ANALYSIS OF CYCLIC FRACTURE TOUGHNESS OF STRUCTURAL MATERIALS UNDER SELF-SIMILAR PROPAGATION OF FATIGUE CRACKS

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ABSTRACT

It is well recognized that the fatigue fracture resistance of metals and alloys at elastic-plastic crack growth can be markedly dependent on the plastic strain constraint factor. In this connection the fatigue fracture resistance of steel , titanium and aluminium alloys are researched at constant plastic constraint factor using the threshold value of $\Delta K = K_{IS}$. Parameter K_{IS} characterises the thresold value of ΔK at which elastic-plastic transition is observed under maximum plastic constraint factor.

KEYWORDS

Cyclic fracture toughness, crack growth, self-similar crack growth, steel, titanium alloys, aluminium alloys.

INTRODUCTION

The modern approaches of the nonlinear fracture mechanics enable the cracking resistance of structural materials to be estimated under similarity of plastic strain constraint factor (PCF). It is well known that the existing spread of data for K_{IC} of plastic materials often reaches 20-50% (following the recommendations of ASTM for determination of K_{IC}). Such a spread is due to the fact that when unstable crack growth is achieved in the case of plastic materials different degrees of PCF may take place, depending on the geometry of a specimen and loading conditions. Besides, the application of large-sized specimens of structural materials, as recommended by ASTM, involves difficulties in estimation of fracture toughness of new alloys while disregard of the effect of PCF prevents prediction of fracture parameters under the effect of a spectra loads. Changes in loading conditions result in change of the crack motion energy which is dependent on the PCF. Consequently, in order to obtain

adequate estimations of fracture toughness it is found necessary to use the method of the similarity theory.
As shown by Ivanova (I976, I982a, I982b) the simplest solution of theory proposed by Sedov (I98I) In according to Ivanova (I982a, I982b) the self-similar transition from quasi-elastic to elastic-plastic crack growth is controlled by the critical value of K_I, which is equal to K_{IS}^{max}.
At the self-similar crack growth the parameter n (Paris and Erdogan, I963) being the exponent in equation

$$da/dN = C(\Delta K)^n \qquad (I)$$

will also acquire a physical substantiation. At the self-similar crack the stress fields at the crack tip may be described with the help of a singular member $K/\sqrt{2\pi r}$, where r is the size of the self-similar zone in the direction of a crack growth. Under these conditions the parameter n in the above equation (I) indicates the sensitivity of the material (in the particular structural state) to the crack (Ivanova, I982a). It makes possible to compare the behaviour of the materials with a crack under similar of PCF at the moment when the limiting state is achieved or when the failure mechanism is changed and maximum exclude the effects of external factors (size of specimen, loading rate, temperature, etc) on the fracture toughness.
In this case the problem is to find the value of parameter n in self-similar conditions and to calculate as the threshold value $\Delta K = K_{IS}$ corresponding to the transition from a quasi-elastic crack growth to an elastoplastic crack growth under maximum PCF as (da/dN) by the equation (I) at $\Delta K = K_{IS}$ and $n = n_{min} = 2$. K_{IS} and n are the most important engineering parameters of the cyclic fracture toughness (Ivanova and others, I982) controlling the duration of the stage of a quasi-elastic crack growth. The parameters K_{IS} and n are interrelated with a linear dependence (Ivanova, I982a), namely

$$K_{IS} = [K_{IS}]_{max} \cdot \frac{n_{max} - n}{n_{max} - n_{min}} \qquad (2)$$

Values of n_{max} and n_{min} in the eq (2) were experimentally established by the recomendations (Ivanova and others, I983). For iron-based alloys $K_{IS} = 40.4$ MPa$\sqrt{m}$, $n_{max} = 6$, $n_{min} = 2$; for titanium-base alloys $K_{IS} = I7.8$ MPa$\sqrt{m}$, $n_{max} = 8$, $n_{min} = 2$; for aluminium-base alloys $K_{IS} = 8.7$ MPa$\sqrt{m}$, $n_{max} = 9$ and $n_{min} = 2$.
Thus, if the parameter n is known it is practicable to determine the cyclic fracture toughness by the value of K_{IS} controlling the lower level of the self-similar elastoplastic crack growth under a maximum elastic-plastic PCF. At $K = K_{IS}$ it is found possible to fulfil the condition of a close compliance between the macroscopic rate of the crack growth (calculated by the macroincrement of the crack propagation) and the microscopic rate (calculated by the use of space of the striation at a maximum PCF). In general case, the correspondence of the aforesaid crack rates may be achieved under different extents of PCF. Let us denote the threshold value ΔK (complying with this general case) with a quantity K, with due regard for the works (Gurevich and Edidovich, I974; Gurevich, I98I). As was revealed there the moment when the threshold value of $\Delta K = K_a$ is attained is followed by a sharp change of acceleration of the crack propagation, This acceleration is determined as the second derivative of the crack length by the number of the cycles, i.e.:

