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Sliding wear behaviors of steam generator tube materials in high temperature water environment

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Abstract

Wear damage of steam generator tubes for nuclear power plants can cause the leakage of radioactive substances. Therefore, the evaluation of the tube integrity is very important in the view point of nuclear safety. In the present study, to investigate the effects of the applied normal load and sliding distance on wear volume in 575 K water environment, sliding wear tests were performed with Inconel 600 and 690 steam generator tube materials mated with 409 stainless steel commonly used as support plate. Based on the accumulated data, the newly modified Archard equation was proposed and then the wear coefficients of tube materials were estimated with both Archard equation and the modified Archard equation. The reliabilities, which are parameters to assess how well a model fits a set of data, for prediction of wear behaviors of Inconel 600 and 690 improved from 20.5% to 65.5% and from 38.5 to 65.3%, respectively.

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1. Introduction

Wear damage of steam generator tubes due to flow-induced vibration (FIV) is one of the severe degradation mechanisms resulting in the leakage of radioactive substances. In other words, wear phenomena such as sliding wear, fretting or fatigue have an effect on the life time of steam generator tubes [1,2]. Thus, the evaluation on the safety and the expectation of the life time of steam generator tubes are very important in the viewpoint of nuclear safety and economy.

According to Connors [3], the major FIV mechanisms cause the tube vibration amplitudes to increase rapidly when a threshold flow velocity is exceeded. The vibration amplitude of tubes can easily be 10 or more times greater than the clearance between the support plate and the tube. So, when steam generator is operated, it is possible that wear mode changes from fretting to sliding due to large-amplitude vibration. Therefore researches on sliding wear behaviors and collecting sliding wear data of steam generator tube materials are needed.

In the present study, to investigate the effects of the applied normal load and sliding distance on wear volume, sliding wear tests were performed with Inconel 600 and 690 steam generator tube materials mated with 409 stainless steel commonly used as support plate in 575 K water environment similar

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to actual operating conditions. Using the accumulated data, the newly modified Archard equation was proposed and then the wear coefficients of tube materials were estimated with both Archard equation and the modified Archard equation.

2. Experimental details

For sliding wear test, Inconel 600 and 690 of the size of 19 mm in diameter and 11 mm in length were used as moving specimens and 409 stainless steel flat strips of the size of 25 mm × 20 mm × 6 mm were used as a fixed specimen. Detailed shape of these specimens and chemical compositions of the test materials are shown in Fig. 1 and Table 1. The apparatus was used for simulating sliding wear between the tube and the support plate in high temperature water is shown in Fig. 2. At the conditions of the sliding amplitude of 4.5 mm and the frequency of 5 Hz, sliding wear tests were performed with increasing sliding distance up to 648 m under an applied normal load from 10 to 40 N in 575 K water environment. Worn surfaces after sliding wear tests were examined to determine the wear mechanism by using scanning electron microscopy and micro-hardness variation of subsurface was also measured to investigate the work hardening. From the accumulated data, the modified Archard equation was proposed by using the Statistical Analysis System (SAS) program.

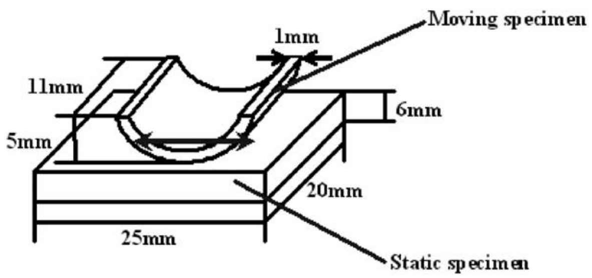

Fig. 1. Detailed shape of the sliding wear specimens.

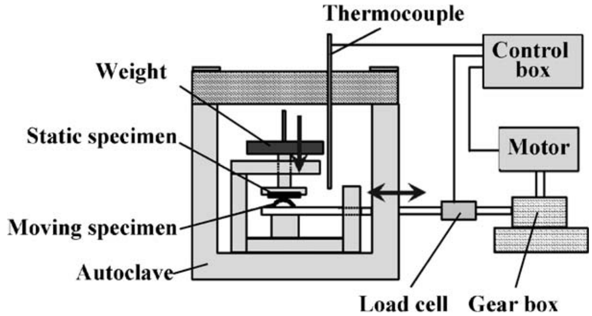

Fig. 2. Schematic diagram of sliding wear test apparatus.

