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Impact Fretting Wear of Steam Generator Tubes

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Abstract

In steam generator, flow-induced vibration results in impact fretting-wear damage due to impacting and rubbing of the tubes against their support plates. In this study, to examine the difference of mechanism between fretting wear and impact fretting wear, the fretting wear and impact fretting wear test were performed in the room temperature water with steam generator tube materials. Each wear coefficient of Alloy 600 and Alloy 690 was evaluated using work rate model applied. The wear coefficients of fretting wear were smaller than those of impact fretting wear in same conditions. From the SEM observation, the cracks and voids were found in subsurface of impact fretting wear specimens. And the characteristic of impact fretting wear test is the formation of plastic deformation zone, voids and cracks.

1. Introduction

Steam generator degradation has been mainly caused by corrosion mechanisms such as stress corrosion cracking on the primary side, called primary water stress corrosion cracking (PWSCC), and wastage, pitting, intergranular stress corrosion cracking (IGSCC), and intergranular attack (IGA) on the secondary side [1]. Recently, there has been much improvement of corrosion resistance of steam generator tubes by replacing Alloy 600, tube material with Alloy 690 or water treatment. Alloy 690 has twice chromium content than Alloy 600 to have more corrosion resistance.

However, from the viewpoint of mechanical properties Alloy 690 would be inferior to Alloy 600 [2]. In addition, because thermal conductivity of this alloy is lower than Alloy 600, the length of tube was increased about 10%, so more severe operating condition was expected. Therefore, impact fretting is regarded as the very important tube failure mechanism. This mechanism is a result of the tube impacting and rubbing of the tube supports of, in severe cases, on adjacent tubes and these interactions are occurred by flow-induced vibration [3]. The thermal energy transfer occurs in heat exchangers by passing one fluid through the tubes and another fluid over the outside of the tubes. Cross-flow over tubes induces tube vibrations [4].

Experimental studies on fretting wear in steam generator tube materials have been performed since early 1970s [5] and proposed many semi-empirical models to predict the tube wear damage. Recently, a work-rate model has been proposed by Frick et al. [6] and widely used as the fretting wear model in steam generator tube materials. To reduce the wear damage in tube materials, wear mechanisms must be examined at various test variables such as applied normal load, sliding amplitude, temperature, counter part materials, etc.

2. Experimental Procedure

To simulate fretting wear or impact fretting wear phenomenon between tube and tube support plate material in the room temperature water, wear test apparatus was used as shown in Fig. 1. The test system consists of wear test machine, load cell, and LVDT. This test machine was employed for evaluating both of the fretting and impact fretting wear behavior under normal static or normal impact load and shear loading conditions. The tube specimen is attached to the sliding unit (cantilever beam), and the tube support plate specimen is mounted to the normal loading unit. Displacements and loads of each specimen are simultaneously and continuously monitored through the load cell and LVDT during the each test. The loading unit can be fixed or not to evaluate static load and dynamic load.

Fretting and impact fretting wear tests in room temperature were performed under various normal loads at constant frequency of about 30㎐, which is the minimum number of vibrations in steam generator tube. The tube specimen oscillated with peak-to-peak amplitude of 25 100㎛. In Fretting wear test, the applied normal load ranged from 20 to 70N, which is the actual range of normal load that occurs between the tube and the support in steam generator due to fretting behavior. In the case of impact fretting wear test, the peak load ranged from 70 to 100N and the frequency of impact load is about 20㎐. All of these tests were performed at the room temperature water during 1 hour.

To compare wear mechanisms between only fretting and impact fretting, each worn surface was examined using SEM after wear test. Before SEM examination, worn surfaces are acoustically cleaned in ultrasonic bath to remove almost all wear debris of loose particles. Cross-sections below the contact surface were also examined using SEM to observe the subsurface after test.

3. Results and Discussions

3.1 Fretting Wear Tests

The fretting wear tests were performed with each combination of nickel-based alloys (Alloy 600 and Alloy 690) and ferritic stainless steels (405SS and 409SS) in the room temperature water and total cycles are about 10^5 .

