Engineering Fracture Mechanics 196 (2018) 206–223

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Prediction of crystallographic cracking planes in single-crystal nickel-base superalloys

C. Busse[a,*], F. Palmert[b], B. Sjödin[c], P. Almroth[c], D. Gustafsson[c], K. Simonsson[a], D. Leidermark[a]

[a] Division of Solid Mechanics, Linköping University, SE-58183 Linköping, Sweden
[b] Division of Engineering Materials, Linköping University, SE-58183 Linköping, Sweden
[c] Siemens Industrial Turbomachinery AB, SE-61283 Finspång, Sweden

ARTICLE INFO

Keywords:
Single-crystal nickel-base superalloys
Anisotropy
Fracture mechanics
Stress intensity factor
Crystallographic cracking

ABSTRACT

The inherent anisotropy of single-crystal nickel-base superalloys brings many difficulties in terms of modelling, evaluation and prediction of fatigue crack growth. Two models to predict on which crystallographic plane cracking will occur is presented. The models are based on anisotropic stress intensity factors resolved on crystallographic slip planes calculated in a three-dimensional finite-element context. The developed models have been compared to experiments on two different test specimen geometries. The results show that a correct prediction of the crystallographic cracking plane can be achieved. This knowledge is of great interest for the industry and academia to better understand and predict crack growth in single-crystal materials.

1. Introduction

In today's world, gas turbines are crucial in the energy generation sector, as their start-up and shut-down times are relatively short, making them perfect candidates for balancing the power grid with respect to inherently intermittent renewable energy sources like wind and solar power [1]. However, more pronounced cyclic loading conditions mean an increased risk for fatigue (primarily thermomechanical fatigue) in critical components. Furthermore, gas turbines are designed to work with very high gas temperatures in order to achieve a good thermal efficiency [2], as increasing the gas temperature in power generating gas turbines lowers the fuel consumption; therefore also lowering costs and reducing pollution [3]. These high temperatures result in high requirements on the materials in the hottest regions. One of the critical regions in a gas turbine is the first turbine stage, where the highest temperatures are present for rotating parts. The turbine blades in this region are often cast in single-crystal form of nickel-base superalloys due to their excellent properties at high temperatures.

The complex material behaviour of single-crystal nickel-base superalloys, like the elastic and plastic anisotropy, makes the modelling of these materials rather complicated. It has been shown that the anisotropy, which is closely linked to the crystallographic structure, has a considerable impact on the yield [4,5], low-cycle fatigue [6,7], thermomechanical fatigue [8–10] and creep behaviour [11,12], to mention a few examples. Thus, the crystallographic structure needs to be accounted for in the modelling context. The same holds true for the fracture mechanical behaviour, where the distinct crystallographic slip planes are potential critical planes for crack initiation [13] and crack growth. Antolovich et al. [14] observed that nickel-base superalloys in single-crystal form show two distinct types of fracture. The first one is characterised by fracture on the {111}-planes, where the γ'-precipitates are sheared. The second fracture type is characterised by cracking normal to the loading direction, *i.e.* Mode I, and shows a microscopically rough

* Corresponding author.
E-mail address: christian.busse@liu.se (C. Busse).

https://doi.org/10.1016/j.engfracmech.2018.04.047
Received 13 February 2018; Received in revised form 18 April 2018; Accepted 27 April 2018
Available online 05 May 2018
0013-7944/

Nomenclature

C_{11},C_{12},C_{44}	material stiffness parameters	r	distance from crack front in x-y plane
K_I,K_{II},K_{III}	Mode I, II and III stress intensity factor	r'	distance from crack front in arbitrary direction
Q, N, μ, λ	functions of the material properties	x,y,z	cartesian coordinates
R_σ	stress ratio	α	crystallographic slip system
S	material compliance matrix	η_1,η_2,η_3	angle between the projection of the dendrites and the vertical axis of the global coordinate system
$\boldsymbol{b}$	slip direction unit vector (Burgers' vector)	γ'	strengthening precipitates
$\boldsymbol{n}$	slip plane normal unit vector	γ,β,ϕ	angle between crack front coordinate axis and r'
$\boldsymbol{s}$	evaluation direction unit vector	ψ	calibration parameter
$\boldsymbol{t}$	unit vector orthogonal to $\boldsymbol{s}$ and $\boldsymbol{n}$	$\boldsymbol{\sigma}$	stress tensor
k_I,k_{II},k_{III}	resolved Mode I, II and III stress intensity factor	ζ_1,ζ_2,ζ_3	angle between the projection of the dendrites and the horizontal axis of the global coordinate system
k_{EQ}	equivalent resolved stress intensity factor		

surface, where the crack tends to avoid the γ'-precipitates instead of shearing them.

