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TRIBOLOGICAL COMPATIBILITY OF SPACER GRID CANDIDATES FOR A DUAL-COOLED ANNULAR FUEL

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ABSTRACT

A dual-cooled annular fuel has been designed to have compatibility with current operating PWR plants for realizing both a considerable amount of power uprating and an increase of safety margins. However, there are many challenging technical issues related to mechanical design of fuel supporting structures. One of those is that it shows a narrow gap between the fuel rods, which needs to modify the spacer grids shapes and their positions. In this study, fretting wear tests have been performed to evaluate the tribological compatibility of two kinds of spacer grids for the dual-cooled annular fuel focusing on the supporting ability with different spacer grid shapes and effect of increased contact surfaces on the wear mechanism with different contact conditions. As a result, the wear volume of simulated dual-cooled fuel rod against spacer grid candidates shows a negligible change up to 80 μm, but significantly increases at a slip amplitude of 100 μm. The variation of initial contact force during the fretting tests was strongly affected by the wear depth increase and wear debris behaviour, which depends on grid shapes. The higher wear volume and maximum wear depth in grid spring with cantilever shape are due to an unstable supportability during the fuel rod vibration while a spacer grid with concave contours in both spring and dimple shows a negligible contact force drop and wear amounts. Based on the fretting wear results of two kinds of spacer grids, tribological compatibility of each spacer grid is analysed focusing on the wear behaviours and supportability during the fretting tests.

INTRODUCTION

Because of both an internal and external cooling channel, a dual cooled annular fuel has advantages of considerably higher reliability and safety compared with a conventional solid fuel. Thus, KAERI has launched an innovative fuel development for a power uprate and enhancement of the safety of the current OPR-1000 (i.e., Korean Standard PWR), see Koo et al. (2012) and Koo et al. (2013). However, this fuel should be designed to have compatibility with current operating PWR plants for realizing both a considerable amount of power uprating and an increase of safety margins. So, there are many challenging technical issues related to mechanical design of fuel supporting structures because it shows a narrow gap between the fuel rods, which needs to modify the spacer grids shapes and their positions compared with current PWR fuel assembly designs. For example, a conventional fuel for the OPR-1000 has a 16x16 array with a 9.5 mm of nominal diameter and 3.35 mm nominal gap between fuel rods. But, the dual-cooled annular fuel proposed as 12x12 array shows that the nominal diameter and thickness of an outer fuel rod are 15.9 mm and 0.87 mm, respectively. So, it is expected that it results in a narrow gap (1.23 mm), and the springs and dimples of the spacer grids for the dual-cooled annular fuel needs to be biased to the corner of the grid cell. This is because a narrow gap must accommodate the thickness of the spacer grid strap and the formation of springs and dimples. Under this limited condition, a spacer grid consisted of springs with a cantilever type and dimples with hemispherical shape (i.e., CSHD), were designed as one of the candidate supporting structure of a dual-cooled fuel. In addition, another spacer grid candidate (i.e., DUO-H) was proposed for improving the thermal hydraulic concerns and the DUO-H spacer grid is modified from the conventional spacer grid of solid fuel and has the same position of the conventional solid fuel by the maximization of high space efficiency in a narrow gap in the dual cooled annular fuel.

However, these candidates should be verified that there are no potential hazards, which experienced in conventional solid fuel system under normal operating conditions such as grid-to-rod fretting (GTRF). Generally, the fretting wear is defined as a material degradation between two contact surfaces with a relatively small amplitude motion, see Waterhouse (1972). The geometry of the contact surfaces was recognized as one of the most important factors determining the fretting wear mechanism of nuclear fuel rods, see Lee et al. (2007), Kim et al. (2003) and Kovacs et al. (2009). As a flow-induced vibration (FIV) due to the primary coolant is an inevitable phenomenon in a nuclear reactor core regardless of the nuclear fuel types, the fretting wear behaviours of spacer grid for dual-cooled annular fuel should be verified at the initial development stage. Therefore, this study is focused on the fretting wear behaviour of the dual-cooled fuel rod with the proposed spacer grid springs for the dual cooled annular fuel. The objectives are to compare the fretting wear behaviour of two kinds of spacer grid springs and their supporting abilities with a variation of the slip amplitude at each spring shape.

