Journal of the Korean Nuclear Society
Volume 34, Number 2, pp.132~141, April, 2002

Effects of Microstructure on the Fretting Wear of Inconel 690 Steam Generator Tube

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(Received January 19, 2001)

Abstract

The effects of microstructure on fretting wear were investigated in Inconel 690 tube. The microstructure observation indicated that the solution annealing temperature and time affected the grain size of the Inconel 690 tubes. The carbide morphology, along grain boundaries, was mainly affected by thermal treatment time and temperature. The wear test results showed that specimens with larger grain size and with coarse carbides along grain boundaries had better wear resistance. Cracks were found in specimens with carbides along the grain boundary, while few cracks were found in carbide free specimens. It seemed that the carbides on grain boundary assisted crack formation and propagation in carbide containing specimens. On the other hand, the micro-hardness of specimen did not have a major role in fretting wear. It could be inferred from the SEM images of worn surfaces that the main wear mechanism of carbide containing specimen was delamination, while that of carbide free specimen was abrasion.

Key Words : steam generator, Inconel 690, fretting wear, grain size, grain boundary carbide, microstructure

1. Introduction

Inconel 690 is used as PWR(Pressurized Water Reactor) steam generator tubing. This alloy contains twice chromium as much as in Inconel 600 alloy to have more corrosion resistance [1]. However, in view of mechanical properties, S/G(Steam Generator) with Inconel 690 would be inferior to S/G with Inconel 600 [2]. Especially, due to the fact that the length of the tube increased by about 10 % because of the low thermal conductivity of this alloy, more severe operating

Tablel. Chemical Composition of Inconel 690 Tube (wt%)

C	Si	Mn	P	S	Cr	Ni	Mo
0.02	0.27	0.28	0.008	0.001	29.4	59.2	0.01
Co	Ti	Cu	Al	Nb	B	N	Fe
0.011	0.28	0.01	0.027	0.01	0.004	0.012	10.5

Table 2. Chemical Composition of Tube Support Plate (AISI 405) (wt%)

C	Mn	P	S	Si	Cr	Ni	Fe
0.08	1.00	0.04	0.03	1.00	13.0	0.60	Bal.

condition was expected. Consequently mechanical damages, such as fretting or fatigue, are likely to occur more than pure corrosion damages.

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. 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 fretting wear [3,4].

Fretting wear occurs as a result of low-amplitude motion between contacting components. This low amplitude motion distinguishes the fretting wear from the more general sliding wear. Fretting wear 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 the mechanical design, e.g., tube/supports clearance, tube-supports area, material combinations and system operating temperature [5].

Previous researches were focused on geometrical parameters between tube and tube support plate, environmental parameters and analytical approaches. And few researches have been performed in the microstructural point of view. So this study is focused on the effects of microstructure of Inconel 690 and improvement of fretting wear property by heat treatments.

2. Experimental Procedure

2.1. Material Preparation

Materials used in present study were received from Korea Heavy Industries and Construction Co. Ltd, which were Inconel 690 TT (thermal treated) of tube shape and AISI 405 of plate shape. Present specimen material has 0.02 % carbon content. Tube support plate material is ferritic stainless steel. Other chemical compositions are listed in table 1 and 2.

2.2. Heat Treatments

Heat treatments were divided into two parts, solution annealing for carbide dissolution and aging for carbide precipitation. To obtain various grain sizes and carbides morphologies, heat treatments were carried out at various temperatures and periods. Solution annealing treatments were performed at 1150 ℃ or at 1070 ℃. Aging treatments were performed at 700 ℃ or at 800 ℃. Detailed heat treatments are listed in Table 3. To prevent reaction involving oxygen, all specimens were thermally treated in vacuum sealed quartz tubes.

2.3. Microstructural Observation and

Table 3. Summary of Heat Treatment Conditions

Designation	SA Temperature	SA Time	TT Temperature	TT Time
AS				
SAH	1150℃	1hr		
SAH701	1150℃	1hr	700℃	1hr
SAH715	1150℃	1hr	700℃	15hr
SAH801	1150℃	1hr	800℃	1hr
3SAH701	1150℃	3hr	700℃	1hr
SAL701	1070℃	1hr	700℃	1hr
SAL715	1070℃	1hr	700℃	15hr

SA : Solution Annealing
TT : Thermal Treatment
AS : As received

Hardness Test

Metallographic specimens were prepared and electrolytically etched in 6 % nital solution at 4 volts for 60 seconds to reveal the microstructural features. Grain size measurements were performed using a linear intercept method according to ASTM E 112 [6]. Phosphoric etching was used to determine the presence of carbides in grain boundary area. The etching was performed at 3 volts for 20 seconds in the solution of 8 parts phosphoric acid and 1 part water. Carbides morphology was examined through SEM (Scanning Electron Microscopy, Philips SEM 515).

