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On the topography of fracture surfaces in bending–torsion fatigue

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Abstract

Fracture surfaces generated under combined bending–torsion fatigue loading in both the low-cycle fatigue and the high-cycle fatigue regions of specimens made of high-strength low-alloy Cr–Al–Mo steel are analysed in terms of topographical characteristics. Parameters reported here are the root mean square roughness, the number of peaks per unit length and the Hurst exponent quantifying various aspects of surface topography. As a main result of the analysis, the critical portion of torque beyond which the character of fracture topography significantly changes is estimated to be within the range of 40–50% of a total loading.

Keywords: Bending–torsion fatigue; Quantitative fractography; Roughness parameters

1. Introduction

Despite a long and considerable effort that has been undertaken by engineers and scientists of many different disciplines, research on fatigue of structures and materials continues unabatedly to be one of the most important topics of both theoretical and experimental interest [1,2]. Nowadays, great attention is focused especially on multiaxial fatigue problems. A significant concern is biaxial fatigue of rotational structural components that usually undergo combined tension–torsion or bending–torsion loading regimes in their service life.

To address this concern, crack paths and interconnections between fracture surface morphology and loading conditions are studied extensively; see e.g. [2–7]. It is now clearly established that a high amount of lower to medium amplitudes of shear loading Modes II and III acting on the crack front leads to an exceptionally complicated crack path. In these cases, the crack propagates in an inextricably complex manner showing local arrests and forming a branch/twist crack morphology or the so-called factory roofs [2–5]. Interaction between both mating fracture surfaces (some combination of sliding, climbing, sticking, slipping and deforming) often

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Nomenclature

σ_a	bending stress amplitude
τ_a	torsional stress amplitude
r	loading ratio
r_c	critical loading ratio
N_f	number of cycles to failure
R_q	root mean square roughness
m_0	number of peaks of the profile per unit length
H	Hurst exponent

makes even a thorough qualitative understanding of fatigue crack propagation difficult [3,4]. On the contrary, a high amount of opening loading Mode I or sometimes high amplitude shears generate a fracture surface that appears macroscopically flat. Despite all mentioned studies, the crucial problem in biaxial fatigue fractography is a significant lack of experimental data.

In the present study, the topography variation generated by a combined bending–torsion loading in both the low-cycle fatigue (LCF) and the high-cycle fatigue (HCF) regimes is characterized using several roughness parameters that describe different aspects of fracture roughness. All characteristics are evaluated for two sets of fracture surface profiles extracted in parallel and perpendicular directions with respect to the local fatigue crack growth direction.

2. Experimental procedure

2.1. Fatigue experiments

Fatigue experiments were carried out by means of a resonance testing machine MZGS-100 using symmetric in-phase bending–torsion loading regimes with both bending and torsion components having a sinusoidal cycle of frequency $f = 29$ Hz. Smooth specimens were made of high-strength low-alloy Cr–Al–Mo steel, which is a material primarily designed for manufacturing of structural components that should have good wear resistance, like gear wheels. A sorbitic microstructure was achieved after a heat treatment (annealing – 920 °C, 25 min, air; quenching – 930 °C, 25 min, oil; tempering – 650 °C, 40 min, air) leading to the yield stress $\sigma_y = 840$ MPa and the ultimate tensile stress $\sigma_u = 950$ MPa. Specimens were loaded at room temperature up to a final rupture.

Experimental settings were based on the Mataka's critical plane criterion [8,9]. Achieved fatigue-life data are collected in Table 1, where σ_a is the bending amplitude, τ_a is the torsion amplitude, r is the loading ratio defined as

$$r = \tau_a/(\tau_a + \sigma_a), \tag{1}$$

Table 1
Experimental data.

Specimen	Type of loading	σ_a (MPa)	τ_a (MPa)	r (–)	N_f (cycle)
L1	Pure bending	790	0	0	102 560
L2		638	236	0.27	14 880
L3	Combined bending–torsion	358	358	0.5	68 400
L4		147	396	0.73	100 160
L5	Pure torsion	0	405	1	100 400
H1	Pure bending	620	0	0	1 229 000
H2		550	200	0.27	1 252 000
H3	Combined bending–torsion	330	330	0.5	1 099 100
H4		140	385	0.73	1 700 150
H5	Pure torsion	0	390	1	4 475 000