KSTLE International Journal, Vol. 3, No. 1, June 2002, pp. 49-53

Fretting Wear and Friction of Inconel 690 for Steam Generator Tube in Elevated Temperature Water

Young-Ze Lee[†], **Min-Kyu Lim and Se-Doo Oh**

School of Mechanical Engineering, Sungkyunkwan University, Suwon, Korea

Abstract : Inconel 690 for nuclear steam generator tube has more chromium than the conventionally used Inconel 600 in order to increase the corrosion resistance. To evaluate the tribological characteristics under fretting condition the fretting tests as well as sliding tests were carried out in elevated temperature water environment. Fretting tests of the cross-cylinder type were done under various vibrating amplitudes and applied normal loads in order to measure the friction forces and wear volumes. Also, the conventional sliding tests of pin-on-disk type were carried out to compare the test results. In fretting, the friction was very sensitive to the load and the amplitude. The friction coefficient decreased with increasing load and decreasing amplitude. Also, the wear of Inconel 690 can be predictable using the work rate model. Depending on normal loads and vibrating amplitudes, distinctively different wear mechanisms and often drastically different wear rates can occur. It was found that the fretting wear coefficients in water were increased as increasing the temperature of water.

Keywords : Fretting wear, sliding wear, Inconel 690, work rate model, stick-slip

Introduction

In order to increase the corrosion resistance of Inconel 600, which has been used for steam generator tube in the most of western nations, new material of Inconel 690 starts to replace Inconel 600. Inconel 690 has more Cr content than Inconel 600. Even though many papers reported the corrosion characteristics of Inconel 690, fretting wear due to flow-induced vibration have not been investigated yet [1].

In nuclear power plant, shell and tube type steam generator and nuclear fuel assembly are consisted of long and thin tubes with fluid flowing both inside and outside of tubes. When pressure of outside fluid is large enough, it may deform the components and the deformation will change the streamline of outside fluid causing the fluid pressure to be changed. When the amount of hydraulic force acting on the tube equals the amount of reacting force in the tube, vibration with large amplitude will be developed in the tube [2]. Therefore, the components are subjected to vibration that is caused by resonant forces of the tube and the fluid. Such behavior, vibration due to interaction of hydraulic dynamic force and inertia, damping effect, and elasticity of a component, is called flow-induced vibration (FIV) and wear in the tubes due to FIV is called fretting wear [3]. Fretting wear occurs due to vibration with very small amplitude between two contacting surfaces and since its mechanism is very complex, fretting wear is very difficult to analyze. Therefore, damage in the tube in steam generator due to fretting wear may cause a very serious problem in the safety of nuclear power plant [4-5].

In this paper, sliding and fretting wear properties of Inconel 690 in air and room temperature water were obtained by varying the normal load and the vibrating amplitude of tubes, or rotating speeds. The conventional span-on-disk type sliding tests were carried out to compare the test results. Fretting wear tests of the cross cylinder type were done in order to measure the friction forces and the wear volumes. Using work rate model, the wear coefficients of Inconel under air and water will also be obtained to predict the wear in steam generator tube, especially on the slip region in fretting. Slip is the most dangerous behavior of tube causing severe wear and microcracks.

Experimental Details

Specimens

For wear test, Inconel 690 was put in relative motion against the supporting part, STS 304, under air and room temperature water. In sliding wear test, Inconel 690 was prepared as pin (3 mm × 1 mm × 10 mm) and STS 304 was machined to round plate (60 mm × 8 mm). In fretting wear test, 60 mm long actual thin tube(19.1 mm × 1 mm), which used in steam generator, was prepared and STS 304 was machined to same size with the thin tube specimen. The chemical compositions and mechanical properties of tested materials are listed in Table 1.