Microhardness was measured on surface of matrix and grain boundary using micro - Vickers hardness tester (Tukon 300). In this measurement, 25 gram load were applied for 15 seconds.

2.4. Wear Test

The test system consists of wear test machine, load

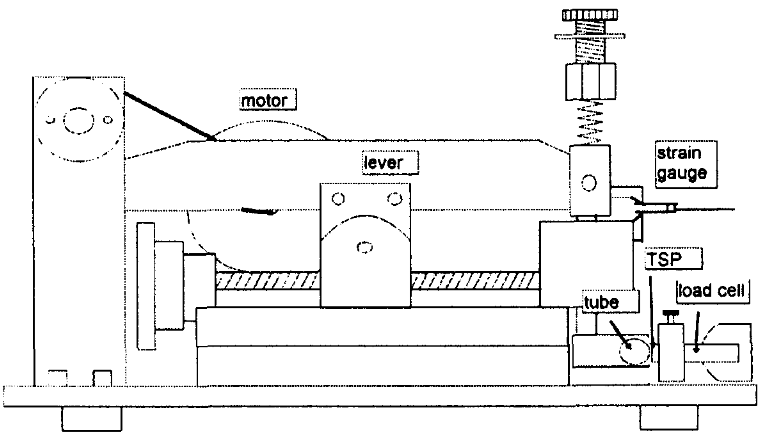


Fig. 1. Wear Testing Machine (TSP : tube support plate, lever : used for change displacement)

Table 4. Results of Grain Size Measurements

	AS	SAL	SAH	3SAH
Grain No.	8.07	7.49	5.53	5.2
Grain size (μm)	25	30	60	80

cell, strain gauge and weighing balance. Load cell and strain gauge are connected to a power supply and a digital multi - meter. The cell was used for measuring normal load during the test. Strain gauge was used to measure the specimen displacement. Fig. 1 illustrates the wear testing machine.

Wear tests were performed in various cycles under the same frequency. Testing displacement was 100 μm. Tests were performed to 27,000, 54,000 and 108,000 cycles. Frequency was fixed at 30 Hz. Tests were performed more than 3 times every experimental condition. Before and after test, each specimen weight was measured 10 times and the average values were taken. Before weighing, each specimen was cleaned in ultrasonic cleaning bath.

