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Wear Mechanism of Tube Fretting Affected by Support Shapes

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Abstract : A fretting wear experiment in room temperature air was performed to evaluate the wear mechanism of fuel rod using a fretting wear tester, which has been developed for experimental study. The main focus was to compare the wear behaviors of fuel rod against support springs with different contact contours (i.e. concave and convex). Wear volume, degree of surface hardening and adhesion tendency of wear particle were examined by the surface roughness tester. The result indicated that with a change of contact condition from contact force of 5 N to 0.1 mm gap, the wear volume of tube increased in the condition of concave spring, but slowly decreased in convex spring. From the results of SEM observation, wear mechanism of each test condition was also dependent on the spring shapes. The wear mechanism of each test condition in room temperature air is discussed.

Key words : Fretting wear, fuel rod, spring, contact geometry, SEM

Introduction

Fretting wear phenomenon generally occurred when two materials contact with relatively small amplitude. In order to decrease fretting-related damage, modification and improvement of contact conditions such as contact geometry, contact area, etc., have been performed in each contact part. Therefore, it could be summarized that improvement methods are to reduce contact stress and relative amplitude between two materials during fretting with modification of supporting design, establishment of additional support, etc. However, if the contact load and relative amplitude at the contact area were irregularly altered and time-dependant, fretting-related damage could severely occur at the supports even though they were established to restrain vibration.

In the pressure vessel of pressurized water reactors (PWR), for example, the fuel rods are held forcefully by the springs (and dimples) of space grid before power operation and some of contact loads are generated at contact area between fuel rods and their support springs (and dimples). After operation, however, the grid materials loosen up and small clearance opens between the fuel rods and their support springs (and dimples) as the fuel rod creeps down onto the fuel pellet. So, it is possible to consider that the contact condition can be changed to have a light contact load and some clearance eventually. Moreover, primary coolant with high flow rate passes through a space within fuel assembly to remove the excessive heat generated during nuclear reaction. These are well known as the main source of flow-induced vibration (FIV). So, both these contact conditions (light contact load or clearance) and high flow rates could produce relative motion between the fuel rods and their support springs (and dimples). In these circumstances, PWR fuel rods are sensitive to fretting wear damage.

Fretting-related degradations due to FIV in nuclear power plants has been concentrated on both fuel rod/spring (and dimple) within fuel assembly in the primary side of reactor vessel and tube/support plate in the secondary side of steam generator (SG) [1,2]. Up to now, experimental studies on fretting wear in the nuclear fuel rods and SG tubes have been extensively performed by many researchers and they proposed many semi-empirical models to predict the fretting wear damage [3]. However, there has been little effort made to understand the wear mechanism of the fuel rod against the grid spring (and dimple). To reduce wear damage, wear mechanisms must be examined at each test variable such as slip motion, spring shape, support condition, etc.

In the present study, a fretting wear experiment was performed with Zircaloy-4 fuel rod against two types of grid springs at room temperature air. The objectives are to examine the effect of the various support conditions followed by the different spring shapes on the fretting wear of the fuel rods and to estimate the possible wear mechanism before high temperature and pressure experiments. The discussion focused on the relationship among the wear volume, the spring shape effect, slipping motion and support condition.

Experimental Procedure

Specimen

The tube and the spring specimens used in this experiment are

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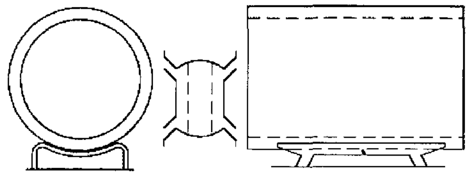
Table 1. Mechanical properties of tested specimen

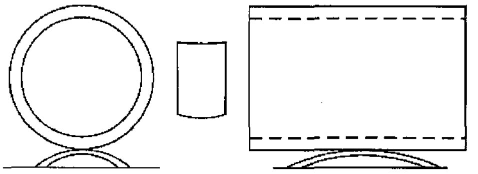
Yield stress	Tensile strength	Elongation	Elastic modulus	Poissons ratio
344.3 MPa	470 MPa	31%	136.6 GPa	0.294

Table 2. Chemical composition of tested specimen [wt.%]

Zr	Sn	Fe	Cr	O	C	Si
Bal.	1.28	0.22	0.12	0.114	0.013	0.01



(a) Spring A (concave)



(b) Spring B (convex)

Fig. 1. Schematic diagram of tube and springs.