Experiment equipment and methods

To study the friction and wear characteristics of Inconel 690, sliding wear test was conducted before fretting wear test. Sliding wear test has advantages such as easy friction force measurement and good friction and wear reproducibility. Also,

---

[†] Corresponding author; Tel: 82-31-290-7444, 82-31-290-5276
E-mail: yzlee@yurim.skku.ac.kr

Table 1. Chemical composition and mechanical property of Inconel 690 and STS 304

Chemical composition	C	Si	Mn	Cr	Ni	Co	Ti	Cu	Fe
Inconel 690	0.02	0.24	0.3	29.5	59	0.01	0.25	0.01	10.6
STS 304	0.03	0.55	1.81	18.3	8.2	0.02	-	-	Bal.

Mechanical properties	Hardness (HRB)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
Inconel 690	82	326	727	45
STS 304	123	270	600	50

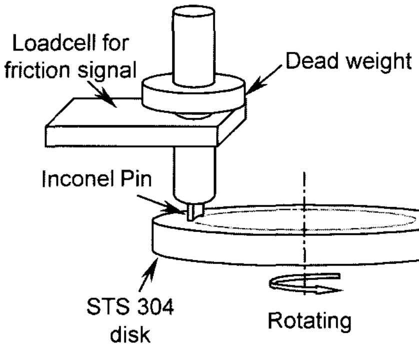

Fig. 1. Schematic diagram of sliding tester.

the test method is standardized. On the other hand, fretting wear test is very difficult to perform and requires very close attention for friction force measurement. Also, different test results may be obtained depending on the characteristics of tester. Therefore, when sliding is taken as slip with unlimited amplitude, it can become a very important test that can verify friction and wear behaviors and fretting test results of thin Inconel 690 tube.

Using the sliding tester shown in Fig. 1, the friction coefficient and wear was measured by putting thin Inconel 690 tube to sliding motion against STS 304 under air and water. The friction coefficient was measured using the load cell attached to the tester and the wear was measured by converting the geometry changes, which was measured with profile meter after cleaning up the specimen with acetone. During the sliding test, the linear velocity of contacting surfaces was fixed to 0.34 m/s and the load was increased from 2.5 N to 12.5 N by step of 2.5 N. And then the load was fixed to 7.5 N and the velocity was changed to 0.18 m/s, 0.42 m/s and 0.65 m/s. The test was ran three times for each condition and then the resulting values were averaged.

For the fretting wear test, the fretting tester shown in Fig. 2 was used. The tester is capable of changing amplitude from 50 μm to 500 μm using cam and frequency can be changed according to output of motor. The load was applied by screw lever using spring. In this investigation, the load was increased from 10 N to 80 N by step of 10 N with the amplitude of 100 μm, 150 μm, 200 μm, 250 μm and 300 μm to observe the fretting wear characteristics, the stick and the slip. The wear of thin tube was obtained by measuring the changes in geometry of specimen using profile meter.

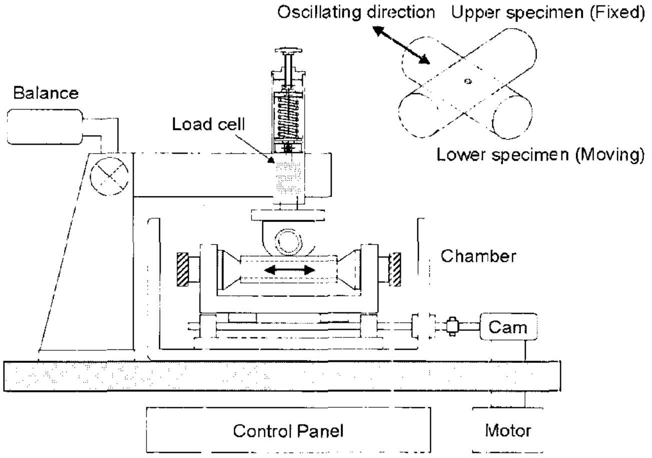

Fig. 2. Schematic diagram of fretting tester.

