The New Criteria of Metals' Bearing Ability Evaluation

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ABSTRACT: *In this paper investigations on development and application of the new criteria of materials' bearing ability are generalized. These criteria, created on the basis of phonon criteria of fracture, allow to solve a row of problems of static and cyclic strength.*

INTRODUCTION

The progress in understanding the phenomenon of fracture from positions of physics and mechanics of solids and materials study has led to the creation of logic base for the choice of materials and constructive parameters, providing safety of loaded constructions. Great attention was paid to the factors promoting fracture and methods of testing. But rather less attention was paid to the creation of fracture criteria, though during the last decades a definite progress in this direction was achieved.

On the basis of theoretical generalization of investigations in the sphere of solids physics the phonon conception of athermal fracture of metals and their alloys has been developed [1,2]. The conception allowed to show the existence of ordered spectrum of equations of local energy capacitance of the given class materials. Determination of independence of revealed levels on alloying and thermal treatment is a principally new achievement. It should be noted, that alloying and thermal treatment certainly influence the materials behavior, but their influence is manifested in the choice of an absorbed energy level by the alloy during the process of fracture. The mentioned energy levels define the limit local energy capacitance and represent the new constants of materials. They were calculated by method of molecular dynamics for a number of industrially important metals with a different type of crystal lattice. The phonon conception of fracture allowed to define more exactly the physical meaning of widely used criteria of fracture mechanics and to calculate values in the wide range of temperatures. A row of physically proved new fracture criteria have been developed. It allowed to solve numerous problems of static and cyclic strength. Achievements, mentioned in the present paper, are generalized with a hope for their widest application in research practice and industry.

PHYSICAL NATURE OF SOME CRITERIA OF FRACTURE MECHANICS

Base Diagrams of Mechanic State

The threshold levels of energy W_i, calculated on the basis of phonon model of fracture [1,2], correspond to the maximum value of the latent energy of cold-work hardening $U_s^{\max}$, absorbed by lattice during the loading before the fracture. In a real solid there are always the micro-volumes, where the stresses relaxation is absent because of some reasons. So all mechanical energy is accumulated in them up to the fracture. Numerous investigations [3] showed, that during the process of simple tension the first centers of irreversible micro-damages in the volume of samples arise in the moment when loading reaches its maximum value, i.e., at the moment when the fatigue limit of a material σ_{TS} is reached. In this case the full specific work of the uniform deformation A_e, including also elastic component , may be accepted as energy criterion of fracture and compared with calculated equations of energy W_i. It is convenient to present the energy criteria W_i and A_e in the dependence on the alloys fluctuation limit. The similar actions were made for the alloys on the basis of Al, Cu, α-Fe and α-Ti [2,4]. The minimum deviations of A_e from W_i indicate that alloying and thermal treatment has rather small influence on the location of energy levels in the spectrum.

In fact the above mentioned constructions represent the base diagrams of mechanical state for each type of alloys. They demonstrate visually the influence of composition, structure and thermal treatment on the alloys' carrying ability and allows to reveal the more perspective of them, located in the upper left corner of the diagram.

Predicting Values of Static Velocity of Fracture K_{ic}

The diagrams mechanical state allow to predict levels of the crack-resistance K_{ic} of those metals and their alloys, for which the spectrum value W_i is known. As it is shown in the work [5], by means of the well known Griffits – Orovan equation it is possible to define the fracture velocity according to the expression:

$$K_{ic} = \sqrt{\frac{2\gamma_{eff}^{\min} E}{1-\mu^2}} = \sqrt{\frac{0{,}8LU_s^{\max} E}{1-\mu^2}} = \sqrt{\frac{0{,}8LW_i E}{1-\mu^2}}, \tag{1}$$

where $\gamma_{\$}^{\min}$ - is a minimum effective surface energy; L – is a constant, having dimension of length and equal to 10^{-3}; E – is an elasticity modulus; μ - is a Poisson's ratio.