3. Results and Discussion

3.1. Microstructure Observation and Hardness

The grain size of the thermally treated

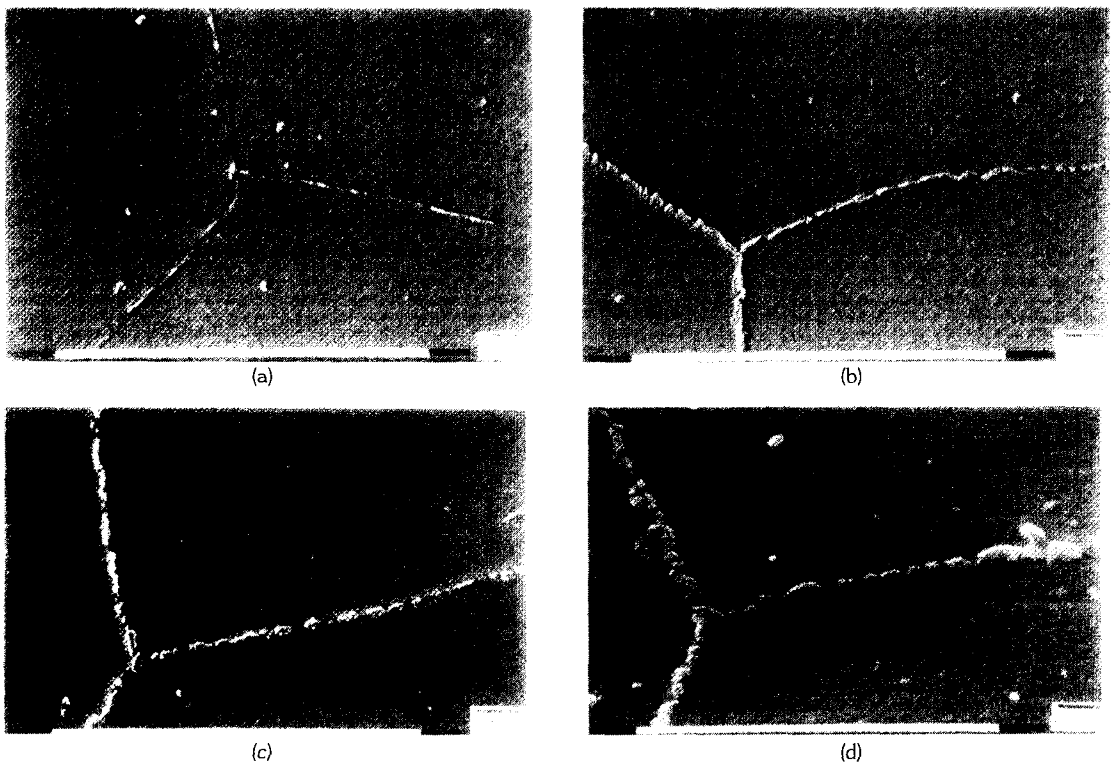


Fig. 2. Carbide Morphology of (a) SAH(solution annealed at 1150℃ for 1hr) (b) SAH701(solution annealed at 1150℃ for 1hr, thermally treated 700℃ 1hr) (c) AS(as-received) (d) SAH801(solution annealed at 1150℃ for 1hr, thermally treated at 800℃ 1hr)

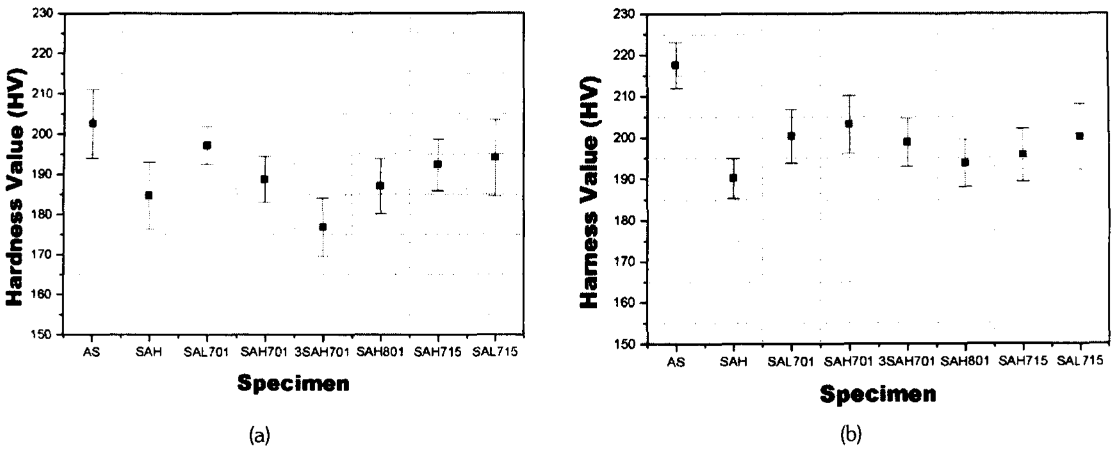


Fig. 3 Hardness Values of (a) Matrix (b) Grain Boundary

specimens was larger than that of the as-received specimen. The grain size of the specimen, solution annealed at 1150℃ for 3 hours, was larger than that of the specimen solution annealed at 1150℃ for 1hour and that of the specimen solution annealed at 1070℃ for 1 hour was the smallest. The grain sizes and ASTM numbers of specimens are listed in table 4.

In Fig. 2, carbide morphologies are observed on the as-received and thermally treated specimens. As shown in Fig. 2, thermal treatment temperature and time influence the carbide morphology of Inconel 690.

From these results, it was clear that only solution annealing affected the grain size of the material, whereas low temperature heat treatments, to precipitate carbides in grain boundary region, little affected the grain size of material. The carbide size of AS specimen was about 0.2μm and that of SAH801 specimen was about 0.5μm. The low temperature heat treatment time and temperature of the low temperature treatment affected the carbides morphology of the material.

The Vickers micro hardness values are shown in Fig. 3. The hardness values in grain boundaries were higher than those in the matrixes. The hardness of grain boundary with few carbides was lower than that of grain boundary with carbides. The difference between grain boundary and matrix was due to the strain energy of grain boundary [7], which was resulted from inclusions or precipitates in grain boundaries.

