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A Study on Sliding Wear Behavior of Alloy 600 Steam Generator Tubes in NPPs

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Abstract

The sliding wear behaviors of Alloy 600 steam generator tube materials mated with 403 and 409 stainless steels were investigated. The sliding wear tests were performed at room temperature in air environment under the applied normal load range of 5-40N and the maximum sliding distance was about 1296m. In the prediction of the wear volume by Archard's equation, the reliability was only 71.8% for Alloy 600 mated with 409 stainless steel and that of Alloy 600 mated with 403 stainless steel was 69.7%. The reliability was considered to be relatively low because the wear coefficient in Archard's equation was assumed to be a constant, regardless of the change in the mechanical properties during the sliding wear. In the present study, the wear volume of Alloy 600 increased linearly with increasing the applied normal load, while it increased parabolically with increasing the sliding distance. Based on the experimental results, Archard's wear predictive equation was modified and the resulting wear coefficient was represented as a function of the sliding distance. The calculation with the modified wear equation showed that the reliability of Alloy 600 against 409 increased from 71.8% to 83.8% and that of Alloy 600 mated with 403 stainless steel increased from 69.7% to 72.7%, compared to Archard's original equation.

1. Introduction

In the nuclear power steam generators, the high flow rates often induce vibration of the tubes, resulting in wear damage due to impact and sliding contact between the tubes and their supports. It has been reported that wear phenomenon is one of the severe degradation mechanisms in steam generator tubes. Thus, the safety of a steam generator and the expectation of life of these tubes have been a matter of serious concern to designer. However, there are not enough researches about wear properties and life estimation of tube materials. [1-3]

Wear phenomenon is the removal of material from surfaces in relative motion by mechanical or mechanical/chemical processes. If the relative motion is large and continuous, the wear is referred to as sliding wear. If the relative motion is small and alternating in nature, and if the rubbing surfaces are not brought out of contact, the wear is referred to as fretting.[4] Toth suggests the transition from fretting wear to reciprocal sliding lies at 50 ㎛, Lewis and Didsbury suggest 70 ㎛, whilst Vingsbo and Soderberg report the transition to take place at just over 300 ㎛.[5-7] Since early 1970s, experimental studies on fretting wear in steam generator tube materials have been performed by some investigators[1-3], whereas there are not enough researches on the sliding wear behaviors of steam generator tube materials.

According to Connors [4], the major flow-induced vibration mechanisms that can cause vibration of steam generator tubes are fluidelastic excitation, turbulence, and vortex shedding. These mechanisms cause the tube vibration amplitudes to increase rapidly when a threshold flow velocity is exceeded. As well as the vibration amplitudes of the tubes can easily be ten or more times greater than the clearance between the support plate and the tube. As steam generator is operated, it is possible that wear mode is a transition from fretting wear to sliding. Thus, researches on sliding wear behaviors and sliding wear data of steam generator tube materials have to be built up.

Generally, Archard's wear equation for adhesive wear can be applied to fretting as well as to continuous sliding conditions. Connors also attempted to correlate the fretting wear rate to tube motion parameters using Archard's wear equation.[4] However, the equation, which considers only the load, the sliding distance, and a specific wear coefficient, is far too simple to cover all the interrelated effects in a real steam generator. In addition, the prediction of wear damage by Archard's equation shows a wide error range and a low reliability because the equation regarded the wear coefficient (k) as a constant and did not consider the changes of mechanical properties of the material during wear.[8]

In the present study, sliding wear experiments were performed with Alloy 600 tube material mated with 403 and 409 stainless steels at room temperature in air environment. The purposes of this study are to investigate the effects of the applied normal load and sliding distance on sliding wear behaviors and to estimate the wear coefficients of Alloy 600 with the various counterpart materials. From the experimental results, the effects of wear parameters on the sliding wear were considered. In addition, a modified wear predictive equation based on Archard's equation was proposed.

2. Experimental Procedure

2.1 Wear Specimen

For the sliding wear test, Alloy 600 tubes used as a moving specimen. 403 and 409 stainless steels were selected as the fixed materials. As shown in Fig.1, the tube specimens were cut 19mm outer diameter by 11mm long from the straight tube and divided longitudinally into three equal parts. Their thickness was 1mm. The support materials were prepared from the flat strip (25mm×20mm×6mm). Surfaces for the wear test were polished with 2000 grit SiC abrasive papers to a roughness value R_a less than 0.02 ㎛. Specimens were cleaned with acetone in an ultrasonic bath and dried by compressed air. Detailed shape of these specimens is shown in Fig. 1.

