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Wear Behavior of Steam Generator Tubes in Nuclear Power Plant Operating Condition

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ABSTRACT

Reciprocating sliding wear tests were performed on steam generator tubes materials at steam generator operating temperature. The material surfaces react with oxygen to form oxides. The oxide properties such as formation rate and mechanical properties are varied with the test temperature and alloy composition. So, it is important to investigate the wear properties of each steam generator tube materials in steam generator operating condition. The tests results indicated that the wear coefficient in work rate model of alloy 690 was faster than that of alloy 800. From the scanning electron microscopy observation, the wear scars were similar each other and worn surfaces were covered with oxide layers. It seemed that the oxide layers were formed by wear debris sintering or cold welding and these layer properties affected the wear rate of steam generator tube materials.

KEY WORDS: steam generator tube, reciprocating wear, high temperature water, oxide layer

INTRODUCTION

Steam generators (S/G) of pressurized water reactors (PWR) are large heat exchangers that use the heat from the primary reactor coolant to make steam in the secondary side for driving turbine generators. The thermal energy transfer occurs in S/G by passing one fluid through the tubes, while another fluid (or fluid gas mixture) is passed through the outside of the tubes. High velocity cross-flow over the tubes induces tube vibration. If the vibration amplitudes become too large, damage or even failure can occur from mechanical degradation such as fatigue or wear [1, 2].

Recently, wear damage of steam generator tube is one of the most severe degradation mechanisms in nuclear power plant. Flow induced vibration occurs due to high flow rates and small clearance between tubes and their supports. It is very hard to remove the tube vibrations. Therefore, many wear damages have been reported in S/G of nuclear power plants. In some nuclear power plants, the S/G suffers peculiar tube leakages. The wear rate of these tubes is faster than that by fretting wear. It was found that faster wear rate was resulted from the wear between tube and lost parts, during construction of S/G, tools like saws and nails were lost in the S/G. Between tubes and lost things, the wear occurs with larger sliding distance and load.

From Vingsbo and Soderberg [3], the wear regimes were divided to four parts, stick, mixed stick and slip, gross slip and sliding. In sliding regime, the wear coefficient remains constant with increasing sliding amplitude. Generally, wear in S/G is affected by parameters governed by fluid flow, e.g., type of tube motion, vibration frequency and impact force at the supports; and also governed by mechanical design, e.g., tube/supports clearance, tube/supports contacting area, material combinations and system operating temperature [4].

Most metals are thermodynamically unstable and react with oxygen to form an oxide [5]. According to Stott [6], the oxide layers may be formed by oxidation of the metal asperities or by compaction of oxidized metallic debris. Oxides properties such as formation rate, strength and composition, are changed with test temperatures. So, it is very important to investigate the effects of environment on wear of S/G tubes. In this study, effects of temperature on the S/G tube wear were investigated.

EXPERIMENTAL PROCEDURE

Materials Preparation

Inconel 690 and Incoloy 800 are used for S/G tube in PWR. Specimens used in the present study were received from Doosan Heavy Industries and Construction Co. Ltd, which were Inconel 690TT and Incoloy 800 tubes. Specimens of tubes 19.05mm diameter by 30mm long, were cut from the as received shape without additional treatments. Chemical compositions are listed in table 1. The hardness of test materials were listed in table 2 and the microstructures are shown in Fig. 1. The contact angle between specimens is 90°. Detailed shape of specimens and specimen contact diagram are shown in Fig. 2.