3. Results and discussion

3.1. Effects of an applied normal load on wear volume

Fig. 3 shows the effects of an applied normal load on sliding wear behaviors in 575 K water environment. At sliding distance of 324 m, sliding wear tests were performed with an applied normal load ranging from 10 to 40 N. As shown in Fig. 3, the increase of normal load from 10 to 40 N resulted in marked increase in wear volume. Wear volume increased

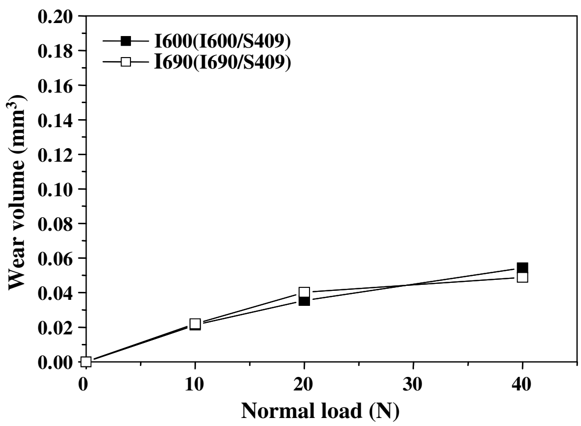

Fig. 3. Effects of an applied normal load on wear volume of Inconel 600 and 690 mated with 409 stainless steel in 575 K water environment.

Table 1
Chemical compositions of Inconel 600, 690 and 409 stainless steel

Specimen	Element									
	Ni	Fe	Cr	Co	C	Si	Mn	Ti	S	P
I600	Bal.	9.806	15.788	0.021	0.05	0.145	0.134	0.34	0.001	–
I690	Bal.	10.844	28.945	0.031	0.03	0.176	0.089	0.234	0.001	–
409SS	0.277	Bal.	11.7	–	0.015	0.621	0.194	0.132	0.0264	>0.03

linearly with increasing an applied normal load for both Inconel 600 and 690. Generally, wear volume increases with increasing load in a region of low load at the same sliding amplitude, but it starts to decrease when the normal load reached a certain level [4]. In 575 K water environment, the applied normal load ranging from 10 to 40 N did not exhibit a peak wear volume after which it should start to decrease; instead, wear volume increased linearly with the applied normal load. As reported by Vingsbo et al. [4], the linear wear behavior shows that the same slip phenomena occurred over an entire surface in the range of applied normal load.

3.2. *Effects of sliding distance on wear volume*

Fig. 4 shows the change of wear volume for Inconel 600 and 690 with increasing sliding distance in 575 K water environment. Sliding wear tests were performed with increasing sliding distance up to 648 m at the conditions of sliding amplitude of 4.5 mm, a frequency of 5 Hz and the applied normal load of 20 N. As shown in Fig. 4, wear volume increased rapidly up to 27 or 81 m, and then it plateaued with further increase in sliding distance. Wear volume increased parabolically up to about 648 m with increasing sliding distance. It means that the wear rate, which is the slope of the curve, slowly decreased with increasing sliding distance.

It is well documented that the wear rate in general decreases by work hardening of the material and the formation of wear protecting layers such as glaze layers on the wear surfaces [5,6]. Fig. 5 shows micro-hardness variations of subsurface of tube materials after sliding test for 2 h, equivalent to sliding distance of 324 m. Micro-hardness of Inconel 600 and 690 changed from about 280 to 270 $Hv_{0.01}$ and from about 320 to 300 $Hv_{0.01}$, respectively. It shows that work hardening did not occur during sliding wear tests. Generally, work hardening and dynamic recovery, which is the softening mechanisms, occurs simultaneously in the deformation of metals and alloys at high temperature [7]. So, during sliding wear tests in 575 K water environment, the effect of work hardening on wear volume is insignificant due to dynamic recovery.

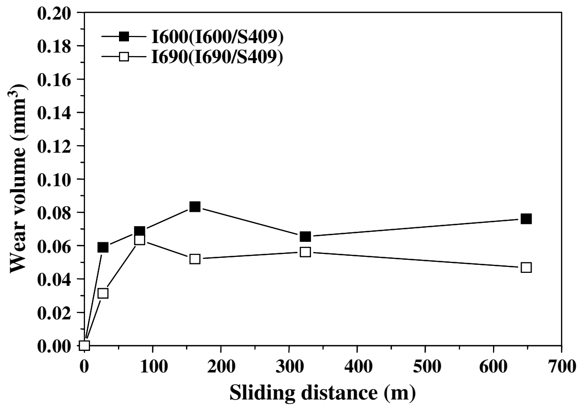

Fig. 4. Effects of sliding distance on wear volume of Inconel 600 and 690 mated with 409 stainless steel in 575 K water environment.

