METHOD FOR DETERMINATION OF THE FATIGUE CRACK EXTENSION RESISTANCE CHARACTERISTICS

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ABSTRACT

The main features of a testing method for determination of crack growth rate and crack extension resistance characteristics of metallic materials under cyclic loading are presented. The method has been worked out on the ground of analysis of appropriate test data of different alloys under various conditions in a broad range of crack growth rates and based on theoretical and experimental investigations of the stress intensity factor validity in determining the fracture process. It is more comprehensive than similar ASTM and BSI standard methods and covers a broader range of crack growth rates (from that corresponding to fatigue threshold to instability onset), includes new specimens and data processing procedures. The method involves plotting crack growth rate curves, their analytical description and calculation of their parameters that under specified conditions are considered as characteristics of fatigue crack extension resistance of a material.

KEYWORDS

Metallic materials, cyclic loading, fatigue crack, growth rate, extension resistance.

INTRODUCTION

As a science, fracture mechanics whose intensive developement began in late 1950s calls for its own research and testing methods. Therefore, in 1967 American Society for Testing and Materials (ASTM) issued the first tentative standard method for fracture toughness (crack extension resistance) of metallic materials under monotonously increasing loading (ASTM Standard E 399). Soon, a similar document was started but for cyclic loading and led to publication of the draft for the ASTM standard limited to constant load amplitude and fatigue crack growth rates above 10^{-8} m/cycle (ASTM Standard E 647) in 1978. This standard has been widely used in many countries, and one such example is its simplified Polish version (PN - 84/HO4333).

Simultaneously with the American standard and independently from it, after long preliminary researches, different authors in the USSR published their methods for determining fatigue crack extension resistance of materials (Panasiuk et al., 1977; Bobrinsky et al., 1977; Branch Standard OST1 90268-78; Yarema et al., 1978); one of these methods (Yarema et al., 1978) has been worked out in H.V.Karpenko Physico-Mechanical Institute of Ukrainian Academy of Sciences, and after four successively extended and improved editions (see, e.g. Yarema, 1979 a) was published as the official normative document "Methodical Instructions" (RD 50-345-82).

In 1981 the draft for a new American standard (Proposed ASTM test method) appeared, covering small (less than 10^{-8} m/cycle) crack growth rates ($\Delta a/\Delta N$ designated hereafter as v); and later a new tentative standard (BSI Document 84/42552) was proclaimed by the British Standards Institution (BSI), which differs little from the American one. In 1988 work on Methodical Instructions was resumed, in order to take into account the latest achievements in fatigue fracture mechanics and experimental procedures, to avoid inconsistencies with the American and British standards,and to adapt certain valuable recommendations of these standards.

The revised Methodical Instructions were expected to become a normative document of the countries-members of the Council for Mutual Economic Assistance. The first version of the new Methodical Instructions was completed in 1990 and published in Moscow with a great delay, though (Yarema, 1993). Further work resulted in the second version of the method considered below.

SCIENTIFIC BASIS OF THE METHOD

The development of the method for determination of the fatigue crack growth rate and fatigue crack extension resistance has been preceded by the analysis of relevant theoretical and experimental researches and techniques, published in last two decades. These were, first, the above mentioned publications (ASTM Standard E 399; ASTM Standard E 647) and the related normative documents (GOST 25.506-85; RD 50-344-82); proceedings of ASTM Simposium dedicated to the methods of investigation of fatigue crack growth (Fatigue, 1981); the review by R.J.Allen, G.S.Booth and T.Jutla (Allen et al., 1988), that would be more appreciated if it enclose Soviet documents; the results of Round Robin on fatigue crack growth (Clark and Hudak 1975), as well as numerous articles that appeared systematically in ASTM Special Technical Publications and periodicals: Engineering Fracture Mechanics, Fatigue and Fracture of Engineering Materials and Structures, Journal of Testing and Evaluation, Transactions of the ASME, Fizyko-Khimicheskaia Mekhanika Materialov (English translation of the journal is known under the title "Soviet Material Science"), Problemy Prochnosti (English translation of the journal is known under the title "Strength of Materials").

However, this method has been developed prevailingly on the basis of the author's rich experience and his purposeful research which began in late 1960s, the results being partially systematized in the monograph (Romaniv et al., 1990). Now, consider them briefly.

All standard methods of testing materials for fatigue crack extension resistance are based on the statement by P.C.Paris, M.P.Gomez and W.E.Anderson (Paris et al., 1961), saying that "since ... during a cycle of loading the stresses and strains near the tip of a crack are completely specified by K_{max} and R we can reasonably assume that any phenomena occuring in this region are controlled by these parameters. The amount of crack extension per cycle of loading is just such a phenomenon." (Here K is stress intensity factor and R is load ratio). This principle has

been thoroughly analysed on the background of experimental data, in order to discover disturbing sources, to establish its validity prerequisites and applicability limits (Yarema, 1977; Yarema, 1987). Proceeding from the obtained results test conditions have been specified and cautions for investigators have been formulated.

In view of general requirements to test specimens (Yarema et al., 1978; Romaniv et al., 1990), the known specimens have been reviewed and the new ones have been suggested: disk and square specimens with a central crack for K-increasing and K-constant testing. For these specimens at various grippings the elasticity problems have been solved (Yarema, 1979 b; Savruk et al., 1982), resulting in formulas for stress intensity factors. On this basis points of load application have been selected and the influence of small deviations from the accepted model has been studied.