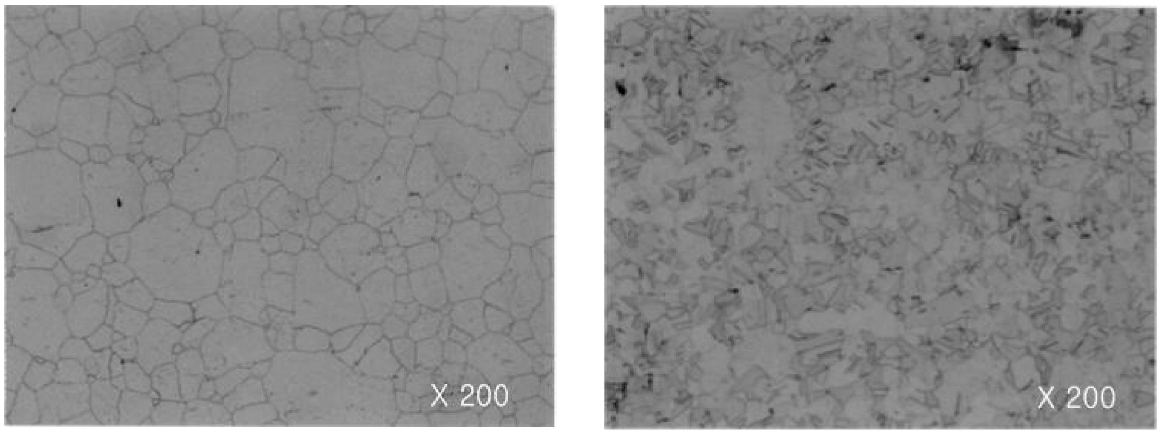
The weight loss of specimens was obtained by weighing before and after experiments using analytical balance with accuracy in the order of 0.1mg. Specimen was cleaned with acetone in an ultrasonic bath and then, dried by compressed air. To minimize errors in weighing, average values from 12 measurements and reference specimen were used.

Table 1. Chemical compositions of Inconel 690 and Incoloy 800 (wt%)

Mat.	Al	C	Co	Cr	Cu	Fe	Mn	Mo	N	Ni	Nb	P	S	Si	Ti
I 690	0.50	0.02	0.02	30	0.5	9	0.5	0.2	0.05	Bal.	0.1	0.1	0.01	0.5	0.5
I 800	0.3	0.015	0.1	22	0.75	Bal.	0.25	-	0.03	34	-	0.2	0.02	0.5	0.5

Table 2. The hardness of test materials

Material	Inconel 690	Incoloy 800
Hardness(Hv)	164	152.4



(a) (b)

Fig. 1 Microstructures of test materials, (a) Inconel 690, (b) Incoloy 800

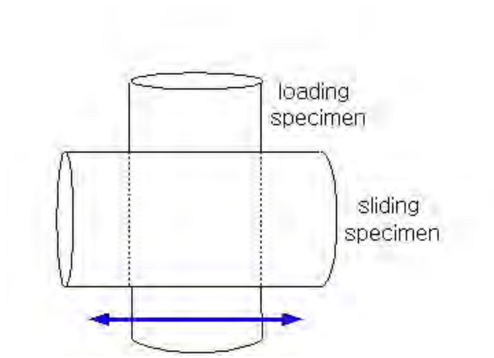


Fig. 2 Sliding specimen setup in autoclave of tube to tube type

Test Rig and Experimental Variables

The test rig was designed to examine the reciprocating wear and rolling wear properties in high temperature water environment. The schematic diagram of test system is shown in Fig 3. The test rig consists of pressure vessel, electric heater sliding and loading units. To drive the sliding unit, the AC motor was used. The cam to convert the rotating motion into linear oscillating motion was attached to the motor. The linear oscillating motion of cam is transmitted to sliding axis. The sliding displacements were controlled with eccentric distance of cam. To measure the load and displacement, the two load cells and strain gauge were attached. And these measuring units were connected to the personal computer for on-line monitoring.

Wear tests of Inconel 690 were performed at various temperatures (25°C, 150°C, 250°C and 290°C) in air and water. Incoloy 800 tubes were tested at fixed temperature (290°C) in water. Water used in experiments was chemically pure without additives and deionized below 0.1μS/cm. The water was aerated and its pH was 6.98. Testing frequency was 10 Hz and displacement was 1,200μm. The test load was 10N. Tests were performed more than 3 times at each experimental condition.