In these tests, wear weight loss of each Alloy alloy was converted to wear volume loss using its density to evaluate the wear coefficient, *K*. In general wear volume loss of each Alloy alloy is depending on the applied work, namely wear volume loss is increasing as the applied work is increasing. Therefore, the data to get from these tests can be applied to work-rate model, which is the most commonly used method to compare the wear characteristics of steam generator tubes [7].

Fig. 2~5 represents each wear coefficient. The wear coefficient of Alloy 600 is larger than Alloy 690 agains the same ferritic stainless steel. The wear coefficient for Alloy 600 with 405SS was $42.65 \times 10^{-15} Pa^{-1}$ while the wear coefficient for Alloy 690 with 405SS was $36.22 \times 10^{-15} Pa^{-1}$ in the room temperature water. And in the same condition, the wear coefficient for Alloy 600 against 409SS was $93.20 \times 10^{-15} Pa^{-1}$ while the wear coefficient for Alloy 690 against 409SS was $69.37 \times 10^{-15} Pa^{-1}$. This indicates that Alloy 690 has better wear resistance than Alloy 600 against same ferritic stainless steel in the room temperature water. This trend was appeared in the room temperature air environment [8]. The chemical compositions of Alloy 600 and Alloy 690 are about the same except the chromium contents. Generally, with increasing chromium contents in nickel, stacking fault energy of nickel decreases [9]. In the case of low stacking fault energy materials, work hardening occurs in a short period because dislocation densities during plastic deformation under worn surface may rapidly increase. Therefore, the difference in the degree of work hardening affects the wear resistance between Alloy 600 and Alloy 690.

Impact fretting wear tests were performed in the same condition of fretting wear test. The wear coefficient of Alloy 600 is larger than Alloy 690 by about 10 % against the same ferritic stainless steel, which is very similar to the fretting wear test result. These results are also assuned due to the difference of stacking fault energy as the case of fretting wear.

3.2 SEM Observation

In general, the mechanism of tube fretting seems to consist of the following stages: the dispersion of surface film by the oscillating movement; adhesion, plastic deformation and metal transfer; for some materials the wear particles become oxidized and form an intermediate zone; the fretting action then produces loose wear particles and finally the cycle repeats.

Photomicrographs of Alloy 600 and Alloy 690 after fretting test as illustrated in Fig. 5-8 show that the wear scars are produced by the adhesive wear and delamination wear mechanisms. Fig. 6 show the worn surface which was tested by 20N normal load. Especially these photomicrographs show the first stage of delamination wear mechanism which is that asperities of the worn surfaces are removed. As shown in Fig.6, the flattened surface can be observed in the whole worn surface.

In the worn surface of impact fretting wear test, there is scarcely the evidence of adhesive wear but delamination wear scars are more severe than in fretting wear test as shown in Fig. 7.

Subsurface examination, after the impact fretting wear, reveals, at most, three characteristic zones. Fig. 8 illustrates the subsurfaces parallel to the sliding direction after the impact fretting wear test. This figure shows three characteristic zones very clearly. The deep substrate consists of the unaffected microstructure (zone 1). The intermediate layer is plastically deformed, and this deformation is typically observable in the microstructure (zone 2). Zone 3 is thought to be a severely plastically deformed. In this case, obvious voids and cracks are visible in zone 3. In zone 2, cracks and voids run essentially parallel to the surface.

On the other hand, in the fretting wear tested subsurface, zone 2 is not obviously distinguished because there is almost no void and no crack as shown in Fig 8. In zone 3, there are plastic deformation features as the impact fretting wear tested surface. This deformation features in zone 3 are very similar to the case of impact fretting wear.

The mechanism of crack nucleation in a wear tested material can be understood as follows. When the surface layer undergoes plastic deformation, voids and cracks can nucleate. Cracks in two phase metals are nucleated around the hard particles due to the displacement incompatibility between the particle and the matrix deforms plastically near the surface with repeated loading, but which occurs when the matrix deforms plastically near the surface with repeated loading, but the hard particles cannot deform.

Also in single-phase metals cracks are present. Interactions of dislocations and the formation of dislocation cells may be responsible. Crack nucleation may be a result of displacement incompatibility between impurity inclusions and the matrix.

