FRACTURE AS A DISCRETE PROCESS

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ABSTRACT

The authors' results are generalized for proving the decisive role of phonon subsystem in metallic materials fracture. It is shown that for the alloys on the given base there is a discrete spectrum of the most important criteria of crack stability under static (K_{Ic}) and cyclic ($\Delta K_{eff,th}$) loadings.

KEYWORDS

Mode; phonons; discreteness; prediction; fracture toughness; effective threshold.

INTRODUCTION

It is known, that under certain conditions the process of materials fracture obtains abrupt, discrete character. This phenomenon is being intensively studied nowadays. The consideration of this in some cases enables to simlify to a great extent and to accelerate obtaining of parameters of crack stability, to predict the material behaviour under different schemes of force loading. While developing the phonon conception of metallic materials fracture, the author (Ragozin, 1988, 1990, 1992) came to a conclusion concerning the decisive role played in fracture by phonon subsystem of crystal lattice. The presence of dislocations in crystals effects the emergence of specific i-mode vibrations in phonon spectrum, the wavelength of which is specified by the effective width of dislocation cores in the corresponding directions of lattice elastic waves propagation. A new conception is introduced about threshold energy levels $W_i = h\nu_i$ (ν_i - vibration frequency of i-mode), absorbable by the lattice during loading. Every metal (and alloy on its base) has specific discrete spectrum of W_i- value that is affected by alloying and thermal treatment only insignificantly. However the latters affect the location in discrete spectrum of main threshold energy level W_i^0 , corresponding to main threshold i_0-mode of vibrations. The fracture of interatomic bonds in crystal lattice takes place just in time of superposition of quantum vibrations (phonons) of i_0-mode. So, energy levels W_i specify local energy limit consumption and they represent new constant values of materials. They have been calculated for a number of industrial important metals with different types of crystal lattice (Fig.1).

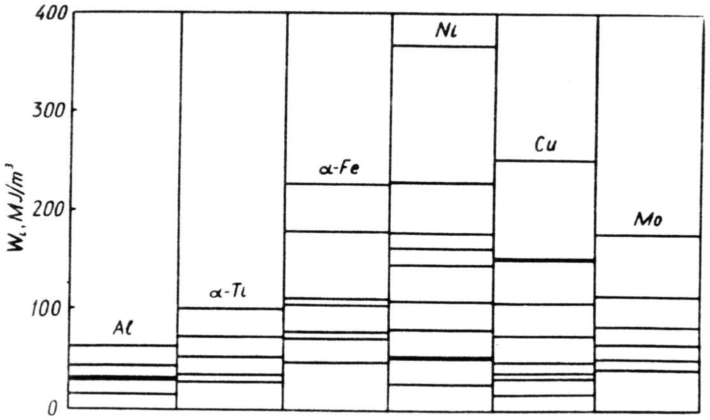

Fig.1. Spectra of energy threshold levels W_i for different metals calculated on the basis of phonon conception of fracture.

Further it is shown that the value of new energy constant values enables to predict values of the most important criteria of materials crack stability during static (K_{Ic}) and cyclic ($\Delta K_{eff,th}$) loadings. For the alloys on the specific base the above criteria are distributed on discrete levels - in full correspondence with conception being developed.

PREDICTED VALUES OF FRACTURE TOUGHNESS K_{Ic}

The process of solid strain may be described according to the first law of thermodynamics by correlation:

$$\Delta U = Q + W, \tag{1}$$

where ΔU - change of body internal energy; Q - thermal effect connected with strain; W - work. During process of strain to fracture work W represents fracture energy W , while ΔU - positive value equal to maximum value of latent energy of cold-work hardening U , i.e. the correlations are true:

$$\begin{gathered} U_s^{max} = Q + W_F \\ Q < 0 < W_F ; \quad |Q| < |W_F| \end{gathered} \tag{2}$$

It is possible to assume that on threshold of unstability under conditions of flat strain the heat release is minimum and hence W_F - value is close to U_s^{max} ($W_F = U_s^{max}$). So the maximum value of strain latent energy is just the value (for a volume unit) the absorption of which specifies criterion K_{Ic} . According to the phonon conception of fracture (Ragozin, 1990) threshold energy levels W_i specify possible limit energy consumption of local volumes of alloys on specific base, i.e. $W_i = U_s^{max}$. This gives possibility to estimate levels of crack stability (K_{Ic}) for the alloys with known spectrum of W_i - values. Using the known equation of Griffith-Orovan, fracture toughness K_{Ic} may be determined from expression (Ragozin, 1984):

