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# A Study on Third Body Abrasion in the Small Clearance Region Adjacent to the Contact Area

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**Abstract: Abrasion in fretting wear mechanism is studied experimentally with the specimens of two different shapes of spacer grid spring and fuel tubes of a nuclear fuel. Reciprocating sliding wear test has been carried out in the environment of air and water at room temperature. Especially, third body abrasion is referred to for explaining the wear region expansion found during the slip displacement increase with constant normal contact force. It is found that the expansion behaviour depends on the contact shape. The small clearance between the tube and spring seems to be the preferable region of the wear particle accumulation, which causes third body abrasion of the non-contact area. Even in water environment, the third body abrasion occurs apparently. Since the abrasion on the clearance contributes wear volume, the influence of the contact shape on the severity of third body abrasion should be considered to improve the grid spring design in the point of restraining wear damage of a nuclear fuel.**

**Keywords:** Third body abrasion, clearance, contact shape, wear dimension

## Introduction

It is known that the fretting wear mechanism is composed of adhesion and abrasion. According to Ko's review [1], it is initiated by adhesion, and when the wear particles are subsequently oxidized, abrasion becomes the primary mechanism. The cycle is repeated during fretting. The ease with which wear particles are dispersed has a significant effect on the severity of the fretting wear damage. Therefore, it is suggested that to restrain wear particle generation and/or to retard the cycle of wear particle generation and dispersion are the ways of restraining fretting wear damage.

Wear particle generation can be explained as a frictional energy dissipation from the contact surface. This is often used for the theory of adhesion. The friction energy is described in terms of a multiplication of shear force and slip displacement on the contact surface. Similarly, if we consider wear at a specific point of the surface, the concept of the friction energy density may be suggested. In this case, the friction energy density is a multiplication of shear traction (instead of force) and slip displacement at that point. This concept is particularly valuable when wear depth is primarily concerned. A good example is the fretting problem of a nuclear fuel.

During reactor operation, the fuel vibrates due to the flow-induced vibration phenomenon caused by coolant flow through the fuel. Simultaneously, relative slip occurs on the contact regions between the fuel rods and spacer grids whose function is to support the fuel rods. This is the fretting condition of a nuclear fuel rod. Since the thickness of the fuel rod tube is very thin (around 0.6 mm, usually), severe wear may cause perforation of the fuel rod tube. This results in the radioactive fission gas inside the tube coming out to the coolant, which should be prohibited from the viewpoint of safety concerns. Therefore, wear depth is a more critical parameter than others such as volume and area.

Contact traction is directly influenced by contact shape. Therefore, contact shape affects the wear depth on the contact surface. In other words, it can be expected that wear becomes deeper at the location of higher traction. This is valid if adhesion is particularly considered. However in abrasion, the generated wear particles can remain on the contact surface or they are dispersed out. If they are dispersed out easily, virgin material is subsequently exposed under the wear condition and the wear can be accelerated. If they are not dispersed out easily but remain and accumulate on the contact surface, the accumulated particles form a load bearing layer so that wear can be restrained [2]. To the contrary, the accumulated particles can cause third body abrasion if the contact normal force is light. The contact shape also affects the behaviour of particle dispersion, which is the concern of this paper.

If very narrow clearance is constituted in the vicinity of the contact region, the particles can be accumulated in that clearance, which can cause third body abrasion in the non-contact region of the clearance. If it occurs, the wear area expands larger than the actual contact area and the wear volume and depth also increase accordingly. So to speak, additional wear can occur due to the third body abrasion of the non-contact region. If the wear volume is concerned for the analysis and/or prediction of wear severity, it is necessary to

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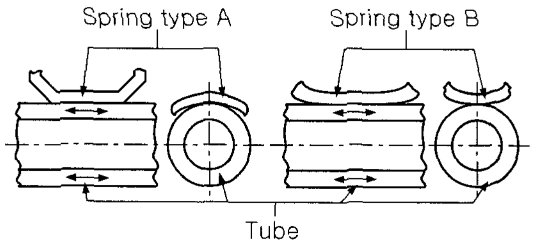


**Fig. 1. Schematic view of the contact configuration between type A and B spring and tube specimens.**

consider this additional wear phenomenon.