Results and discussion

Sliding wear test

The friction coefficient was measured by sliding Inconel 690 against the counter part, STS 304, under air and water. For the measurement, each test was ran 3 times or more and measurements were taken for 5 minutes after 20 minutes were passed from the beginning of each run to stabilize the friction coefficient. The measured values were averaged for each run and then each averaged values were averaged again for the entire runs. As they are presented in Table 2, the sliding linear velocity was fixed at 0.34 m/s and the contact load was increased from 2.5 N to 12.5 N in the step of 2.5 N. Also, the experiment was carried out for sliding linear velocities of 0.18, 0.42, and 0.65 m/s under the normal load of 7.5 N. Such test conditions were chosen based on the fretting wear test conditions. The results from the experiment shows that the normal load and the sliding linear velocity do not have much effect of the friction coefficients. The final averaged friction coefficients were 0.54 for Inconel 690 in air. And, Table 3 shows friction coefficients under the room temperature water. The average friction coefficients were 0.4.

Fig. 3 shows the measured friction coefficient values of Inconel 690 under air and room temperature water, respectively. As shown in the figure, friction coefficient was unstable initially since the lubricating behavior of water was not very active but it stabilized later on.

Fig. 4 is the sliding-wear curves for Inconel 690 using

Table 2. Coefficient of friction value of Inconel 690 pin against STS 304 disk specimen at each test condition in air

Linear velocity (m/s)	Test number	1	2	3	Average
	Normal load (N)	Inconel 690	Inconel 690	Inconel 690	Inconel 690
0.34	2.5	0.56	0.57	0.57	0.57
	5.0	0.56	0.58	0.59	0.58
	7.5	0.61	0.59	0.54	0.58
	10.0	0.54	0.56	0.51	0.54
	12.5	0.54	0.55	0.50	0.53
0.18	7.5	0.55	0.59	0.54	0.54
0.42		0.54	0.55	0.52	0.56
0.65		0.55	0.55	0.56	0.55

Table 3. Coefficient of friction value of Inconel 690 pin against STS 304 disk specimen at each test condition in water

Linear velocity (m/s)	Test number	1	2	3	Average
	Normal load (N)	Inconel 690	Inconel 690	Inconel 690	Inconel 690
0.34	2.5	0.39	0.40	0.40	0.40
	5.0	0.41	0.31	0.39	0.40
	7.5	0.39	0.31	0.39	0.39
	10.0	0.39	0.30	0.41	0.40
	12.5	0.40	0.31	0.39	0.40
0.18	7.5	0.41	0.29	0.40	0.40
0.42		0.40	0.30	0.41	0.40
0.65		0.40	0.29	0.40	0.40

estimated wear volumes at each test condition. The wear coefficient under air and room temperature water were 3.67×10^{-13} Pa^{-1} and 1.43×10^{-13} Pa^{-1}, respectively. The reason for differences in wear coefficients is believed to be due to the difference in wear amounts resulting higher wear under air.

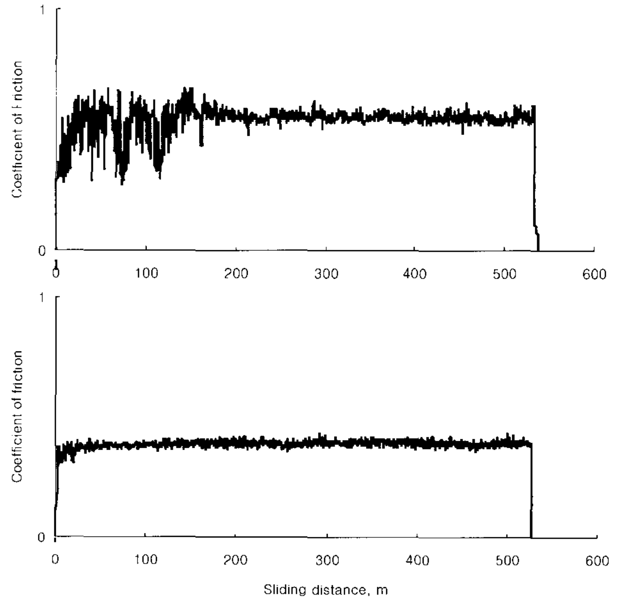

Fig. 3. Variation of friction coefficient of Inconel 690 against STS 304 in air and water at room temperature.