2.2 Sliding Wear Test

To simulate sliding wear phenomena between tube and their support material**,** an apparatus with tube-on-plate configuration is prepared as described in Fig.2. The sliding wear tests were performed at room temperature in air environment. To evaluate the effect of the normal load on sliding wear behaviors, the specimen oscillated under applied normal load range of 5-40N at a sliding amplitude of 4.5mm and a frequency of 5Hz. The maximum sliding distance was around 1296m under an applied normal load of 20N, a sliding amplitude of 9mm and a frequency of 5Hz. The weight loss of specimen was measured by weighing before and after tests using micro balance with accuracy in the order of 10^{-4} g. The total weight loss of the specimen was converted into the wear volume. From the experimental results, the effects of an applied normal load and sliding distance on the wear volume were investigated.

2.3 Worn Surface Examination

The tested specimens were acoustically cleaned in ultrasonic bath and removed wear debris or loose particles. After cleaning, the observation of the worn surfaces after sliding wear test was done by using SEM. Micro-hardness variations of the matrix below worn surfaces were measured to compare the difference of work hardening with material combinations. Micro-hardness tests were performed more than five times each specimen with micro-vickers hardness tester under a load of 10 g. TEM was used for the detail microstructure observation of worn surfaces and the confirmation of the work hardening. TEM specimens were prepared by electro-polishing in a solution of methyl alcohol-10% perchloric acid at 10 V and - 50 ℃ and ion-milling for 1 hour.

3. Results and Discussion

3.1 Effect of an applied normal load and sliding distance

Figs. 3 and 4 show the effect of an applied normal load and sliding distance on the wear volume of the tube and its support materials. Generally, it was reported that the wear volume increase linearly with increasing the applied normal load, sliding amplitude, frequency and sliding distance.[3] According to Archard’s equation, the wear volume (*V*) of a material is inversely proportional to its hardness (*H*) and linearly proportional to sliding distance (*S*) and normal load (*F*), that is [9]

$$V = \frac{KFS}{H} \qquad (1)$$

where *K* is a dimensionless constant known as the wear coefficient.

As shown in Fig. 3, the wear volume increased linearly with increasing an applied normal load at sliding amplitude of 4.5mm and a frequency of 5Hz. However, Fig. 4 represents that the wear volume increased parabolically as sliding distance increased under an applied normal load 20N and the sliding speed of 45mm/s for 10, 30minutes, and 1, 2, 3 and 4 hours. Fig. 5 shows that the wear behavior of Alloy 600 mated with 409 and 403 stainless steels. It is shown from Fig. 5 that the wear volume increased as the applied work, defined as an applied normal load multiplied by sliding distance (F×S), increased. As shown in Table. 1, from the calculation of Archard's equation, the reliabilities of Alloy 600 mated with 409 and 403 stainless steels were 71.8% and 69.8%, respectively. However, Archard's equation does not reflect the effects of the mechanical properties of the materials during sliding wear but simply concerns the applied work. Therefore, it is considered that the Archard's equation has low reliability. To predict wear volume of steam generator tube, Archard's equation has to be modified.

3.2 Worn Surface Examination

As shown in Fig. 4, relationship between the wear volume and sliding distance was not linear but parabolic. It is considered that the properties of materials changed during sliding wear. It has been known that the transition of sliding wear behavior is commonly due to the material transfer and work hardening.[10]

To examine the material transfer, the wear surfaces of Alloy 600 after the wear tests at various sliding distances were observed using SEM and energy dispersive spectrometer (EDS) analysis. Fig. 6 (a) and (b) represent the worn surfaces of Alloy 600 after the sliding wear test for 1 and 4 hour, respectively. Fig. 6(a) and (b) shows the adhesive layer formed during the sliding wear. While, as a result of EDS analysis, oxide layer was found in Fig. 6(b). Generally, in reciprocating wear, the frictional heat is high enough to lead to oxidation of surface and compaction of wear debris.[11] In addition, an increase of sliding wear test duration enhanced the compaction and oxidation tendency of debris. So, the oxide layer or wear particle layer after sliding wear test for 4hours was more formed than in case of sliding wear test for 1hour. For sliding distances of 162 m, Ni and Fe components of Alloy 600 were uniformly distributed in the wear surface of Alloy 600. However, for the sliding distance of 1296 m is the zone where the wear volume increased parabolically in Fig. 4, it was found that Fe components of 409 stainless steel were transferred to the wear surface of Alloy 600. The material transfer and the oxide layer formation resulted in disturbing the pure metal to metal contact.

