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Microstructurally-dependent model for predicting the kinetics of physically small and long fatigue crack growth

O.M. Herasymchuk *

G.S. Pisarenko Institute for Problems of Strength of the National Academy of Ukraine, Kyiv, Ukraine

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ABSTRACT

Based on the proposed concept of the fatigue threshold stress intensity factor ranges, a model has been developed that describes the kinetics of physically small fatigue crack and long fatigue crack growth. The model allows the calculation of the crack growth rate under the regular fully-reversed uniaxial loading from the data on the static characteristics of mechanical properties and the microstructure of the initial material. The crack depth at which the cyclic plastic zone size ahead of the crack tip will exceed the grain size should be considered as a criterion of the small-to-long crack transition. Under high-cycle fatigue conditions physically small fatigue crack growth will be divided into two phases of growth: the first phase is when the crack propagates along the slip planes of individual grains, and the second one is when the crack changes the mechanism of growth and propagates in the plane perpendicular to the loading direction. The model validity has been tested using the experimental data on the growth of the long cracks in specimens of titanium alloy VT3-1 in seven microstructural states and the small cracks in specimens of titanium alloy Ti–6Al–4V and aluminum alloy 2024-T3. Good agreement between the calculated and experimental results is obtained.

1. Introduction

A fatigue crack initiated from an approximately flat and smooth surface (or a blunt and shallow notch) of a specimen, in ambient air and room temperature, grows in three phases [1]: (i) a microstructurally short crack (MSC), which is located within a single microstructural element (a grain) of depth d; (ii) a physically small crack (PSC) from d to the depth l'_i when an abnormal nonmonotonic growth is observed and the crack closure (CC) effect is absent or is slightly influencing, the depth of the PSC from the surface is about 10 grain sizes [2]; (iii) a long crack (LC) from l'_i to l_t when it grows according to the Paris law to the depth l_t, which is adopted as the fatigue fracture criterion.

Under high-cycle fatigue (HCF) conditions, i.e., when the maximum stress in the cycle $\sigma_{\max}$ is considered to be less than the proportionality limit σ_p under monotonic loading, a MSC initiates and propagates, as a rule, along the persistent slip band in a surface grain, for the majority of metals and alloys. The use of the continuum mechanics to describe the material behavior in this phase (which is also known as stage I of fatigue fracture) is rather questionable. Therefore, to describe the fatigue fracture process at stage I under HCF conditions, separate approaches are used [3]. To describe the crack growth kinetics in the second and third phases (or at stage II of fatigue fracture), the linear elastic fracture mechanics (LEFM) approaches can be successfully employed, only with consideration of the main distinctive features in the PSC behavior as compared to the LC. These distinctive features can be stated as follows [4]:

- an extremely wide scatter in the experimental results of measurement of the PSC growth rates;
- PSCs grow with the applied stress intensity factor (SIF) ranges ΔK, significantly less than the LC fatigue threshold SIF range ΔK_{th};
- high PSC growth rates are observed even at such low levels of ΔK;
- high PSC growth rates decrease with an increase in the applied driving force of ΔK, thus violating the principles of the continuum mechanics;
- a considerable interaction between the PSC and microstructure: retardation at grain boundaries and a drastic increase in the growth after passing the grain boundary when the crack length is several grain sizes;

* Tel.: +380 44 286 2957; fax: +380 44 286 1684.
E-mail address: kov2@ipp.kiev.ua

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Nomenclature

a, c, h	hexagonal close-packed crystal lattice parameters	m_s	Schmid factor ($m_s = \cos\varphi \cdot \cos\gamma$)
b	Burgers vector module	φ	slip plane normal-load direction angle
d	grain size	γ	slip direction-load direction angle
dl/dN	fatigue crack growth rate	ν	Poisson's ratio
E	elastic modulus	N	number of load cycles
ΔK	stress intensity factor range	R	stress ratio
ΔK_T	stress intensity factor range for the physically small crack-to-long crack transition	r_{pc}	cyclic plastic zone size
ΔK_{th}	fatigue threshold stress intensity factor range for long crack	σ_a	cycle stress amplitude
$\Delta K_{th,d}$	fatigue threshold stress intensity factor range for microstructurally short crack	σ_f	internal friction stress in the crystal lattice
$\Delta K_{th,eff}$	effective fatigue threshold stress intensity factor range	$\sigma_{\max}$	maximum cycle stress
$\Delta K_{th,in}$	internal fatigue threshold stress intensity factor range	σ_p	proportionality limit
$\Delta K_{th,l}$	fatigue threshold stress intensity factor range for physically small crack	σ_{-1}	fatigue limit at the symmetric load cycle
$K_{I\max}$	maximum stress intensity factor of the mode I	Y, Y_1, Y_2, Y'	geometry factors (stress intensity factor corrections)
l	surface half-penny crack depth	CC	crack closure
l_o	fictitious crack length	HCF	high cycle fatigue
l_i	intermediate physically small crack depth at $\sigma_{-1} < \sigma_a \leqslant \sigma_p$	HCP	hexagonal close-packed
l_i'	physically small crack depth at the transition point to long crack	FCGC	fatigue crack growth curve
l_s	intermediate physically small crack depth at $\sigma_a = \sigma_{-1}$	KT	Kitagawa–Takahashi diagram
l_t	final long crack depth (fatigue fracture criterion)	LC	long crack
M	Taylor factor ($M = 1/m_s$)	LCF	low cycle fatigue
		LEFM	linear elastic fracture mechanics
		MSC	microstructurally short crack
		PSC	physically small crack
		PZ	plastic zone
		SIF	stress intensity factor