These appearances of voids, cracks and plastic deformation in the subsurfaces after fretting and impact fretting wear test explain that delamination wear mainly occurred on the surfaces of test materials

4. Conclusions

In the present study, to evaluate the difference between fretting and impact fretting wear of steam generator tube materials, fretting and impact fretting wear tests were performed using the same test apparatus with Alloy 600 and Alloy 690. From those experimental results following conclusions were obtained.

(1) As the applied work increased, the wear rates of steam generator tube materials in the room temperature water linearly increased. This results means that work-rate model can be applied to the wear of steam generator tube materials. So, the wear coefficients of Alloy 600 and Alloy 690 were evaluated using work-rate model.

(2) In the same conditions (fretting wear test or impact fretting wear test) the wear coefficient, K of Alloy 600 is larger than Alloy 690 due to the difference of stacking fault energy with chromium contents between Alloy 600 and Alloy 690.

(3) The wear coefficient for the impact fretting wear test is larger than for the fretting wear test. The observation of the worn surfaces confirmed that the mechanisms of fretting wear test are mainly adhesive wear and delamination wear and that those of impact fretting wear test are primarily delamination wear and abrasive wear.

(4) In the observation of the subsurfaces which were tested with dynamic loading and sliding (impact fretting), cracks and voids appeared below the deformation layers (zone 2), but with only sliding, there are almost no cracks and no voids. This observation confirmed that the dynamic loading is effective to the work hardening of the subsurface and deformation layer.

References

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Table 1 Chemical composition and mechanical properties of test materials

	Cr	Fe	C	Si	Mn	Ti	P	S	Co	Ni	Y.S.	U.T.S.
Alloy 600	**16.81**	9.1	0.026	0.32	0.81	0.35	0.008	0.002	0.012	Bal.	283.5	682.6
Alloy 690	**29.5**	10.4	0.02	0.33	0.26	0.32	0.004	0.001	0.012	Bal.	316.5	708.7
405SS	11.5 ~14.5	Bal.	0.08	1.00	1.00	0.1 (Al)	0.04	0.03	-	-	326.2	410.94
409SS	10.5 ~11.75	Bal.	0.08	1.00	1.00	6x%C	0.045	0.045	-	-	442.3	466.06

