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Casting defects and high temperature fatigue life of IN 713LC superalloy

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

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ABSTRACT

High-cycle high temperature fatigue life of a superalloy IN 713LC in as cast state and after hot isostatic pressing was experimentally determined for symmetrical cycling and cycling with tensile mean stress of 300 MPa. Fatigue tests were conducted at 800 °C in laboratory air. It has been found that the hot isostatic pressing improves the fatigue life. Large casting defects are sites of fatigue crack initiation in both states of the alloy. The hot isostatic pressing reduces the size of casting defects, however the broad scatter band of the lifetime data remains. Determination of casting defects size by optical microscopy on metallographic sections and an analysis of the size distribution by extreme value statistics indicates two types of defects: (i) small isolated defects and (ii) defect clusters consisting of complicated interconnected shrinkages in the three-dimensional space. The size distribution of both types of defects follows the extreme value statistics. This enables to estimate the maximum size of a defect likely to occur in a defined volume. The predicted maximum defect size in a volume of a fatigue specimen reasonable corresponds to the size of defect observed on the fracture surface of failed specimen.

1. Introduction

A cast IN 713LC superalloy is a low carbon variant of IN 713, which has been used since a long time for high temperature applications like integral wheels of turbine engines or in the mass-production of turbocharger wheels. It possesses qualifications for good casting properties, no heat treatment is required and it has relatively low cost. On the other hand its grain size is often large and castings contain porosity, microshrinkages and other inhomogeneities. The fatigue life exhibits a large scatter, which is substantially higher in the high-cycle fatigue region (HCF) than in the low-cycle fatigue region (LCF). This is evidently a weak point for the application of this alloy in cyclically loaded components where good HCF fatigue strength is required.

There are several methods for minimizing casting defects. None of them is able to eliminate defects completely. Hot isostatic pressing (HIP) technology was found to have beneficial effect on creep/fatigue performance of IN 713 [1]. Namely in comparison with the as cast materials the HIP led to an increase of material strength under creep/fatigue conditions and moreover narrowed the scatter of creep data. Tensile strength and strength in bending tests of IN 713 was also positively affected by HIP [2]. Beneficial effect was found also for fatigue lifetime both in LCF and HCF regions [3]. Nevertheless in all the mentioned cases the materials after HIP procedure were not defect-free. A fine-grain casting processes resulting in improvement of mechanical properties also do not guarantee the defect free products. The microporosity observed after centrifugal casting in IN 713LC causes an early fracture and leads to a drop of tensile stress [4].

The fracture mechanics enables the defect tolerant approach to fatigue design, however the basic premise here is that the size, shape and the distribution of the pre-existing defects is known. Though various non-destructive methods of defect detection are available, like visual, X-ray, ultrasonic magnetic or acoustic, the reliable prediction of fatigue strength or lifetime of components with defects remains a serious problem for engineering practice.

The studies of internal dislocation structure and development of surface relief of fatigued IN 713 in LCF region at elevated and high temperatures performed by Petrenec et al. [5] and Obrtlík et al. [6] show that highly inhomogeneous dislocation structure develops. Formation of dislocation rich slabs in the form of thin bands and ladder like bands was observed. These bands play an important role in often observed long Stage I fatigue crack propagation in Ni-base superalloys [7–9]. Fatigue cracks propagate crystallographically along the {111} crystallographic planes and form mutually inclined facets on the fracture surface. It is believed that the crystallographic propagation in early stages of fatigue cracks in coarse-grained structure contributes to the generally high scatter of fatigue life data of cast superalloys [10,11]. The initiation of fatigue cracks in IN 713 takes place predominantly on microshrinkages and pores, seldom on carbides [12].

The aim of this paper is to quantitatively evaluate the effect of HIP procedure on high-cycle fatigue life of IN 713LC and on casting

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* Corresponding author.
E-mail address: kunz@ipm.cz (L. Kunz).

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defect reduction. Attention is focused on size distribution of casting defects and prediction of maximum defect size.

2. Material and specimens

Specimens for fatigue testing were machined from conventionally cast rods of 20 mm in diameter and 100 mm in length. Specimens were manufactured from three, from the point of view of casting technology, nominally identical batches cast in one foundry subsequently within some months. 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 gauge length of cylindrical specimens with button end heads was 35 mm and the diameter of the gauge length was 5 mm, Fig. 1. The final operation of specimen machining was fine grinding. The surface roughness was $R_a = 0.4$.

Twenty-five specimens form the batch 3 were processed by HIP. The finally machined specimens were heated at the temperature 1160 °C at a pressure of 1000 bar for 3 h. The cooling rate was 10 °C/min and the process was performed under Ar atmosphere down the 900 °C, later on the cooling was conducted on air.