Therefore, we tried to study the phenomenon of third body abrasion in an actual example case, that is, the contact between the spacer grid and fuel rod of a nuclear fuel assembly. The effect of contact shape (spring end profile) on third body abrasion is investigated in detail. Two different shapes of spring are experimented with in air as well as water at room temperature for this purpose. Wear dimension is analysed in detail and compared with the contact dimension obtained from finite element analysis. What is primarily of concern in this paper is the expansion behaviour of the wear dimension due to third body abrasion, which is affected by the contact shape. It is also expected that the present research will contribute to the improvement of the spring shape from the point of restraining wear damage.

## Experiment

### Specimen

The material of the tube and the plate spring specimen is the same, zirconium alloy, which is used for nuclear fuel of light water reactors. The diameter and the thickness of the tube specimen are 9.5 mm and 0.6 mm, respectively. It was cut to be 50 mm from as-received tubes for fuel rod fabrication. As a contacting body against the tube specimen, plate spring specimens (spacer grid springs) are used, which have two different contact shapes: type A has a concave contour along the circumferential direction of the tube and is flat with coined (chamfered) edges along the tube axis; type B has convex contours in both the transverse and axial directions of the tube. These contact configurations are illustrated in Fig. 1.

The reason for the concave contour of the type A spring is to increase the contact area (especially, the width) so that the contact stress can be distributed widely. It is intended that the widened contact area restrains wear. The contact length along the tube axis is regarded to be the same as the flat length (4.1 ± 0.02 mm), which is the distance between the coining locations at both edges. On the other hand, contact stress is expected to decrease with a contact length increase in the case of the type B spring. This is possible since type B constitutes a non-conformal contact (i.e., contact length depends on the contact normal force). In short, both types of the experimented plate spring are designed for restraining wear by increasing the contact area. Before the experiments, each tube and spring

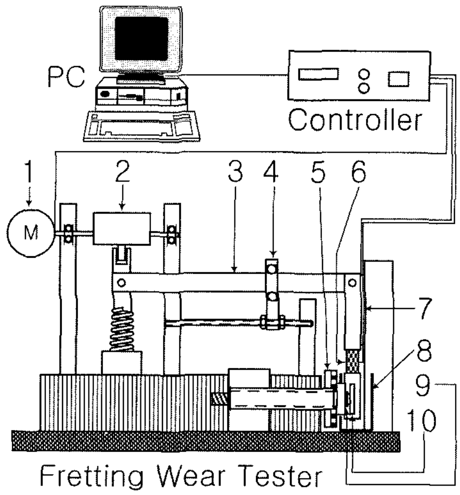


**Fig. 2. Fretting wear tester; 1: Servo-Motor, 2: Eccentric Cylinder, 3: Lever, 4: Movable Hinge, 5: Rotating Device, 6: Biaxial Loadcell, 7: LVDT, 8: Water Tank, 9: Stationary Specimen (Spring), 10: Oscillatory Specimen (Tube).**

specimen is cleaned with acetone in the ultrasonic bath. The average surface roughness ($R_a$) of the tube and spring reads 0.76 mm and 0.67 mm, respectively.

### Wear tester

Fig. 2 shows the schematic view of the wear tester used for the present experiment. Reciprocating sling motion between the contacting specimens is performed using servomotor, eccentric cylinder and the lever system. The sling amplitude and frequency, which are measured using LVDT and FFT, can be adjusted. Besides the air environment test, the experiment can be done with the specimens under water below boiling temperature. Details of the tester have already been presented [3], so it is not reproduced here.

### Experiment method

The environmental condition of the present fretting wear experiment was under-water as well as in-air at room temperature. The slip displacement between the tube and plate spring varied as 10, 30, 50, 80 and 100 $\mu$m with the normal contact force being 10 and 30 N. The slip direction was the same as the axial direction of the tube. The frequency of the reciprocating oscillation was set at 30 Hz, which was the first natural frequency of the fuel rod. Each experiment ended when the number of reciprocating cycles reached $10^5$.

