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Three-dimensional morphology of fracture surfaces generated by modes II and III fatigue loading in ferrite and austenite

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ABSTRACT

This work is focused on an experimental study of shear-mode crack propagation in the ARMCO iron and the X5CrNi18–10 austenitic steel near the crack-growth threshold. Three experimental setups are used for a generation of cracks in simple-shear, compact tension-shear and torsion specimens. The crack path and the surface topography are studied by means of 3-dimensional reconstruction of fracture surfaces using stereophotogrammetry in a scanning electron microscope. Measurements by means of the profile analysis are used to determine local deflection and twisting angles of the crack with respect to the remote shear direction. The tendency to mode I crack branching is found to be much higher in austenite than in ferrite where both modes II and III cracks propagate close to the plane of maximal shear stress.

1. Introduction

Determination of shear-mode crack propagation characteristics in the near-threshold region is more difficult than that of opening-mode crack growth ones at least for two reasons. The first reason is connected with the existence of friction forces generated by sliding of crack-wake asperities. These forces reduce the crack driving force and their magnitude depends on several factors as material, crack length and pre-crack type (e.g. [1–3]). Since the pre-crack is usually generated in mode I loading, there is an additional complication with different crack closure levels that affect the near-threshold behavior of shear-mode cracks. Therefore, a reasonable comparison of results obtained by various authors could be done only in terms of the effective crack driving force ΔK_{eff}. That is, unfortunately, not available for shear-mode crack growth data hitherto.

The second reason is related to a competition between shear and opening loading modes during propagation of shear-mode cracks that can lead to so called mode I branching (e.g. [4–6]). This phenomenon is mostly observed in the near-threshold region while in the high loading ranges the cracks propagate usually in a co-planar manner, i.e., nearly along the maximum shear plane (e.g. [7]). A smooth long crack under a simple in-plane shear can get a maximum support of mode I loading ($\Delta K_I \approx 1.15\ \Delta K_{II}$) by deflection from the shear plane to planes close to $\alpha_{cII} \approx 70°$ (e.g. [8]). The formation of the mode I segments corresponds to a rotation around the axis parallel to the crack front which is relatively easy: the tilt plane intersects the main crack plane along the line. On the other hand, the mode III crack segments under a simple out-of-plane shear can get an additional mode I support only by twisting around the axis perpendicular to the crack front. However, the plane of such twisted element and that of the main crack intersect just in one point. Thus, in reality, the twisting can occur only

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Nomenclature

a	total crack length (notch + fatigue pre-crack + half length of shear-mode propagation)
α_{II}	deflection angle measured on a profile running parallel to the shear direction for mode II
α_{III}	twisting angle measured on a profile running parallel to the shear direction for mode III
α_{cII}	theoretical angle α_{II} for deflection of the mode II crack to local mode I
α_{ifrIII}	theoretical angle α_{III} for initial stage of factory-roof formation
α_{cfrIII}	theoretical angle α_{III} for final stage of factory-roof formation
α_{cIII}	theoretical angle α_{III} for a discontinuous twisted crack element at a straight crack front
α_{ssIII}	measured mean value of the angle α_{III} related to simple-shear loaded specimens
β_{II}	twisting angle measured on a profile running perpendicular to the shear direction for mode II
β_{III}	deflection angle measured on a profile running perpendicular to the shear direction for mode III
CTS	compact tension shear
d_m	mean grain size
d	inner diameter of the cylindrical specimen with circumferential notch
D	outer diameter of the cylindrical specimen with circumferential notch
F	force applied on the CTS loading device (mode II)
FEM	finite element method
φ	cylindrical specimen position polar angle
K_{II}	stress intensity factor in mode II
K_{III}	stress intensity factor in mode III
ΔK_I	stress intensity factor range in mode I
ΔK_{II}	stress intensity factor range in mode II
ΔK_{III}	stress intensity factor range in mode III
ΔK_{eff}	effective stress intensity factor range
ΔK_{IIeff}	effective stress intensity factor range in mode II
ΔK_{IIIeff}	effective stress intensity factor range in mode III
l	longitudinal coordinate of the fracture surface profile
N	number of applied loading cycles
R	cyclic ratio
SEM	scanning electron microscope
SIF	stress intensity factor
σ_y	yield strength
t	thickness of the CTS specimen
T	torque (torsional specimen)
w	width of the CTS specimen
ξ	d/D ratio
Y_{II}	geometrical factor for mode II (CTS specimen)
Y_{III}	geometrical factor for mode III (torsional specimen)
z	vertical coordinate of the fracture surface profile

on microscopic ledges of the main crack front or at suitably oriented elements of the microscopically spatial crack tip, generally in the mixed mode I + II + III.

In the case of torsional loading, however, the mode III cracks can get some mode I support just by a deflection from the maximum shear plane. This is the reason why in the near-threshold region, semi-elliptical II + III micro-cracks in notched specimens under torsion often propagate along planes deflected from the maximum shear plane under the mixed mode I + II + III [9]. Such an initial mixed-mode shear growth is often stopped by a formation of mode I branches leading to the factory-roof fracture morphology (e.g., [10]). Some simple concepts for a description of mode I branching condition for mode II cracks were also proposed [8,11] but their verification is difficult due to a lack of effective values of ΔK_{IIeff} and ΔK_{IIIeff}. Moreover, a prevalent majority of previous studies on mode I branching was based either on macroscopic assessments or microscopic 2D observations of the crack path geometry only.

The aim of this study is to find and describe a three dimensional picture of microscopic crack path geometry formed under modes II and III near-threshold loading conditions in three types of specimens made of ARMCO iron and an austenitic steel. A special technique was used to obtain nearly friction and closure-free pre-cracks driven by effective values of stress intensity ranges very close to applied (remote) ΔK_{II} and ΔK_{III} ones. The results of this experimental study will provide a basis for a more detailed understanding of micromechanisms of shear-mode crack propagation in metallic materials.

2. Materials and experimental procedures

The first material that was used was ARMCO iron (99.99% Fe), hereafter called ferrite, as a representative of a body-centered-cubic metal (bcc). The material was cold-drawn resulting in the yield strength, σ_y, of ∼150 MPa and a mean grain size,