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Effect of Heat Treatment on Fatigue Crack Growth Rate of Inconel 690

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ABSTRACT

The effects of heat treatment on fatigue crack growth rates (FCGRs) of Inconel 690 have been investigated in terms of carbide morphology and grain size. Cycling tests in air at room temperature have shown that FCGR in low stress intensity factor range (ΔK) region can be effectively reduced by increasing the grain boundary carbide precipitate size and grain size. Decrease in FCGR is attributed to the crack tip blunting at the precipitates of grain boundary chromium carbides.

1. Introduction

Inconel 690 has been developed as a substitute for Inconel 600 which has suffered many degradation phenomena such as primary water stress corrosion cracking (PWSCC), intergranular attack (IGA), pitting, etc. [1]. But mechanical properties of Inconel 690 are known to be inferior to Inconel 600 [2] while its chemical properties are much improved. Considering that the recent accident of Mihama unit 2 in Japan was related to fatigue failure and that the low thermal conductivity of Inconel 690 leads to the increment of total length of tubes about 10%, a better understanding on the mechanical properties and proven data on the fatigue property of Inconel 690 are especially required. A number of studies on Inconel 690 have been carried out, of which most of them are dealt with microstructure-related corrosion properties [3-5] or tensile properties [6-9]. And there are several papers about the effect of chromium carbides on fatigue crack growth rate (FCGR) of Inconel 600 [10,11]. So, it is interesting that any fatigue crack propagation test on Inconel 690 has not been published yet. The purpose of the present study is to investigate the effect of heat treatment on the fatigue crack propagation of Inconel 690 with relation to the carbide morphology.

2. Experimental

The as-received Inconel 690 of Inco Alloys Inc. has a nominal composition of 30% Cr, 59.8% Ni and 0.025% carbon.

Compact tension (CT) specimens were machined for fatigue testings according to ASTM E 647 [13] as shown Fig. 1. Inconel 690 specimens were solution-annealed at 1070℃ (hereafter, denoted as L) and 1150℃ (denoted as H) for one hour and then heat-treated at 700℃ (denoted as l) and 750℃ (denoted as h) for 5 (denoted as S) to 15 (denoted as L) hours. So every specimen was numbered in the three digits of combination of low (L) or high (H) solution annealing temperature, low (l) or high (h) heat-treatment temperature, and long (L) or short (S) heat-treatment times.

Fatigue tests were performed on the heat-treated Inconel 690 specimens and as-received Inconel 690 specimens in air at room temperature using an electro-servo hydraulic dynamic testing machine of Instron model 8501. Cyclic loading was given in a sine waveform of 10Hz with a stress ratio (R) of 0.2 at constant loading amplitudes. Crack length and crack closure were monitored by the crack tip clip gage using compliance method. In every test, the test load was chosen according to the requirement of ASTM E 647.

To observe the presence of intergranular carbide precipitates, dual etchings were done using nital and phosphoric acid solution. The morphology of carbides were observed by scanning electron microscopy (SEM). To investigate the dislocation configuration around carbide morphology, thin foils for transmission electron microscopy (TEM) were prepared from just beneath the surface of fatigue fractured specimens. After mechanical thining, foils were jet electropolished in a solution of 10% perchloric acid and 90% metanol at -20℃.

3. Results and Discussion

3.1. Microstructure

The grain size of the specimen solution-annealed at 1150℃ is larger than that of solution-annealed at 1070℃. The average grain size of as-received Inconel 690, solution-annealed at 1150℃ and 1070℃ was 45μm, 90μm and 135μm respectively which was larger than that of usual steam generator tubes of 30μm [8]. Significant grain growth was seen in the specimens solution-annealed at any temperature of 1070℃ and 1150℃, but there was no additional grain growth during thermal treatment at the temperatures of 700℃ and 750℃. As shown in Fig. 2, HhL Inconel 690 specimens reveal larger sizes of carbides than LlS Inconel 690. Different solution annealing treatments resulted in different yield strength, however no large difference in tensile tests was seen due to the different thermal treatment time and temperature.

3.2. Fatigue Crack Growth Rate

In Fig. 5, fatigue crack growth rates in steady state region are expressed in terms of the Paris-Erdogan equation [14] of :

$$\frac{da}{dN} = C(\Delta K)^m , \qquad (1)$$

where da/dN is in mm/cycle and the stress intensity factor range of ΔK is in MPam$^{1/2}$. The C and m values are empirical material constants. Fatigue test results are plotted as a function of ΔK. Table 1 shows small values of C and m values of larger than the other materials, and both of Inconel 600 and Inconel 690 show very slow FCGRs in the near threshold region but FCGRs rapidly increases as ΔK increases. In general, m values fall in 2 to 4 in theoretical and experimental investigations. However, it is known that increase in m values to 4 or higher can be made in case of the presence of brittle static modes [15], low temperature fatigue testing [16], and increasing the applied mean stress [15]. In the present fatigue tests, large m values of Inconel 690 are suggested to be mainly related to the high values of applied mean stress and characteristics of carbides.