$$K_{Ic} = \sqrt{\frac{2\,\gamma_{eff}^{min}\,E}{1-\mu^2}} = \sqrt{\frac{0{,}8\,L\,U_s^{max}\,E}{1-\mu^2}} = \sqrt{\frac{0{,}8\,L\,W_i\,E}{1-\mu^2}}, \tag{3}$$

where - γ_{eff}^{min} minimum value of effective surface energy, corresponding to minimum value of fracture toughness K_{Ic}; L - constant value with linear dimension and equal to 10^{-3}m; E - elasticity modulus; μ - Poisson's ratio. Fig.2 presents predicted K_{Ic} - values for alloys with known spectrum of energy threshold W_i -values calculated by correlation (3) (Fig.1).

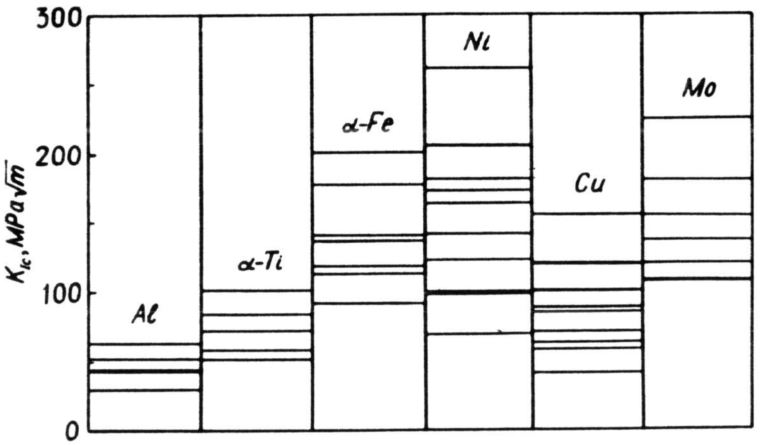

Fig.2. Spectra of predicted values of fracture toughness K_{Ic} for alloys on base of Al, Ti, Fe, Ni, Cu and Mo.

The extensive comparison of predicted K_{Ic} - values with the experimental ones proved good agreement of theory and experiment in case if the action of negative factors sharply reducing the level of alloys fracture toughness would be brought to minimum. These factors are: high level of residual stresses, separation of grains along boundaries effecting early fracture, exfoliation, preliminary cold strain.

As an example Fig.3 shows horizontal lines for predicted values of fracture toughness for aluminium (a) and titanium (b) alloys. It shows also experimental K_{Ic} - values depending on yield point σ_{ys} for many important industrial alloys of aluminium (Kudryashov and Smolentsev, 1976) and titanium (Drozdovsky, 1983) with different conditions of manufacturing and methods of specimens strengthening. Fig.3 proves that experimental K_{Ic} - values are really located close to the calculated discrete levels of fracture toughness.

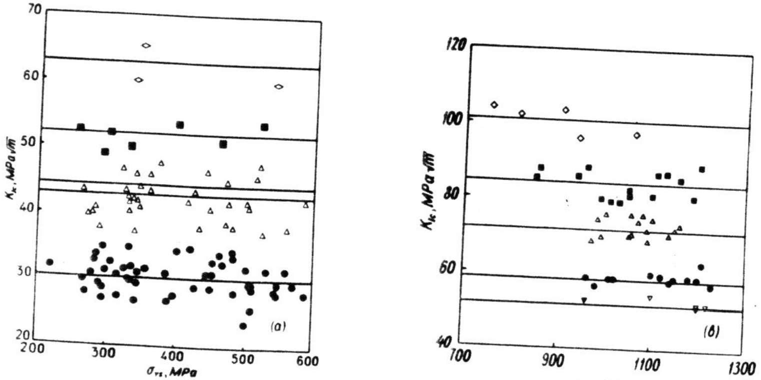

Fig.3. Calculated and experimental values of fracture toughness for aluminium (a) and titanium (b) alloys.

PREDICTED VALUES OF EFFECTIVE THRESHOLD $\Delta K_{eff,th}$

Strain and fracture of metals are accompanied by different physical phenomena, including emergence of electromagnetic radiation in wide range of frequencies up to X-ray range (Tupik et al., 1985; Deriagin et al., 1985). On the basis of these observations it was assumed (Ragozin, 1992) that during propagation of a fatigue crack the high frequency electromagnetic radiation emerge that penetrates metal and affects its thin structure: size of fragments (cells or subgrains) forming in plastic zone ahead of crack tip is determined by halfwavelength of penetrating radiation. At initial step of the crack development the size of fragments in its turn specifies striation spacing (Grinberg, 1985). Taken all this into consideration, and also under condition, that energy absorbed near the crack tip equals to one of energy threshold W - values for the specific material, a formula has been drawn (Ragozin, 1992) for calculation of range of effective threshold ratio of stresses intensity as:

$$K_{eff,th} = 2,5\sqrt{W_i E \lambda_p} \quad , \qquad (4)$$

where λ_p - radiation wavelength ($\lambda_p = 2\pi c/\omega_p$, where c - velocity of light, ω_p - plasma frequency).