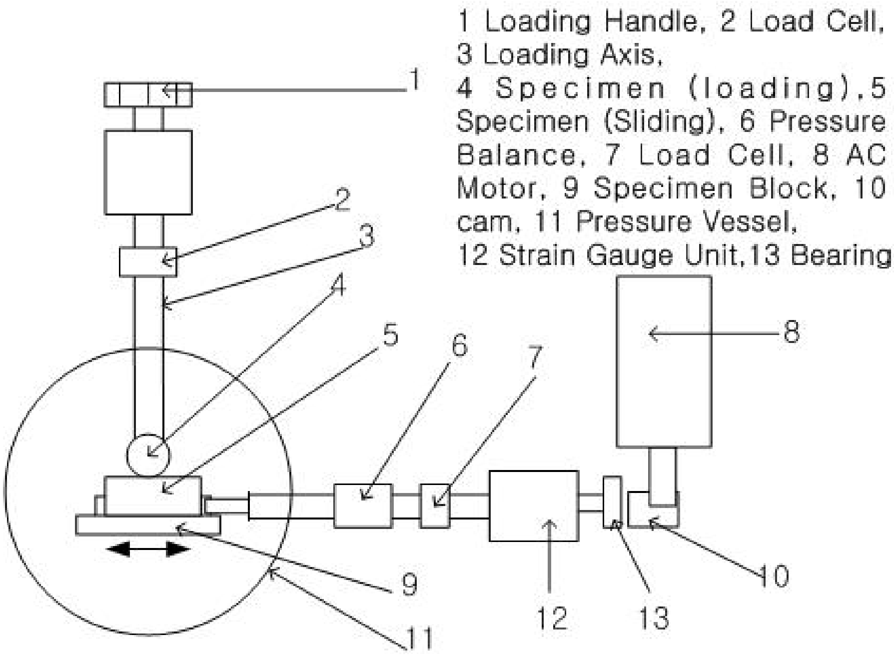


Fig. 3 Schematic diagram of high temperature wear test rig

Application of the Work Rate Model

Many researchers proposed various semi-empirical models of modifying the Archard wear equation. Frick [7] proposed the modified wear equation and a work-rate model. The work rate is defined as the normal component of contact force, F, integrated over the real sliding distance, S.

$$\dot{W} = \frac{1}{t}\int F ds \tag{1}$$

Expressing Archard's wear equation in rate form and replacing the product of force and sliding distance with work rate results in

$$\dot{V} = K\dot{W} \tag{2}$$

In this equation the K is dimensional wear coefficient. The work rate model has been widely used to evaluate and estimate wear damage in S/G tubes. From the results of wear tests, the wear coefficients of work rate model were calculated.