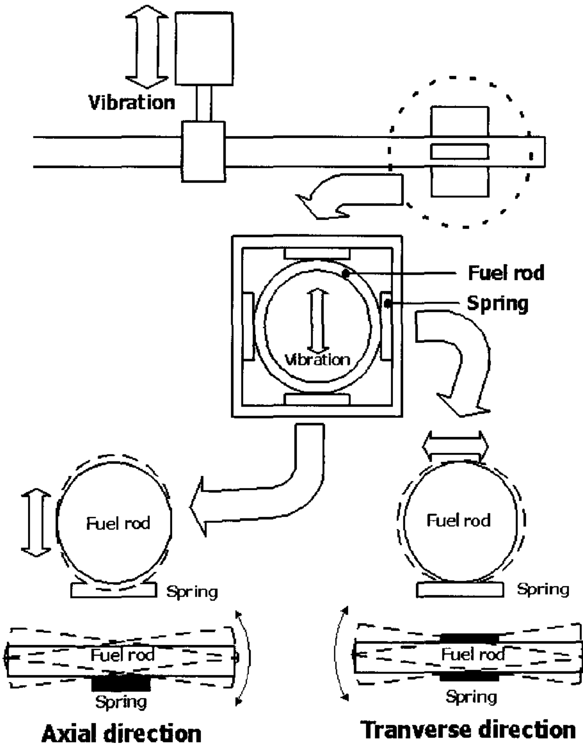


Fig. 2. Schematic diagram of fretting wear tester.

made of Zircaloy-4, which is used as nuclear fuel cladding and main components of fuel assembly materials. The chemical compositions and mechanical properties are listed in Table 1 and 2. The fuel rod specimen, 9.5 mm diameter, 0.6 mm thickness by 40 mm long, is cut from the straight rod. The springs are fabricated by pressing and punching a Zircaloy-4 sheet with a thickness of 0.46 mm. For the variations of the contact conditions, two different spring shapes are used and marked as A and B as shown in Fig. 1. Since spring A is designed to have a concave contour, it is expected that these springs are wrapped around the tube specimen in transverse direction of the contact region while tube pressing can be widened compared with the spring of convex or flat contour. While spring B have a convex contour, so this spring is intended to have a line contact with the tube specimen in their axial length. Also, while spring A has a relatively sharp corner with chamfer treatment, spring B at both spring ends does not contact with tube specimen because of its convex contour.

Slip Motion and Fretting Wear Tester

To simulate the fretting wear phenomena between the fuel rod and the support spring, new fretting wear tester is particularly designed for the present experiments [4]. A schematic diagram of the tester and contact region are depicted in Fig. 2. This tester consists of a dc servomotor, eccentric cylinder, lever, movable hinge, etc., and can control the test variables such as frequency, relative amplitude, normal load and clearance between fuel rod and spring specimens, etc. The interval between the specimen assemblies is 522 mm and the range of amplitude between fuel rod and spring is adjustable by changing the center rod amplitude which varies following the lever position. From the schematic diagram of rod/spring specimen assembly illustrated in Fig. 2, it is possible to simulate four contacts between the fuel rod and grid spring with 90° intervals as an actual configuration in a fuel assembly. Because the rotating motion of servomotor is changed to the reciprocating motion of the center rod in its radial direction, the fuel rod moves up and down within the rod/spring specimen assembly as shown in Fig. 2. At this time, we can divide the slipping motion into two types. One is seesaw motion on the contact area between specimens in axial direction. The other is oar motion, which is described as the oscillation in transverse direction within the plane of parallel to the contact area. To simply the above slip motion in this experiment, these are called axial and transverse slip, respectively.

Test condition

Three conditions were selected in order to simulate fretting wear phenomenon of fuel rod against grid spring. The conditions are designed to describe the variation of contact condition between fuel rod and grid spring during power operation in PWR. Before power operation, the fuel rods are held tightly by the springs of space grid. After operation, however, some grid materials loosen up due to the reduction of spring stiffness and the fuel rod creeps down onto the fuel pellet. This contact condition can be described as a light contact load and no clearance. With increasing operation time, a gap between fuel rod and grid spring could be generated. Inbetween, we can suppose the condition of null contact load but no clearance, which is referred to as just contact in this paper. In this experiment, therefore, the test conditions of contact load of 5 N, just contact (contact load of 0 N and no clearance) and 0.1 mm gap between fuel rod and spring are used and denoted as L, J and G conditions, respectively. All tests were performed with the center rod amplitude of 0.7 mm at a frequency of 30 Hz up to 10^6 cycles. After the experiment, the worn surface of fuel rod specimen is measured by using a surface roughness tester in order to calculate the wear volume of the fuel rod specimen [5].