The investigations of fatigue crack growth covering all characteristic ranges of its rates, in metallic materials with different crystaline structures and microstructures, chemical and phase composition (steels, Al, Ti and Mg alloys) at normal and low (to 77 K) temperatures, in vacuum, air of different humidity,in water and water solutions have been carried out. Data processing ended in construction and analytical description of crack growth rate curves (v-K curves) and determination of characteristics of the materials' fatigue crack extension resistance. The results of these investigations have been presented in a series of articles mostly in the journal "Fizyko-Khimicheskaia Mekhanika Materialov" in 1975-1986.

Based on the date obtained and those available in literature, the principal characteristic features of the v-K curves and their defining parameters have been established, and abnormalities related to different reasons have been considered (Yarema, 1978; Yarema, 1981 a). These data permitted to choose characterics of fatigue crack extension resistance and laid the basis for Annex A5.

Based on the study of feasibility of the known and new expressions to describe the v-K curves (Yarema and Melnychok, 1982), a new mathemanical model has been proposed (Yarema, 1983). It is simple in use and its parameters are the characteristics of fatigue crack extension resistance of the material.

Besides, the certain particular phenomena that refer directly to the method have been investigated: crack delay after the test interrupt and heat treatment; crack closure and the validity of the effective crack intensity factor range; influence of the amount of crack extension between measurements, and the crack front tilt on the accuracy of determination of the stress intensity factor; plastic zones at a crack tip, etc.

GENERAL CHARACTERISTICS OF THE METHOD

Standardization of testing method has two equally significant goals: to protect the generally accepted complete method by the official document and to recommend from numerous methods to use the most effective and adequate method at today's level of knowledge, providing comparability and reproducibility of the test results. The suggested method covers a broader scope of problems than other standard methods and, hence, attains both, the first goal and, to a great extent, the second one, especially, in its original parts.

Like all standard methods, this method is valid as a whole, if under test conditions (variations of the specimen form and shape, temperature, environment, etc.) there is strong regression type dependence of the crack growth rate on the stress intensity factor, and the influence of other factors does not exceed natural data scatter. Restrictions imposed by the method to provide such dependence and especially its unambiguity do not contradict the requirements of the analogous documents, but they are more detailed. In addition to rigorously specified basic tests, the method involves special tests where the conditions are imposed with regard to their particular aim. The method covers all rates of fatigue crack growth until instability onset. In this connection, it provides tests at the increasing, constant (for specific investigations of the influence of certain factors), and decreasing (to achieve low crack growth rates) stress intensity factor range.

As for other standards, the final objective of this method is to find empirical relationship between the crack growth rate and the range (or the maximum value in a cycle) of the stress intensity factor; however, while other methods only declare it this one gives the appropriate procedures. It provides plotting of the crack growth rate curve and determination of its parameters which are characteristics of fatigue crack extension resistance of the material under the given conditions. These parameters relating to certain segments of the v-K curve are fatigue crack growth threshold (ΔK_{th}, K_{th}) and fatigue fracture toughness (K_{fc}), as well as a coefficient and exponent of the Paris equation which is modified so that these quantities were independent (Yarema, 1981 b). The characteristics are determined directly from the v-K curve and/or calculated by the least square method on the basis of the above mentioned mathematical model. The opinions of such procedure can differ: mechanical engineers are accustomed to mathematical analysis and need quantitative characteristics, whereas material scientists can confine, in some cases, to curves plotted by eye. Whatsoever, the curve's determining parameters can be useful for comparison of fatigue crack extension resistance of materials under precisely specified conditions and, also, for reproduction of the v-K curve even when their role as the material's characteristics becomes doubtful.

Besides two standard specimens, i.e. a rectangular specimen with a central crack in tension (CCT) and a compact specimen with an edge crack in eccentrical tension (CT), the method recommends the specimen of a rectangular section in simple (as in the British standard) and pure bending, as well as a compact specimen with a central crack in tension, that has certain advantages. Alongside with the compact specimens their disk modifications are also permissible. If it is the approved necessity, one may also use other specimens for special tests if they satisfy conditions specified in Annex A4. Here the special specimens for tests at the constant stress intensity factor range are considered too. For this the results of the author's investigations (Yarema, 1979; Savruk et al., 1982) are used as well as those obtained by the others (Markochev and Kraiev, 1976; Srawly and Gross, 1967; Mostovoi et al., 1967).

Stress intensity calibrations for standard specimens yield the same results as those in the American standards (ASTM Standard E 399; ASTM Standard E 647); however, they differ from the latter for they were received by means of approximation of numerical values by simpler expressions (Yarema et al., 1985).

In the presented method a simple and sufficiently universal code system has been chosen to designate the specimens (Annex A2); codes for crack orientation and its growth direction with respect to the parent product wherefrom the specimen is cut out have been taken from American standard (ASTM Standard E 616). Also, certain recommendations and procedures have been borrowed therefrom. There are, in particular, the method for decreasing the range of the stress

intensity factor preserving its gradient stability, the incremental polynomial method for calculating the crack growth rates, etc. The requirements of this method are modified so that they do not contradict the American ones.

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