International Journal of Fatigue 32 (2010) 908–913

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

High-cycle fatigue of Ni-base superalloy Inconel 713LC

Ludvík Kunz [a,*], Petr Lukáš [a], Radomila Konečná [b]

[a] Institute of Physics of Materials, Academy of Sciences of the Czech Republic, Žižkova 22, 616 62 Brno, Czech Republic
[b] University of Žilina, Univerzitná 1, 010 26 Žilina, Slovak Republic

ARTICLE INFO

Article history:
Received 8 January 2009
Received in revised form 16 February 2009
Accepted 23 February 2009
Available online 10 March 2009

Keywords:
IN 713LC
High-cycle fatigue
Effect of mean stress
Fractography
Casting defects
Extreme value statistics

ABSTRACT

Fatigue strength of three nominally identical batches of cast Ni-base superalloy Inconel 713LC under load symmetrical cycling and cycling with tensile mean load was experimentally determined in high-cycle fatigue region at a temperature of 800 °C in air. Examination of fracture surfaces, crack initiation sites, microstructure and casting defects has been performed. Statistical method of largest extreme value distribution has been applied to characterize the casting defect distribution. The aim of the study was to evaluate the mean stress effect on high-cycle fatigue life, to explain the scatter of fatigue life data and a scatter related to material produced under nominally identical production conditions.

1. Introduction

Conventionally cast superalloys were developed to reach superior high temperature creep properties required by gas turbine industry. With the exception of the first considerations more than fifty years ago, the high-cycle fatigue (HCF) properties were believed to be less germane to reliability of gas turbines [1]. Because they were considered to be less prominent, the HCF high temperature data related to superalloys are not readily found in literature even for often applied engineering superalloys. This holds also for nickel-base cast superalloy IN 713LC, a low carbon variant of IN 713, which has been used for low pressure blades and vanes since the fifties of the last century. The up to now research attention concerning the fatigue performance of this alloy was paid mainly to the low-cycle fatigue (LCF) life [2] and to the thermomechanical fatigue behaviour, because both phenomena may be significant during start-up and shut down of engines [3]. LCF behaviour, dislocation structure and cyclic strain localization in IN 713LC was studied recently by Petrenec et al. [4]. Though IN 713 is an old engineering material, it has been expanding in the European gas turbine industry in recent years. In order to develop new prediction fatigue life methods of components the generation of high quality material test data is necessary [5].

Inevitable casting porosity is a typical feature of cast superalloys. Though it is relatively small in volume, usually below 1%, it can reduce the rupture life and rupture ductility under sustained creep loading [6]. The influence on fatigue life is even stronger and increases from LCF to HCF region. The presence of defects generally results in scatter of fatigue life. Hot isostatic pressing technology can be used for closing of porosity, but this treatment is expensive and in the case of creep properties ambiguous improvement was reported. Generally, the scatterband of Larson-Miller parametric plot of the stress rupture capability is narrower after hot isostatic pressing when compared to the untreated material. Beneficial effect was reported also for S–N curves both in LCF and HCF regions, but no detailed or statistical studies are available [1].

The microstructure, inevitable microshrinkages and large casting defects present in castings depend critically on casting conditions. The defect size and distribution can vary substantially even in nominally identical material and when nominally identical casting conditions are applied. That is why the fatigue data of cast materials exhibit generally large scatter, particularly as regards the fatigue limit. Fatigue cracks may initiate at defects, which are often below the resolution of non-destructive defectoscopy, i.e., on defects existing in "defect free" components from the engineering point of view. The initial fatigue crack propagation can be of internal type and the propagating crack can be hidden for a long time.

Typical feature, often observed in Ni-base alloys is a long crystallographic Stage I propagation [7–9]. For crack initiation a decohesion model has been proposed long time ago by Duquette et al. [10]. The model explains the often but not always observed crystallographic facets, which are of large dimensions and comparable with the grain size. However, the relation of crystallographic type

* Corresponding author. Tel.: +420549246327; fax: +420541218657.
E-mail address: Kunz@ipm.cz (L. Kunz).

0142-1123/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijfatigue.2009.02.042

of fatigue crack initiation to material structure, casting defects and parameters of fatigue loading is by far not explained and understood.

The object of this work was to determine the fatigue strength of IN 713LC at 800 °C in HCF region and to analyze the influence of microstructure, particularly the casting defects and their distribution on fatigue crack initiation and fatigue life. The examination of fatigue strength was performed both for symmetrical loading and for cyclic loading with tensile mean stresses.

2. Material and specimens

Three, from the point of view of technology, nominally identical batches denoted as 1, 2 and 3 were used for experimental determination of HCF strength of IN 713LC superalloy. Conventionally cast rods of 20 mm in diameter and 100 mm in length were manufactured by nominally identical casting process. The batches were cast subsequently in one company. All rods were controlled by conventional X-ray non-destructive defectoscopy and were found "defect free", which means that the defect size should be below the resolution limit of the method, which is about 0.5 mm.

