SAFE DAMAGE FATIGUE CRITERIA

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In the paper on the basis of accepted physical model an attempt was made to calculate new material constants - the criteria of safe damage K_{1w} (K^{0}_{1w}) by reaching which the stable growth phase of fatigue crack ends and its accelerated propagation starts. These constants common for the given base alloys can be used for estimation of admissible critical sizes of fatigue crack l_d, which does not lead to emergency situation.

INTRODUCTION

In the beginning of the 1960-s by the structure design a new principle of safe damageability under which the emergence of fatigue crack of the definite length l_d in exploitation is admitted to be possible, began to be used. The term “safe damageability” means that the crack appearance of the length l_d should not result in breakdown. In the papers (1,2) it was proposed that the admissible critical sizes of fatigue crack l_d could be determined from the value of stress intensity factor K_{1w} - the value K_1 ($ÄK_1$) under which the stable phase of fatigue crack ends and accelerated propagation begins. The authors believe that the value K_{1w} should be fundamental by the calculation of safely damageable structure elements. By experimental investigation it was determined that for one base alloys the criterion K_{1w} appears to be a certain constant independent of composition and thermal treatment. For aluminium alloys the average value K_{1w} proved to be 20,7 MPa$\sqrt{m}$, for titanium alloys - 36,4 MPa$\sqrt{m}$.

Unfortunately, these pioneer investigations have not been further developed. In the given paper it is demonstrated that fatigue criteria K_{1w} proposed by the authors (1,2) can be calculated from the first principles on the basis of phonon conception of fracture (3 - 5). Thus, we can assume that criteria K_{1w} are related to fundamental criteria of cyclic crack resistance and effective fatigue threshold $ÄK_{eff,th}$ as well as minimum of fatigue spacing stations S_e can be also referred to these criteria (5).

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THEORETICAL BASIS

Fracture phonon conception of metal materials has been developed by one of the authors on the basis of a decisive role of crystal lattice phonon subsystem in fracture. The presence of dislocation in crystals causes the appearance of specific i-mode vibrations in phonon spectrum the wavelength of which is defined by the effective width of dislocation cores in the corresponding directions of the lattice elastic waves propagation. A concept of threshold energy levels $W_i = h\nu_i$ (ν_i - vibration frequency of i-mode) which a lattice can absorb during loading until fracture has been introduced. Each metal (and alloys on its base) has its discrete spectrum of W_i - value, which is slightly affected by alloying and thermal treatment. However, the latters influence the position of principal threshold energy level W_i^k in discrete spectrum corresponding to the principal threshold i^k - mode of vibrations. It is by absorption of threshold energy W_i^k, that the final fracture of a specimen (a piece) occurs, though breakdown of atomic bonds in local volumes takes place by rendering all threshold levels W_i . The latter is of great importance by preparation of material for final fracture and can be employed by working out the criteria of safe damage. Thus, energy levels W_i specify the limiting local energy capacity and represent new constant values of materials. They were calculated by the molecular dynamics method for several commercially important metals with different types of crystal lattice. The knowledge of these new energy criteria permits one to solve a number of applied problems. In particular, using the known relation by Griffith - Orovan the discrete spectrum of all possible values of fracture toughness K_{Ic} for alloys on the given base can be calculated from the following formula (4):

$$K_{Ic}^{(i)} = \sqrt{\frac{0{,}8LW_iE}{1-\mu^2}}\,, \qquad (1)$$

where **L** - constant having a length dimension and equal to 10^{-3} m; E - modulus of elasticity; ì - the Poisson’s ratio; i – ordinal number of the energy level.
The final fracture of the specimen with a crack for each concrete alloy takes place at the following condition:

$$K_{Ic}^{(k)} = \sqrt{\frac{0{,}8LW_i^kE}{1-\mu^2}} \qquad (2)$$

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. In particular, it was shown (7) that as a result of interaction with dislocation structure and cracks an ultrasonic wave passing through a crystal stimulates electromagnetic radiation with the frequency of this wave and with that twice lower.

In full conformity with the above observations it was assumed by the author (8), that when the originating hypersonic waves of frequency ν_i(the waves are formed in crystals in accordance with phonon conception of fracture (3 -5)) pass through dislocation structure and cracks electromagnetic radiation with the frequency of these waves and with the one twice lower ($\nu_i^0 = \nu_i/2$) is being stimulated. The arising electromagnetic oscillation will interact with the growing crack. Similar interaction will occur only in case when the length of the originating radiation wave λ_i is less than the crack size, otherwise, the waves will not "feel" the crack. Moreover, the crack may perceive the wave energy only in quantums.