Worn surface observation

To compare and analyze the fretting wear mechanism at each test condition, the worn surface of the fuel rod was examined using scanning electron microscopy (SEM) after fretting wear test. Also, we examined the stylus scratch on worn surface created during wear volume measurement at each tested fuel rod in order to compare the relative adhesion strength of wear particle layers with a matrix and the hardening behavior of deformed surface on the fuel rod during fretting wear.

Results and Discussion

Wear volume and depth

Fig. 3 shows the relationship between support conditions and the average wear volume of tube specimen against each spring. In this test, the average wear volume is calculated from the results of three or four experiments of the same test condition. It is shown that the average wear volume differ considerably depending on the support conditions. In G condition, spring A shows relatively poor wear resistance of tube specimen compared with spring B. However, spring A shows relatively high wear resistance in L condition in contrast to spring B. Therefore, average wear volumes and their variation tendencies were changed with both spring types and support conditions.

To confirm whether worn area is concentrated in local region of tube specimen, the average wear depth is also measured at each test condition and their results are shown in Fig. 4. The variations of average wear depth with different test conditions are almost similar to those of wear volume. This means that tube wear occurred in almost all contact areas, not only in the local region during fretting wear.

When the contact condition between the tube and spring changes from contact force of 5 N to 0.1mm gap (namely, L-J-G condition), superior wear resistance was offered by spring B. Conversely, the tube wear volume by spring A was found to increase with decreasing contact load, such that it exhibited a higher wear resistance than the spring B condition at contact load of 5 N, but lower wear resistance at 0.1 mm gap condition. However, average wear volumes by spring A condition in axial slip and spring B condition in transverse slip were changed little as the test condition varies from L condition to J condition. Main difference of tested springs is the contact shape on the fuel rod corresponding to the different spring shapes as shown in Fig. 1. Therefore, the worn surfaces of fuel rods at each test condition were examined in detail using SEM to investigate the cause of the difference in wear volume.

Effect of contact condition

To investigate the wear mechanism and deformation behaviour on the tube by spring A in the case of axial slip, SEM observation was conducted and typical results are shown in Fig. 5. In L condition, almost all worn surfaces revealed the formation of compacted particle layers that are similar to plastic flow caused by severe plastic deformation. Besides, there are many different sizes of wear particle compacted on the worn surface during fretting wear. These wear particle layers seems to be generated from the agglomeration of wear debris. So, the wear debris with relatively large sizes became more and more finer particles, and these were trapped on the suitable sites of contact surfaces or escaped from the contact areas. As the axial slip continues, these trapped fine wear particles are compacted on the worn surface under the contact

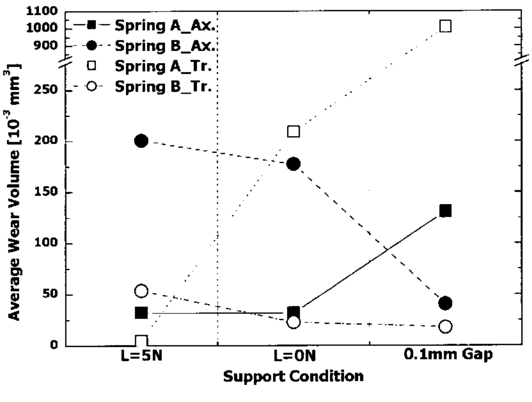


Fig. 3. Effect of contact geometries on the wear volume of fuel rod.

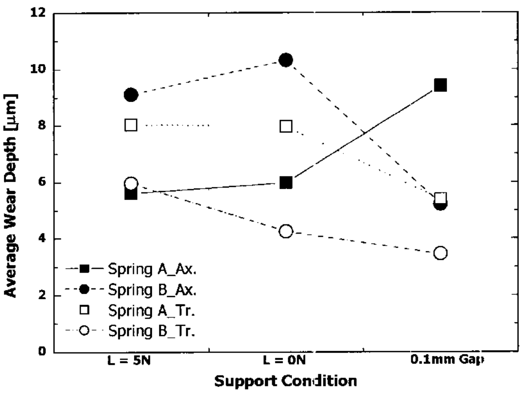


Fig. 4. Variation of average wear depth at each test condition.