The cast microstructure is dendritic in nature. An example of the structure in a transversal section of a cast rod from the batch 2 is shown in Fig. 1. The grain size of material of all three batches determined by means of linear intercept method, was 3 ± 0.5 mm. Light microscopy of polished surfaces revealed numerous casting defects of variable shape, size and distribution. An example of casting defects as observed on a longitudinal axial section of a cast rod can be seen in Fig. 2. The defects are sometimes single, but in many cases they form groups.

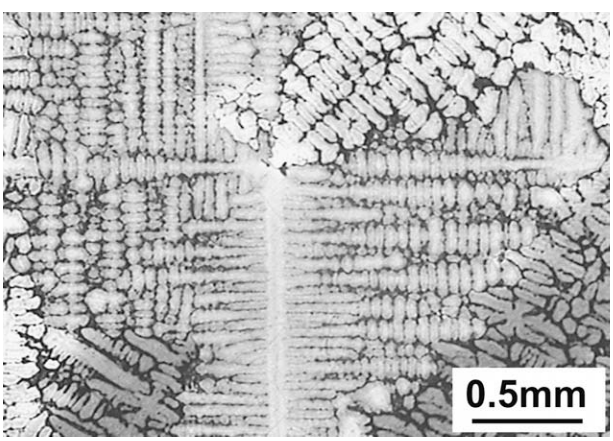

Fig. 1. Dendritic structure in transversal section of the specimen gauge length, batch 2.

For experimental determination of HCF performance cylindrical button-end specimens of 5 or 6 mm in diameter and with 35 mm long gauge length were machined from cast rods. The final operation of specimen machining was fine grinding.

3. Experimental

Two 100 kN resonant testing systems operating under controlled load were used for fatigue testing in HCF region at temperature of 800 °C. The mean load was controlled since the start of heating. It was kept zero as long as the specimen was not at the desired temperature for at least two hours. Then the chosen non-zero mean load was set up during several seconds. After that the resonant system was switched on. The full load amplitude was reached by a ramp during several hundreds of loading cycles. The frequency of loading was either 105 ± 3 or 110 ± 3 Hz according to the applied resonant fatigue machine. Tests were run in laboratory air. The heating was performed in an electric furnace. The long-term stability of temperature of specimen gauge length was within ± 1 °C. The temperature gradient at the central part of the gauge length was smaller than 3 °C/cm.

Examination of casting defects was performed on specimens after fatigue testing. Longitudinal axial sections having dimensions of about 5 × 20 or 6 × 20 mm were cut out by electrospark machine from the gauge length of the specimen in such a way that their one shorter side the intersected fracture surface. The sections were metallographically prepared and observed by light microscopy. Image analysis software was used to determine the size of casting defects. Twenty five different places having area $S_0 = 1.827\ \text{mm}^2$, which were located on each longitudinal section were examined. The size of casting defects observed was expressed in terms of square root of projected area of defects, denoted as $(\text{area})^{1/2}$ parameter. This way of evaluation of defect size has been shown to be useful for prediction of fatigue behaviour of materials containing various types of defects [11].

The fracture surfaces and fatigue crack initiation sites were observed both by light and scanning electron microscopy.

4. Results

Fig. 3 shows the HCF S–N data for load symmetrical cycling. The S–N data obviously exhibit a large scatter. The differences in the life of particular specimens at the same stress level are most pro-

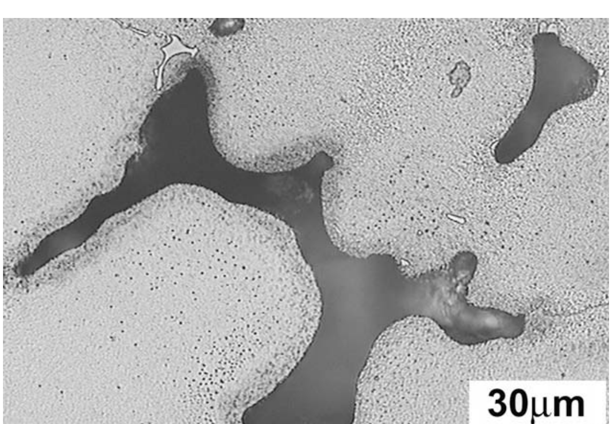

Fig. 2. Casting defect in longitudinal section of the specimen gauge length.

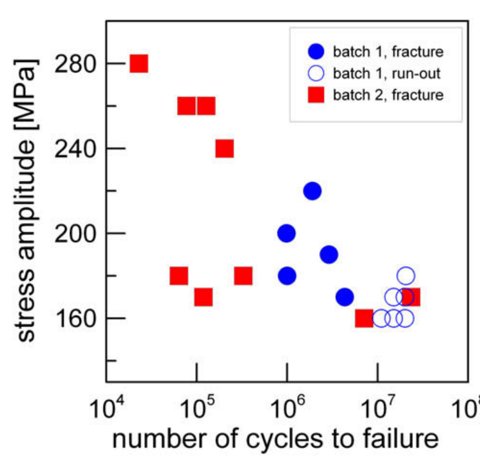

Fig. 3. High-cycle S–N data of IN 713LC for symmetrical loading.