Fatigue cracks in single-crystal nickel-base superalloys tend to switch from Mode I to crystallographic cracking, where the crack grows along one of the internal crystallographic slip planes [15–18]. Insufficient knowledge of how to handle the crystallographic cracking behaviour leads to large safety margins and conservative designs, which in turn decreases efficiency. Hence, it is important to establish a parameter describing the crack driving force in these materials that accounts for the observed behaviour. Furthermore, the transition from Mode I to crystallographic cracking is also important, as the latter is associated with a higher crack propagation rate [19].

Previous research [16,20–22] points out the importance of the crystallographic orientation, including the misalignments, as the deviation from the ideal crystallographic orientation, formed during the casting process, has a non-negligible influence on the stress distribution, and thus on the mechanical behaviour and fatigue life. This is important for the industry, where the crystallographic orientations in single-crystal components at stress raising features are generally unknown, due to the rarely controlled secondary orientation in the casting process. Different fracture mechanics approaches for single-crystal superalloys are available in the literature, where Resolved Shear Stresses (RSSes) are commonly used in single-crystal crack growth modelling applications [15,23,24]. Telesman and Ghosn [18], as well as Gell and Leverant [25], proposed that the RSSes on the respective crystallographic slip plane can be used to predict the crystallographic fracture plane. Telesman and Ghosn [18] presented an octahedral stress intensity factor parameter that couples a Resolved Shear Stress Intensity Factor (RSSIF) with a Resolved Stress Intensity Factor (RSIF) based on the normal stress acting on the corresponding slip plane. Their work and most of the previous research was done in terms of two-dimensional (2D) analyses, due to its simpler nature. Tinga [15], Ranjan and Arakere [26] and Qiu et al. [27] presented frameworks with RSSIFs in a three-dimensional (3D) context based on the anisotropic Stress Intensity Factors (SIF) derived by Sih et al. [28]. However, these anisotropic SIFs are restricted to the special case where locally the plane perpendicular to the crack front must be a plane of material symmetry. This is not valid for most crack front shapes or when a deviation from the ideal crystallographic orientation is present.

Another approach was proposed by Sabnis et al. [29], where a microdamage model is used to predict the crack initiation and crack growth. The anisotropic continuum damage mechanics model couples crystal plasticity with damage induced on the crystallographic planes and predicts a realistic crack path in a four-point bending specimen. However, they state that their constitutive model is insufficient for a quantitative comparison with experiments.

In this paper, two different models are presented and evaluated in order to find a reliable prediction of the first global crystallographic cracking plane. The models include the calculations of anisotropic SIFs resolved on the crystallographic planes in a 3D context for arbitrary crack front shapes and crystallographic orientations based on the work of Hoenig [30]. An equivalent RSIF parameter is proposed based on these anisotropic SIFs, which is used to predict the active global crystallographic cracking planes after a transition from Mode I cracking. Validation of the models has been done by isothermal crack growth testing at 500°C for two different specimen geometries, where the crystallographic misalignments, due to the casting procedure, have been taken into account.Furthermore, no fatigue crack growth rate data is presented or used in this work.

The presented methodology is applicable to arbitrary 3D Finite-Element (FE) simulation contexts and crystallographic orientations. This aspect is of high importance for industrial applications, where a physical-inspired model, such as this, can be used to more accurately predict the crack growth in single-crystal components, and thus increase the efficiency of the design as well as the maintenance intervals. The authors are not aware of similar research using 3D-calculations of RSIF parameters based on anisotropic SIFs for arbitrary crack front shapes and crystallographic orientations.

2. Material and experiments

2.1. Material

The investigated material is a single-crystal nickel-base superalloy of face-centred cubic structure (FCC) developed by Siemens Industrial Turbomachinery AB, similar to the alloy described by Reed et al. [31]. Its main alloying elements, in order of decreasing wt %, are as follows: Ni-Cr-Ta-Co-Al-W-Mo-Si-Hf-C-Ce.