After each experiment, wear scar on the tube was investigated and measured using an optical microscope. Wear contours in the depth direction were logged by a surface roughness tester, from which the maximum depth was extracted. The stylus of the roughness tester was passed through the wear scar repeatedly with an increment of 20 mm along the transverse direction of the tube, which yielded a three dimensional shape of the wear region. Finally wear volume was evaluated using a specially developed program [4].

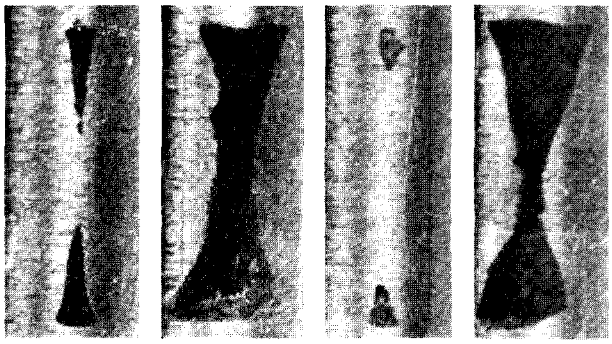


**Fig. 3. Microscopic view of wear scar on tube by type A spring in air test at (a) 10 N-50 μm (b) 10 N-80 μm (c) 30 N-80 μm and (d) 30 N-100 μm (see Figs. 7 and 8 for wear dimension).**

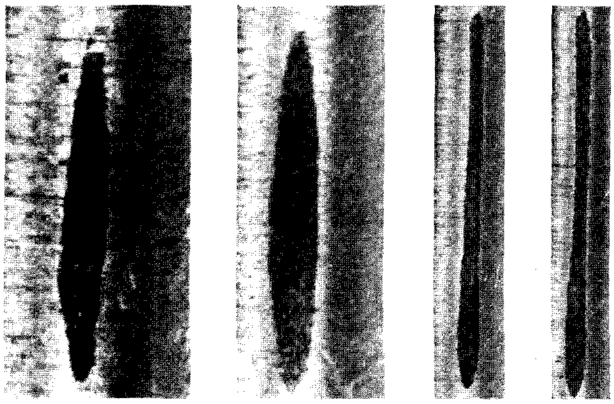


**Fig. 4. Microscopic view of wear scar on tube by type B spring in air test at (a) 10 N-50 μm (b) 10 N-80 μm (c) 30 N-80 μm and (d) 30 N-100 μm (see Figs. 7 and 8 for wear dimension).**

## Experimental Results and Discussions

### Wear scar observation

Figs. 3 and 4 show typical wear shapes on the tubes after $10^5$ cycles of type A and B springs, respectively. In the case of the contact with type A, the wear shape appears very different corresponding to the slip displacement (Fig. 3). When the slip displacement is relatively small at each contact force (10 N-50 μm and 30 N-80 μm), the wear appears separately in the vicinity of both edges. Wear width is wider at the edges and narrows inward to the center of the contact. So the overall shape is two triangles as shown in Fig. 3 (a) and (c) if the wear is separated. However, as the slip displacement increases, the separated wear scars expand inwards and outwards simultaneously in the longitudinal and circumferential directions of the tube, respectively. So, a butterfly wings-like shape is obtained as shown in Fig. 3 (b) and (d).

The length increase of the wear scar is not found regardless of the contact force and slip displacement in the case of the type A contact. However, the width increase is considerable as the slip displacement increases. The reason for the width increase is regarded to be that the wear particles generated on the contact surface accumulate in the circumferential clearance region constituted between spring A and the tube. In other words, it is caused by third body abrasion. It is not anticipated that the particles can be accumulated in the very large clearance regions outside the contact edges in the axial direction (due to coining). That results in almost no increase in wear length. It is readily expected that the width increase becomes considerable as the amount of particles increases, which is possible as the slip displacement increases.

In the case of the contact with the type B spring, a slender ellipse shape of wear is found in all the experiments as given in Fig. 4. The wear length in the direction of tube axis grows as the normal force increases. It verifies the typical characteristic of non-conformal contact. Besides, it was found that the length also increases considerably as the slip displacement increases under the same normal force. It cannot be explained from the non-conformal contact configuration. Instead, it can be explained by third body abrasion.