EXPERIMENTS

Specimen

Two kinds of spacer grid specimens were prepared using a Zirconium plate with a thickness of 0.46 mm. In this study, CSHD spring and dimple were formed at a biased position with a cantilever shape and a hemispherical contour. Thus, cantilever shape is intended to have a line contact with the rod specimen while hemispherical shape is a point contact. However, DUO-H spring and dimple both have concave contours, which were expected to have area contacts with a wrapping around the fuel rod in a circumferential direction of the contact region. In this experiment, CSHD spring and dimple, DUO-H spring, and dimple are denoted as Cs, Cd, Hs and Hd, respectively. Fig.1(a) shows the grid specimen used in this study. Also, a fuel rod specimen is manufactured from the punching process of a Zirconium plate to simulate enlarged diameter of outer fuel rod as shown in Fig. 1(b). Its thickness is the same with the spacer grid specimen and the radius is maintained as the same outer diameter of dual-cooled fuel rod (i.e., 7.95 ± 0.05 mm).

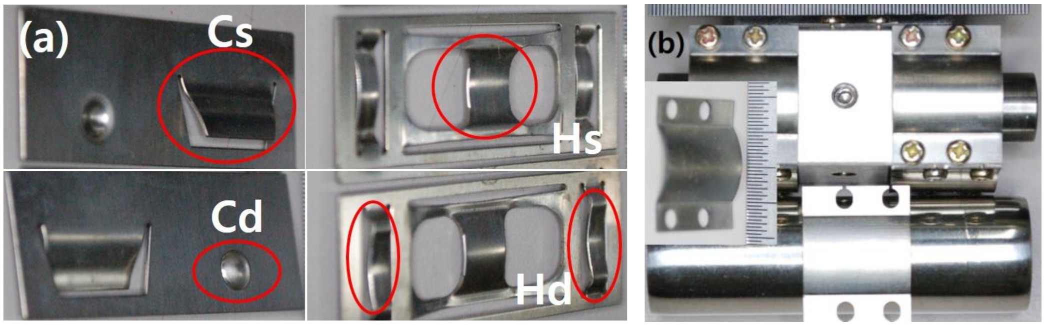

Figure 1. (a) Spacer grid candidates for dual-cooled annular fuel and (b) simulated outer fuel rod specimen used in this study.

Fretting Wear Tests and Wear Measurement

In this study, a fretting wear tester for GTRF was used for comparing the previous results of solid fuel rod tests and its schematic view is described in Fig. 2. A fuel rod specimen was attached to a vibration jig, which was reciprocated to the rod axial direction. During the fretting wear tests, normal and friction forces, relative slip amplitude, and vibrating frequency were monitored and analysed to estimate the change of wear mechanism. The grid spring and dimple specimens were fixed to a stroke mechanism and gradually pushed to the fuel rod specimen until a normal load reached 10 N. After then, the vibration jig attached to the fuel rod specimen was oscillated in the fuel rod axial direction with a peak-to-peak amplitude of 50, 80 and 100 μm at a frequency of 30 Hz. All tests were carried out in an unlubricated condition up to fretting cycles of 10^6. After the wear tests, the worn area was observed by an optical microscope for analysing and measuring the wear scar characteristics and the worn area including its length and width, respectively. The wear volume and depth profile were measured by a 3-D surface profilometer and their results were compared for each test condition.

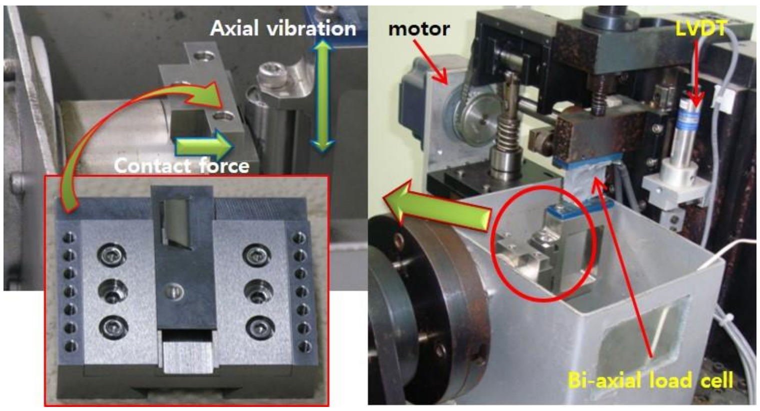

Figure 2. Schematic view of fretting wear tester for examining wear resistance of spacer grid.