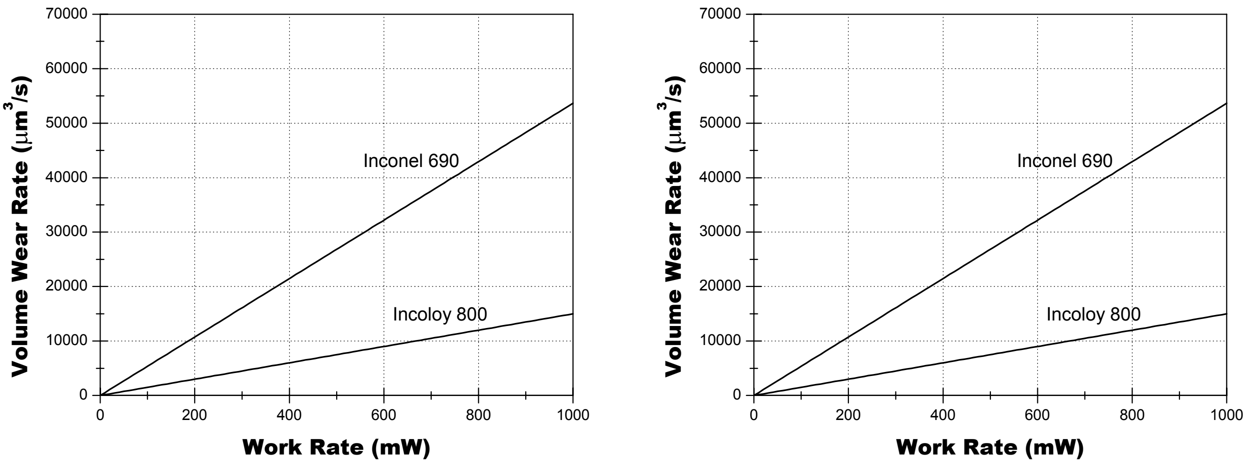
RESULTS AND DISCUSSIONS

Wear Test in Steam Generator Operating Temperature

Fig. 4 shows the wear rate in 290°C, 10MPa water environment (near the steam generator operating condition) of Incoloy 800 and Inconel 690 steam generator tube materials. The wear rates were calculated using the work-rate model [7, 8]. The wear rate of Inconel 690 was 4 times faster than that of Incoloy 800 material. At high temperature, it seemed that wear rate difference between Inconel 690 and Incoloy 800 was due to the oxide layer and mechanical property differences. To know the surface composition, the EDAX analyses were carried out. From the analyses (Fig. 5), the oxygen and chromium were about the same on worn surfaces. However, the contents of iron and nickel were different from each other. Based on the study on the development of wear-protective and load-bearing layers on the surfaces, Jiang [9] proposed that the changes of wear rate are closely associated with the formation of oxidized, or partially oxidized, load bearing layers on the wear surfaces. According to these results, the oxide layer of Incoloy 800 was more protective than that of Inconel 690 in high temperature water. It seemed that wear rate difference of two alloys was affected by the oxide layer composition.

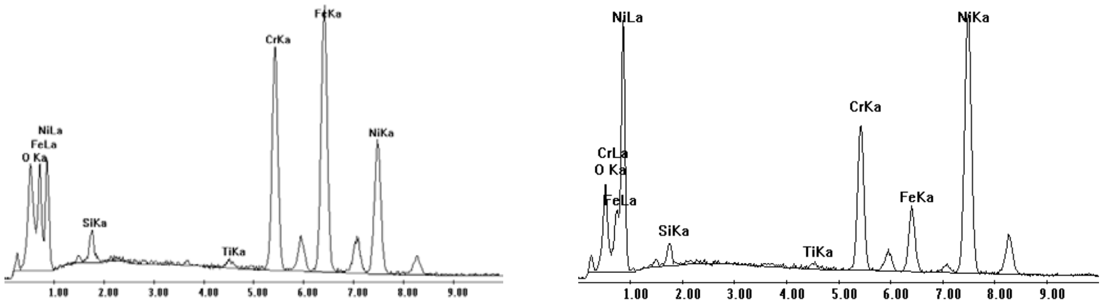
Effects of Test Temperature

To investigate the effects of temperature on the wear of Inconel 690 steam generator tube material, tests were performed at various temperatures (25°C, 150°C, 250°C and 290°C). Fig. 6 shows that the variation of wear loss



(a) (b)

Fig.4 Results of wear test in 290°C water; using work rate model,
(a) loading specimen, (b) sliding specimen



(a) (b)

Fig. 5 Worn surface composition of Incoloy 800 and Inconel 690 tested tested in 290°C water
(a) Incoloy 800 (b) Inconel 690

due to the test temperatures in water environment. In Fig. 6, the wear loss increases at temperatures between 25 and 150°C and then it decreases at temperatures between 150 and 290°C. The maximum wear loss was observed at 150°C. These wear loss variations with temperature are similar to other researchers [10]. As test temperature increased, the formation rate and properties of the oxide varied. Between 25 and 290°C, there were little mechanical property changes. Oxidation can occur at areas of real contact even at extremely low partial pressures. There is enough oxygen in most waters to produce significant reaction with the surface of the metals [5, 11]. For many alloys, it has been widely reported that development of oxides between sliding metal or alloy surface can reduce friction and wear [12]. According to Stott and Jiang, the oxide layers may be formed by oxidation of the metal asperities or by compaction of oxidized metallic debris and there exists a critical temperature. Below this temperature, the wear protective layer from the wear debris is not very well compacted, so the wear rates are high. Above this temperature the wear protective layer is compacted, so the wear rates are relatively low.

