Materials Science & Engineering A 623 (2015) 68–77

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Influence of crystal orientation on the thermomechanical fatigue behaviour in a single-crystal superalloy

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ARTICLE INFO

Article history:
Received 24 September 2014
Received in revised form
31 October 2014
Accepted 8 November 2014
Available online 18 November 2014

Keywords:
Single-crystal superalloy
Crystal orientation dependence
Thermomechanical fatigue
Deformation mechanisms
Finite element applicability

ABSTRACT

In this study, the influence of crystal orientation on the thermomechanical fatigue (TMF) behaviour of the recently developed single-crystal superalloy STAL-15 is considered, both from an experimental and a modelling perspective. Experimental results show that there is a strong influence of the elastic stiffness, with respect to the loading direction, on the TMF life. However, the results also indicate that the number of active slip planes during deformation influence the TMF life, where specimens with a higher number of active slip planes are favoured compared to specimens with fewer active slip planes. The higher number of active slip planes results in a more widespread deformation compared to a more concentrated deformation when fewer slip planes are active. Deformation bands with smeared and elongated $\gamma'-$precipitates together with deformation twinning were found to be major deformation mechanisms, where the twins primarily were observed in specimens with several active slip planes. From a modelling perspective, the crystal orientation with respect to the loading direction is quantified and adopted into a framework which makes it possible to describe the internal crystallographic arrangement and its entities in a material model. Further, a material model which incorporates the crystal orientation is able to predict the number of slip planes observed from microstructural observations, as well as the elastic stiffness of the material with respect to the loading direction.

1. Introduction

The need for understanding thermomechanical fatigue (TMF) behaviour of single-crystal nickel-based superalloys is growing for the gas turbine industry. One way to increase the turbine efficiency is to increase the turbine entry temperature, and over a long period of time a lot of effort has been put into developing materials that can withstand higher temperatures, see *e.g.* [1]. However for the new generation of gas turbines it is not only the turbine entry temperature that needs to be increased, the turbine engine will also operate under different load conditions compared to what has been done previously. Thus, more gas turbines have to be used as a complement for the increasing number of renewable energy sources, for example when the wind is not blowing or when the sun is not shining [2]. This means a higher number of starts and stops of the engine compared to earlier conditions when the engine instead runs at steady-state condition over longer periods of time. As the temperature within the turbine is increasing, new and advanced cooling techniques are implemented in the design of hot section components, such as the gas turbine blade. These new cooling techniques result in higher stresses and temperature gradients within the components. More complex stress gradients together with an increasing number of start-ups and shut-downs means that TMF testing, where both mechanical strain and temperature are cycled, must be considered in manifesting realistic loading conditions. In addition to TMF testing, the ability to model the TMF behaviour becomes more important for the gas turbine industry when estimating the service lives of hot section components. That the importance of understanding the TMF mechanisms is growing is visible in the literature, where the area of TMF in single-crystal superalloys is expanding [3–10].

Gas turbine components made of single-crystal nickel-base superalloy material are produced by investment casting, see *e.g.* [11]. The preferred growth direction for nickel, and other face-centered-cubic (FCC) alloys, is the [001] crystal direction [12]. This direction is also beneficial from a fatigue point of view, since this direction has the lowest stiffness and therefore the best fatigue properties under strain-controlled fatigue. In the casting process a grain selector is used to single-out a grain which is allowed to expand in the mould. This grain selector has a large influence on the crystallographic orientation of the component, and it has been shown that the length and the angle of the spiral of the grain selector are critical parameters [13]. To further improve the crystal orientation of the components in the casting process, a cellular automation finite element (FE) simulation can be

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http://dx.doi.org/10.1016/j.msea.2014.11.026
0921-5093/

performed to investigate the grain density and texture prior casting [14,15]. It is thus crucial that the casting process is performed with matter of precision, as the mould might exhibit a misalignment in crystal orientation, and this could later lead to unexpected mechanical properties or failure.

Since single-crystal materials are anisotropic, the crystallographic orientation will significantly influence the mechanical properties, such as yielding [16,17], low-cycle fatigue (LCF) [18,19], fatigue–creep interaction [20,21], and creep [22]. During strain-controlled fatigue, materials with a low stiffness are superior, and pure nickel has the following stiffness in the nominal main crystallographic orientations: $E_{\langle 001\rangle} = 125$ GPa, $E_{\langle 011\rangle} = 220$ GPa and $E_{\langle 111\rangle} = 294$ GPa [12]. Even though gas turbine blades are casted with the [001] direction upwards, properties in the other main orientations may be of interest. For example, crack propagation is sometimes observed on the blade platform and this propagation is significantly influenced by the properties in other crystal orientations, such as the [011] direction, or in a notch where a multiaxial state is present. Studies concerning the crystal orientation influence on the TMF behaviour are rarely seen in the literature, however it has been shown that the [001] crystallographic direction shows longer TMF life compared to the [011] direction when similar mechanical strain ranges were compared [23].