Fretting wear test (in air)

Fig. 5 represents the changes in wear volume for Inconel 690 tube at the amplitudes of 250 μm in air, while the normal load is increased from 10 to 80 N. As shown in fretting wear curve, wear volume for Inconel 690 under air was higher than under water. From the test, it was observed that the wear volume increased initially. However, the wear volume began to decrease after the normal load was reached 30 N. And there was no wear occurring when the load reached 70 N.

In general, the wear volume increases proportionally as applied normal load increases in sliding wear test. However,

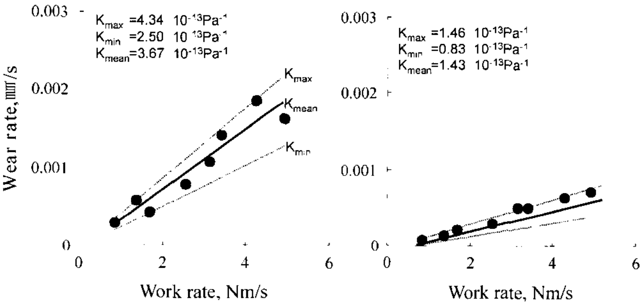

Fig. 4. Sliding wear coefficient of Inconel 690 pin with STS 304 disk in air and water.

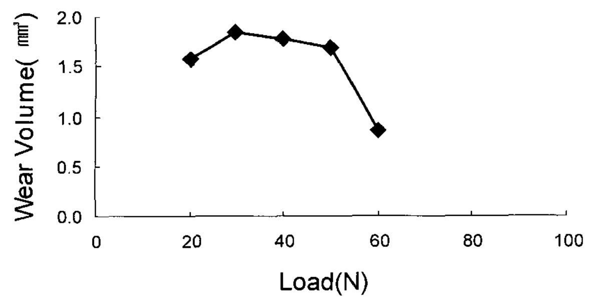

Fig. 5. Change of wear volume with variations of normal load in air at RT.

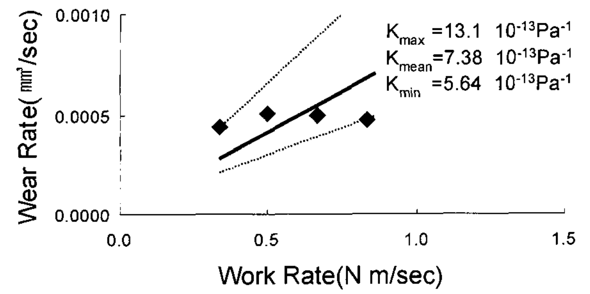

Fig. 6. Wear coefficient of Inconel 690 in air at RT.

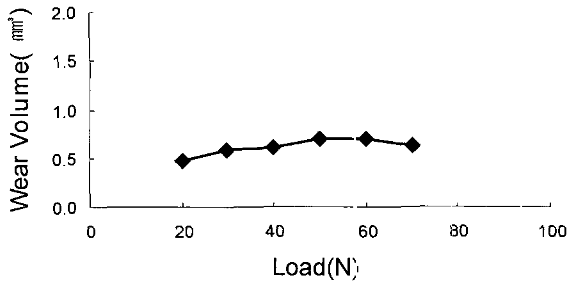

Fig. 7. Change of wear volume with variations of normal load in water at RT.