When comparing predicting values K_{ic} with experimental ones we have obtained [5] a good conformity of the theory and experiment. The method of fracture velocity definition under the temperatures, different from the room ones, became significantly complicated. Therefore possibility of the crack resistance prediction, depending on the temperatures [6], is of particular interest. For the non-cold-brittle metal materials the problem is solved for the whole temperature interval of their possible application, for the cold-brittle ones - for the temperatures exceeding their fragile-tough passage.

The Minimum Critical Length of a Crack

As it is known, there is a certain size of the micro-crack a_0, not influencing the fatigue limit. It is supposed, that a_0 does not depend on the form of a solid and the way of its loading, but it is defined by material's nature only. According to the experimental data the estimation of this constant has been carried out for some metal materials. However definition of a crack's depth a_0 by experimental way is exceptionally laborious task. Therefore search for the analytical methods of definition of this value is rather urgent task. One of such methods was suggested in the work [7], where for the first time attention was paid to the possible interaction of growing crack with electromagnetic field, arising under deformation and fracture of crystals. In accordance with the accepted model the crack, having reached the definite for each material length a_i, begins to absorb energy from electromagnetic field surrounding it, what should lead to the sharp increase of its growth. The accepted physical model allowed to define numerical values of the new constant. It was shown that there is a discrete spectrum of values a_i, typical of each metal (and alloys on its base). Alloying and thermal treatment, having practically no influence on numerical values of a_i in the spectrum, define the level a_0 (from the spectrum), which is inherent in the given particular alloy. It is expediently to use the constant of materials a_i when analyzing the threshold situations. Let us consider only one example. Threshold conditions of fatigue cracks growth within the frames of linear mechanics of fracture is presented in the following form:

$$\Delta K_{th} = Y\sigma_{th}\sqrt{\pi a}, \tag{2}$$

where ΔK_{th} - is a threshold amplitude of the stress intensity coefficient; Y – is a calibration coefficient, taking into account the geometry of a sample and type of loading; $\Delta\sigma_{th}$ - is a threshold stress for arbitrary crack with a length a. The value $\Delta\sigma_{th}$ is increased together with decrease of a crack length and approaches to the endurance limit of a material $\Delta\sigma_{w}$ for the very short cracks. In the latter case taking into consideration the constant a_i we will have the following:

$$\Delta K_{th} = Y\Delta\sigma_{w}\sqrt{\pi a_i}, \tag{3}$$

If behavior of samples with cracks of different length up to $a = a_i$ is described by linear mechanics of fracture, then parameter ΔK_{th} must be invariant one with respect to the cracks' size. However, experimental researches have shown that parameter ΔK_{th} correctly defines the endurance limit only for samples, having a crack with a length, significantly exceeding a_i. Some hypotheses were put forward to explain this fact. But none of them can explain the new experimental results [2], affirming about discrete character of changes σ_{th} depending on the crack length. If we take into consideration the discrete character of a phenomenon when analyzing the process of fracture in micro-volumes (short cracks), then it should be more correct to present the equation (2) in the following form:

$$\Delta K_{th} = Y\Delta\sigma_{th}^{N}\sqrt{\pi N a_i} \tag{4}$$

where N = 1,2,3,…; $Na_i = a$ - values of equation parameters under N=1 characterize the process of a smooth sample testing. Whence

$$\Delta\sigma_{th}^{N} = \frac{\Delta K_{th}}{Y_N\sqrt{\pi N a}} = \frac{Y\Delta\sigma_w}{Y_N\sqrt{N}} \tag{5}$$

Comparison with experimental data has shown [2], that expression (4) reflects the dependence $\Delta\sigma_{th}$ on a crack length in a correct way.