Solution annealing treatments decreased the hardness. For the same low temperature heat treatment condition, the longer solution annealing time was, when the solution annealing time was longer, the hardness became lower. Specimen that was not low temperature heat treated had the lowest hardness values in grain boundaries and matrixes. These results are in good agreement

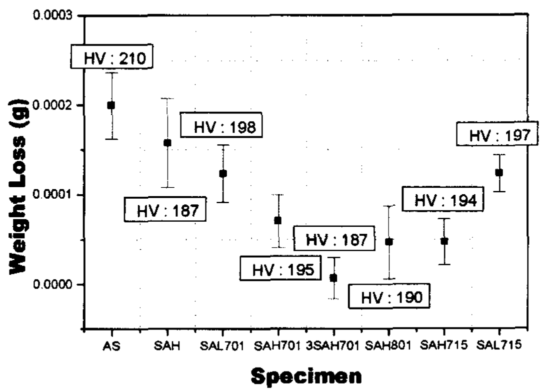
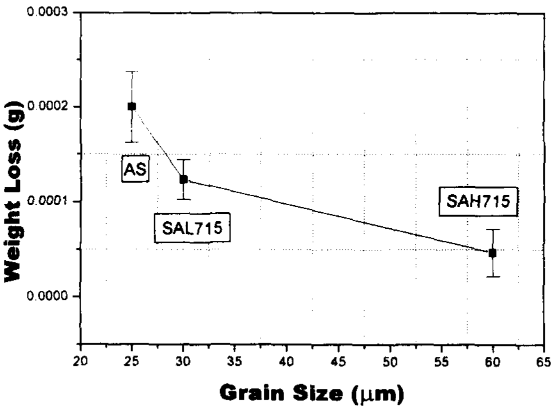
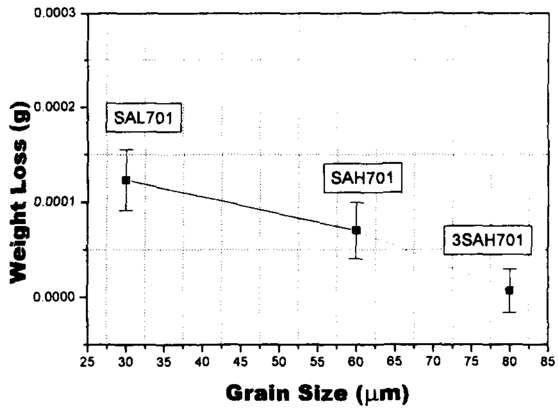


Fig. 4. Weight Loss Related to Hardness of Specimens



(a)



(b)

Fig. 5. Weight Loss Related to Grain Sizes of (a) Thermally Treated at 700℃ for 15hr (b) Thermally Treated 700℃ for 1hr

with other investigators [8].

3.2. Effect of Hardness

The mechanical properties were affected by both the high temperature and low temperature for solution annealing and for carbide precipitation [9, 10]. To investigate the effect of hardness on wear property of Inconel 690, wear loss data are correlated to hardness. Fig. 4 shows that much harder specimens does not have a good wear resistance. If the Archard' s wear equation was right the hardest as-received specimen would wear least. However, the softer, heat treated specimens wore less than the as-received specimen.

This phenomenon was discussed by Ko [5] and Suh [11]. The reason for this little dependence of wear property on hardness is that the fretting wear is primarily caused by a shear mechanism, so the hardness of the material does not have significant effects on wear resistance [4, 5]. According to the test results, the hardness was not a major variable that determined the wear property of Inconel 690.

3.3. Effect of Grain Size

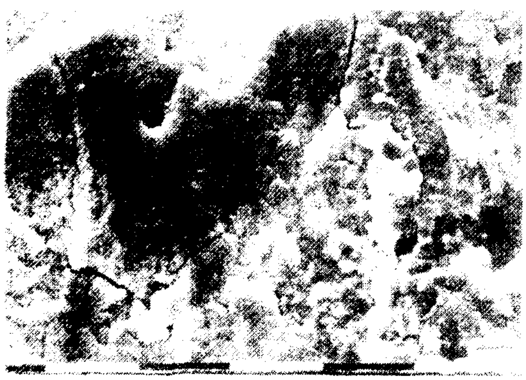
As in table 4, high temperature thermal treatments increase the grain size of the Inconel 690. Because the tests were performed to find the grain size effect, the low temperature thermal treatment was carried out on the same condition. Then the carbide morphology of specimens was similar to each other even at different grain sizes.

