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Fatigue behaviour and life prediction of lateral notched round bars under bending–torsion loading

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ABSTRACT

Fatigue behaviour of lateral notched round bars made of DIN 34CrNiMo6 high strength steel under single bending, single torsion and combined bending–torsion was studied. Crack initiation and crack growth were monitored in situ using a high-resolution digital system. Fracture surfaces were examined by scanning electron microscopy and were replicated with a three-dimensional laser scanner. The notch effect was analysed using the equivalent strain energy density concept and the fatigue life predictions were carried out through the Coffin–Manson model. Criteria based on the principal stress field were proposed to predict the most likely initiation sites, surface crack paths and surface crack angles. Finally, very good correlations between experimental and predicted fatigue lives were observed, particularly for lives greater than 10^4 cycles.

1. Introduction

High strength steels cover a broad spectrum of applications due to both good strength-to-weight ratio and corrosion resistance. DIN 34CrNiMo6, in particular, combines deep hardenability, high ductility, toughness and strength. These features make it ideal for critical components, such as shafts, axles, torsion bars, bolts, crankshafts, connecting rods, among others.

In general, these components experience severe service conditions and complex loading. On the other hand, they have geometric discontinuities introduced into the design for functional purposes which act as stress concentrators. Even under nominal elastic behaviour, the maximum stresses at the notches can exceed the yield strength. Under these circumstances, premature fatigue failure can occur.

Fatigue failure often occurs from cracks initiated at notches. It is usually described as a sequential process consisting of three main stages, i.e. crack initiation, crack propagation and final fracture. Therefore, in order to develop durable products against fatigue as well as to assess the remaining lifetime of a component or to establish maintenance procedures, it is essential to understand the behaviour of surface cracks subjected to stress concentration effects and multiaxial cyclic loading.

Fatigue behaviour of notched specimens subjected to multiaxial loading has been handled by many authors. Nevertheless, cases involving combined bending–torsion rarely have been addressed in literature [1–8]. On the other hand, these studies

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Nomenclature

$2b$	surface crack length
$2b_0$	initiation crack length at the notch surface
a	crack length
a_0	crack initiation length
B	bending moment
b	fatigue strength exponent
c	fatigue ductility exponent
k'	cyclic hardening coefficient
n'	cyclic hardening exponent
N	number of cycles
N_i	number of cycles to crack initiation
N_p	fatigue life prediction
N_f	number of cycles to failure
r	correlation coefficient
R	stress ratio
T	torsion moment
T_σ	scatter band index
ε'_f	fatigue ductility coefficient
θ_p	principal direction
σ_a	normal stress amplitude
σ'_f	fatigue strength coefficient
σ_m	mean normal stress
$\sigma_{vML,\max}$	maximum local von Mises equivalent stress
$\Delta\varepsilon$	normal strain range
$\Delta\sigma$	normal stress range
$\Delta\sigma_0$	fatigue limit stress range of the unnotched specimen
$\Delta\sigma_{vML}/2$	local von Mises equivalent stress amplitude
ΔK_{th}	range of the threshold value of the stress intensity factor
ΔK_{th0}	range of the threshold value of the stress intensity factor for $R = 0$
$\Delta\tau$	shear stress range
τ_a	shear stress amplitude
τ_m	mean shear stress
σ_{ii}, τ_{ij}	components of stress tensor

have been focused mainly on round bars with circumferential notches or transverse circular holes. However, mechanical components also contain solid circular cross-sections with lateral notches. In this way, the study of these geometries in terms of multiaxial fatigue is a matter of great importance.

This paper investigates the fatigue behaviour of lateral notched round bars made of DIN 34CrNiMo6 subjected to different loading histories, namely single bending, single torsion and combined bending–torsion. It also presents criteria to predict the most likely initiation sites, surface crack paths and surface angles at the early stage of crack growth as well as a fatigue life prediction model based on local equivalent von Mises stresses. Tests were conducted under constant-amplitude loading with stress ratios close to zero. The detection of crack initiation was carried out in situ using a high-resolution digital system. Fracture surfaces were examined by scanning electron microscopy and were replicated with a three-dimensional laser scanner. A finite element model was developed to evaluate the stress–strain state at the notch region.

2. Experimental procedure

2.1. Material and specimens

The material used for this study was a DIN 34CrNiMo6 high strength steel. The material was provided by the supplier as oil quenched and tempered (Q&T). Its mechanical properties are summarised in Table 1. The coefficients and exponents of the Coffin–Manson law (see Eq. (5)) as well as the cyclic hardening coefficient and the cyclic hardening exponent are presented in Table 2.

The specimens were machined from extruded 20 mm-diameter round bars. The surfaces were subjected to high-speed mechanical polishing with progressively finer grit silicon carbide papers followed by 6 μm diamond paste.