Threshold Fatigue Criteria

The most informative characteristic of micro-relief of fatigue fractures are the fatigue grooves, allowing to evaluate the detail's longevity in the stage of the cracks' development. It is known, that for metal materials the distance between the grooves (at the initial stage of a crack growth) has the same order and does not depend on conditions of deformation, temperature, surroundings and frequency. There has been put forward a hypothesis [8], that the value of fatigue grooves' step is multiple to semilength of the wave of plasma oscillations, arising under the progress of turnpike cracks. On the basis of the accepted model the minimum step of fatigue grooves s_e has been calculated for the metals with the known value of plasma frequency w_p. Comparison with experimental results [8] has shown that the minimum step of the fatigue grooves for the alloys is rather close to the calculated value s_e of the alloy base. The value of fatigue grooves' minimum step s_e ($s_e = \lambda_p / 2$, where λ_p - is a length of the plasmon wave) allowed to calculate the effective threshold coefficient of the stresses intensity $\Delta K_{eff,th}$ [8]:

$$\Delta K_{eff,th} = \vartheta 894 \sqrt{\frac{LW_i E\lambda_p}{(1-\mu^2)a_i}} \tag{6}$$

or

$$\Delta K_{eff,th} = K_{ic} \sqrt{\frac{\lambda_p}{a_i}} \tag{7}$$

There is a discrete spectrum of the threshold equations of energy W_i, typical of each metal and alloys on its base. Hence, in accordance with ratio (6) the discrete spectrum of values $\Delta K_{eff,th}$ will also be typical of them. The analysis of experimental data $\Delta K_{eff,th}$ according to literature references for aluminum alloys and steels has shown, that these values are really grouped close to calculated threshold levels $\Delta K_{eff,th}$. Similar good correspondence is remains also under the temperatures, differing from the room ones [9].

THE NEW LOCAL CRITERIA OF FRACTURE

As it was above mentioned, the additional crack-driving forces (energy) arise in crystals under some definite conditions. It was shown [10-14], that crack-driving forces are responsible for a number of anomalous phenomena and for behavior of materials under the loading in particular. The present section includes the results of investigation of the nature of these phenomena and new fundamental local fracture criteria.

Mirsa A. has revealed [15] the phenomenon of electromagnetic radiation origin under the plastic deformation and solids fracture. Later on comprehensive investigation of this phenomenon has led to the discovery of a number of new facts. In particular, it was shown [16], that ultrasonic wave, passing trough the crystal and interacting with dislocation structure and cracks, stimulates the electromagnetic radiation with the frequency of this wave and with a half of its frequency. In accordance with mentioned observations it was accepted [10], that electromagnetic radiation, passing through the dislocation structure and cracks of the hypersonic wave with a frequency $\nu_i (W_i = h\nu_i, h$ - is a Planck's constant), is stimulated with the frequency of these waves and with a half of their frequency. The last one is obviously connected with existence of the zero oscillations. Conversely, the electromagnetic oscillations arising, will interact with a generating crack. Such interaction will take place only if the waves' length of the arising radiation λ_i will be commensurable with the crack's size. Otherwise the wave will not "feel" the crack. Besides, the crack can percept waves' energy only in quantum. Additional crack-driving forces (energy) arising may be defined by the expressions:

$$G_i = h\nu_i.\lambda_i = hc \tag{8}$$

$$G_i^0 = \frac{h\nu_i}{2}.\lambda_i = \frac{hc}{2} \tag{9}$$

where G_i and G_i^0 - are crack-driving forces respectively from the main and zero oscillations; c – is a velocity of light. If we assume, crack growth a later on takes place discretely with a step $a_i = \lambda_i$, then values G_i and G_i^0 remain invariant of the crack length. Values of the new constants were calculated [10,14] for many metals. Since these constants are defined by fundamental constants of materials, then they will also be correct for the alloys on the base of these metals.