Thus, a formed crack when reaching a critical length being quite definite for each material begins to absorb energy from the surrounding electromagnetic field. This must result in a sharp increase of the crack growth rate. The arising additional crack-driving forces can be determined by the expressions:

$$G_i = h\nu_i \times \lambda_i = hc \tag{3}$$

and

$$G_i^0 = \frac{h\nu_i}{2} \times \lambda_i = \frac{hc}{2}, \tag{4}$$

where c - velocity of light. The appearance of the above forces is equivalent to the increase of the operating stresses intensity coefficients in local volumes by a magnitude respectively:

$$\boldsymbol{K_{Ii} = \sqrt{\frac{G_i E}{1-\mu^2}}} \tag{5}$$

and

$$\boldsymbol{K_{Ii}^0 = \sqrt{\frac{G_i^0 E}{1-\mu^2}}}, \tag{6}$$

Numerical values of new constants under room temperature for some pure metals are given in Table 1. Since these constants are defined by fundamental material ones, the criteria presented in Table 1 will be also correct for alloys on the base of these metals.

TABLE 1 - Several constant values of metals

Metal	G_i	G_i^0	E	ì	K_{Ii}	K_{Ii}^0
	(kN/m)		(GPa)		(MPa$\sqrt{m}$)	
Mg	8.56	4.28	42.2	0.33	20.1	14.2
Al	11.96	5.98	70.6	0.32	30.7	21.7
Ti	11.26	5.63	110	0.31	37.0	26.2
Fe	16.82	8.41	206	0.28	61.3	43.4
Ni	18.24	9.12	210	0.31	65.2	46.1
Cu	16.82	8.41	115	0.34	46.8	33.1
Mo	12.72	6.36	317	0.33	67.2	47.5

The notion of additional energy (forces) emergence in crystal local volumes makes it possible not only to explain the origin of accelerated propagation phase of fatigue crack, but also to predict the beginning of this phase. If for a safe damage criterion we take value K_{1w} by reaching which accelerated propagation of fatigue crack begins in accordance with the model being developed this criterion can be determined by the expression:

$$K_{1w} = \sqrt{\frac{\left(G_{Ic}^{(1)} - G_i\right)E}{1-\mu^2}} = \sqrt{(K_{Ic}^{(1)})^2 - K_{Ii}^2} \qquad (7)$$

and

$$K_{1w}^0 = \sqrt{\frac{(G_{Ic}^{(1)} - G_i^0)E}{1-\mu^2}} = \sqrt{(K_{Ic}^{(1)})^2 - (K_{Ii}^0)^2}\ , \qquad (8)$$

where $G_{Ic}^{(1)}$ are critical values of crack-driving forces, corresponding to the first threshold energy level W_1. From this moment stress intensity factor achieves critical values ($K_{Ic}^{(1)}$) in material local volumes and conditions for accelerated crack development are being created.

NUMERICAL RESULTS. EXPERIMENT AND DISCUSSION

Table 2 illustrates numerical values of the above mentioned criteria. Obtaining of the value K_{1w} marks the end of the stable stage of fatigue crack growth and the beginning of its quick spreading. Precisely these values of K_{1w} are to be considered as criteria of the safe materials' damageability and should be taken as a basis for the calculation of critical values of the fatigue crack l_d. It is important to emphasize that obtaining of the above mentioned critical stage corresponds to the beginning III stage of fatigue only for those alloys which have the lowest value of static toughness of fracture ($\boldsymbol{K}_{Ic}^{(1)} = \boldsymbol{K}_{Ic}^{(k)}$).