As it was mentioned above there is a characteristic discrete spectrum of energy threshold levels W_i for every metal or alloy on its base. Then according to correlation (4) they would also have characteristic discrete spectrum of $\Delta K_{eff,th}$, -values. The Table presents levels $\Delta K_{eff,th}$, calculated by equation (4) for industrial important metals (and alloys on their base).

Table. Calculated levels of effective threshold stress intensity ranges in Al, Ti, Fe, Ni, Cu and Mo at room temperature air.

Metals	$\Delta K_{eff,th}$, MPa $\sqrt{m}$										
	1	2	3	4	5	6	7	8	9	10	11
Al	0.72	1.02	1.06	1.24	1.50						
Ti	1.18	1.33	1.64	1.93	2.30						
Fe	2.23	2.73	2.86	3.30	3.40	4.31	4.85				
Ni	1.63	2.31	2.35	2.87	3.32	3.84*	4.07*	4.26*	4.82*	4.84*	6.13*
Cu	0.85	1.20	1.30	1.47	1.83	1.74*	2.06*	2.07*	2.45*	2.47*	3.17*
Mo	3.26	3.28	3.65	4.15	4.68	5.47	6.81				

* with package defects

It is known that experimental determination of $\Delta K_{eff,th}$, is quite labour intensive process. The sufficient quantity of experimental data for analysis by the value of this threshold is available only for aluminium alloys and steels. The wide comparison (Fig.4) of calculated values $\Delta K_{eff,th}$, (Table 1) with experimental values $\Delta K_{eff,th}$, obtained by the different authors was carried out just for these materials: Al-alloys - (Akiniwa et al., 1988; Bignonnet et al., 1986; Branco, 1992; Lefrancois et al., 1986; Minakawa et al., 1986; Newman et al., 1988; Petit and Zeghloul, 1986; Scheffel and Detert, 1986; Zaiken and Ritchie, 1985; Zhao et al., 1986), steels - (Aoki et al., 1986; Braid et al., 1987; Guerra and Branco, 1984; Henaff and Petit, 1992; Masuda et al., 1980; Ostash et al., 1987; Reinhard, 1991; Romaniv et al., 1984; Tkach and Lenets, 1985). Since closure of crack may be neglected under high levels of asymmetry ratio R (> 0.7)$\Delta K_{eff,th}$, is equal to ΔK_{th} , under R > 0.7 [Liaw et al., 1983].

$\Delta K_{eff,th}$ - values under R > 0.7 are also presented on Fig.1. One may easily observe good agreement of calculated and experimental $\Delta K_{eff,th}$, -values.

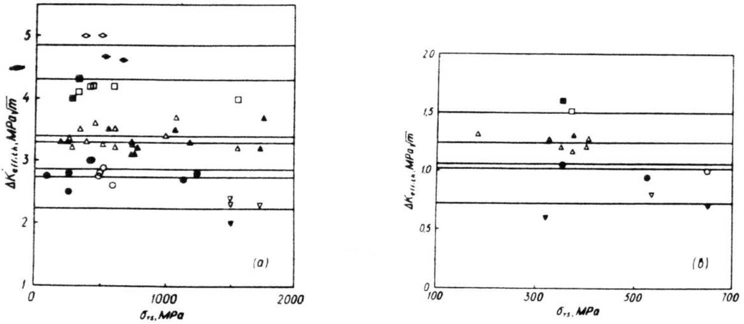

Fig.4. Calculated spectrum of $\Delta K_{eff,th}$, value for steels (a) and aluminium alloys (b) and experimental data of different authors. Dark symbols - $\Delta K_{eff,th}$; light symbols - ΔK_{th} (when R > 0.7).

CONCLUSION

So, the existence of discrete spectra of the most important criteria of crack stability (K_{Ic},$\Delta K_{eff,th}$) is well supported experimentally. The data presented here is only a part of active investigations the results of which also prove, that fracture is not only discrete, but to a large extent quantum process as well. Further studies would illustrate this.

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