NEW FUNDAMENTAL FRACTURE CRITERIA

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For the first time attention has been paid to possible interaction between the growing crack and electromagnetic field occurring under plastic strain and material fracture. On the basis of the analysis made new fundamental criteria of fracture have been derived. With metal materials for example it has been shown that new criteria make it possible to predict the emergence of the critical stage under fatigue connected with transition from stable development of fatigue crack to the unstable (intermittent) one.

INTRODUCTION

As it is known (1 - 5) under certain conditions the crack propagation process takes a discontinuous and intermittent character sharply increasing the probability of a sudden brittle fracture. Extensive research of this phenomenon for the cycling loading conditions has revealed some mechanisms of its development (4, 5). It has been shown that the threshold value of the stress intensity factor K^{1}_{fc} , beginning from which intermittent crack growth is observed, is independent of the specimen's dimensions, load ratio of the loading cycle and the cycle freguency. The specimen's dimensions do not affect the length of the brittle crack jump, the length of the stable crack growth region and the number of loading cycles before the crack jump. The jump lenth is irrespective of the crack length from which its jump starts and as a rule it exceeds the size of the plastic zone in the crack tip.

The performed investigations, however, have not disclosed the nature of the phenomenon being observed. The problem concerning the prediction of the occurrence of the crack development stage dangerous for the structure durability remains unsolved. In the present paper the possible nature of the phenomen is discussed and on the basis of the developed ideas the criteria

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determining the stage beginning of the intermittent crack growth have been offered.

THEORETICAL BASIS

In the 1970 - s a phenomenon of electromagnetic radiation origin under plastic strain and fracture of solids was discovered (6). Later, a thorough study of this phenomenon revealed a series of new facts (7, 8). In particular it has been shown that as a result of interaction with dislocation structure and crack an ultrasonic wave passing through a crystal stimulates electromagnetic radiation with the frequency of this wave and with that twice lower. The amplitude of the arising signal is unaffected by the crystal orientation. By the emergence of the crack the disturbance of radiation spectrum is observed. In its turn the disturbance spectrum is unchangeable while going from one crystal plane of fracture to another and by varying the loading mode.

The experimental results presented have laid the foundation of the following physical model developed on the basis of the phonon conception of fracture suggested by the author (9, 10). In accordance with the fracture phonon conception quite a definite discrete spectrum of natural frequencies of atom modes in the lattice corresponds to every real crystal material. In this spectrum atom mode frequencies ν_i are less than the Debya's frequency approximately by an order of magnitude. They are determined by the type of dislocations specific for a given solid structure and theoretically can by calculated for any crystal. When the originating hypersonic waves pass through diclocation structure and crack, electromagnetic radiation with the frequency of these waves and with that twice lower $(\nu_i^0 = \nu_i / 2)$ is being stimulated in full conformity with the above observations. The latter probably corresponds to the frequency of zero modes. The signal amplitude will be maximum at the moment of the crack initiation. In their turn, the arising electromagnetic modes will interact with the crack being formed. Similar interaction, however, will occur only in case when the length of the originating radiation wave is less than the crack size, otherwise, the waves will not "feel" the crack. Moreover, the crack may sense the wave energy only in quants.

Thus, in conformity with the accepted model a formed crack, when reaching a critical length being quite definite for each material, begins to absorb energy from the surrounding electromagnetic field which results in a sharp increase of the crack growth rate. In other words when the growing crack reaches a certain threshold size ($a_i = \lambda_i$, where $\lambda_i = c/\nu_i$; c - velocity of light) there appears additional crack - driving force resulting from its interaction with the surrounding electromagnetic field sharply increasing the growth of this crack :

$$G_i = h\nu_i \cdot \lambda_i = hc, \qquad (1)$$

where G_i - crack - driving force (dimensions of G_i : $J \cdot m / atom$ or J/m^2 or N/m) ; h - Plank's constant. Griffith's criteria for macroscopic and microscopic fracture coincide (11). Having that in mind one can assume that the emergence of the force mentioned above implies the effective stress intensity factor in microvolume for example under conditions of plane strain:

$$K_{Ii} = \sqrt{\frac{G_i \cdot E}{1-\mu^2}}\ , \qquad (2)$$

where E - Young's modulus; μ - Poisson's ratio. If it is assumed that subsequently (by $a > a_i$) the crack growth occurs in a discrete way with the step a_i ($a = N{\cdot}a_i$, where $N = 1,2,3...$), the value G_i remains invariant to the crack length. Numerical values of the new constant G_i for certain pure metals at the room temperature are given in Table 1. As this constant is defined through fundamental material constants, data represented in Table 1 can be used for alloys based on these metals. Obviously, criterion G_i practically is not dependent upon temperature.

TABLE 1 - Several constant values of metals.