From an industrial perspective in designing gas turbines, concerning the fatigue life, it is of great significance that the proper behaviour is predicted in an FE-simulation. As gas turbine blades are casted with the longitudinal direction parallel to the nominal [001] crystal orientation within an error margin of less than 10°, thus the misalignment needs to be addressed in an FE-analysis to be able to fully capture the effect of the misalignment. Furthermore, it has been shown by FE-simulations that the variation in primary and secondary crystal orientations influence the fatigue life [24], where the secondary crystal orientation from the casting process had a pronounced effect on the LCF life of a single-crystal turbine blade. Moreover, the effect of aligning the secondary crystal orientation to the notch of a test specimen and evaluating the LCF life through FE-simulations was investigated in [25]. The influence of crystal orientation on a single-crystal turbine blade was evaluated in [26], and the conclusion drawn was that the deterministic approaches for fatigue life assessment are only valid in a certain crystal orientation. In addition, it has been shown, through FE-simulations, that the misalignment from the axial direction of the crystal orientation has a significant effect on the vibration characteristics of a turbine blade made of the single-crystal nickel-base superalloy DD6 [27].

It is well recognised that, during strain-controlled fatigue, the fatigue life of a single-crystal superalloy is highly dependent on the crystal orientation due to their anisotropic elastic properties, see *e.g.* [28] regarding a LCF loading condition. There it was shown that when the elastic stiffness is taken into account, the influence from the crystal orientation on the fatigue life almost disappears. The aim of this study is to investigate this concept from a TMF perspective; does the material stiffness solemnly influence the TMF life or are there other factors that may influence the TMF life? Based on this, out-of-phase (OP) TMF testing of STAL-15, which is a recently developed high chromium containing single-crystal nickel-base superalloy with excellent oxidation/corrosion properties aiming for land-based gas turbine applications [29–31], was conducted. In addition, the aspects in dealing with the crystal orientation dependence in an FE-context are also accounted for.

2. Experiments

2.1. Methods

The single-crystal nickel-based superalloy STAL-15, with chemical composition Ni, 4.5Al, 4.9Co, 15.6Cr, 0.1Hf, 1.0Mo, 8.1Ta and 0.25Si in wt% was considered in this study. The material was solution heat treated for 5 h at 1300 °C before a two-stage ageing process at 1100 °C for 6 h followed by 850 °C for 20 h was performed. Smooth TMF specimens with an approximate diameter of 6.35 mm and a parallel length of 25 mm were machined from cast bars. An Instron servohydraulic TMF machine with induction heating and forced air cooling was used, where the machine was carefully aligned prior testing to prevent buckling of the specimens. Thermocouples were spot-welded on the specimens to control the temperature. A strain-controlled OP TMF cycle ranging from 100 to 850 °C at $R_\varepsilon = -\infty$ with a heating rate of 5 °C/s was used with a 5 min dwell time applied at maximum temperature during each cycle, see Fig. 1. A high-temperature extensometer with a gauge length of 12.5 mm was used to control the mechanical strain ranges which were chosen in order to obtain realistic fatigue lives compared to real gas turbine blades. In total, 12 TMF tests were performed in this study, see Table 1 for further details regarding the testing conditions and experimentally obtained data.

The crystallographic orientation (load direction), in accordance with the stereographic triangle, that the respective specimens have can be seen in Fig. 2. Two main groups of specimens can be observed: one close to the [001] corner of the stereographic triangle (A–F) and another cluster of specimens between the [011] and [111] corners (G–L), henceforth called *group* 1 and *group* 2. The crystal orientation of the respective specimen was determined using x-ray diffraction and is quantified by the primary and secondary crystallographic orientation angles, θ and ϕ. Since only smooth test specimens were investigated, no regard was taken to the direction of the secondary crystal orientation as it has no influence on the observed fatigue behaviour. The experimental moduli of elasticity E_{exp} was measured between 100 °C and 250 °C during the first TMF cycle for each specimen. The number of cycles to failure N_f was determined as a global load-drop of 10% from the trend line of the maximum tensile stress occurring in each cycle. The trend line was adopted to the maximum tensile stress curve between 30% and 70% of the number of cycles until the test was terminated, where the termination criterion was defined as 60% load-drop, see Fig. 3.

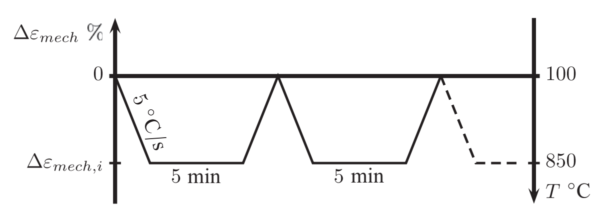

Fig. 1. The OP TMF cycle which was used in the experiments of this study, where $i = A, B, \ldots, L$ represents the respective tests.

Table 1
Material data of the TMF test specimens.

Group	Specimen	$\Delta\varepsilon_{mech}$ %	$\Delta\varepsilon_{in}$ %	$\theta°$	$\phi°$	E_{exp} GPa	N_f
1	A	1.0	0.018	3.9	3.0	118.1	477
	B	1.1	0.051	1.3	5.7	109.8	515
	C	0.9	0.0045	1.0	33.0	114.5	1346
	D	1.2	0.099	3.2	33.4	101.5	428
	E	1.24	0.105	2.0	23.4	105.6	255
	F	1.31	0.179	1.9	25.4	109.5	223
2	G	0.6	0.063	38.8	32.8	245.2	224
	H	0.5	0.005	31.4	0.1	191.6	696
	I	0.45	0.017	40.2	33.3	234.8	490
	J	0.35	0.004	42.6	26.7	233.1	1098
	K	0.64	0.096	40.3	22.0	208.7	36
	L	0.33	0.007	41.4	28.1	234.6	6380