfaces. But, the difference of the worn surface morphologies could apparently be found in the directional characteristics of the agglomerated debris folds. This result indicates evidence for a migration path of the generated wear debris. In contrast to the dry condition, no distinguishable difference between the two springs in the distilled water condition was found for their worn surface morphologies.

The plastic deformation layer and/or the wear debris layer are well developed on the worn surface in all the test conditions. In the dry condition, it is apparent that the wear debris is detached by filling up wear particles between the agglomerated debris folds or deformed folds and bare surface and then cracking by the slip motion as noted with arrows. However, the plastic deformation layers were well developed in the water condition. They have a specific thickness which is similar to their grain sizes (i.e. about 4-6 μm) and microcracks propagate to depth direction.

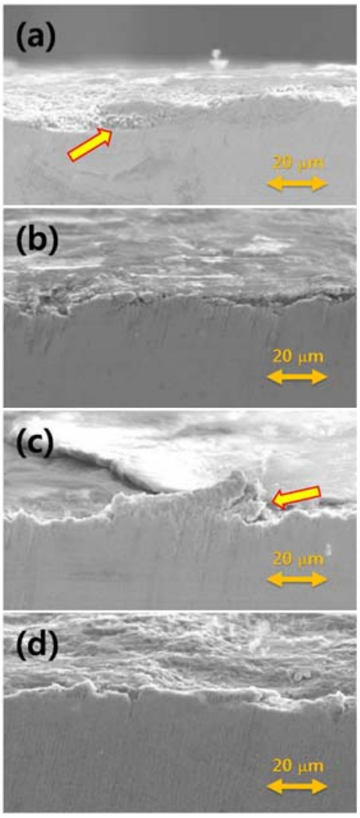


Fig. 2. SEM observation results of sectioned surfaces at the fretting cycles of 10^7: (a) spring A in dry; (b) spring A in water; (c) spring B in dry; (d) spring B in water.

The previous experiment [5] has demonstrated that, in Inconel alloys with their grain sizes of 30~50 μm, a specific thickness of the deformation layer is also generated in the water condition and its thickness is about 5 μm when the fretting tests has been performed with similar load and slip amplitude conditions. This result indicates that the formation mechanism of the wear debris from the plastic deformation layer and its size could be affected by test environment and applied normal load even though material effect was not considered in this study. Therefore, it is expected that, with increasing number of cycles, the wear debris detachment of nuclear fuel rod under elastically deformable contacts could be explained by the formation of wear debris layer, the debris removal paths with spring shapes, the directional characteristics of the agglomerated debris folds and the specific thickness of the plastic deformation layer.

4. Conclusions

From the results of subsurface observation, the formation mechanism of the wear debris from the plastic deformation layer and its size could be affected by test environment and applied normal load even though material effect was not considered in this study.

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