It has been known that Alloy 600 has very low SFE.[12,13] In the case of low SFE materials, the dislocation densities under worn surface during plastic deformation may rapidly increase and work hardening occurs in a short period.[10] In studies on wear of steam generator tube materials, the work hardening rate is known to be an important factor affecting the wear resistance of materials.[14-16]

The micro-hardness variations below worn surfaces of steam generator tube materials tested at room temperature in air environment for 1 hour are shown in Fig. 7. As shown in Fig. 7, the micro-hardness variations of surfaces before sliding wear test were about 270HV. However, the worn surfaces were highly work-hardened to more than approximately 400 HV. These results were confirmed by TEM observations of the worn surfaces of Alloy 600 mated with 409 stainless steel for 1 hour, as presented in Fig. 8. The slip phenomenon with one direction predominantly appeared on worn surfaces of Alloy 600. As a result, the formation of plastic deformed layer decides wear rate due to a close relationship with the wear volume. From these results, it is considered that the increment of material loss was decreased due to the material transfer, the formed oxide layer and work hardening.

3.3 Modified Archard's Equation

Recently, work-rate model has been suggested as wear predicting model of steam generator tube materials. This model is based on the Archard’s equation (eq. 1) and shows that wear rate increases linearly with increasing normal load, amplitude, frequency and sliding distance.[17] While, the wear volume of material after wear depends inversely on the its hardness. However, it is not always true that relation between hardness and wear volume has only an inverse proportion.[14] In addition, as shown in Fig. 4, wear rate did not proportionally increase with an increase in sliding distance. In Fig.5 and Table.1, in the prediction of the wear volume by Archard’s equation, the reliabilities were 71.8% and 69.7% for Alloy 600 mated with 409 and 403 stainless steels, respectively. The reliabilities were considered to be relatively low because the wear coefficient in Archard’s equation was assumed to be a constant, regardless of the changes of the mechanical properties during the sliding wear. Therefore Archard's equation has to be modified for the prediction of wear damage.

In the present study, the wear coefficient was modified as a function of the sliding distance for the Alloy 600 mated with 403 and 409 stainless steel. As the modified Archard’s equation describes, the wear volume (*V*) of a material due to being linearly proportional to normal load (*F*), that is

$$V = K(s)F\ , \quad K(s) = ks^{n} \qquad (2)$$

where *K* is the wear coefficient which is modified as a function of the sliding distance, and k and s is constant.

Based on eq. (1) and eq. (2), we compared with the wear coefficient of Archard’s equation and the modified Archard’s equation in Fig. 5 and Fig. 9, respectively. As shown in Table. 1, in all material combinations, the reliability of modified Archard’s equation is higher than that of Archard’s equation. Especially, in the case of the material combination of Alloy 600 and 409 stainless steel increased from 71.8% to 83.8%. As the results, the wear coefficient which is modified as a function of the sliding distance induced the improvement of reliability in the sliding wear damage prediction of steam generator tube materials.

4. Summary

From the sliding wear test of Alloy 600 mated with 403 and 409 stainless steels, the following conclusions could be achieved.

Firstly, the sliding wear tests on Alloy 600 mated with 403 and 409 stainless steels showed that the wear volume increased linearly with increasing the applied normal load, but it increased parabolically as the sliding distance increased. It is considered that work hardening and the material transfer caused the non-linear behavior during the sliding wear.

Secondly, in the prediction of the wear volume by the modified Archard’s equation based on Archard's equation, the reliability of Alloy 600 was improved. The relatively low reliabilities were considered that the wear coefficient (k) in Archard's equation was assumed to be a constant regardless of the changes of mechanical properties during the sliding wear. In the present study, the wear coefficient (k) was changed as a function of the sliding distance. Especially, according to the modified wear equation, the reliability of Alloy 600 mated with 409 stainless steel improved from 71.8% to 83.8%.

Acknowledgment

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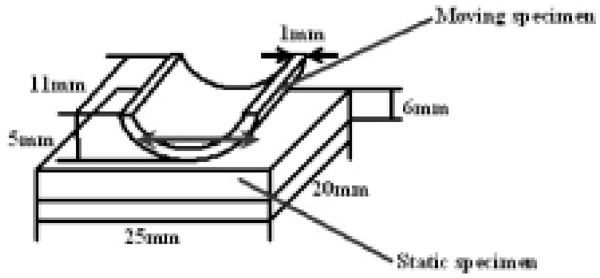


Fig. 1 Detailed shape of the sliding wear specimens.

