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Low cycle fatigue of a directionally solidified nickel-based superalloy: Testing, characterisation and modelling

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ABSTRACT

Low cycle fatigue (LCF) of a low-carbon (LC) directionally-solidified (DS) nickel-base superalloy, CM247 LC DS, was investigated using both experimental and computational methods. Strain-controlled LCF tests were conducted at 850 °C, with a loading direction either parallel or perpendicular to the solidification direction. Trapezoidal loading-waveforms with 2 s and 200 s dwell times imposed at the minimum and the maximum strains were adopted for the testing. A constant strain range of 2% was maintained throughout the fully-reversed loading conditions (strain ratio $R = -1$). The observed fatigue life was shorter when the loading direction was perpendicular to the solidification one, indicating an anisotropic material response. It was found that the stress amplitude remained almost constant until final fracture, suggesting limited cyclic hardening/softening. Also, stress relaxation was clearly observed during the dwell period. Scanning Electron Microscopy fractographic analyses showed evidence of similar failure modes in all the specimens. To understand deformation at grain level, crystal plasticity finite element modelling was carried out based on grain textures measured with EBSD. The model simulated the full history of cyclic stress-strain responses. It was particularly revealed that the misorientations between columnar grains resulted in heterogeneous deformation and localised stress concentrations, which became more severe when the loading direction was normal to a solidification direction, explaining the shorter fatigue life observed.

1. Introduction

Nickel based superalloys are widely used as turbine blades and discs in gas turbines operating at high temperatures. The presence, at microstructural level, of $L1_2$ ordered γ'-precipitates in the γ-matrix phase enhances high-temperature mechanical properties of these alloys. These two phases, γ and γ', are typically solid solution strengthened with refractory elements Co, Fe, Mo, W and Ta. Their remarkable high-temperature properties are a result of a combination of various elements in the γ-matrix and γ'-precipitates [1,2]. These elements also improve the oxidation resistance and reduce γ/γ' mismatch [3–5]. Sizes and morphologies of the strengthening γ'-precipitates are controlled by means of varied manufacturing and heat-treatment processes. Recent studies have shown that mechanical properties are strongly influenced by sizes [2,6], distribution [7], volume fraction [8,9] and morphologies [2,10] of the γ'-precipitates. In addition, grain structures and textures [11] resulting from heat-treatment processes [2,9,12] were also found to influence significantly the properties of nickel-based superalloys. In directionally solidified (DS) nickel-based superalloys, preferred crystallographic orientations were obtained with a special casting processes; however, the different growth rates of favourably and unfavourably oriented dendrites led to the growth of grains with different orientations [13].

Columnar grains, aligned with a principal-stress axis, are preferred in turbine blades as they constrain the participation of perpendicularly-oriented grain boundaries in high-temperature fatigue/creep [14]. Compared to the case with a loading axis parallel to the solidification direction, grain boundaries perpendicular to the loading axis affect the deformation behaviour of the material. This results in higher stiffness [5,15], but fatigue/creep-load bearing capabilities are substantially affected. For temperatures between 650–850 °C, tensile and creep behaviour are more dependent on loading direction with respect to that of

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Table 1
Nominal chemical composition by weight percentage for CM247.

Element	Al	Co	Mo	Ta	W	Cr	B	C	Zr	Nb	Ti	Fe	Cu	Hf	Ni
wt%	5.7	9.0	0.6	3.1	9.7	8.5	0.02	0.08	0.02	0.1	0.6	0.2	0.02	1.2	Bal.

solidification [16]. Crack-growth behaviour, however, is more sensitive to temperature variations than to changes in the loading direction (with respect to the direction of solidification) [17]. Furthermore, a superior fatigue-life response was reported for specimens with notches oriented normal, as opposed to parallel, to a dendrite-growth orientation [18]. In the work of Shi et al. [16] and Moore and Neu [19], the increase in stress concentration around notched regions resulted in decreased fatigue resistance. By using the Basquin and Coffin-Manson empirical relationships, a significantly shorter fatigue life was reported when loading was changed from parallel to 45° orientation with respect to the solidification direction [20]. Moore and Neu [19] also reported that the rate of loading and the imposition of a dwell at maximum/minimum load significantly affected fatigue life at higher temperatures. Such effects were also found for specimens loaded in parallel to the solidification direction.