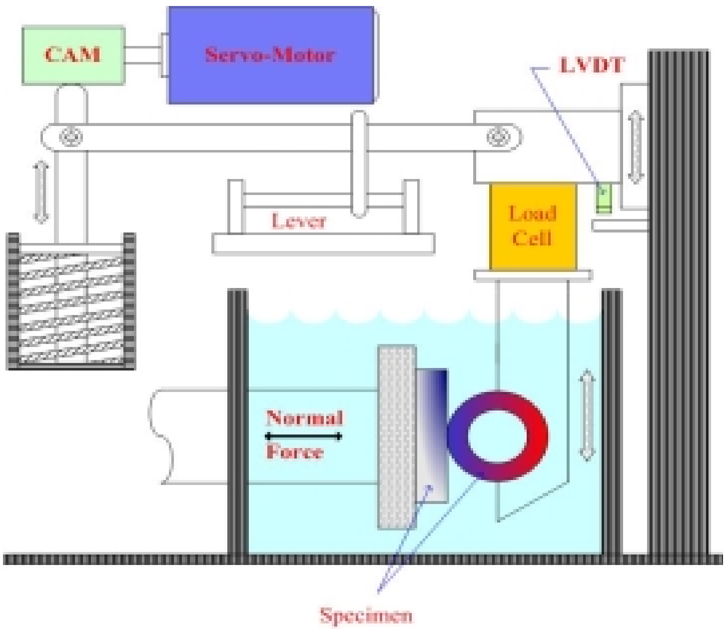
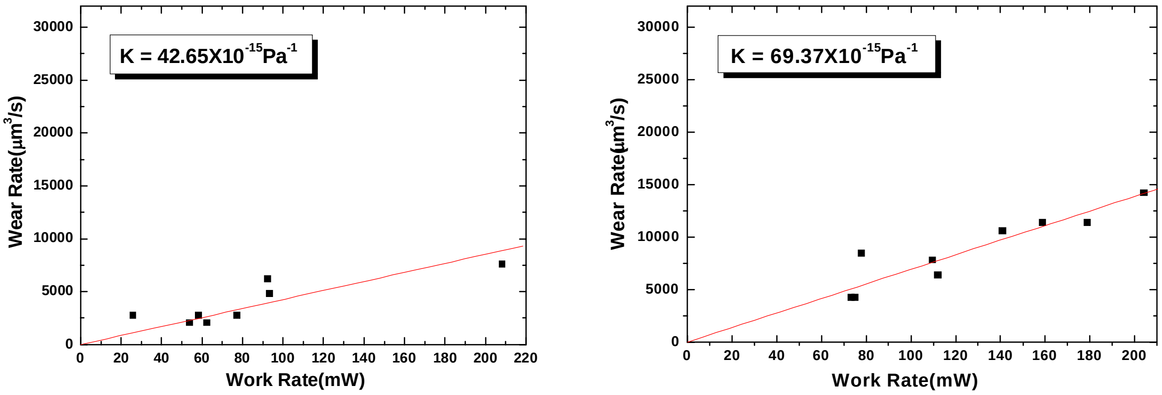
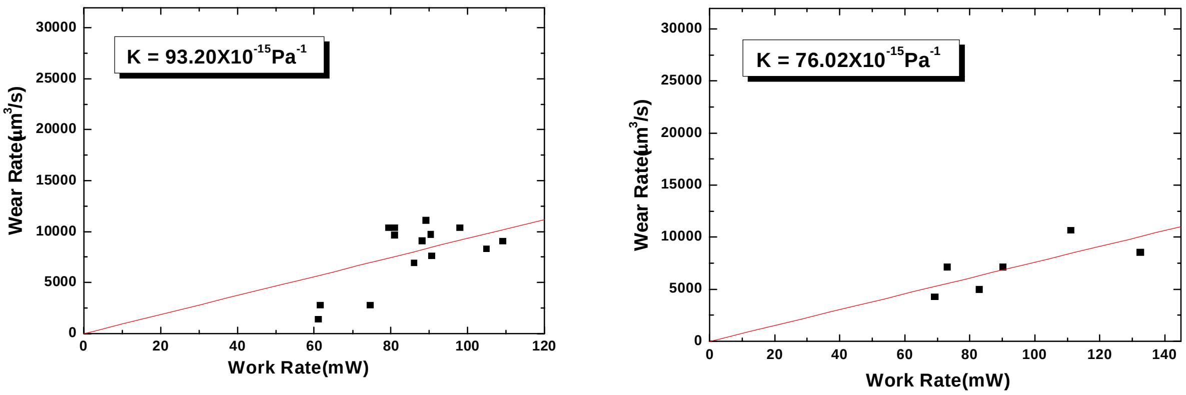


Fig.1 Fretting Wear Test System



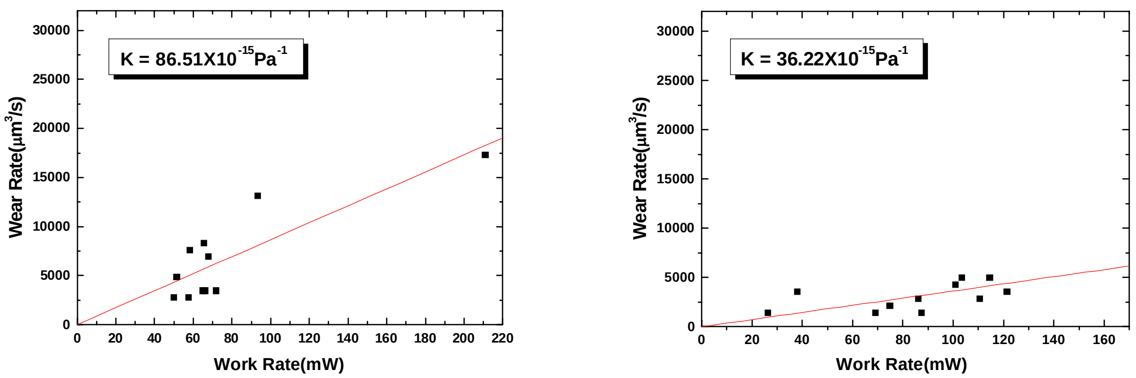
(a) (b)

Fig. 2 Evaluation of each wear coefficient, *K* from the work rate model after fretting wear test (a) Alloy 690 against 405SS (b) Alloy 600 against 405SS