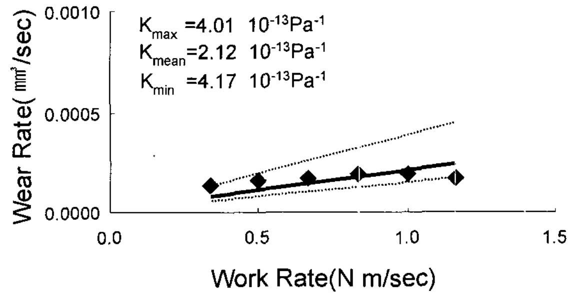

Fig. 8. Wear coefficient of Inconel 690 in water at RT.

increase in applied normal load between two surfaces, which are in cyclic motion due to microscopic vibration as in fretting wear tests, acts as an element that interfaces with the sliding motion resulting the wear volume to be decreased. This is typical wear behavior in fretting wear caused by microscopic vibration that is called stick-slip. Fretting wear that accompanies with stick-slip, it can be divided into four regimes based on its wear mechanism. They are (1) Stick regime: where almost no wear occurs unlike in early stage of fretting wear and at very small oscillation amplitude; (2) Stick-slip regime: where stick and slip coexist for cracks to be generated actively in there boundary; (3) Gross slip regime: where slip occurs on entire wear scar and wear volume increases rapidly; (4) Sliding regime: where sliding that is acting on two surfaces, which is not due to cyclic vibration but moves with an amplitude too big to observe as a fretting behavior. Therefore, such stick-slip behavior exists in the fretting wear curve in Fig. 5.

Wear regime shifts gradually from slip regime to stick regime as applied normal load increased under certain amplitude when two surfaces are experiencing the fretting wear behavior. In other words, when the tube made of Inconel 690 and the support made of STS 304 are experiencing fretting wear with amplitude Of 250 μm, wear behavior due to gross slip was observed below the normal load of 30N. When the load is above 60N, wear behavior due to stick was observed and between 30N and 60N, wear behavior due to stick-slip was observed. Because fretting wear of the material was rapidly increased in slip regime, fretting characteristics were found out in slip regime.

Therefore, to investigate the effect of fretting wear behavior on the fretting wear in Inconel 690, the wear coefficients in both air and water environment were estimated using work rate model, which is the most commonly used method to compare the wear characteristics of steam generator tubes. In work rate model, wear rate is linearly dependent on the work rate, which is the product of normal load, vibrating frequency, and amplitude during testing time. Proportional constant has same dimension, mm³/N · m, as the wear coefficient of Archard equation. Fig. 6 represents the wear coefficients in gross slip regime. The wear coefficient was 7.38 × 10^{-13} Pa^{-1} in air.

Fretting wear test (in water)

Fretting wear tests with Inconel 690 were performed to estimate its characteristics for fretting wear at room temperature and high temperature in the water.

When the applied normal load ranged from 10 N to 80 N under fretting behavior, and amplitudes of 250 μm were applied, Fig. 7 shows wear amount of Inconel 690. The test results in the water gradually increase with applied normal load throughout all regime unlike in the air, and there is not wear decrement affected by Stick-Slip between surfaces in the water. Thus, there is total slip regime in fretting behavior while the water acts as lubricant.

Fig. 8 reveals the wear amount of Inconel 690 varied with normal loads and amplitudes using the wear coefficient K of the work rate model, or $K = 2.12 \cdot 10^{-13}$ Pa^{-1}. Also, we investigated the temperature effect on Inconel 690 in the water. Fig. 9 shows that the higher temperature is, the more the wear amount of Inconel 690 at 50°C and 80°C. This is because increasingly produced oxide layers are wiped out by water during the temperature increase repeatedly. The wear amount at high temperature is more than that at room temperature. Fig. 10 shows the wear coefficient at amplitudes of 250 in air and water environment. The wear coefficient in water of 50°C and