RESULTS AND DISCUSSION

Wear Behaviours

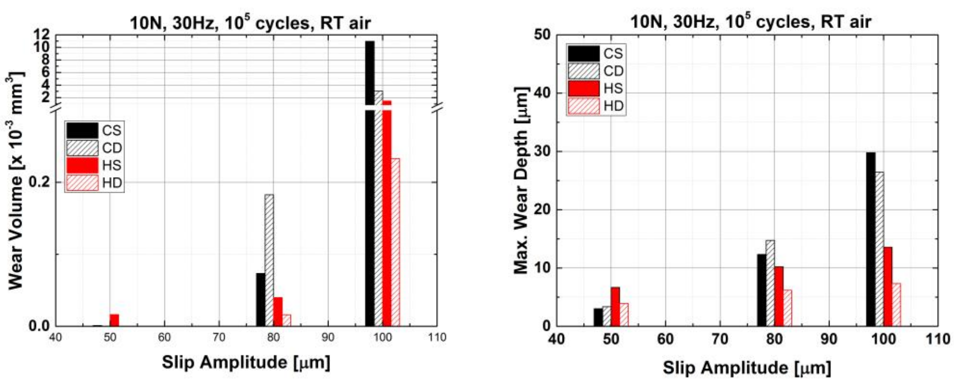

Figure 3. Variation of wear volume and maximum wear depth with increasing slip amplitude.

Fig. 3 shows the variation of measured wear volume and maximum wear depth with increasing relative slip amplitude. Regardless of spacer grid shapes, it is difficult to find a remarkable change of the wear volume at up to 80 μm, but significantly increases at a slip amplitude of 100 μm. Also, it is apparent that wear volumes of Cs and Cd specimens are dramatically increased while those of the Hd is negligible and Hs result shows gradually increase. This result indicates that DUO-H spacer grid have a more wear resistant rather than CSHD. However, it is interesting that simulated fuel rod against both dimple specimens shows relatively small wear volume rather than spring specimens even though each dimple have a high stiffness value. However, the maximum wear depth shows a gradual increase regardless of each specimen. Thus, the variation of wear volume could be affected by the worn area expansion due to each spacer grid shape. Thus, it is necessary to examine the worn surface focusing on the grid shape effects of each spacer grid.

Worn Area Progress

Figs. 4 shows the summary of worn surface observation and wear scar measurement of the dual-cooled fuel rod with increasing relative slip amplitude. It is apparent that the worn area of the Cs specimen was generated at both ends of the spring contact region, and then gradually broadened to the centre of contact length of the fuel rod. However, the Cd specimen shows a circular shape except for its diametric size. Gradual change of worn area at Cd specimen clearly shows the protruded area on the worn surface, which is expected to retard area expansion as the wear depth increases. Therefore, different results between wear volume and maximum wear depth in the Cs and Cd conditions can be explained by worn area expansion. In the Hs and Hd conditions, however, they both have area contacts in the circumferential direction, and the wear scar shapes show an ellipse to axial direction of fuel rod. Also, their worn areas show an evenly distributed protruded area that was transferred from the spacer grid specimen or generated wear debris layer. In the Hs and Hd conditions, a relatively smaller wear volume and maximum wear depth are expected due to the formation of a wear resistant surface with spacer grid shapes.

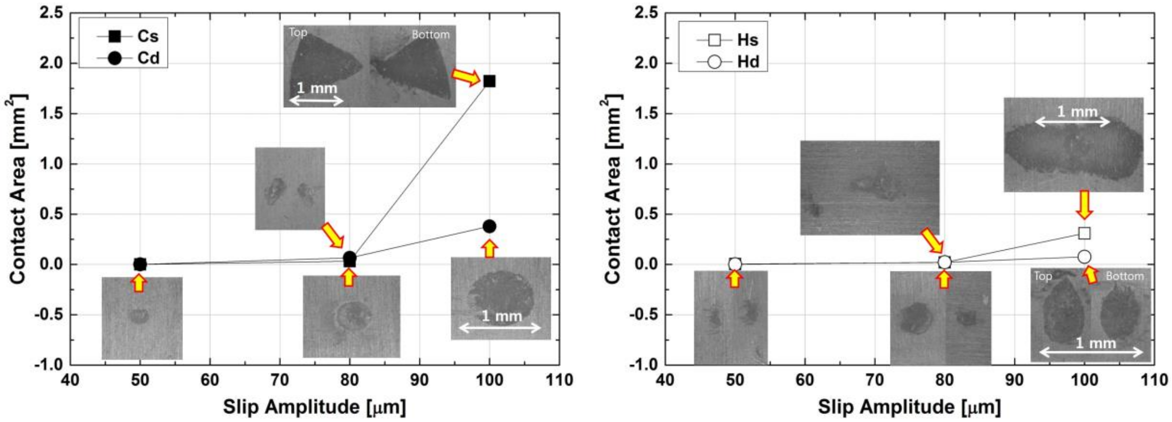

Figure 4. Worn surface morphology and calculated worn area after the fretting wear tests.