– an average PSC growth rate at low levels of load decreases with increasing ΔK, sometimes reaching the minimum, after which it increases again, gradually approaching the LC growth rate;
– for the same applied ΔK, PSCs grow more rapidly than LCs.

The above features were revealed from the experimental data on PSC and LC growth represented in a way traditional for LEFM, that is, when the applied ΔK was expressed in terms of the remote stress range $\Delta\sigma$ and crack length l:

$$\Delta K = \Delta\sigma \cdot Y\sqrt{\pi l} \quad (1)$$

where Y is the SIF geometry correction factor for the corresponding shape and size of the crack and body, and the loading conditions.

After revealing these differences, many detailed analytical and numerical models to describe PSC growth have been developed during the last 30 years [5]. However, the engineering methods require, as a rule, more simple approaches that can be easily used to predict the fatigue life during the development of novel advanced materials and the design of structures made of them.

The goal of the present paper is the development of a relatively simple model for the PSC and LC growth rate based on LEFM with consideration of the CC effect, according to which it is possible to calculate the fatigue life at stage II of fatigue fracture, having only the data on the static characteristics of the mechanical properties and microstructure of the initial material, i.e., in the absence of fatigue tests data. To do this, it was required: (i) to find the relationship between the fatigue threshold SIF ranges for a MSC, PSC, and LC, that is, to define $\Delta K_{th,d}$, $\Delta K_{th,l}$ and ΔK_{th}, respectively; (ii) to establish the criteria for the PSC-to-LC transition, that is, to determine the length l_i' at which the PSC can be already considered as a long one, depending on the load level; (iii) to derive the equations of growth rate for every phase of growth, which include only the parameters of microstructure and static strength.

2. Concept for fatigue threshold SIF ranges of material

At first, it should be noted that all the calculations given here are related to the fully-reversed uniaxial loading ($R = -1$). Therefore, it is assumed that $\Delta K = K_{I\max}$, as adopted by ASTM [6] for $R = -1$, as a result of which the stress range in all the calculations is expressed in terms of the amplitude value of $\sigma_a = \sigma_{\max}$. Thus, in the process of fully-reversed cyclic load, both PSC and LC are considered to grow only during the tension half-cycle.

For the MSC of the order of grain size d in depth to further propagate into adjacent (in depth) grains, it should have the SIF range that exceeds the so-called *microstructural* threshold SIF range $\Delta K_{th,d}$, that is, the minimum applied driving force required for the MSC to overcome the grain boundary. Using the LEFM approach, this SIF range can be expressed in terms of the minimal amplitude of the applied stress equal to the fatigue limit σ_{-1} in the following way:

$$\Delta K_{th,d} = \sigma_{-1} Y_1 \sqrt{\pi d}, \quad (2)$$

where Y_1 is the geometry factor for the deepest front point of the planar semi-circular surface crack of radius d located at the following angles (near to $\pi/4$): the angle γ between the shear direction and the load direction and angle φ between the normal to the shear plane and the load direction, since under HCF ($\sigma_{-1} \leqslant \sigma_a \leqslant \sigma_p$), a MSC initiates and grows through the maximum shear stress plane.

In its turn, the fatigue threshold SIF range, ΔK_{th}, for a LC will define the minimum applied driving force of the crack of depth $l \geqslant l_s$ with consideration of the maximum CC effect. By analogy with (2), ΔK_{th} an be expressed in terms of σ_{-1} in the following way:

$$\Delta K_{th} = \sigma_{-1} Y_2 \sqrt{\pi l_s}, \quad (3)$$

where Y_2 is the geometry factor for a planar semi-circular surface crack of radius l_s located normal to the loading direction and the infinite half-space surface in the assumption that this crack of depth