In recent years, various constitutive models, based on either crystal plasticity or phenomenological formulations have been proposed, to capture various behavioural aspects of nickel-based superalloys. It is noteworthy, however, that most of the models for DS alloys were concentrated on creep and tensile deformation rather than fatigue behaviour. Since crack-growth behaviour showed higher temperature dependency than orientation of the loading direction, the study [17] modified the Paris law to capture this effect by making the stress intensity factor range and the Paris law constant temperature dependent. Predictions based on this modification were then in good agreement with test data for crack growths at temperatures of 600 °C and 850 °C. Shi et al. [16] presented a continuum elasto-viscoplasticity model, which was an extension of the Chaboche constitutive model to capture material rate-dependent and anisotropic deformation behaviour. The model was then applied to study a directionally solidified nickel-based superalloy at 760 °C and 850 °C, and its results agreed well with experimental data. Crystal plasticity-based modelling was employed to study effects of defects such as carbides, oxides or other particles on fatigue crack initiation. Also Shenoy et al. [21] modelled these defects as inclusions resulting in stress concentrations around them which influenced low-cycle-fatigue (LCF) crack nucleation behaviour.

In DS alloys, considerable anisotropy is apparent in material deformation when the loading axis is changed from parallel to perpendicular to the solidification direction. Anisotropy appears to be an inherent characteristic of DS nickel-based superalloys, based on the results reported by other researchers on their deformation [3], fatigue [22] and creep [23] behaviour. This was also confirmed in studies based on computational modelling [24,25]. However, no attempt was made to elucidate a connection between anisotropic behaviour and alloy's microstructure. In previous studies, the grain structures and textures employed were just assumed and failed to explain the behaviour satisfactorily. Therefore, in this paper, we presented a study of fatigue behaviour of a DS nickel-based superalloy, by employing a combination of testing, microstructural characterisation and numerical modelling. The synergetic influence of imposed dwells (at the maximum and minimum load levels) and varied loading rates on the LCF behaviour was particularly studied, for loading both along the solidification direction and normal to it. Using a low-carbon directionally-solidified nickel-based superalloy CM247 LC DS, strain-controlled LCF tests were conducted at two different strain rates and dwell times at an elevated temperature (850 °C). To understand the underlying failure mechanism, fracture surfaces were characterised using SEM. In particular, characterisations using EBSD was carried out to establish grain structures and textures, which allowed us, for the 1st time, to consider abnormal grains formed during material processing (a cluster of smaller grains with orientations distinctively different from those of the major columnar grains). Furthermore, these EBSD data were used as input into the finite element (FE) study, and the simulation results were employed to elucidate anisotropic fatigue behaviour observed in the tested specimens.

2. Materials, testing and characterisation

2.1. Materials

The material studied in this paper is a DS nickel-based superalloy with a low carbon (LC), content, designated as CM247 LC DS. The chemical composition by weight percentage (wt%) is shown in Table 1. The studied material underwent a three-stage standard heat treatment process. The first stage was a 2.5 h solution heat treatment at 1246 °C, followed by cooling, which resulted in precipitation of a uniform fine γ/γ'-microstructure. The second stage was a 4.5 h heat treatment at 1080 °C to yield the optimum size distribution of γ'-precipitates. The final stage was an aging treatment at 870 °C for 24 h. The final product had a density of about 8.32 g/cm^{-3}, with a solvus temperature of 1160 °C.

2.2. LCF tests

Plain cylindrical specimens were machined for this study, with an extensometer gauge length of 12.5 mm and a diameter of 6.4 mm. Four specimens (two types) were prepared, two with the solidification direction aligned with the loading axis (L specimens) while the other two

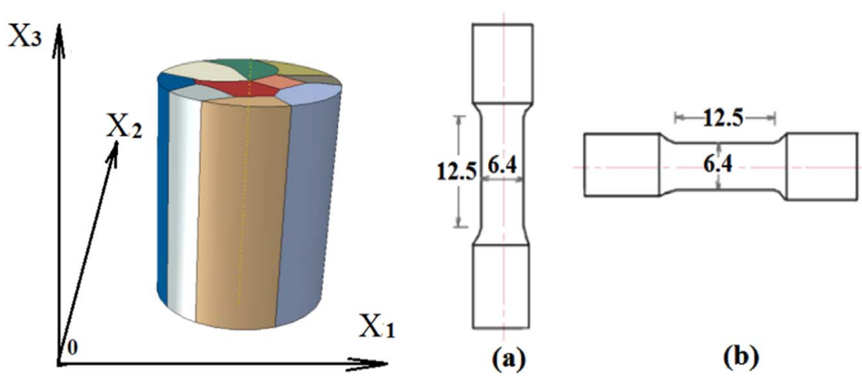

Fig. 1. Schematic diagram showing two orientations of specimen with loading direction coincident (a) or normal (b) to the direction of solidification (dimensions in mm).