Effect of solution annealing temperature : In Fig. 5(a), HlL Inconel 690 shows lower FCGR than that of LlL Inconel 690 in low ΔK region. However, as ΔK increased, FCGRs resulted in a reverse phase. As shown in Fig. 3, fatigue crack propagates in the intergranular mode in low ΔK region. So, it is believed that in low ΔK region, fatigue crack grows along grain boundaries while grain boundary carbides of large size in HlL Inconel 690 acts as barriers to the propagation of cracks. In high ΔK region, where fatigue crack grows to a large size, fatigue crack propagates in a transgranular mode, and the role of carbides as barriers to fatigue cracking seems to be no longer active. In this region, grain boundaries seem to act as major barriers to plastic flow in the zone ahead of the crack tip [17]. Therefore, in high ΔK region, the FCGR of LlL Inconel 690 is smaller than that of HlL Inconel 690.

Effect of thermal treatment temperature : Effects of different thermal-treatment temperature on FCGRs are shown in Fig. 5(b). Both of LlL and LhL Inconel 690 specimens were solution-annealed at the same temperature and for the same heat treatment time, but LlL Inconel 690 was thermally treated at 700℃ and LhL Inconel 690 was thermally treated at 750℃. As one can see in Fig. 5(b), there was no large difference in FCGR of two specimens. That is, the effect of difference in thermal treatment temperature on FCGR was not seen in the present test.

Effect of thermal treatment time : Effects of different thermal treatment time on FCGRs are shown in Fig. 5(c). LIL Inconel 690 was thermally treated at 700℃ for 15 hours and LIS Inconel 690 was thermally treated at the same temperature for 5 hours. LIL Inconel 690 of longer thermal treatment times resulted in larger carbides than LIS Inconel 690, leading to lower FCGR than LIS Inconel 690 in low ΔK region. As ΔK increased, the role of carbides was disappeared, and the two specimens had nearly same FCGRs.

Effect of Carbide morphology : In Fig. 5(d), HIL Inconel 690 shows the lowest FCGR in low ΔK region while as-received specimens show the lowest FCGRs in high ΔK region. The FCGR of LIS Inconel 690 is always larger than that of as-received Inconel 690. This result suggests that carbides act as major barriers to fatigue cracking in low ΔK region, and in high ΔK region, grain boundaries act as major barriers to fatigue cracking. In Fig. 4, HhL Inconel 690 was solution-annealed at higher temperature than LIS Inconel 690 so that much more dislocations were expected to be removed in Hhl Inconel 690 than LIS specimen. But, opposite morphologies were shown in TEM observations. It is thought that intergranular chromium carbides act as dislocation sources and consequently induce more homogeneous plastic deformation. In Inconel 600, Brummer *et al.* [10] suggested that the distribution of the grain boundary carbides may induce a mechanical effect where carbides reduce crack tip stress state by crack tip blunting and thus decrease the cracking susceptibility. Shalaby *et al.* [11] indicated that the enhancement of corrosion fatigue resistance of Inconel 600 was attributed to the intergranular precipitation of chromium carbides. In case of Ni-base superalloys, high precipitation volume fraction gives the crack propagation resistance at room and high temperature [18,19]. And, Iizuka *et al.* [20,21] suggested that precipitates reduce FCGR by inhibiting brittle intergranular fracture in steels. From these results, most probable microstructure against fatigue cracking is large chromium carbides at the grain boundaries without violating ASME requirements for mechanical properties.

4. Conclusions

Fatigue tests have been performed with compact tension (CT) specimens to study the effects of heat treatment on fatigue crack propagation rates in Inconel 690. From the test results, main conclusions can be drawn as follows .

Chromium carbides at the grain boundaries reduced FCGRs in low ΔK region of Inconel 690 specimen which was solution-annealed at 1150℃ and heat-treated at 750℃ for 15 hours. Decrease in FCGR is attributed to the crack tip blunting at the grain boundary carbide precipitates as far as the fatigue cracking is intergranular fracture mode.

Microstructures of fatigue fractured Inconel 690 specimens showed that the distribution of grain boundary chromium carbides act as dislocation sources to lead to crack tip blunting due to the homogeneous plastic deformation.

