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Methodology for fatigue crack growth testing under large scale yielding conditions on corner-crack specimens

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ABSTRACT

In this paper results of fatigue crack growth tests performed under both small and large scale yielding conditions on corner-crack specimens are presented for a turbine shaft steel. It can be shown, that the crack opening stress is the main factor influencing the fatigue crack growth rates. In order to account for plasticity effects numerical simulations are performed, which yield solutions for the *J*-integral. Those solutions are transferred to cyclic loading conditions by using the effective cyclic *J*-integral. Finally, all crack growth tests can be described within a single scatterband.

1. Introduction

Higher participation of solar- and wind-farms in electricity production would demand for fast compensation of instabilities in an electrical network powered by a combination of steam and gas turbines. Due to fluctuations of the renewable energies during every day, a fast start-up and shut-down of a gas turbine engine will be required by end-users instead of so called base-mode, when the engine is in operation for a few days and longer. The operation flexibility of the gas turbine engine has an impact on the lifetime of hot gas components that could suffer more from low-cycle fatigue (LCF) damage than from oxidation and creep failure modes.

The mechanical integrity of the component is among others ensured by using finite element calculations in order to identify the critical locations and loadings. The cycling operation conditions of a gas turbine have an impact on the stress level and its redistribution at the critical locations. As an indirect measure for the integrity of the system, the (cyclic) plastic zone size can be used. Since the results depend on the expected boundary conditions with regard to thermal and mechanical loadings, the mechanical integrity check must be performed for the most severe operation conditions. Under those conditions, plastic zone sizes are expected, which can be no longer treated in the sense of small scale yielding (SSY).

The lifetime of a gas turbine component is divided in into two phases. The first phase is low cycle fatigue (LCF) crack initiation. The methodologies for LCF assessment including large plastic zones is well established and experimental techniques are defined. The second phase deals with the evaluation of the component lifetime in the presence of cracks. In order to ensure the mechanical integrity of a gas turbine component only the stable crack propagation phase could be allowed.

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Nomenclature

Symbol

a	crack length
A	area
A_{CS}	cross-section area of the corner-crack specimen (here 8×8 mm^2)
C	constant from the Paris-law
d	depth of the eroded starter notch
$d_{n'}$	function of the hardening behavior from the HRR crack-tip field
da/dN	crack growth increment per cycle
E	Young's modulus
$f(\frac{a}{W})$	geometry function for the stress-intensity factor
f_{0°	geometry function for the stress-intensity factor at the specimen surface
f_{45°	geometry function for the stress-intensity factor in the middle of the specimen
h	length of the grip system
J	J-integral
J_{sim}	J-integral simulated with ABAQUS
K_I	stress-intensity factor
m	exponent from the Paris-law
n'	cyclic Ramberg–Osgood hardening exponent
N	number of cycles
N_f	number of cycles at final crack length
N'	Ramberg–Osgood hardening exponent
r	specimen radius
R_σ, R_ε	load ratio with respect to stress or strain
u	displacement
U	potential signal
W	specimen width
Y_{Area}	geometry function to correlate the (cyclic) J-integral with $\int \sigma du'$
Δ	denotes a range
ε	strain
ϕ	angle along the crack front
ν	Poisson ratio
σ	stress
σ_{app}	applied surface traction at the specimen grip
σ_Y	yield stress defined at 0.2% plastic strain
σ_{CY}	cyclic yield stress defined at 0.2% plastic strain from the point of load reversal

Abbreviations

BM	beachmark
CC	corner-crack
CT	compact-tension
CTOD	crack-tip opening displacement
HRR	refers to the singular crack-tip fields according to Hutchinson, Rice and Rosengren
LCF	low cycle fatigue
LSY	large scale yielding
RT	room temperature
SSY	small scale yielding

Sub/superscripts

eff	crack closure is considered
grip	refers to the grip system of the testing machine
min/max	minimum/maximum value
op	refers to the value at crack opening

The methodologies for fracture mechanics are well established under SSY conditions and the lifetime assessment is a standard procedure. In the presence of large plastic strains, i.e. under large scale yielding conditions (LSY), most fracture mechanics concepts are limited to monotonic loading conditions and only a few of them were extended to large cyclic plasticity.