Fig. 5 shows the changes of wear loss according to the grain size. In Fig. 5(a) and (b), the wear loss decreases with increasing grain size. As-received specimen wore more than larger grain size specimens with the same carbide morphology, and low temperature solution annealed specimen wore more than high temperature solution annealed specimen. The trend in Fig. 5(b) is similar to the test results shown in Fig. 5(a), specimens with various grain sizes and finer carbide morphology. These results found that the larger grain size specimen had better wear resistance than the smaller grain size specimen with the same grain boundary morphology.

The SEM images of worn surface are shown in Fig. 6. The similar patterns were observed on the worn surface of each specimen with carbides in grain boundary regardless of grain size and carbide morphology. From the SEM images, rough worn

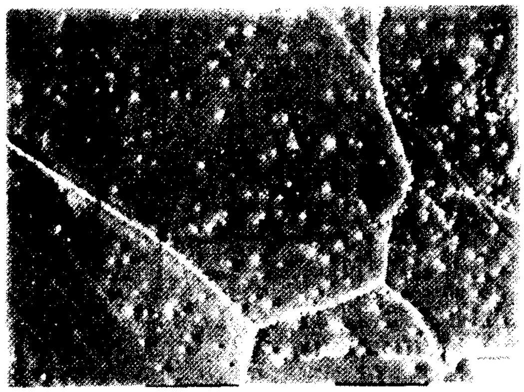
(a)

(b)

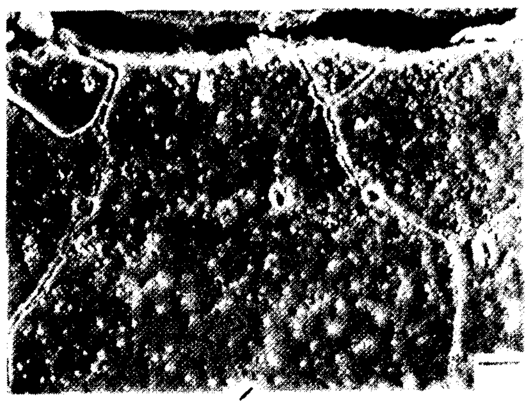


(c)

Fig. 6. Image of Worn Surface Related to Grain Size of (a) AS(as-received) (b) SAL715 (solution annealed at 1070℃ for 1hr, Thermally Treated at 700℃ for 15hrs) (c)SAH 715 (solution annealed 1050℃ for 1hr, thermally treated at 700℃ for 15hrs)



(a)



(b)

Fig. 7. SEM Image of Surface Section (a) Grain Boundary (b) Cracks in Grain Boundary

surfaces were observed and cracks were found in worn and unworn surfaces. In Fig. 7, the subsurface crack propagation is observed along the grain boundary.

According to Suh [11,12], cracks could be formed by decohesion between matrix and inclusions or precipitates. As the crack extended and reached the critical length, the delamination of sheet occurred. In this test, the chromium carbides in grain boundary enhanced the formation and propagation of surface and subsurface crack.

From these results, grain boundary area may be an important role in wear property. The grain