3. Experiments

A 100 kN resonant testing system Amsler 10HFP®1478 with VibroVin® controlling software operating under controlled load was used for fatigue testing in HCF region at a temperature of 800 °C. Two sets of fatigue tests were performed: load symmetrical tests characterized by mean stress of 0 MPa and tests with tensile mean stress of 300 MPa. During the start-up of the tests the mean load was kept zero as long as the specimen was not at the desired temperature 800 °C for at least 2 h. Then the resonant system was switched on in the case of the stress symmetrical testing. In the case of non-zero mean stress the mean load was applied during several seconds and without a delay the cycling was started. The full load amplitude was reached by a ramp during several hundreds of loading cycles. The frequency of loading was of about 115 Hz. 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.

The size and the distribution of casting defects were analyzed by an extreme value statistics. The method, originally applied to very small defects in high strength steels by Murakami [13], was shown to be applicable also for large casting defects in light materials, e.g. [14,15]. The casting defects in IN 713LC were observed on metallographically prepared axial sections of the specimen gauge length of 5 × 20 mm in dimension or on transversal sections of 5 mm in diameter. Altogether 25 different places of the area $S_0 = 1.83\ \text{mm}^2$ located on several sections were analyzed. The size of defects was evaluated in terms of their square root area by means of image analysis software and finally treated by statistical method based on extreme value theory.

4. Results

The HCF fatigue life at 800 °C of as cast specimens is shown in Fig. 2. Data for load symmetrical cycling, i.e. with the mean stress zero are shown together with data characterizing the fatigue life at the tensile mean stress of 300 MPa. The S–N data exhibit substantial scatter, which is obviously higher for the symmetrical fatigue loading. The lines in the figure represent the power law best fit of the experimental points corresponding to the specimens failed for $N_f \leqslant 10^7$. Arrows denote the run-out specimens. As expected, the S–N curve for fatigue loading with the tensile mean stress is shifted towards lower stress values. The shift makes nearly 100 MPa for the lifetime of the order of 10^4 cycles to failure and slightly decreases with increasing number of cycles.

Fractographic observation of fatigue fracture surfaces shows that in all cases the fracture was initiated on large casting defects, nearly always in the specimen interior. An example of the initiation site in as cast material can be seen in Fig. 3. A large casting defect is encircled by en ellipse. The arrows indicate the boundary of a fish eye.

The results of the experimental determination of fatigue life of specimens processed by HIP are shown in Fig. 4 for load symmetrical cycling and cycling with the tensile means tress of 300 MPa. The experimental points exhibit similar scatter like the data of the as cast material. The full and the dashed lines in Fig. 4 represent the best fits of S–N points of failed specimens. The limit for run-out specimens was again 10^7 cycles.

The coefficients of the power law fit $\sigma_a = AN_f^{-b}$ and the coefficients of determination R^2 for as cast material and material after HIP are summarized in Table 1. Further, there are also the fatigue limits determined by power law fits for $N = 10^7$ cycles there.

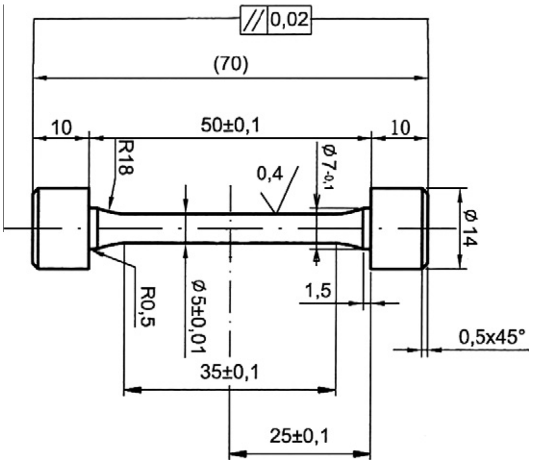

Fig. 1. Specimen for fatigue tests.

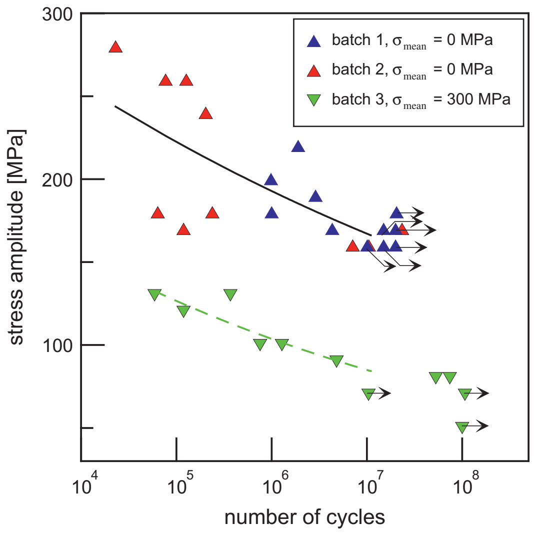

Fig. 2. High-cycle S–N data of IN 713LC in as cast state. Stress symmetrical loading and cycling with tensile mean stress of 300 MPa.