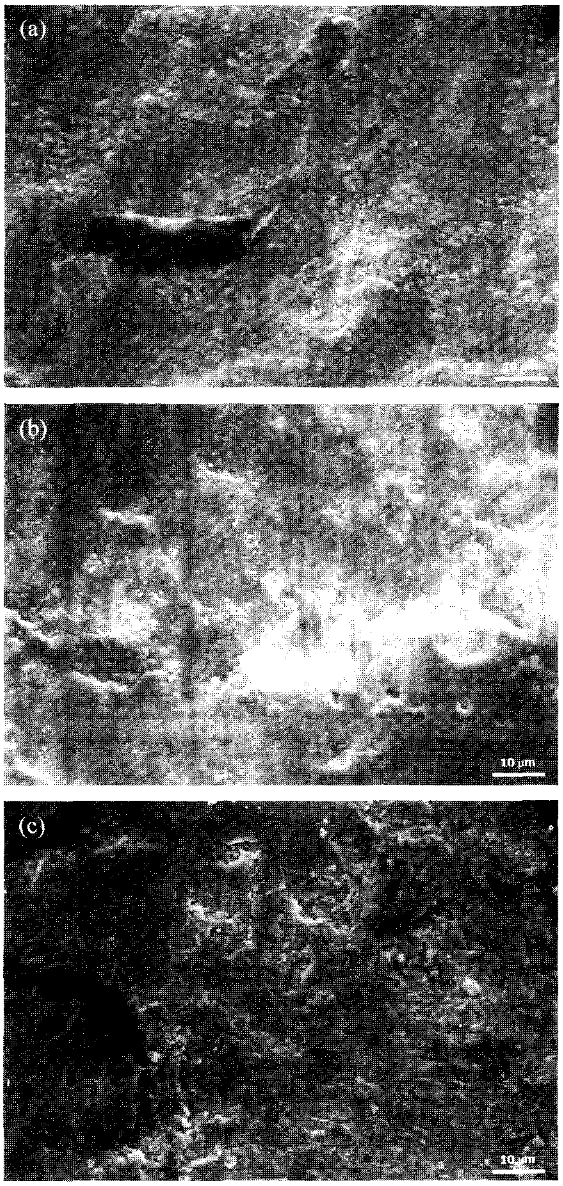


Fig. 5. SEM results of worn surface (A type spring) (a) L condition (contact load of 5 N) (b) J condition (Just contact) (c) G condition (0.1 mm gap).

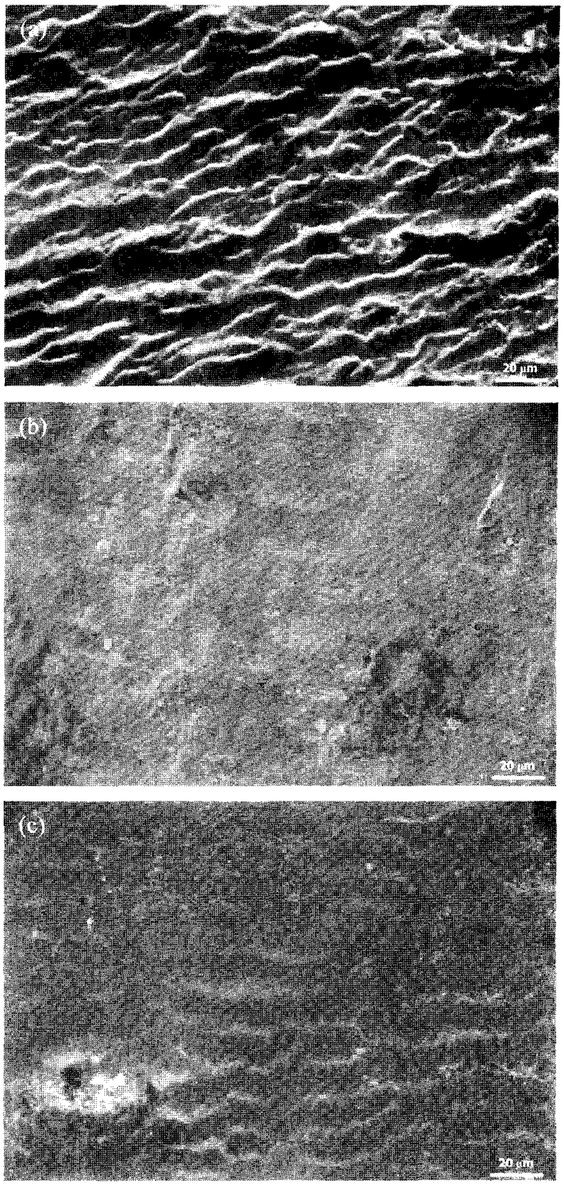


Fig. 6. SEM results of worn surface (B type spring) (a) L condition (contact load of 5 N) (b) J condition (Just contact) (c) G condition (0.1 mm gap).

load and built up the wear particle layers.