TABLE 2 - Calculated values of the safe damage criteria ($MPa\sqrt{m}$)

Criteria	Metal						
	Mg	**Al**	**Ti**	**Fe**	**Ni**	**Cu**	**Mo**
$\boldsymbol{K}_{Ic}^{(1)}$	26.5	30.3	51.9	92.2	69.6	41.0	102.9
$\boldsymbol{K}_{1w}$	17.3	-4,9	36.4	68.9	24.4	-22.6	77.9
$\boldsymbol{K}_{1w}^{0}$	22.4	21.1	44.8	81.3	52.1	24.2	91.3

For such metals as Al and Cu (and also Ag, Pt, Pd and Cd according to the preliminary data [9]) the criterion $\boldsymbol{K}_{1w}$ is a negative value (Table 2). It means that the above materials have completely enough level of additional energy $\boldsymbol{G}_i$ required for the damage of local volumes ($\boldsymbol{G}_i > \boldsymbol{G}_{Ic}^{(1)}$). Therefore even occasionally appeared crack begins its intensive growth (such peculiarity is the main reason of absence of physical fatigue limit [9]). The growth of fatigue cracks in such materials should be characterized by continuously increasing acceleration. As a criterion of the safe damageability for them the criteria $\boldsymbol{K}_{1w}^{0}$ should be taken. When obtaining the above criterion the inflection in the direction of the more intensive growth of the crack will be observed on the acceleration curve.

Figure 1 illustrates the results of experimental research on determination of the safe damageability criteria in aluminium and titanium alloys. According to the presented data it can be seen that the processes of the fatigue cracks growth in these groups of materials are significantly different. If titanium alloys have the stable stage of fatigue crack growth, then the same process in aluminium alloys is characterized by constantly increasing acceleration in the whole investigated interval of the values $\boldsymbol{K}_{max}$. For titanium alloys the corner point on the acceleration curve of the moving crack is very close to the calculated value $\boldsymbol{K}_{1w}$, and for aluminium alloys it is very close to the value $\boldsymbol{K}_{1w}^{0}$ (Table 2).

Static toughness of fracture of aluminium alloy AD – 33T1 corresponds to the lowest possible level ($\boldsymbol{K}_{Ic}^{(1)} = \boldsymbol{K}_{Ic}^{(k)}$). In accordance with the above analysis for the given alloy the obtaining of the criterion $\boldsymbol{K}_{1w}^{0}$ marks also the passage to the III fatigue stage. It may be seen in the Figure 1a that acceleration of the moving crack in this case increases more significantly than in the rest investigated alloys, having the higher level of static fracture toughness.

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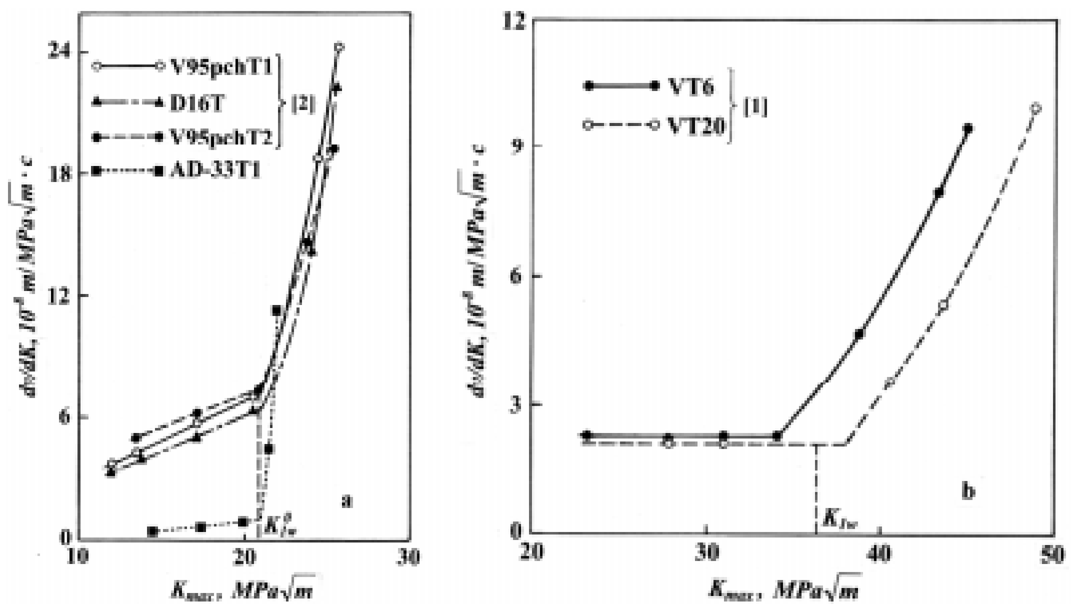

Figure 1 Acceleration curves of fatigue crack in aluminium (a) and titanium (b) alloys plates