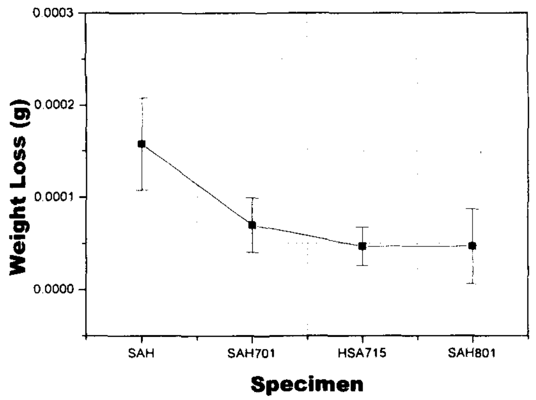


Fig. 8. Weight Loss Related to Carbide Morphology

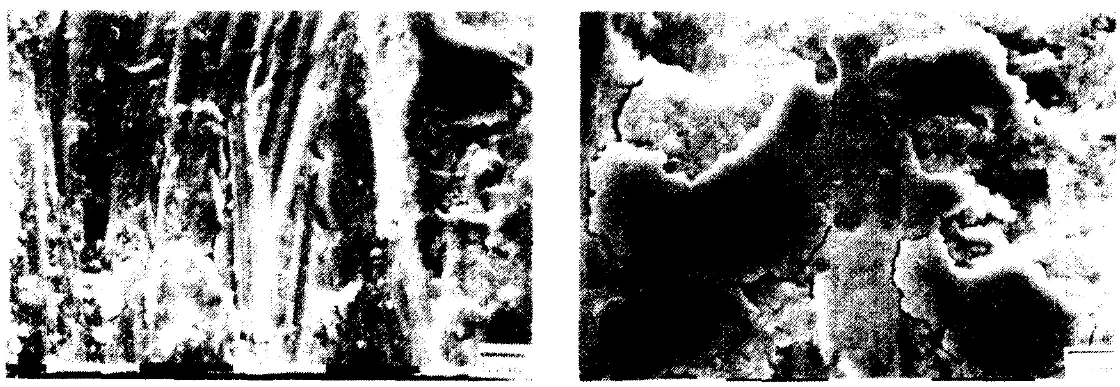
boundary area decreased with increasing grain size of the specimen. The reduced grain boundary area with carbides decreased the sites of crack formation and propagation when the mechanism of wear was delamination. Consequently, the wear resistance can be improved by making the grain size larger.

3.4. Effect of Carbide Morphology

To observe the effect of carbide morphology, aging treatments were performed at various conditions, after the high temperature thermal treatments were carried out at the same temperature (1150℃) for the same period (1 hr) to get the same grain size. Heat treatment results are shown in Fig.2, the carbide morphology varies with aging condition.

Fig. 8 shows that the wear resistance of the specimens with the same grain size and various grain boundary carbide morphologies. The weight loss of the specimen with few carbides in grain boundary was the largest and the weight loss of the specimen with relatively fine carbide morphology was slightly larger than that of the specimen with relatively coarse carbide morphology. From these results, the carbides in grain boundaries turned out to influence the weight loss of wear.

In Fig. 9, the worn surface of the specimen with few carbides is shown different from other specimens with carbides in grain boundary. The worn surfaces of the specimen with few carbides showed a texture pattern. This pattern was similar to worn surfaces by abrasive mechanism [13]. And SEM images of other specimens with carbide



(a) (b)

Fig. 9. SEM Images of Worn Surface Related to Carbide Morphology
(a) SAH (solution annealed at 1050℃ for 1hr) (b) SAH 715 (solution annealed at1050℃ for 1hr, thermally treated at 700℃ for 15hr)

showed rough worn surface and cracks. These rough surface and cracks were observed on worn surface by delamination mechanism [12].

According to these results, the wear mechanism of the specimen with few carbides was different from that of the specimen with carbides in grain boundary. In carbides free specimen, the surface deformation was easy. The third body could be easily formed [14]. So it was confirmed that the wear occurred with abrasive mechanism in carbides free specimen. In the specimen with carbides, carbides in grain boundary may lead to crack formation and propagation site by delamination mechanism [12]. The cracks were nucleated near the carbide precipitates, so the mean free path of crack propagation is average distance between carbides. Since the mean free path of crack propagation is small in continuous carbide, many crack formation sites appear. The continuous carbides morphology enhances more crack formation and propagation than discontinuous carbides. Hence the discontinuous carbide morphology improves the wear resistance of Inconel 690.

4. Conclusions

1. Grain size and hardness of Inconel 690 were dependent upon solution annealing temperature and time. The carbides morphology in grain boundary was dependent upon the aging time and temperature.
2. The hardness of Inconel 690 was not correlated with weight loss in fretting wear. Because the fretting wear was mainly caused by shear force. It seemed that the hardness of Inconel 690 was not a critical variable in fretting wear.
3. The larger grain size specimen wore less than other smaller grain size specimens with same carbide morphology.
4. In carbide free specimen, few cracks were found in the test. The wear behavior was abrasive in later test period. Specimen with coarse carbides had high wear resistance than that with fine carbides.
5. Cracks were found on surface and subsurface in the specimen with carbides in grain boundaries.

Cracks in subsurface propagated along the grain boundaries. Hence, it seemed that the carbide in grain boundary assisted the crack formation and propagation.

Acknowledgement

This work has been carried out by the support of Korea Electric Power Company under the scheme of G 7 project and also was partially supported by the Brain Korea 21.

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