The worn surface compositions were investigated in specimens tested in water (Fig. 6). The worn surfaces were rich in oxygen except 150 °C tested specimen. The oxygen content of unworn surface was 3-4 at%, while, on worn surfaces, the oxygen contents were 10-20 at%. It seems that these increases of oxygen contents of worn surfaces were due to the oxidation of wear debris. From the test results, between 25 and 150°C, the wear loss was found to increase with increasing temperature, whereas between 150°C and 290°C the wear loss decreased with increasing temperature. Below 150°C, the oxide layers were not very well compacted, so the hard oxide particles from broken-down oxide layer or oxidized metal debris affected the wear rate of materials. Beyond 150°C, well compacted or asperity formed oxide layers act as a wear protective layer. Hence, it seemed that the oxide layer transition of Inconel 690 occurred at around 150°C in water environment.

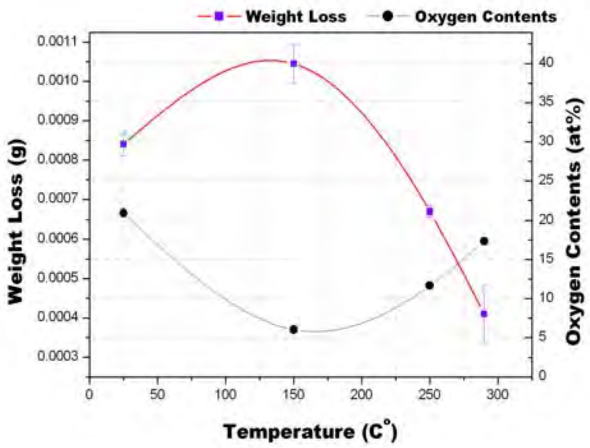


Fig. 6 Changes of weight losses and worn surface oxygen contents with increasing temperature,