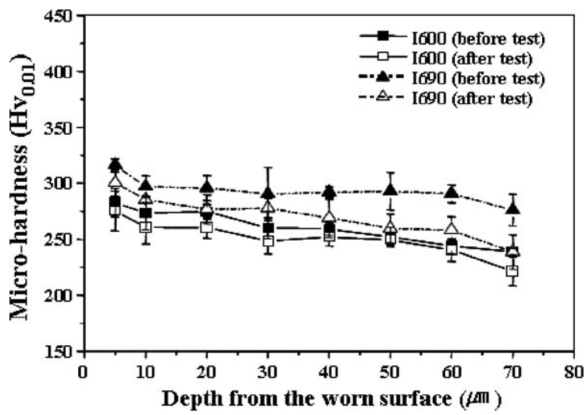

Fig. 5. Micro-hardness variation below the worn surfaces of Inconel 600 and 690 after sliding wear test for 2 h in 575 K water environment.

Fig. 6(a) and (b) shows the glaze layers adhered on the worn surfaces of Inconel 690 at sliding distance of 27 and 648 m, respectively. Energy-dispersive X-ray spectroscopy analysis shows that the black areas and spots on the worn surfaces were mainly composed of Fe, Ni and O elements. Thus, it is considered that Fe elements of 409 stainless steel transferred to the surfaces of Inconel 690 during the sliding wear. The transferred Fe and Ni debris were oxidized and led to subsequent formation of the glaze layers. The glaze layers were broadened with increasing sliding distance, as shown in Fig. 6(a) and (b). The formation of glaze layers decreases the wear volume by preventing the direct metal to metal contact between the asperities of sliding surfaces. Thereby, the wear rates of Inconel 600 and 690 mated with 409 stainless steel decreased gradually with increasing sliding distance. As a result, sliding wear behavior deviated from the linearity as observed.

In addition, one of the reasons for the decrease of the wear rate is the reduction of contact stress

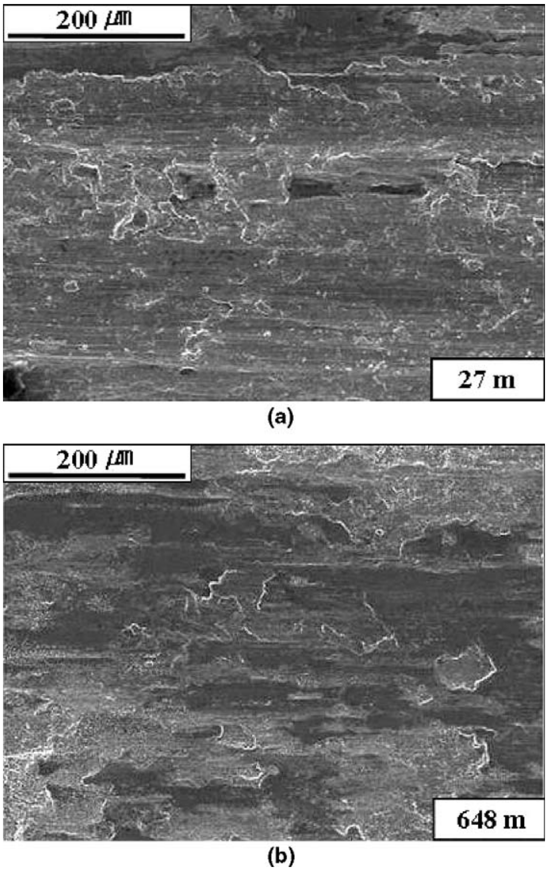

Fig. 6. SEM images of the worn surfaces of Inconel 690 (a) 27 m and (b) 648 m in 575 K water environment.

caused by the increased contact area. However, it was very difficult to estimate quantitatively the contact area in the present tube-on-plate configuration. The contact area increases rapidly at the beginning of sliding wear like in the present tube-on-plate configuration and eventually reaches a constant value with increasing sliding distance [8]. As stated previously, it is considered that the contact area of the present specimen did not increase further due to the reduction of wear rate caused by the formation of glaze layers with sliding distance. In other words, the reduction of contact stress had significant effect on the decrease of wear rate only at the beginning of sliding wear. After the contact stress reached a constant value, the accumulated wear volume did not increase further owing to the formation of glaze layers. Even though it is difficult to pinpoint which is the main mechanism for the parabolic wear behavior at the present time, it is likely that both the formation of glaze layers and the reduction of contact stress contributed the parabolic wear behavior in 575 K water environment.