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Nomenclature

LlS : A specimen which is solution annealed at 1070°C for 1hour and thermally treated at 700°C for 5hours
LlL : A specimen which is solution annealed at 1070°C for 1hour and thermally treated at 700°C for 15hours
LhS : A specimen which is solution annealed at 1070°C for 1hour and thermally treated at 750°C for 5hours
LhL : A specimen which is solution annealed at 1070°C for 1hour and thermally treated at 750°C for 15hours
HlS : A specimen which is solution annealed at 1150°C for 1hour and thermally treated at 700°C for 5hours
HlL : A specimen which is solution annealed at 1150°C for 1hour and thermally treated at 700°C for 15hours
HhS : A specimen which is solution annealed at 1150°C for 1hour and thermally treated at 750°C for 5hours
HhL : A specimen which is solution annealed at 1150°C for 1hour and thermally treated at 750°C for 15hours

Table 1. Material constants in relation to ΔK and ΔK_{eff}

Condition	C	m	C_e	m_e
As-received Inconel 690	2.85×10^{-13}	6.09	9.36×10^{-13}	5.77
LlS	2.62×10^{-13}	6.15	6.75×10^{-12}	5.16
LlL	2.16×10^{-14}	6.96	4.47×10^{-13}	6.05
LhS	4.38×10^{-13}	5.93	1.68×10^{-12}	5.58
LhL	8.71×10^{-15}	7.21	7.77×10^{-13}	5.88
HlS	2.88×10^{-15}	7.64	5.66×10^{-14}	6.82
HlL	2.35×10^{-17}	9.19	3.31×10^{-17}	9.18
HhS	3.66×10^{-17}	9.05	2.49×10^{-16}	8.56
HhL	3.17×10^{-16}	8.27	1.25×10^{-14}	7.16

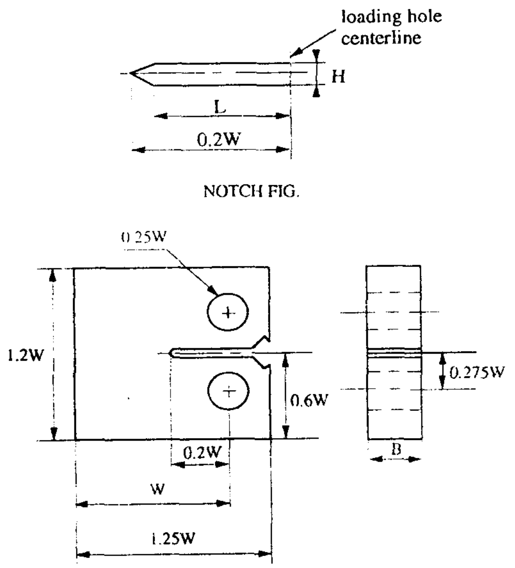


Fig. 1 Geometry of CT specimen (ASTM E 647).

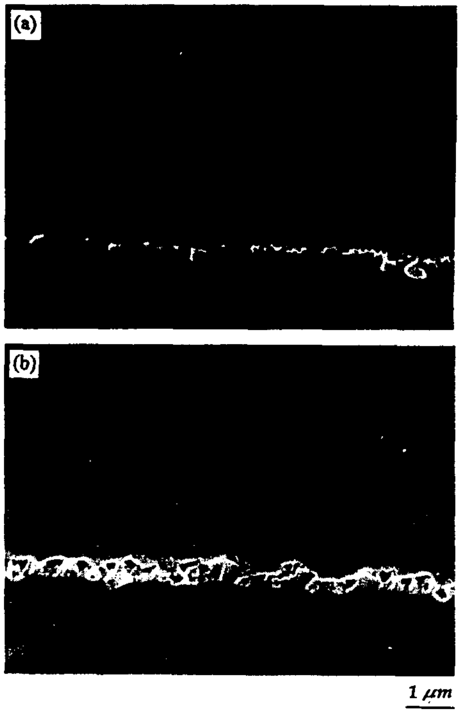


Fig. 2 Carbide morphology (a) LIS (b) HhL

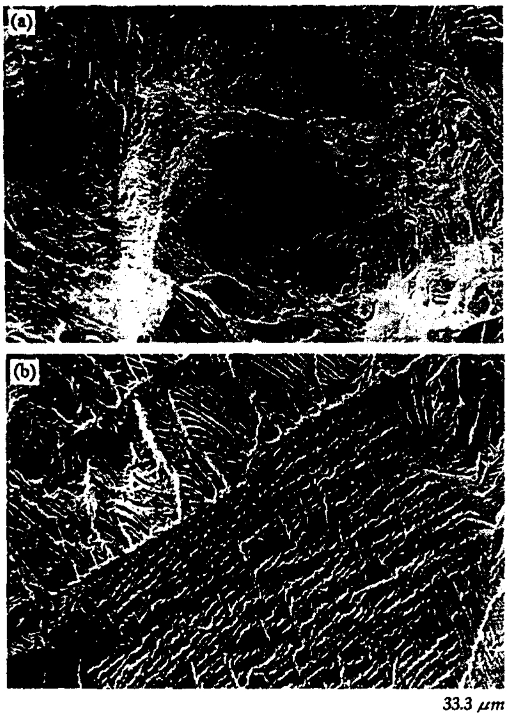


Fig. 3 Fatigue fracture mode of HhL Inconel 690
(a) intergranular fracture (low ΔK region)
(b) transgranular fracture (high ΔK region).