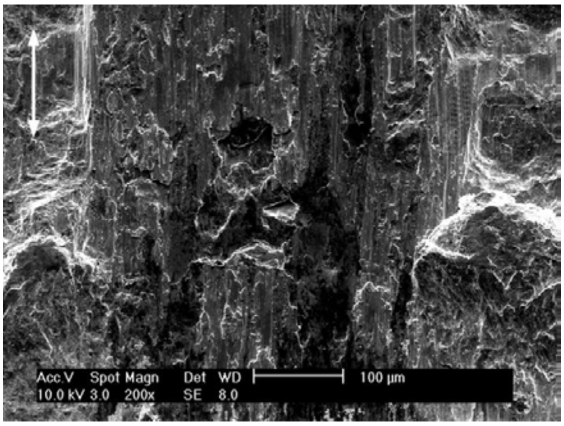
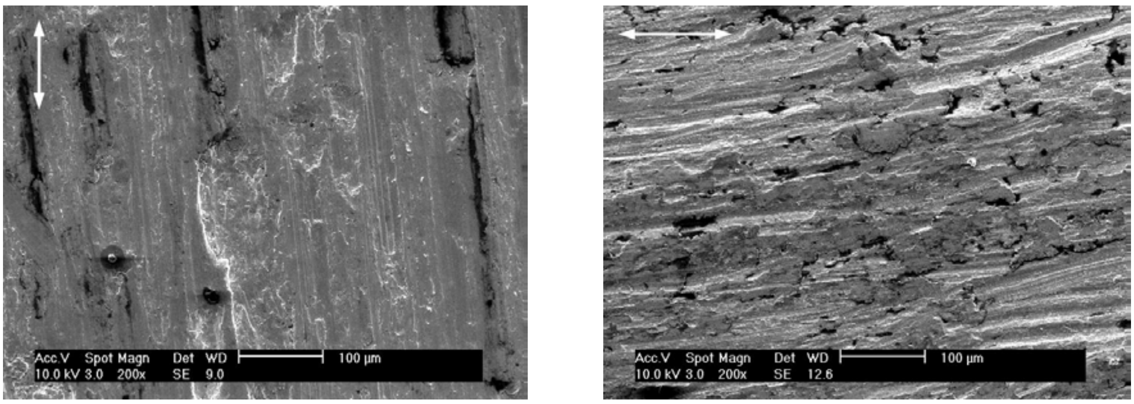
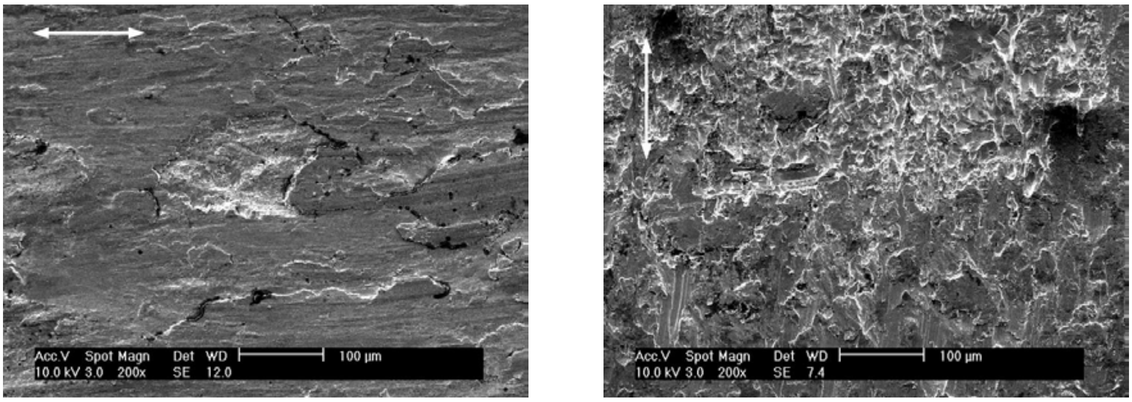


Fig. 7 SEM image worn surface of Incoloy 800 at 290°C water



(a) (b)



(c) (d)

Fig. 8 SEM images of worn surface of Inconel 690 in water environment
(a) at 25°C, (b) at 150°C, (c) at 250°C, (d) at 290°C

SEM Image Observation

To investigate the effects of test variables and the wear damage behavior of the surface observations of worn surface were performed after acoustic cleaning in ultrasonic cleaning bath. The abrasion and deformation scars and oxide layers were observed (Fig. 7). The abrasion and deformation scars seemed to be generated by loosed fine wear particles during abrasive wear. Wear layers seemed to be formed by wear particle adherence to the material surface or delamination of oxidized layer.

In Fig. 8 (a), (b), the abrasion and deformation patterns were observed. These patterns were observed on the surface of 150°C specimen (Fig. 8 (b)). From the SEM and EDAX investigation, it was found that as test temperature increased, the proportion that covered with oxide layers increased and abrasive and deformation patterns disappeared. In worn surface of specimen at 250 and 290°C (Fig. 8(c), (d)), most areas covered with oxide layer and the fractured oxide layers were observed.

From SEM observation, the oxide layers were formed at the surfaces and these layers existed more at the higher temperature range. And it seemed that these layers act as a wear protective layers.

CONCLUSION

Reciprocating sliding wear tests were performed in high temperature water and air environment on steam generator materials. From those experimental results following conclusions were drawn.

1. At 290°C, wear rate of Inconel 690 was higher than that of Incoloy 800.
2. In water environment test, the wear rates were affected by temperature. It was found that the oxide particle layers were formed on worn surfaces and their oxygen contents changed with temperature variation.
3. The wear loss increased with decreasing oxygen concentration of worn surface. From test results, the weight loss variations with temperature were affected by oxide layers on worn surfaces.

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