A Study on the Fatigue Crack Growth Rate of Inconel 690 with relation to the Carbide Morphology

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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. But mechanical properties of Inconel 690 are known to be inferior to Inconel 600 while its chemical properties are much improved. A number of studies on Inconel 690 have been carried out, most of which are related with corrosion properties or tensile properties. And there are several papers about the effect of chromium carbides on fatigue crack growth rate (FCGR) of Inconel 600. The purpose of this 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

As-received Inconel 690 of Inco Alloys Inc. has a nominal composition of 30% Cr, 59.8% Ni and 0.025% carbon. 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 specimens in air at room temperature. Cyclic loading was given in a sine waveform of 10Hz with a stress ratio (R) of 0.2 at constant loading amplitudes.

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.

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 sizes of as-received Inconel 690, solution-annealed at 1150□ and 1070□ were 45 μm, 90 μm and 135 μm respectively. Significant grain growth was observed in the specimens solution-annealed at both temperature of 1070□ and 1150□, but there was no additional grain growth during thermal treatment at the temperatures of 700□ and 750□. HhL Inconel 690 specimens shows larger sizes of carbides than LlS Inconel 690.

3.2 Effect of solution annealing temperature

In Fig. 1(a), HlL Inconel 690 shows lower FCGR than that of LlL in low □*K* region. However, as □*K* increase, FCGRs results in a reverse phase. Fatigue crack grows along grain boundaries in low □*K* region while grain boundary carbides of large size in HlL acts as barriers to the propagation of cracks. In high □*K* region, where fatigue crack grows to a large size, fatigue crack propagates in a transgranular mode, and the carbides seems to be no longer barriers to fatigue cracking. In this region, grain boundaries seem to act as major barriers to plastic flow in the zone ahead of the crack tip. Therefore, in high □*K* region, the FCGR of LlL Inconel 690 is smaller than that of HlL Inconel 690.

3.3 Effect of thermal treatment temperature

Effects of different thermal-treatment temperature on FCGRs can be shown in LlL and LhL. As a result, 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 this study.

3.4 Effect of thermal treatment time

Effects of different thermal treatment time on FCGRs are shown in Fig. 1(b) LlL was thermally treated at 700□ for 15 hours and LlS was thermally treated at the same temperature for 5 hours. LlL of longer thermal treatment times resulted in larger carbides than LlS, leading to lower FCGR than LlS in low □*K* region. As □*K* increase, the role of carbides is disappeared, and the two specimens have nearly same FCGRs.

3.5 Effect of Carbide morphology

In Fig. 1(c), HhL shows the lowest FCGR in low □*K* region while as-received specimens show the lowest FCGRs in high □*K* region. The FCGR of LlS is always higher than that of as-received Inconel 690. This result suggests that carbides act as major barriers to fatigue cracking in low □*K* region, and in high □*K* region, grain boundaries act as major barriers to fatigue cracking. From the Fig 2, HhL was solution-annealed at higher temperature than LlS so that much more dislocations are supposed to be removed in Hhl than LlS specimen. But, opposite morphology results are shown in TEM observations as shown in Fig 2. It is thought that intergranular chromium carbides act as dislocation sources and consequently induce more homogeneous plastic deformation. In Inconel 600, Brummer *et al.* suggested that the distribution of the grain boundary carbides may induce a mechanical effect where carbides reduce crack tip stress by crack tip blunting and thus decrease the cracking susceptibility. Shalaby *et al.* 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. 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

Chromium carbides of Inconel 690 at the grain boundaries reduce FCGRs in low □*K* region due to the crack tip blunting as long as the fatigue cracking is within the intergranular fracture mode.

The distribution of grain boundary chromium carbides act as dislocation sources which lead to crack tip blunting due to the homogeneous plastic deformation.

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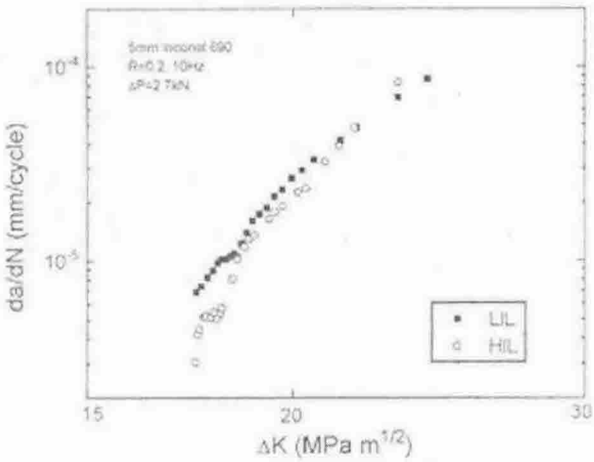
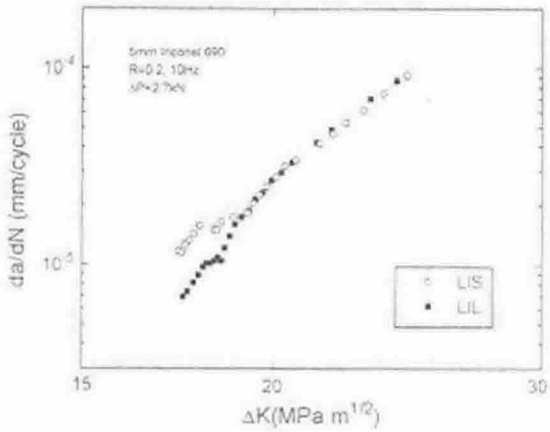
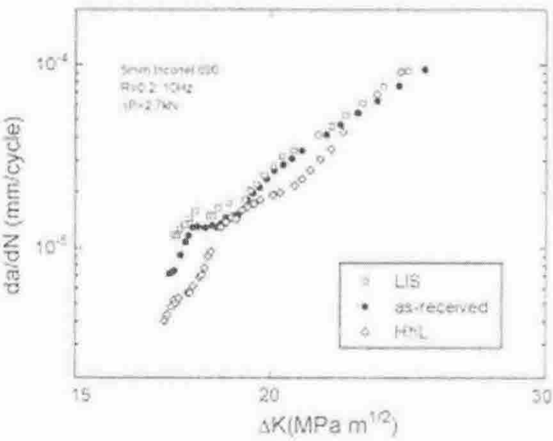


(a)

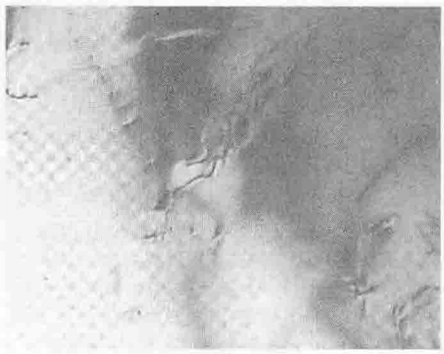


(b)

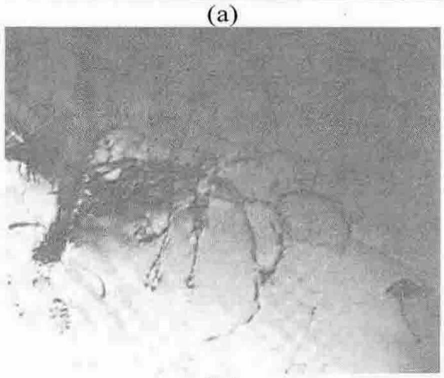


(c)

Fig. 1 Comparision of FCGR in relation to □*K*



(a)



(b)

Fig. 2 Dislocations beneath the surface of fatigue fractured specimens of (a) LIS (b) HhL