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Prediction of effective mode II fatigue crack growth threshold for metallic materials

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ABSTRACT

The fatigue crack growth threshold consists of the intrinsic component (effective threshold) and the extrinsic component (crack closure). Theoretical formulae for prediction of the mode II effective threshold in metallic materials are presented. The model is based on physical interpretation of experimental findings. For a given material the dominant local crack growth mode at the kinked crack front of a remote mode II loaded crack is identified and the local stress intensity factor is expressed, which represents a new concept for estimation of the mode II effective threshold. The local crack growth mode depends on microstructure and crystallographic structure of the material. Moreover, new experimental data for mode II effective thresholds of the Ti6Al4V alloy ($\Delta K_{\mathrm{IIeff,th}} = 1.8$ MPa m$^{1/2}$) and pure zirconium ($\Delta K_{\mathrm{IIeff,th}} = 1.3$ MPa m$^{1/2}$) are presented. These data extended the available database for metallic materials and confirmed a broad validity of the proposed theoretical relationships.

1. Introduction

The damage mechanism in metals is usually connected to movement of dislocations and, therefore, controlled by the shear stress. Thus, the long cracks loaded in remote mode II can in principle propagate along the maximum shear stress plane, i.e., without deflection to the local mode I growth as still presumed not so long ago. Indeed, more recent experimental studies [1–5] revealed that both remote mode II and mode III long cracks propagate under the dominance of either the local mode I or the local mode II. The tendency to grow under different deflection angles depends on the crystallographic structure and microstructure of the material [6,7]. The contribution of the local shear or the local opening mode should be, therefore, distinguished for different materials. The existing criteria for mixed-mode crack propagation based on continuum mechanics, as the maximum shear stress or the maximum tangential stress criterion [8], cannot be generally applied since they presume a certain crack growth direction independently of the material.

A local shear-mode propagation of long cracks was verified experimentally for pure ferritic steel (the ARMCO iron) and pure niobium, which are both the bcc metals [9,10]. Materials with a low number of slip systems or with barriers for dislocation motion exhibit local mode I crack branching. This holds for the fcc metals such as the stainless steel or nickel, and for multiphase materials such as the feritic-pearlitic steel [11]. In order to study the propagation direction as well as the crack

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Nomenclature

ARMCO	American rolling mill company
bcc	body centred cubic
fcc	face centred cubic
hcp	hexagonal close-packed
SEM	scanning electron microscope
SIF	stress intensity factor
a	total crack length
b	magnitude of the Burgers vector
E	Young's modulus
G	shear modulus
k_1	local mode I SIF component at the kinked crack front
k_2	local mode II SIF component at the kinked crack front
l	longitudinal coordinate of the fracture surface line profile
$n_{\alpha,\mathrm{I}}$	function of the deflection angle α in Eq. (10)
$n_{\alpha,\mathrm{II}}$	function of the deflection angle α in Eq. (12)
N	number of applied loading cycles
R	cyclic stress ratio
z	height coordinate of the fracture surface line profile
α	deflection angle of the local crack kink from the original remote mode II crack plane
$\Delta a/\Delta N$	crack growth rate averaged during ΔN loading cycles
Δk_1	local mode I SIF range component at the kinked crack front
$\Delta k_{1,\mathrm{dl}}$	mode I threshold of SIF range based on a model of cyclic movement of dislocations
Δk_2	local mode II SIF range component at the kinked crack front
$\Delta k_{2,\mathrm{dl}}$	mode II threshold of SIF range based on a model of cyclic movement of dislocations
$\Delta K_{\mathrm{Ieff,th}}^{\mathrm{theor}}$	theoretically predicted effective mode I threshold of SIF range
ΔK_{II}	mode II threshold of SIF range
$\Delta K_{\mathrm{IIeff,th}}$	effective mode II threshold of SIF range
$\Delta K_{\mathrm{IIeff,th}}^{\mathrm{exper}}$	experimentally measured effective mode II threshold of SIF range
$\Delta K_{\mathrm{IIeff,th}}^{\mathrm{theor\ I}}$	theoretically predicted effective mode II threshold of SIF range according to the local mode I mechanism
$\Delta K_{\mathrm{IIeff,th}}^{\mathrm{theor\ II}}$	theoretically predicted effective mode II threshold of SIF range according to the local mode II mechanism

propagation threshold, the dominant crack growth mechanism should be first identified for each material and the corresponding local mode I or local mode II component at the crack front should be taken into account. This approach is used in this work in order to determine the effective mode II thresholds for various metallic materials.

The fatigue crack growth threshold consists of the intrinsic component (resistance to cyclic crack tip plasticity) and the extrinsic component (crack tip shielding) [12]. The intrinsic component is also called the 'effective threshold' and it was thoroughly studied for mode I long cracks. A simple relationship for the mode I intrinsic (effective) threshold of the stress intensity factor (SIF) range has the form of the product of the elastic modulus, E, and square root of the magnitude of the Burgers vector, b [13]:

$$\Delta k_{1,\mathrm{dl}} \propto E\sqrt{b}. \tag{1}$$

This proportionality is based on a simple model of an ideal crack in a single crystal and cyclic movement of dislocations emitted from the crack tip [14]. Experiments on real polycrystalline metallic materials confirmed this proportionality. Different values of the constant in front of the product were reported. For example, the value of 3/4 correlates well with the experimental values for pure metals [6]. For alloyed metals, the value is expected to be somewhat higher, for example the value of 1.0 correlates well with the experimental data for various steels [15] and aluminium alloys [16]. In the latter work, each of the different aluminium alloys after various heat treatments, which resulted in a wide range of yield stresses, had the effective threshold of about 0.85 (0.8–0.9) MPa m$^{1/2}$. It demonstrates that the effective threshold can be determined for a certain metal (alloys with the same matrix metal) independently of its microstructure. The relationship (1) has a clear physical meaning and takes only basic constants of the material (E and b) into account. A good agreement with experiments makes it a powerful tool for predictions. The intrinsic threshold represents a lower physical limit of loading, below which the crack will not propagate even when all closure components are minimized.

The aim of this paper is to find a relevant relationship for prediction of the intrinsic threshold under the remote mode II crack loading. In order to do so, a detailed analysis of the mixed-mode I + II loading conditions at a locally deflected crack is introduced. Moreover, new experimental results for two materials (Ti6Al4V alloy and pure zirconium) are presented to