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Initiation and propagation of fatigue cracks in cast IN 713LC superalloy

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ABSTRACT

Fatigue life, initiation and propagation of cracks at 800 °C in a cast Ni-base superalloy IN 713LC were experimentally studied in high-cycle fatigue region. Load symmetrical cycling and cycling with high tensile mean load were applied. Both crystallographic crack initiation resulting in long Stage I crack growth and non-crystallographic Stage II propagation were observed. High scatter of fatigue life data was explained by: (i) variability in microstructural conditions for crystallographic crack initiation and propagation and by (ii) influence of casting defect size distribution. The fractographic observation supports the slip band decohesion mechanism of crack initiation and an important role of cyclic slip localization in persistent slip bands.

1. Introduction

Fatigue crack initiation and early crack propagation resistance predestinate high-cycle fatigue (HCF) performance of engineering materials. These two periods of fatigue damage often represent the decisive part of the fatigue lifetime of components. Both the crack initiation and early crack propagation are highly sensitive to material microstructure. In most crystalline metals and alloys fatigue crack initiation occurs along crystallographic slip planes at an external surface [1]. This mode of cracking has been called Stage I. The corresponding fatigue fracture surface (or fatigue crack length) is usually small and limited to one surface grain. Crack initiation and propagation in the Stage I take place along crystallographic slip planes having high cyclic resolved shear stress. The crack length at which the propagation mode changes from the crystallographic Stage I to the non-crystallographic Stage II depends mainly on material, temperature and the stress amplitude.

Cyclic deformation and cyclic slip localization in Ni-base superalloys, which are f.c.c. with slip systems {1 1 1} ⟨1 1 0⟩ occurs heterogeneously in planar bands lying along the crystallographic {1 1 1} planes. As a result, very often extensive long Stage I cracking is observed. Antolovich [2] summarizes that crystallographic Stage I crack propagation has been observed in both single crystal and polycrystal nickel-base superalloys. The extent of crystallographic crack propagation appears to be influenced by temperature [3] environment and frequency [4], and in the case of long cracks by stress intensity factor amplitude K_a [5,6]. Decisive role of the cyclic slip localization and initiation of cracks in slip bands was confirmed both for plain and notched bodies [7,8]. However, the details of the mechanism and the role of the cyclic slip bands in the fatigue crack initiation and early crack propagation at high temperature in Ni-base superalloys is not fully elucidated.

Conventionally cast polycrystalline Ni-base superalloy IN 713 is an engineering material, which has been used in turbine industry since the fifties of the last century. Surprisingly, the high-cycle high temperature fatigue life data are quite rare in the open literature. The knowledge on the influence of mean stress on fatigue behaviour is even more limited; the only

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available constant life diagram can be found in [9]. On the other hand, fatigue behaviour of this material is the current concern of the leading European gas turbine producers; more detailed material data are necessary to improve the existing standard design and prediction tools [10].

A typical feature of HCF strength of cast superalloys is high scatter of fatigue life data. This effect is attributed to casting defects, microshrinkages and other inhomogeneities, which are often sites of the fatigue crack initiation. Their influence can be diminished by hot isostatic pressing technology. Its beneficial effect on fatigue performance was reported [11], however, the results often fall short of expectations. In the case of materials exhibiting various modes of fatigue crack initiation and early crack propagation one of the reasons for the large scatter may be the variability of conditions for crack initiation and early propagation.

This work is focused on an investigation of HCF crack initiation, propagation and fatigue life of conventionally cast superalloy IN 713LC loaded at 800 °C in air in a symmetrical cycle and in an asymmetrical cycle with tensile mean stresses of 300 and 400 MPa. The aim was to get a new set of experimental fatigue life data and to discuss and explain the observed large scatter in terms of crack initiation and propagation mechanisms. Based on fractographic observation and transmission electron microscopy an alternative mechanism of decohesion model for fatigue crack growth in Ni-base superalloys was proposed.

2. Material

IN 713LC was conventionally cast as rods of 20 mm in diameter and 100 mm in length. The chemical composition of the alloy studied is given in Table 1. All cast rods were controlled by conventional X-ray defectoscopy with the resolution limit of 0.5 mm. They were found "defect free" in this sense.

The microstructure of cast IN 713LC is of dendritic nature. An example of a dendritic structure in transversal section of a cast rod is shown in Fig. 1. The microstructure at higher magnification can be seen in Fig. 2. The dendritic regions are characteristic by fine and homogeneous γ/γ' structure. Colonies of large γ' particles, microshinkages and casting defects are present in the interdendritic regions.

Casting defects as observed on a polished axial metallographical section of the gauge length of a specimen are shown in Fig. 3. Their distribution is not uniform. They are often grouped and form clusters. In the three-dimensional space the defects form interconnected systems.

3. Experimental

High temperature fatigue tests were conducted on cylindrical button end specimens with 35 mm gauge length and 5 mm in diameter. The specimen gauge length was fine ground. Tests were performed at 800 °C in laboratory air at controlled load in a 100 kN resonant testing machine. The frequency of sine wave loading was 105 ± 3 Hz. The start-up procedure of a test consisted of heating up the specimen at controlled zero load. One hour after the desired temperature was reached the mean stress has been applied within some seconds and subsequently the resonant system was switched on. The load amplitude was reached during a ramp of a length of about 500 cycles.

Table 1
Chemical composition of IN 713LC superalloy (wt.%).

C	Mn	Si	Cr	Ti	Al	Fe	B	Zr	Nb	Ta	Mo	Co	Cu	P	S	Ni
0.007	<0.05	0.06	11.63	0.77	5.91	0.18	0.12	0.12	2.36	0.09	4.66	0.30	<0.05	0.007	0.004	Bal.

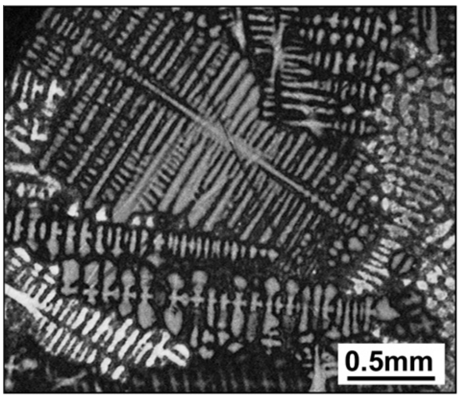

Fig. 1. Dendritic structure in transversal section of the specimen gauge length.