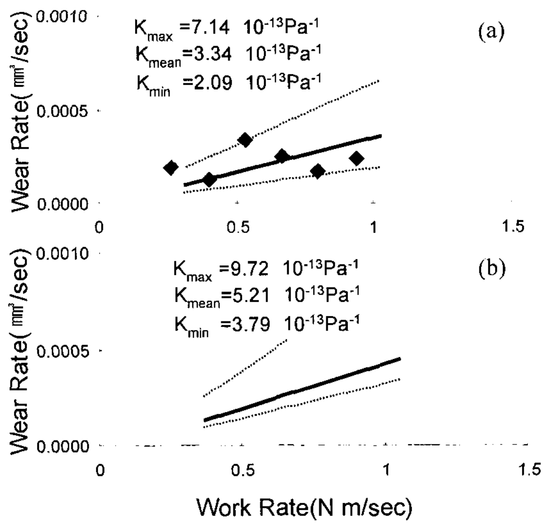

Fig. 9. Wear coefficient of Inconel 690 in water; (a) at 50°C; (b) at 80°C.

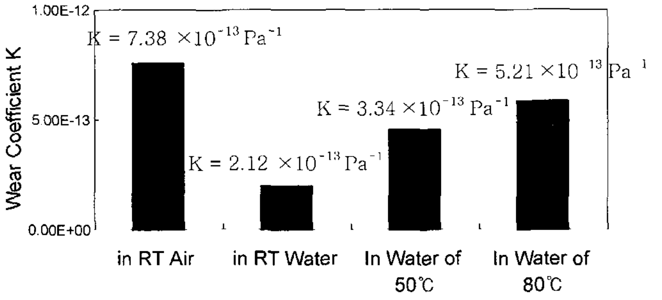

Fig. 10. Mean values of Inconel 690s wear coefficient of in various test conditions.

80 were 3.34×10^{-13} Pa^{-1} and 5.21×10^{-13} Pa^{-1}, respectively. Thus, wear coefficient increases as the temperature of water rises.

Conclusions

In this study, fretting and sliding wear tests were conducted under (air and room temperature) water to investigate the friction and wear characteristics of thin tube materials of steam generator in nuclear power plant, Inconel 690 using thin tube supporting part material, STS304, as the counter part. As the result, the following conclusions were obtained.

1. Wear coefficient of Inconel 690 is 7.3810^{-13} Pa^{-1} and 2.1210^{-13} Pa^{-1} under air and room temperature water, respectively. Thus, wear amount of Inconel 690 under air is higher than under water.
2. Wear coefficient of Inconel 690 is 2.12 10^{-13} Pa^{-1} under room temperature(24) water, 3.3410^{-13} Pa^{-1} under water of 50, and 5.2110^{-13} Pa^{-1} under water of 80. Thus, the wear resistance increases as the temperature was lower under the water environment. Slip regime was dominant in fretting wear under water.

References

1. Tayor, C. E. and Pettigrew, M. J. *et al.*, "Vibration Damping in Multi-span Heat Exchanger Tubes," J. of Pressure Vessel Technology, Vol. 120, pp. 283-289, 1998.
2. Ko, P. L. and Basista, H., "Correlation of Support Impact Force and Fretting-Wear for a Heat Exchanger Tube," J. of Pressure Vessel Technology, Vol. 106, pp. 69-77, 1984.
3. Ko, P. L. and Taponat, M. C. *et al.*, "Wear Studies of Materials for Tubes and Anti-vibration Bars in Nuclear Steam Generators," J. of Pressure Vessel Technology, Vol. 118, pp. 287-300, 1996.
4. Fisher, N. J. and Chow, A. B. *et al.*, "Experimental Fretting-Wear Studies of Steam Generator Materials," J. of Pressure Vessel Technology, Vol. 117, pp. 312-320, 1995.
5. Guerout, F. M. and Fisher, N. J., "Steam Generator Fretting-Wear Damage: A Summary of Recent Findings," J. of Pressure Vessel Technology, Vol. 121, pp. 304-310, 1999.