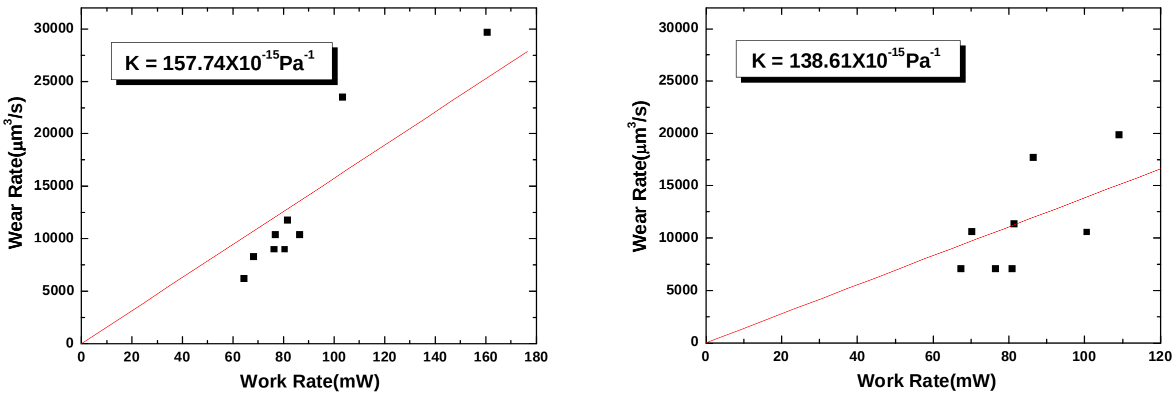
(a) (b)

Fig.3 Evaluation of each wear coefficient, *K* from the work rate model after fretting wear test (a) Alloy 600 against 409SS (b) Alloy 690 against 409SS



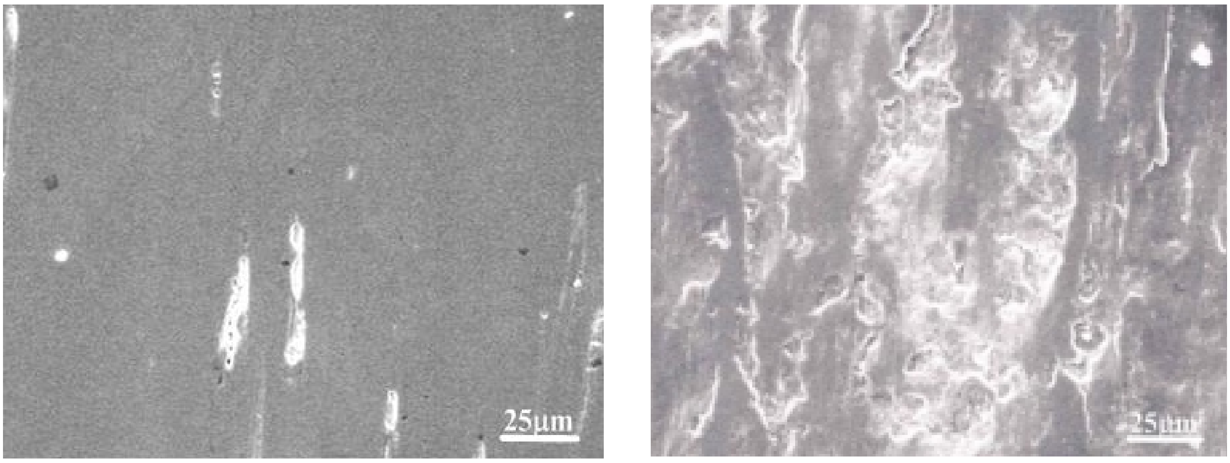
(a) (b)

Fig. 4 Evaluation of each wear coefficient, *K* from the work rate model after impact fretting wear test (a) Alloy 600 against 405SS (b) Alloy 690 against 405SS