Supportability of Spacer Grids

Generally, one of the principal roles of spacer grid is to provide both a lateral and vertical support for fuel rods and to allow for a differential thermal expansion and growth of the fuel rods. In addition, spacer grid should be retained fuel rods with a sufficient spring contact force to prevent contact damages by flow-induced vibration (FIV). Fig. 5 summarized the variation of the contact force during the fretting tests at each spring and dimple condition. The contact force was considerably changed in the Cd condition, while the Hs condition did not have a significant change at up to 10^5 cycles. Also, the Cs and Hd conditions only show an irregular change of contact force at the initial stage. The repeated load drop is expected due to changed contact positions between the fuel rod and spacer grid. This is because of the formation and fracture of the protruded wear debris with increasing number of cycles. Therefore, the variation of contact force can be explained by the spring stiffness and formation of wear debris between the contact surfaces. If the spacer grid spring and dimple have relatively high stiffness values, it is expected that the elastic deformation under the initial normal force results in a smaller displacement. As the spring and dimple specimens were firmly fixed during the fretting tests, the contact force drop is closely related to the relaxation of contact force due to the wear depth increase or change of contact position. As the Cs and Cd specimens are contacted at a biased position of the centre of the dual cooled fuel rod, the contact position is easy to change due to their line and point contacts compared with the Hs and Hd conditions. Consequently, the higher wear volume and maximum wear depth in the Cs and Cd conditions are due to an unstable supporting ability during the fuel rod vibration and the DUO-H spacer grid is considered a reasonable candidate for a dual cooled fuel rod from the view point of fretting wear resistance.

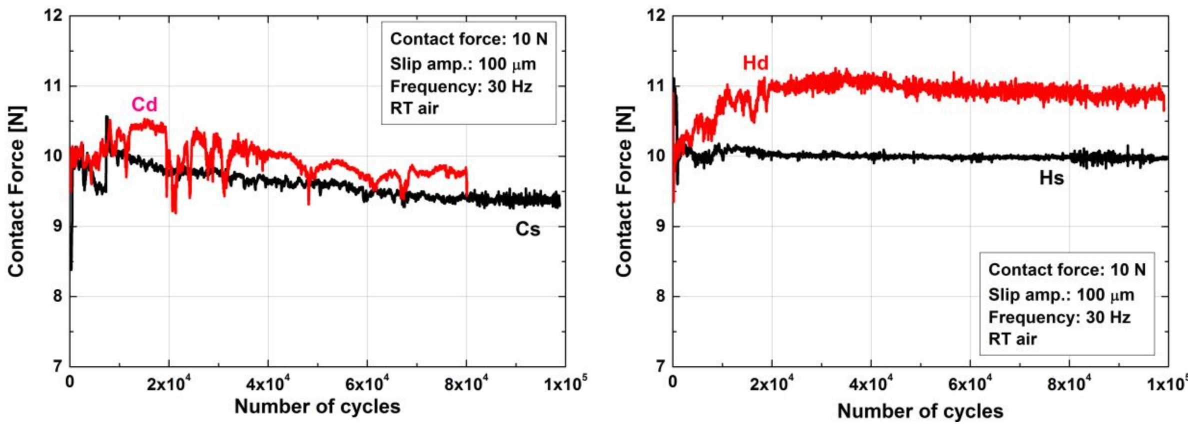

Figure 5. Variation of initial contact force with increasing number of fretting cycles.

SUMMARY

Fretting wear tests of a dual-cooled fuel rod have been performed using two kinds of proposed spacer grids at the room temperature unlubricated condition. With increasing relative slip amplitude, the wear volume has no significant change at up to 80 μm, but rapidly increases at a slip amplitude of 100 μm. During the fretting wear tests, initial contact force at both spring specimens was gradually changed and it was strongly affected by worn area expansion and wear debris behaviour, which depends on spacer grid shapes. The higher wear volume and maximum wear depth in the cantilever spring (Cs) and hemispherical dimple (Cd) conditions showed an unstable supporting ability. Consequently, the proposed DUO-H spacer grid is considered a reasonable candidate for a dual cooled fuel rod from the view point of fretting wear resistance.

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