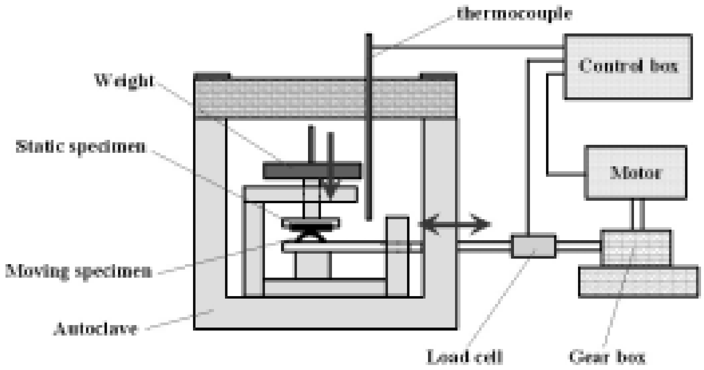


Fig. 2 Schematic diagram of sliding wear test apparatus.

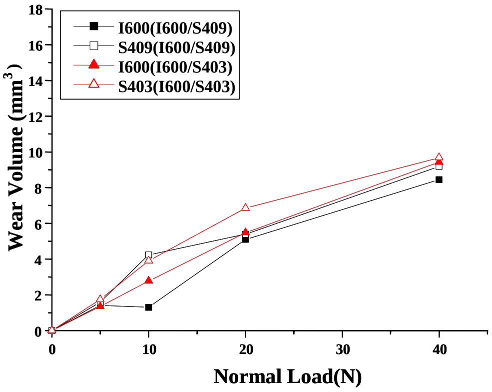


Fig. 3 Effect of an applied normal load on wear volume of Alloy 600 against 403 and 409 stainless steels at room temperature in air environment under a frequency of 5Hz and a sliding amplitude of 4.5mm for 2 hours.

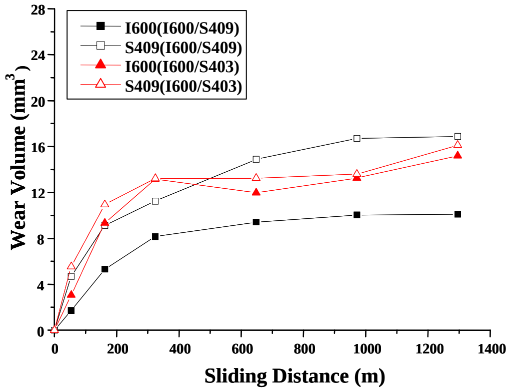


Fig. 4 Effect of sliding distance on wear volume of Alloy 600 against 403 and 409 stainless steel at room temperature in air environment under a normal load 20N, a frequency of 5Hz and a sliding amplitude of 9mm.

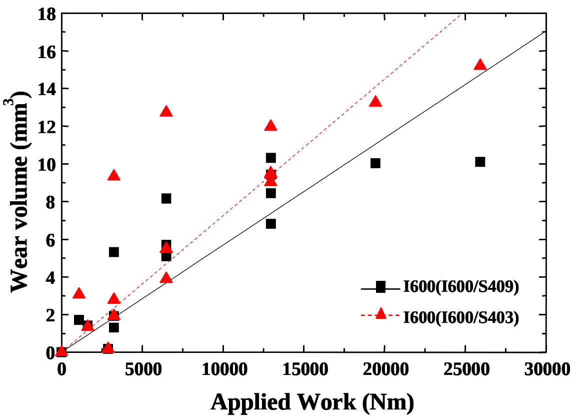
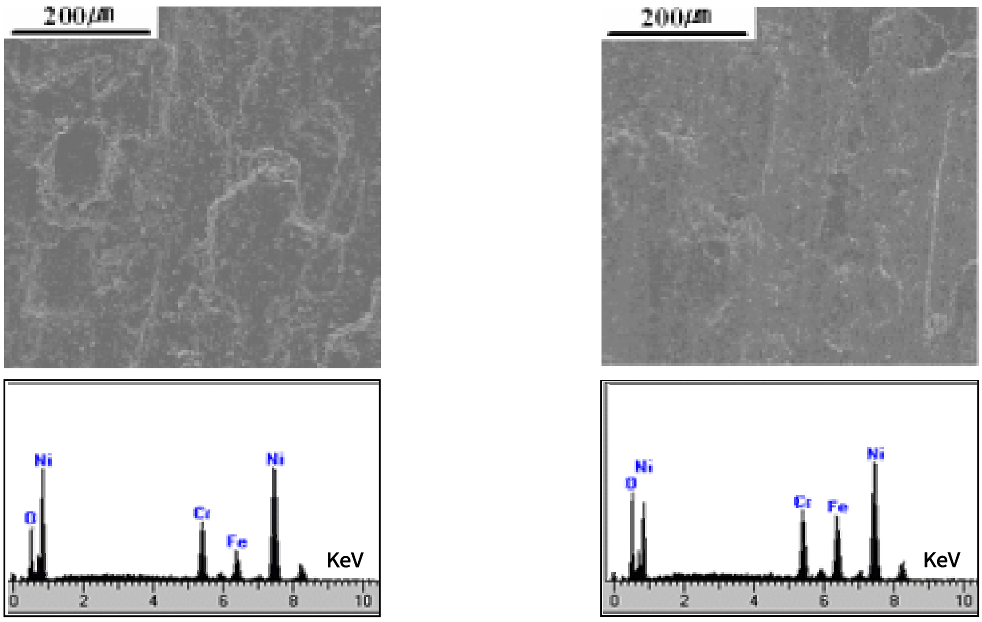


