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Mode I fatigue crack-propagation mechanism based on the renewal stochastic damage-accumulation model

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Abstract

A mechanism of mode I fatigue-crack propagation, which involves the initiation and opening of the cleavage-mode crack, is proposed. This approach uses a renewal stochastic damage-accumulation model for crack propagation, in which the parameters are defined based on the dislocation density and the elastic energy of dislocation. The calculated results of $\Delta K_{\rm eff}$ for da/dn agree with the experimental data. $\Delta K_{\rm eff\,th}$ is calculated under the condition that the energy of cleavage-crack initiation is equal to that given from the outside of material. The plastic-zone size is calculated based on the number of dislocations on each slip line contained within it.

Keywords: Mode I fatigue-crack propagation; Stochastic damage-accumulation model; Cleavage-crack initiation; Crack opening; $\Delta K_{\rm eff}$ threshold

1. Introduction

Over 20 years ago, one of the authors of the current paper and his co-worker proposed a stochastic damage-accumulation model for fatigue-crack propagation [1], taking the inhomogeneity of materials into consideration. This model assumed that the region near the crack tip is composed of a two-dimensional configuration of small elements. Under repeated stress, fatigue damage accumulates inside each element. When the damage that has accumulated in a certain element exceeds its strength, the element fails and the crack propagates to the element. Moreover, the strength of an element is a random variable, and the form of the distribution function is derived from physical arguments. Thus, (1) it was shown that the crack propagation rate is proportional to some power of the stress-intensity range ΔK [2] and, at the same time, (2) the distance $\langle X\rangle$ propagating for one step of intermittent crack growth and (3) the cycle number $\langle N\rangle$ expended for one step were obtained. The model supported the occurrence of striation based on the calculated result that

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Nomenclature

a	a crack length
b	Burgers vector
c_0	a parameter that represents the extent of accumulated damage per cycle
D	the assumed process region in the damage accumulation model
d_0	the scale of small material elements in the damage accumulation model
E	elastic modulus
$\mathcal{g}$	energy release rate
G	shear modulus
L	length of the dislocation segment; random variable
l_0	the mean of L
l_c	minimum length of a dislocation segment
m	number of dislocations on one slip line
m_0	number of dislocations necessary to nucleate a micro-crack
n	cycle number for repeated loading stress
N	cycle number expended for one step of crack growth; random variable
R	effective radius of the stress field of dislocation
S	stress amplitude
S_Y	yield strength
U	threshold value of damage accumulation (element's strength measured with a unit of damage)
W	energy of a nucleated crack with a length d_0
w	the breadth of region D in the direction of crack propagation
w_p	length of the slip band in the plastic zone at the crack tip
X	the distance for crack growth to propagate for one step; random variable
γ_S	surface energy
δ	a constant
ΔK	range of the stress-intensity factor
ΔK_{eff}	effective value for ΔK
$\Delta K_{eff\,th}$	threshold for ΔK_{eff}
$\Delta\phi_t$	range of the crack tip opening displacement
ε_p	plastic strain at the arrival time to the lower yield point
ν	Poisson ratio
ρ_U	the value of dislocation dipole density at the instant of crack initiation
$\sigma(i,j)$	average of the damage per cycle accumulated in (i,j)-element

$\langle N \rangle$ decreased to 1 with an increase of ΔK. However, this was only a mathematical model, and the physical meanings of the parameters were unclear.

Recently, progress has been made in two directions. Firstly, the physical meaning of the above-mentioned parameters has been clarified through the study of fatigue-crack initiation [3]. Secondly, the slip-deformation behavior near the crack tip has been observed using an atomic-force microscope (AFM) by Jono et al. [4], and the relationship between the slip deformation and the propagation behavior of the crack has been revealed.

In the current paper, the original stochastic damage-accumulation model of crack propagation is initially explained. Then, the physical meanings of the parameters in the model are discussed, based on the dislocation theory. Finally, a mode I fatigue crack-propagation mechanism is proposed, taking into consideration the results observed by Jono et al. The results calculated using the renewal model are compared with the experimental data using 3% silicon iron [5]. $\Delta K_{eff\,th}$ is derived under the condition that the energy of cleavage-crack initiation is equal to that given from the outside of material. The plastic-zone size is also calculated based on the numbers of dislocations in each slip line contained within it.