So to speak, the wear particles generated from the contact surface move outwards in the axial as well as the transverse direction. The small clearance region formed outside the contact could be a possible region for particle accumulation. If it happens, wear dimension increases due to the particle motion between the tube and spring. Since the reciprocating sliding motion of the experiment was in vertical direction, it is easy to assume that the passage of the particles was preferably vertical. The sizes of the clearance and its region formed along the axial direction must be smaller than that along the transverse direction in the case of the type B spring. This results in the considerable increase of wear length and relatively small increase in wear width as the slip displacement increases.

If the width increase in type A and the length increase in type B are caused by the particle accumulation in the

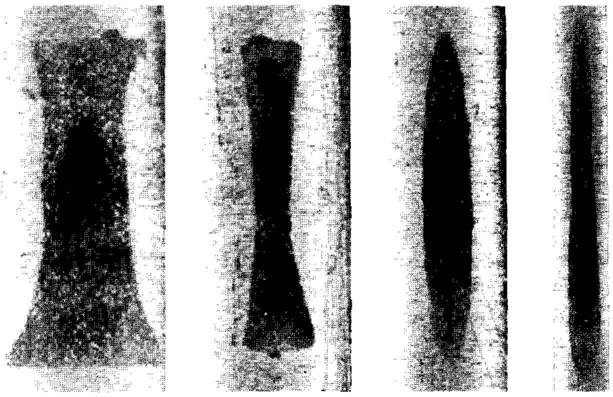


**Fig. 5. Microscopic view of wear scar on tube in water test by type A spring at (a) 10 N-80 μm (b) 30 N-100 μm and by type B spring at (c) 10 N-80 μm and (d) 30 N-100 μm (see Figs. 7 and 8 for wear dimension). Contrast between central and brim regions is distinct compared with the air test results shown in Figs. 3 and 4 due to the wear particle dispersion by water.**

clearance, it is worth re-investigating to see such phenomena from the under-water experiments. This is because the water environment may disperse the particles out easily and fast so that the increase of the width (by type A) and the length (by type B) may not be considerable differently from the air test results. The dimension of the wear scars will be discussed in detail later in this paper. However, it can be said here at least that the dispersion of the particles in the clearance region was distinctive also when the experiment was conducted in water. Fig. 5 shows the typical wear scars obtained from the under-water experiments. It is found that the edges of the wear region are dimmed gray rather than black as seen in the air tests. Besides referring to the expansion of wear dimension, it provides the evidence of cleaning of the particles by water during the experiments.

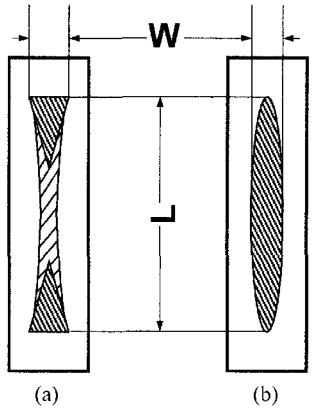


**Fig. 6. Definition of wear length (L) and width (W) in the case of the contact with (a) type A and (b) type B spring.**

## Analysis of Contact Length

It is necessary to know the actual contact length between the tube and the spring to investigate third body abrasion in the clearance region. This is because the postulated third body abrasion in the clearance can be verified if the wear dimension is larger than the contact dimension. In the case of the contact with the type A spring, it was regarded that the contact length was almost similar to the length of the flat region (4.1 ± 0.02 mm) due to its design feature of a rigid body translation rather than an elastic deformation when the normal force was exerted. However, the contact length in the case of the type B spring should be evaluated since it must be dependent on the normal force. To accommodate the non-symmetrical surface contour of type B and the thin thickness of type A and B, finite element (FE) analysis has been carried out to evaluate the contact length.