In J condition, relatively small amount of wear particle are distributed on the worn surface in compared with L condition. Moreover, it is difficult to observe the evidence of the formation of severe wear particle layer. The deformed folds which are generated by axial slip appeared on worn surface. The generation of wear particles is closely related with the edge fracture of deformed fold and some of wear particles remained near the fractured fold because this site is more suitable for particle trapping. Therefore, it seems that wear particles in J condition are easily removed from contact surfaces except the above suitable sites because there is little contact load.

However, if a gap is existed between the fuel rod and spring such as G condition, it is clearly appeared that worn surface was covered with wear particle layers that have much cracks. Also, impact load due to gap between specimens acts as hammering on locally high roughness region according to the fine particle agglomeration. Although it is appeared that the worn area consists of the sparsely flat deformed layers and wear particles as shown in Fig. 5, it is thought that the adhesion strength between wear particles or flat deformed layers and matrix according to the impact load is somewhat weaker when compared with L condition.

Before SEM observation, wear volume was measured using a surface roughness tester and scratches or gouges were generated on the worn surface at regular intervals. The width and depth of the scratches or gouges generated during wear volume measurement could be reduced if the wear particle layer or the deformed layer was hardened during fretting wear.

Fig. 7. Variation of worn surface morphology with slip direction on tube by spring A (a) Axial (b) Transverse.

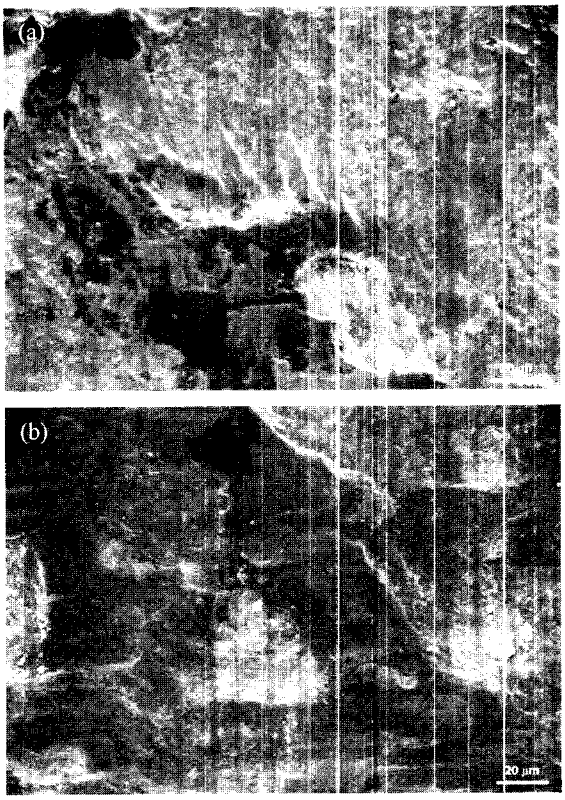


Fig. 8. Comparison of wear mode between axial and transverse slip (a) Axial (b) Transverse.

So, when we compare the width of scratches in Fig. 5, it is clearly distinguished that the scratch in G condition is wider than that in other conditions. This result can be connected to the low adhesive degree of wear particle layer onto matrix, especially, in G condition. Besides, it is well known that the wear particle layers were more resistant to sliding wear and seemed to act as load-bearing layers [6]. Therefore, the differences of wear volume in the case of spring A originated in the formation behavior of wear particle layers and the adhesive tendency with matrix at each support condition.

Fig. 6 shows the morphology of tube worn surface in the case of spring B resulted from axial slip. In L condition, the deformed folds that have a wave-type are dominantly appeared on worn surfaces. In this figure, it is impossible to detect the evidence of either wear debris which is trapped at the suitable sites or the formation of wear particle layers. This means that almost all wear debris was released from contact areas even though the contact load existed. However, these deformed folds disappeared almost in J condition and both flat deformed matrix and fine wear debris adhered to matrix clearly appeared on the worn surfaces. This is attributed that a part of fine wear particles could be adhered to matrix by the hammering effect due to axial slip when generated wear particles were crushed into fine debris between contact surfaces.