Anomalous (Nonmonotone) Change of Characteristics of Powder Materials' Crack-Resistance Depending on the Porosity

Nonmonotone change of the powder materials' crack-resistance depending on the porosity has been observed in a number of works [12]. Some authors explain this anomaly by change of the strained condition near pores and redistribution of ingredients on the boundary of grains in the structure with closed porosity. Others connect it with the change of linear tension of the cracks' front. To explain the mentioned anomaly it is possible to use some statements of the analyzed above phonon conception, not excepting some influence of structural factors. According to this conception energy capacity of the alloy should be sharply decreased under the definite for the given material critical distances between pairs by means of internal additional forces originating. Thus, the main parameter, responsible for the "failure" of crack-resistance, is the distance between pairs. Experiments, carried out with steels [12,13] and alloys Ti, have proved the above mentioned statement and possibility of precise prediction of conditions, when powder materials will have underestimated values of the crack-resistance characteristics.

Nature of Physical Fatigue Limit

The phenomenon of fatigue materials' fracture has been investigated for more than 150 years already. However, up to the present moment there is no reply to the question: why do some materials have physical fatigue limit, but others do not have? The solution of this problem has a great practical meaning, since in the second case we are forced to define the conditional fatigue limit on the increased base, what connected with significant additional material expenses. It is possible to understand the nature of the stated phenomenon, taking into consideration the effect of additional crack-driving forces, originating in crystals under the process of fracture. If the arising crack-driving force G_i is enough for the local volume fracture, i.e., if $G_i > G_{Ic}^{(1)}$ ($G_{Ic}^{(1)}$ - is a critical value of the crack-driving force, equal to the lowest threshold level of energy in the spectrum W_i), then conditions for the accelerated growth of origination fatigue crack emerge. According to the modern ideas the unspreading fatigue crack of the definite size in a material corresponds to the physical fatigue limit. In view of the above mentioned it is evident that the last one may remain stable only in condition, if for the given material $G_i < G_{Ic}^{(1)}$. This inequality is the main criterion of the physical fatigue limit. On the base of this criterion it is possible to clarify the presence of physical fatigue limit in a material without conducting the laborious experiments.

Criteria, Defining the Beginning of the Spasmodical Cracks' Growth Stage

It is known [17-19], that process of the cracks' spreading has a discontinuous spasmodical character under some conditions. As a result, the probability of a sudden fragile fracture sharply increases. Wide researches of this phenomenon for the conditions of cyclic loading revealed some general regularities of its manifestation [17,18]. It was shown, that threshold value of the stresses' intensity coefficient $K_{fc}^{(1)}$ (beginning from which the spasmodical crack's growth is observed) does not depend on the sample's volume, coefficient of the loading cycle asymmetry and cycles' frequency. The length of a jump does not depend on the crack length, beginning from which the jump takes place, and exceeds the size of a plastic zone in the tip of a crack. Conducted researches, however, did not reveal the nature of this

phenomenon. The problem of prediction of appearance of dangerous for the vitality of constructions stage in the cracks' development remained unsolved.
The idea of additional forces (energy) appearance in local volumes of the real crystals allows not only to explain the origin of critical stage in development of the fatigue limit, but also to predict the approach of this stage [10]. In accordance with the developed model the critical stage approaches when the stresses' intensity coefficient reaches the threshold value $K_{fc}^{(1)}$, defined by the ratio:

$$K_{fc}^{(1)} = \sqrt{\frac{(G_{Ic}^{K} - G_i)E}{1-\mu^2}} \tag{10}$$

where G_{Ic}^{K} - is a critical value of the crack-driving force. Beginning from this moment the stresses' intensity coefficient reaches the critical value K_{Ic}^{K} in the local volumes of a material. Thus, it causes conditions for the unstable cracks' growth. The results of comparison of calculated and experimental values of the criterion $K_{fc}^{(1)}$ have showed, that new material's constants may be used for prediction of the dangerous stage appearance in the cracks development. Within the frames of the suggested model the main above mentioned peculiarities of the phenomenon find their explanation.

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