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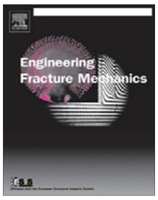

Optical in situ investigations of overload effects during fatigue crack growth in nodular cast iron

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ABSTRACT

An innovative pulsed reflection microscope (PRM) is used for optical in situ investigations of overload effects during fatigue crack growth in nodular cast iron. The optical system is based on the principle of a reflected-light microscope and can be integrated in any standard testing machines. Using the PRM the microstructural processes near the crack tip are visualized when an overload is applied. With the help of the presented optical system, the microstructural phenomena responsible for the acceleration effects in nodular cast iron are elucidated for the first time. Furthermore, scanning electron microscopy is used a posteriori to investigate the crack profiles and the fracture surfaces of the fatigue crack for the different stages of the overload event.

1. Introduction

Nodular cast iron is nowadays widely used for engineering applications because of its excellent castability, cost effectiveness and good mechanical and fracture mechanical properties. Due to these technological advantages, nodular cast iron is utilized in particular for safety relevant components like nuclear shipping casks [1] or parts of wind energy turbines [2]. Since nodular cast iron is a highly inhomogeneous material, consisting of a ferrite matrix and embedded graphite particles, the probability of fatigue cracks emanating from such defects must be taken into account in the fracture mechanics assessment. Within this context, it also has to be considered, that the components might be subjected to variable amplitude loading during operation [3,4].

Fatigue crack growth in nodular cast iron has been investigated in the last two decades by many authors, see e.g. [5–8]. A compendium of fracture mechanics data for different types of cast iron is provided in [9]. However, all this literature is concerned only with fatigue crack growth under constant amplitude (CA) loading. Keeping in mind the loading situation of real components, Hübner et al. [10] investigated fatigue crack growth in nodular cast iron under variable amplitude loading for the first time. They discovered load history effects in terms of crack growth acceleration after a single overload (OL) without any retardation in the fatigue crack growth rate. These effects are completely different from observations in homogeneous materials like aluminium and steel, where crack growth retardation occurs after single overloads, see e.g. [11–13]. This fact leads to non-conservative lifetime predictions for nodular cast iron if conventional interaction models are used. Thus, the OL effects in nodular cast iron were further investigated on the macroscopic scale by Mottitschka et al. [14]. They performed extensive experiments with different OL ratios, all showing crack growth acceleration. To the authors' knowledge, similar OL effects, i.e. considerable crack growth acceleration without retardation, have been presented in the literature only for

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Nomenclature

a	crack length
a_{ol}	crack length at overload
Δa_{ol}	crack extension due to overload
B	specimen thickness
c_{ol}	relative crack growth rate at overload
$\frac{\mathrm{d}a}{\mathrm{d}N}$	fatigue crack growth rate
$\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_{\mathrm{ca}}$	fatigue crack growth rate under constant amplitude loading
$\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_{\mathrm{ol}}$	fatigue crack growth rate at overload
E	Young's modulus
$f\left(\frac{a}{W}\right)$	geometry function
f_0	volume fraction of graphite particles
F	applied force
F_{max}	applied maximum load
F_{min}	applied minimum load
F_{ol}	applied overload
K_{I}	mode I stress intensity factor
K_{Iq}	critical stress intensity factor for crack initiation
F_{max}	stress intensity factor at maximum load
K_{min}	stress intensity factor at minimum load
K_{ol}	stress intensity factor at overload
ΔK	cyclic stress intensity factor
ΔK_{fc}	critical cyclic stress intensity factor
ΔK_{ol}	cyclic stress intensity factor at overload
ΔK_{th}	threshold value
L	specimen length
R	stress ratio
R_{ol}	overload ratio
r_{p}	size of plastic zone
S	support distance
Δt	pulse time
W	specimen width
ε_{r}	elongation at rupture
κ_{ol}	absolute overload ratio
μ	roughness
ν	Poisson's ratio
χ	form factor (nodularity)
σ_{uts}	tensile strength
σ_{y}	yield stress
CA	constant amplitude
LED	light emitting diode
LEFM	linear elastic fracture mechanics
PRM	pulsed reflection microscope
OL	overload
OLR	overload ratio
SEM	scanning electron microscopy
SENB3	single-edged-notched specimen under three-point bending

a high viscosity bone cement by Evans [15]. Furthermore, Borrego et al. [16] reported on the influence of incoherent dispersed particles in aluminium alloys on fatigue crack growth resulting in small acceleration effects after OLs.

Fatigue crack growth in inhomogeneous materials was basically investigated by Ritchie [17], who found different mechanisms leading to crack tip shielding. Later, Skullerud et al. [18] studied the influence of casting defects on the fatigue limit of aluminium alloys. The damage mechanisms in nodular cast iron were studied under monotonic loading by Dong et al. [19,20] using scanning electron microscopy (SEM). Liu et al. [21] analysed the development of microvoids under strain loading. They found that void coalescence is the failure mechanism for neighboring graphite particles. Regarding widely spaced particles, there is nucleation of small voids in the matrix material between the graphite particles prior to final failure by necking of the matrix.

Comprehensive investigations of the damage mechanisms on the micro-level in nodular cast iron under monotonic and cyclic loading by using SEM have been conducted in the last years by the working group at Università di Cassino [22–25]: The