A commercial code ABAQUS (version 6.1) was used in the FE analysis. Four-point shell element was used for the spring. As for the tube, a solid element was used with arranging three elements stacked along the thickness. Elastoplastic analysis was carried out to accommodate the possible plastic deformation in the spring during the exertion of the normal force. For the material properties of the spring and tube, $E$ = 108.332 GPa, $\sigma_{ys}$ = 344.3 MPa, $\nu$ = 0.294 where $E$ is the elastic modulus, $\sigma_{ys}$ the yield strength and $\nu$ the Poisson ratio. As a result, the contact length induced by type A appeared 4.07 mm regardless of the force. It is very close to the actual value (i.e., 4.1 ± 0.02 mm). So we concluded soundly that the method of FE implementation for the present analysis was reasonable. On the other hand, it was evaluated that the contact length induced by type B was 1.20 mm and 7.20 mm in the case of the normal force of 10 and 30 N, respectively. Our expectation is verified through the FE analysis since the contact length by type B depends highly on the force, which is not the case for type A.

## Detail Analysis of Contact Dimension

In this section, the behaviour of wear scar dimension observed in Figs. 3-5 are analysed in detail. To provide a better understanding, the shape of the wear scar and the definition of the dimension are illustrated in Fig. 6. It should be noted that the wear length is defined as the distance between the outer-most edges in the case of the wear caused by the type A spring even though separated wear scars are observed.

Firstly, the behaviour of wear length is investigated. Fig. 7 shows that the wear length induced by the type A spring is almost the same regardless of the variation of normal force and slip displacement, and the environment as well. While, the length increases considerably as the normal force and the slip displacement increase in the case of the type B spring. Especially, the increment is very apparent when the force increases. If we compare the observed wear length with the evaluated contact length (i.e., 1.20 and 7.20 mm when 10 and 30 N, respectively), they are almost similar to each other at 10 N-30 $\mu$m and 30 N-50 $\mu$m in the air environment. The wear length increases continuously as the slip displacement increases at each normal force.

A possible explanation for this result is third body abrasion caused by wear particle movement in the clearance region outside the actual contact. The clearance between the tube and spring is very narrow and relatively longer in the case of the contact with type B compared with that of type A, since type A has chamfered edges. Dispersion of the generated particles may well be harder if the clearance is narrower, which results in a considerable increase of wear length in type B.

Environmental effect gives another interesting result especially for type B. Wear length is larger or similar when the experiment is conducted in water rather than in air. No wear in the water environment was found shorter than what was found in air. This implies that the wear particles can also be accumulated in the clearance region and cause third body abrasion even in the condition of easy particle dispersion by water. It also means that the particles cause abrasion before they are dispersed out by water. In the reverse, it can be said that the water environment does not disperse the particles out as soon as they are generated.

A similar result is found in the investigation of the behaviour of width increase in the case of type A. However, in this case, type A shows further distinctive effects of third body abrasion rather than type B as shown in Fig. 8. This is expected from the geometrical interpretation (see Fig. 1). The circumferential clearance must be much narrower and longer in the case of the

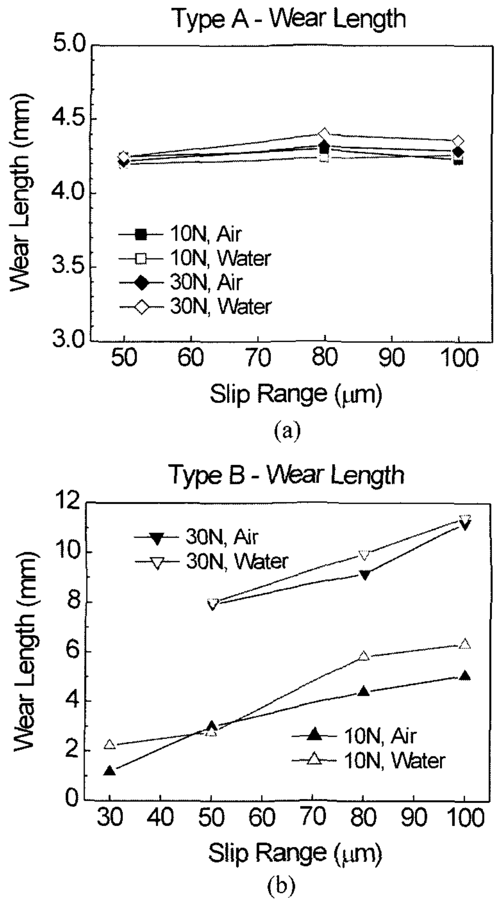


**Fig. 7. Variation of wear length with respect to the slip displacement and normal force for (a) type A and (b) type B springs.**