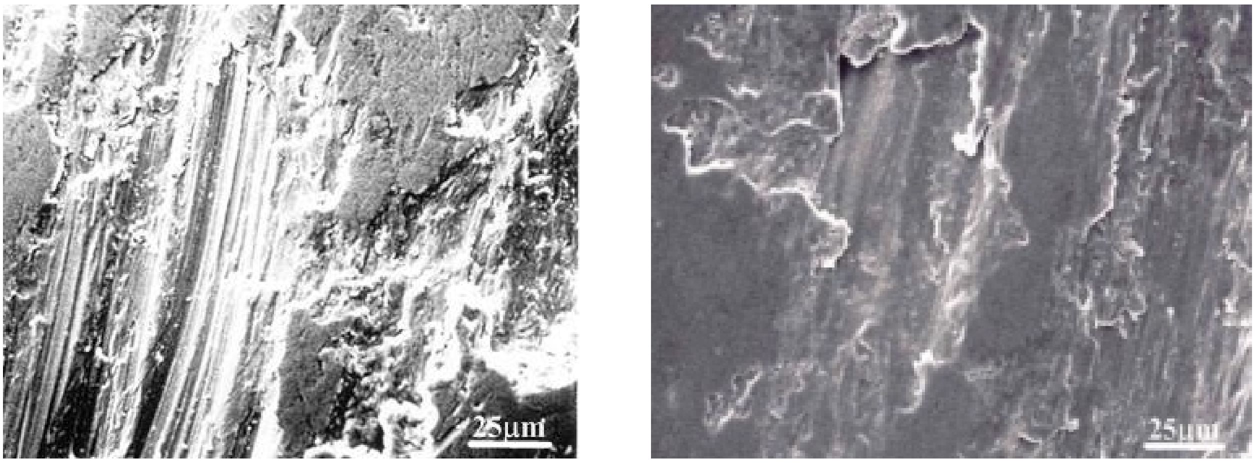
(a) (b)

Fig. 5 Evaluation of each wear coefficient, *K* from the work rate model after impact fretting wear test (a) Alloy 600 against 409SS (b) Alloy 690 against 409SS



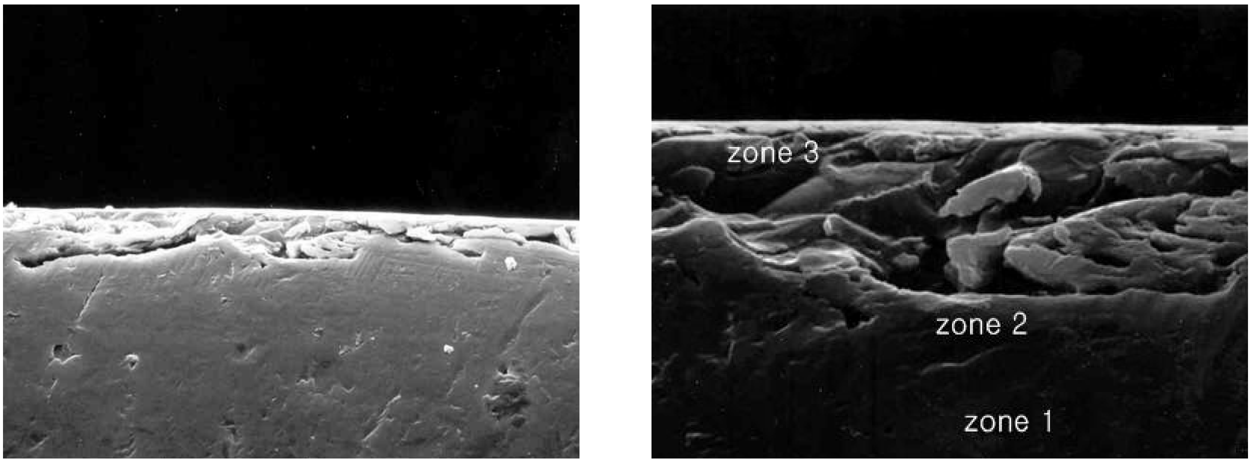
(a) (b)

Fig. 6 SEM microphotographs of fretting wear test surfaces
(a) Alloy 600/405SS, (b) Alloy 690/405SS



(a) (b)

Fig. 7 SEM microphotographs of impact fretting wear test surfaces
(a) Alloy 600/405SS, (b) Alloy 690/405SS



(a) (b)

Fig. 8 SEM microphotographs of the subsurface of Alloy 600 after the impact fretting wear test against 405SS
(a) ×2500 (b) formation of voids and cracks in plastic deformation layer (×10000)