G condition shows that there are small amounts of deformed folds with relatively large spacing and wear debris were released by fracture of fold edge after plastic deformation. Thus, in spite of the convex shape at spring B condition, it is thought that the impact load by 0.1 mm clearance is not enough to generate large deformation as well as surface deformation since the impact load occurred discontinuously between contact surfaces.

From the above results, when the fuel rod is supported by concave springs such as spring A, the wear resistance of fuel rod is determined by the formation behavior of wear particle layers according to the support conditions. However, if the fuel rod contacts with convex shape (Spring B), the wear volume is controlled by the degree of deformation concentration during axial slip between contact surfaces. In other words, it is thought that the surface deformation and formation of debris are more efficient under the contact load than in the existence of clearance because wear particles were released from worn surface after severe plastic deformation and fracture followed.

Effect of slip direction

To explain the cause of different wear volumes between slip directions, worn areas of tube against spring A in J condition was examined at axial and transverse slip using SEM and their results are shown in Fig. 7. In axial direction, worn surface consists of both region covered with fine wear particles (white color) and a flat deformed zone due to axial slip. In this figure, some of flat deformed zones are oblique by about 45° and distributed throughout the worn surface. This means that the oblique stroke which occurred during axial slip and the brims of the concave spring could act as a guide which enabled it to produce shear load due to impact contact to the fuel rod even though just contact condition. Therefore, wear damage of tube specimen could be concentrated on the contact area between the fuel rod and the edge of concave spring. However, it is difficult to observe the wear particles in transverse vibration. This implies that it is relatively easy to release wear particle from contact surface and the generated wear particles seem to be easily removed due to the transverse slip when compared with the axial slip.

To confirm the exact wear mechanism according to the variation of slip direction, more detail figures are given in Fig. 8. The particle-agglomerated layers are developed on the worn surface in the case of axial slip. So, wear mechanism of tube specimen by spring A in the case of axial slip and just contact condition is clearly related to both the particle layers torn out by adhesion and wear debris removal from these layers after crack propagation. In transverse vibration, however, the worn surface reveals that the thickness of particle layers is somewhat thin and transverse scratches or gouges are dominantly appeared due to third body abrasion. This means that when the fuel rod vibrates transversely inside the concave springs together with the existence of a small gap, it is possible that the fretting wear damage will dramatically increase because wear particles are easily released by third body abrasion during fretting wear.

Conclusions

In the present work, fretting wear experiment was performed with Zircaloy-4 fuel rod against three types of grid springs in air at room temperature. From those experimental results, the following conclusions were obtained;

(1) With variation of the support conditions from contact load of 5N to clearance of 0.1mm, the wear volume of fuel rod against concave spring increased. But, that against convex spring gradually decreased.

(2) The differences of wear volume against the concave spring originated in the formation behavior of wear particle layers and the adhesive tendency with matrix at each support condition. However, in the case of the convex spring, the wear volume is controlled by the degree of deformation concentration during the axial slip between contact surfaces.

(3) The brims of concave spring could act as a guide that enabled to produce shear load due to impact contact to the fuel rod.

(4) When the fuel rod vibrates transversely and opens a certain gap against concave spring, it is possible that the fretting wear damage will increase because wear particles are easily released by abrasion during fretting wear.

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References

1. N. J. Fisher *et al.*, "Fretting-wear of zirconium alloys," Nuclear Engineering and Design, Vol. 213, p. 79-90, 2002.
2. S. Fouvry *et al.*, "An elastic-plastic shakedown analysis of fretting wear", Wear, Vol. 247, p. 41-54, 2001.
3. N. J. Fisher *et al.*, "Experimental fretting-wear studies of steam generator materials," J. Pressure Vessel Technology, Vol. 117, p. 312-320, 1995.
4. H. K. Kim *et al.*, "Development of fuel rod fretting wear tester," Proceedings of KSTLE autumn meeting, p. 245-251, 2001.
5. H. K. Kim *et al.*, "Fretting wear of laterally supported tube," Wear, Vol. 250, p. 535-543, 2001.
6. J. Jiang *et al.*, "The role of triboparticulates in dry sliding wear," Tribology International, Vol. 31, p. 245-256, 1998.