Fig. 5 The wear coefficient of Alloy 600 with the counterpart materials by Archard's equation.



(a) 1 hour

(b) 4 hours

Fig. 6 SEM images and EDS spectrums represent the worn surfaces of Alloy 600 after the sliding wear test for 1 and 4 hours.

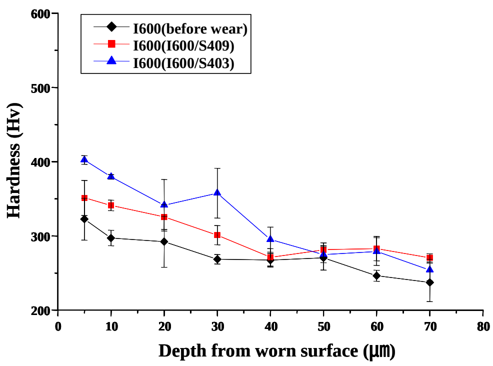


Fig. 7 Micro-hardness variation below the worn surfaces of Alloy 600 after sliding wear test for 1 hour at room temperature in air.

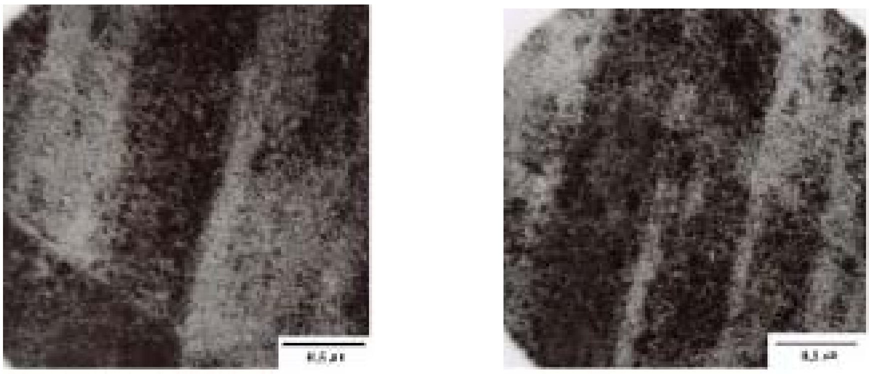


Fig. 8 TEM images of worn surface after sliding wear test in room temperature air for 1 hour.

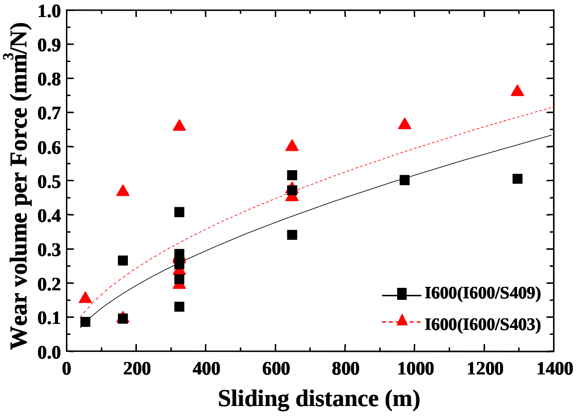


Fig. 9 The wear coefficient of Alloy 600 with the counterpart materials by the modified wear equation.

Table. 1 Comparisons of the reliabilities and wear coefficients estimated by Archard's and modified Archard's equation

	Archard's equation		**Modified Archard's equation**	
	Reliability	**K**	**Reliability**	**K(s)**
I600/S409	**71.8%**	**$57.1*10^{-15}$ Pa^{-1}**	**83.8%**	**$70.3*10^{-14}s^{1.61}$**
I600/S403	**69.7%**	**$72.8*10^{-15}$ Pa^{-1}**	**72.7%**	**$128.7*10^{-14}s^{1.63}$**