Metal	G_i (kN/m)	E (GPa)	μ	K_{Ii} $(MPa\sqrt{m})$
Mg	8.56	42.2	0.33	20.1
Al	12.0	70.6	0.32	30.7
Ti	11,2	110	0,31	37,0
Fe	16,8	210	0,28	62,0
Ni	18,3	210	0,31	65,2
Cu	16,8	128	0,34	49,4
Mo	12,7	317	0,33	67,2
W	12,6	397	0,30	74,0

The notion of the fact that under certain condition of additional energy (force) the real crystals appear in local volumes allows not only to explain the occurrence of the above critical stage in the fatigue crack development but to predict the emergence of this stage with great accuracy. According to the model developed the critical stage comes when the stress itensity factor reaches the threshold value K^1_{fc} , being defermined from the expression:

$$K^{1}_{fc} = \sqrt{\frac{(G_{Ic} - G_{i}) \cdot E}{1 - \mu^{2}}}, \tag{3}$$

where G_{Ic} - critical value of crack - extension force. Beginning from this moment in local material volumes stress intensity factor reaches the critical values (K_{Ic}) and the conditions are created for the unstable crack growth. It should be underlined that the critical stage comes with all materials. Within this stage, however, the crack development occurs in different ways with various groups of materials depending probably on the energy level required for fracture. At the low level of this energy (by materials in the embrittled state) when the critical stage comes, the unstable crack growth is possible. It is not excluded that the relevant structure plays a certain role in the emergence of such instability. At the critical stage by high level of fracture energy the crack growth rate sharply increases, but the trasition from the stable crack development to the intermittent one may not occur, because the excess of energy is partially absorbed by the neighbouring volumes.

The value G_{Ic} can be defined by the process of calculation (12) according to the mechanical properties or directly by the static crack - resistance test. In the latter case it is not appropiate to turn to the value G_{Ic}, but one should define the criterion K^{1}_{fc} by the expression:

$$K^{1}_{fc} = \sqrt{K^{2}_{Ic} - K^{2}_{Ii}} \tag{4}$$

The values of K_{Ii} for pure metals are also given in the Table 1. It should be noted that the direct method of determination of G_{Ic} (K_{Ic}) for materials with high level of residual stresses (steel after hardening and low tempering, materials after welding, ets.) is not acceptable, because in this case the obtained values G_{Ic} (K_{Ic}) appear to be underestimated (13), and don't characterize the true value of fracture energy.

ANALYSIS AND DISCUSSION

Available experimental data confirm the correctness of the statements being developed and demonstrate that the new criteria can be used for prediction of dangerous stage in the crack development. Especially close coincidence of the experimental values K^{1}_{fc} and those calculated by the expression (4) obtained by different authors was observed in those cases when the beginning of the unstable (intermittent) crack development was determined with the help of acoustic emission signals (14, 15). For example by studying the unstable development of fatigue cracks in embrittled steel 15H2MFA (K_{Ic} = 67.6 $MPa\sqrt{m}$) the value K^{1}_{fc} = 27.1 $MPa\sqrt{m}$ has been obtained (15). The calculation by the expression gives K^1_{fc} = 26. 9 $MPa\sqrt{m}$. Two alternate versions are usually realized. If the initial value of the stress intensity factor K^0_{Imax} exceeds the value K^1_{fc} , intermittent crack growth starts from the first cycles, as for example in experiments on alluminium alloys (1) and steels (2). If $K^0_{\mathrm{Imax}} < K^1_{fc}$, then a certain incubation period, during which stress intensity factor increases from K^0_{Imax} to threshold value K^1_{fc} , precedes the unstable period of crack growth, as in experiments on steels (5, 15).

The main peculiariaties of the phenomenon stated in the introduction have been explained and discovered within the scope of the model being suggested. By reaching the value K^1_{fc} in lokal volumes adjacing the tip of the developing main crack the critical situation occurs and the first jump of the crack by the value λ_i takes place. Further growth of this crack till the loss of general stability will proceed according to the condition:

$$K_{Ic} = \sigma_N \sqrt{\pi\lambda_i N}, \tag{5}$$

where $\lambda_i N$ - the size of a brittle crack jump; N = *1,2,3...*; σ_N - effective local stress. From the expression (5) it follows that the jump size is defined only by the wave length of the arising radiation and is independent of the length of the initial main crack and the specimen's size. The value σ_N for the greater subsequent jumps of the crack is created during the process of preliminary stationary growth of the main crack before these jumps. In conformity with the expression (5) with increasing jump length the required amplitude of the effective local stress is decreased as compared to the initial one (at the moment of the first jump) according to the law $1/\sqrt{N}$. Hence the value of the fatigue crack growth between the jumps and the number of cycle loading before the crack jump is also decreased.

The role of the new constant G_i probably will be essential for materials of other nature as well. For example the calculations demonstrate $G_i >> G_{Ic}$ for ceramic materials. Hence, certain experimental data indicating the difficulty of growing "good" crack in such materials have become clear: the initiated fatigue crack immediately loses its stability.

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