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Simulation of crack growth under low cycle fatigue at high temperature in a single crystal superalloy

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Abstract

Crack growth tests have been performed at 950 °C with Single Edge Notch specimens of the Ni-based single crystal superalloy PWA1483. In particular, several orientations and frequencies have been investigated, thus allowing the assessment of the influence of these parameters on the crack growth rate. In addition, oxidation experiments have been carried out to characterize the kinetics of the outer oxide scale growth at the same temperature.

On the other side, crack growth has been simulated with the Finite Element program ABAQUS in real test conditions by the node release technique. The nodes are released according to the measured crack growth rate.

The simulation results are compared with the test results on the basis of the computed Crack Tip Opening Displacement (CTOD). For this purpose, the crack is propagated until a stabilized value of the CTOD is obtained. This is usually the case when the crack has crossed the initial plastic zone. The procedure provides an evaluation of the effects of cycle frequency, crystal orientation, plasticity and oxide induced crack closure.

Keywords: Finite element analysis; Low cycle fatigue; Creep-fatigue; Crack growth; Nickel-based superalloys

1. Introduction

Blades in gas turbines or aero-engines undergo a combination of creep and cyclic thermomechanical loading corresponding to start up, steady state operation and to shut-down. The blades of the first stages are nowadays frequently made of single crystal Ni-based superalloys due to their higher creep resistance. Film cooling allows for even higher service temperatures but the stress concentrations at the cooling holes and the local damage induced by drilling the holes are known to promote cracking [1]. The prediction of the crack behaviour under high temperature cyclic loading in the single crystal alloy is thus an essential step of any blade lifting procedure.

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Nomenclature

a	crack size
a_p	pre-crack size
a_0	initial crack size in the simulation
A, B, C	specimen orientations as defined in Table 1
b	magnitude of the Burgers vector
$\mathbf{C}$	elastic stiffness tensor
CTOD	crack tip opening displacement
$\mathbf{E}^e$	elastic strain
f	frequency of the loading
$\mathbf{F}$	deformation gradient
$\mathbf{F}^e$	elastic part of the deformation gradient
$\mathbf{F}^p$	plastic part of the deformation gradient
h_{elem}	initial thickness of the elements used to represent the oxide layer
h_{outer}	thickness of the external oxide layer
k	Boltzmann constant
K	stress intensity factor
$\mathbf{m}$	slip direction
$\mathbf{n}$	normal to the slip plane
S	nominal load
L_e	element size in the crack growth region
N	number of cycles
r^p	plastic zone size
$R = S_{min}/S_{max}$	load ratio
t	time
T	absolute temperature
V	electric potential
V_f, V_d, V_s	activation volumes for dislocation glide, dynamic and static recovery, respectively
w	channel width
W	specimen width
x	scalar back stress at the slip system level
$\mathbf{X}$	tensorial back stress
y	distance between the potential probes and the notch
$\boldsymbol{\alpha}$	strain-like state variable responsible for back stresses
δ	local exposure time to air
ε^{ox}	uniaxial expansion due to external oxide growth
$\boldsymbol{\Psi}$	Mandel stress
γ	amount of plastic shear on a slip system
μ	shear modulus
$\boldsymbol{\pi}$	second Piola–Kirchhoff stress relative to the intermediate configuration
ρ	state variable proportional to the dislocation density
$\boldsymbol{\sigma}$	Cauchy stress tensor
v	cumulated plastic shear on a slip system
τ	resolved shear stress on a slip system
τ^{Orowan}	Orowan stress

Superscripts

o	octahedral slip systems
c	cubic slip systems