3.3. Prediction of sliding wear behaviors in 575 K water environment

In prediction of wear behavior using Archard equation as represented in Eq. (1), the wear coefficient was assumed to be a constant and wear volume is linearly proportional to sliding distance and the normal load [9]

$$V = KFs, \tag{1}$$

where V is the wear volume, F is the applied normal load, K is the wear coefficient and s is sliding distance. Therefore, the equation cannot adequately explain the present non-linear wear behavior with increasing sliding distance in 575 K water environment. Hence, Archard equation regardless of the material combinations and the changes of mechanical properties, was modified and the wear coefficient $K(s)$ was introduced as function of sliding distance

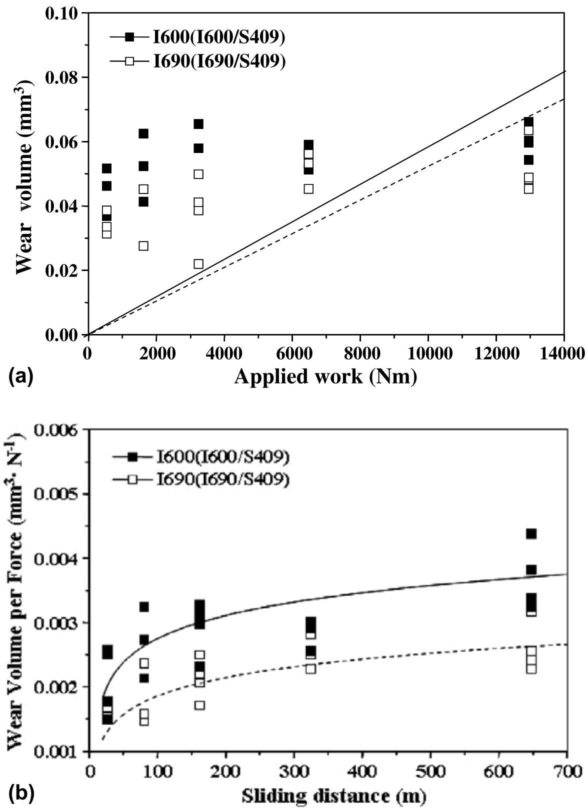

Fig. 7. The wear coefficients of Inconel 600 and 690 mated with 409 stainless steel by (a) Archard equation and (b) the modified Archard equation.

Table 2
Comparison of the reliabilities and wear coefficients estimated by Archard equation and the modified Archard equation

Specimens	Archard equation		Modified Archard equation	
	K (Pa^{-1})	Reliability (%)	$K(s)$ (m Pa^{-1})	Reliability (%)
I600/409SS	5.84×10^{-15}	20.5	1.25×10^{-12} s$^{0.21}$	65.5
I690/409SS	5.23×10^{-15}	38.5	1.80×10^{-12} s$^{0.16}$	65.3

in order to represent the parabolic wear behavior. The modified Archard equation is as follows:

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

where V is the wear volume, F is the applied normal load, $K(s)$ is the modified wear coefficient and k and n are constants. Fig. 7 and Table 2 shows the wear coefficients and the reliabilities for the wear behavior for Inconel 600 and 690 using both Archard equation and the modified Archard equation. The reliability is the parameter to assess how well a model fits a set of data and the values were calculated from the accumulated data by using statistical analysis system (SAS). As shown in Fig. 7(a), when using the original Archard equation, wear volume should increase linearly with the applied work which is defined as the applied normal load multiplied by sliding distance. However, the real wear data did not show the linear behavior. Thus the predicted reliabilities of the wear behaviors of Inconel 600 and 690 were as low as 20.5% and 38.5%, respectively. Meanwhile, when the modified Archard equation used, the wear coefficient of Inconel 600 was 1.25×10^{-16} s$^{0.21}$ m Pa^{-1} and that of Inconel 690 was 1.80×10^{-16} s$^{0.16}$ m Pa^{-1}. Compared with Archard equation, the reliabilities for prediction of wear behaviors of Inconel 600 and 690 improved from 20.5% to 65.5% and from 38.5% to 65.3%, respectively. As shown in Fig. 7(b) and Table 2, even though the modified Archard equation is not available for generalized prediction of the wear behavior, these results show that it well explains the parabolic wear behavior with increasing sliding distance.

In 575 K water environment, wear volume was very small and no major difference between two Inconel materials at sliding distance up to 648 m. For further studies, it is needed to investigate the sliding wear behavior at longer sliding distance and various temperatures.

4. Summary

From the results of this study, we found no major difference in the sliding wear behaviors of Inconel 600 and 690 steam generator tube materials mated with 409 stainless steel in 575 K water environment. Wear volume increased linearly with the applied normal load, and it increased parabolically with sliding distance. In the present tube-on-plate configuration, the parabolic increase of wear volume of the Inconel 600 and 690 was considered to be due to the formation of glaze layers on the specimen surfaces and the reduction of contact stress with increasing sliding distance. For prediction of the parabolic wear behavior, the modified Archard equation was proposed and then the wear coefficient $K(s)$ was modified as function of sliding distance. The modified Archard equation well explained the parabolic wear behavior with increasing sliding distance in 575 K water environment.

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