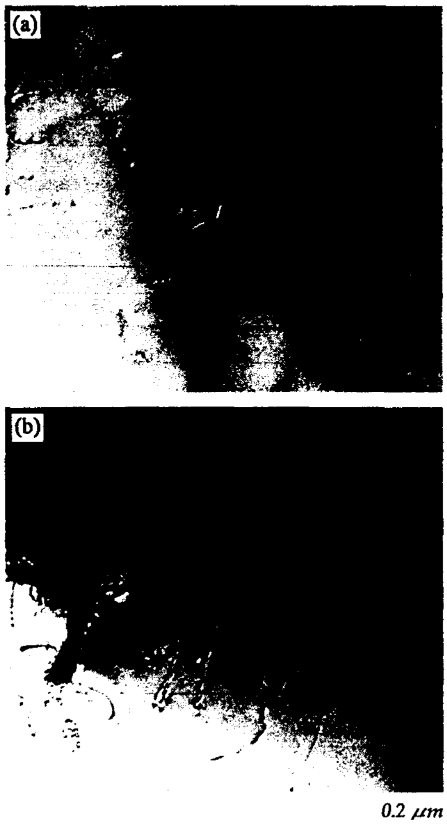
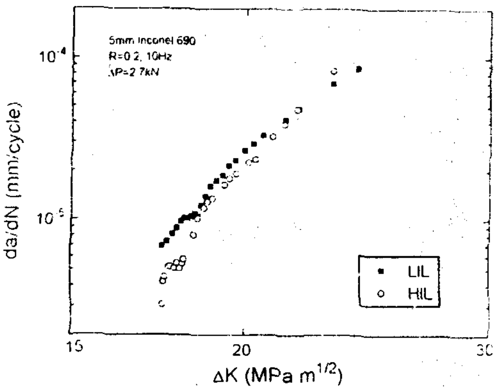
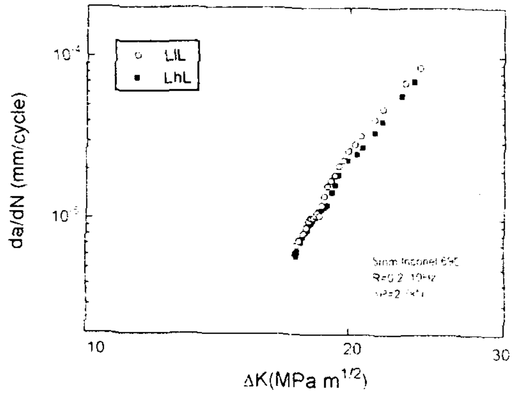


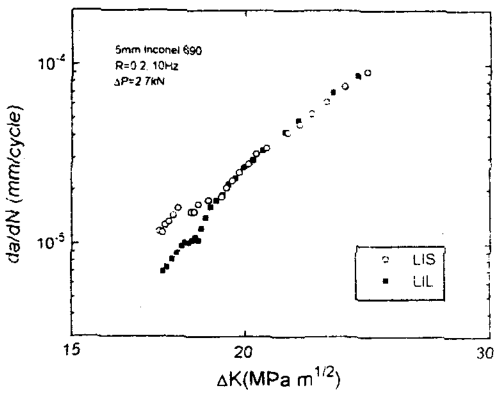
Fig. 4 Microdeformation characteristic of Inconel 690 (a) LIS (b) HhL.



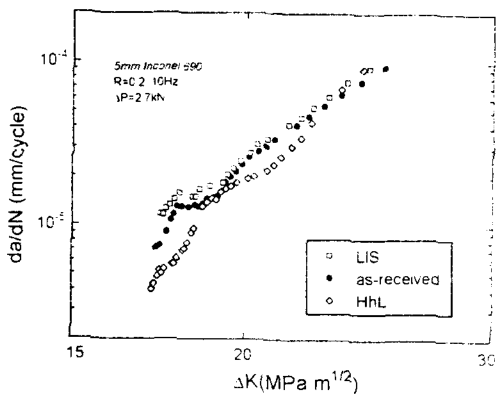
(a)



(b)



(c)



(d)

Fig. 5 Comparison of FCGR in relation to ΔK