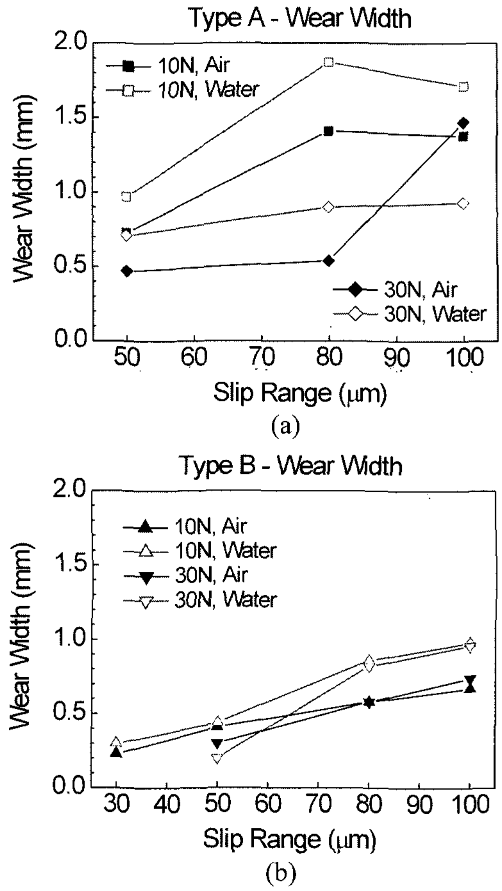


**Fig. 8. Variation of wear width with respect to the slip displacement and normal force for (a) type A and (b) type B springs.**

contact between the tube and type A than that and type B. It is also found that the width increases considerably when the slip displacement increases from 50 to 80 $\mu$m at 10 N in both the air and water environments, and 80 to 100 $\mu$m at 30 N in the air environment. One interesting finding is that such a width increase is not found in water at 30 N-100 $\mu$m. Besides this, the increase behaviour of wear width in the case of type A is exactly the same as that of wear volume if we recall the previous result of the critical slip range [5]. So, the wear volume increase in the case of type A is primarily caused by the width increase; and that of type B is by the length increase.

It gives us another idea for the geometric parameter of a spring which can restrain wear damage such as the radius of the transverse curvature in the case of a concave-contoured spring (presently type A) and the radius of the axial curvature in the case of a convex-contoured spring (presently type B). Also, another valuable point is the sensitivity of wear width or length increase on wear depth. As aforementioned, wear depth is a more critical parameter in fuel fretting wear. As a supposition, if the depth increase rate during the width increase is slower than that during the length increase, it can be assumed that type A would give a better performance for wear resistance. On the contrary, type B would be better if the depth increase rate is not sensitive to the wear length increase.

On the other hand, the wear volume increase rate was found higher in the water environment than in the air environment [6]. The same result is found for the wear width and length in the present experiment. This implies that the role of water accelerates the particle dispersion from the contact surface rather than lubricating the surface, which results in a faster repetition of the adhesion-abrasion cycle in the fretting wear mechanism. It must be one of the reasons that more severe wear occurs in the water environment.

## Conclusions

This paper is concerned primarily with possible third body abrasion, which can occur in the clearance region outside the actual contact. From the reciprocating sliding wear experiment with a small amplitude (fretting) using the concave and the convex-contact shapes against the tube, the followings were drawn as conclusions.

1. As the slip displacement increases, wear width increase is apparent in the case of the contact with the concave contour; while, wear length increase is considerable in the case of the contact with the convex contour. To explain the wear length and width increase above under the same contacting force for each contact shape, the third body abrasion can be referred to.

So to speak, the generated wear particles can accumulate in the narrow clearance region adjacent to the actual contact and cause abrasion.

2. Since the wear dimension appears larger in the water environment than in the air, the role of the water is the easy dispersion of the wear particles rather than a lubricant.

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