$$acc = dV/dN = d^2a/dN^2 \qquad (3)$$

where acc is the acceleration of the crack propagation, V is the rate of the crack growth, is the crack length and N is the number of the loading cycles. This parameter features is sensitivity to change of the main failure mechanism governing the rate of growth of a fatigue crack (Gurevich and Edidovich, I974).
The relationship between the acceleration of the crack propagation and the number of the loading cycles can be described by a piecewise linear function and has a salient point of $\Delta K = K_a$ corresponding to the start of the accelerated growth of the fatigue crack.
Consequently, the degree of PCF characteristic of an elasto-plastic transition may be determined by the use of the coefficient of PCF $\mathcal{M}_L^* = K_{IS} / K_a$. When $K_a = K_{IS}$ or $\mathcal{M}_L^* = I$, then the maximum PCF are realised while $\mathcal{M}_L^* = (\mathcal{M}_L^*)_{min}$ complies with the minimum PCF. The use of parameters K_{IS} and $\mathcal{M}_L^*$ enables the cyclic fracture toughness of the structural materials to be determined by means of small (model) specimens. The present investigation persued the following objectives: (a) study of the relation between the parameters of K_{IS} and the threshold value of $K = K_a$, which corresponds to the achievement of the condition of a proximity of the macroscopic rate and microscopic rate of the crack growth, for which purpose use was made of scanning electron microscopy and fatigue tests of large-sized specimens of linear fracture mechanics (aluminium alloys) were perfomed; (b) determination of both the threshold value of K_{IS} on small (model) specimens and realized the degree of PCF by use of acceleration of the crack propagation (titanium alloys, steels).

TEST MATERIALS AND METHODS

Subjected to the test were aluminium alloys DI6T and AMr6H2, α - titanium alloy OT4-I, commercially pure titanium BTI-0, as well as steel 30XГCA. The chemical composition of the alloys (in weight percent) and its mechanical properties are presented in Tables I-4.

TABLE I Chemical Composition of Aluminium Alloys

Alloy grade	Mg	Mn	Cu	Zn	Fe	Si	Ti
DI6T	I.6	0.65	4.670	0.20	0.28	0.I9	-
AM 6H2	6.2	0.55	0.0I7	-	0.2I	0.I3	0.23

TABLE 2 Chemical Composition of Steel 30XГCA

C	Mn	Si	P	S	Cr	Ni	Cu
0.29	0.94	I.02	0.009	0.005	I.9	0.25	0.I8

TABLE 3 Chemical Composition of Titanium Alloys

Alloy grade	Al	Mn	Fe	Si	H	N	C	O
OT4-I	I.0	0.80	0.30	0.I5	0.0I5	0.05	0.I	0.I5
BTI-0	-	-	0.30	0.I5	0.0I5	0.05	0.I	0.I5

TABLE 4 Mechanical Properties of Tested Materials

Grade of material	σ_B	$\sigma_{0.2}$	δ
	MPa	MPa	%
DI6T	554	395	I4.4
AMr6H2	422	330	9.6
BTI-0	420	335	53.0
OT4-I	650	520	38.0
30XГCA (I)	I620	II80	I.4
30XГCA (II)	I560	I080	2.48

The cyclic tests of the aluminium alloys were performed with the aid of flat specimens with a central notch, measuring 300x xIoox6 mm, under repeated tension with a loading frequency of 20-35 Hz. The tests were accomplished by means of testing machine "Instron". The specimens have central notch, 0.2 mm wide; precrack made by use electroerosive method. The relative length of the notch was $2a_0 / W$ = 0.I - 0.22. The notch was oriented at right angle to the direction of rolling. The specimens of titanium alloy, titanium and iron alloy measured I00x300x0.6 mm and were subjected to a repeated tensile test with the aid of a testing machine, type "Schenk". So as to have the development of the fatigue crack well observed the preliminarily polished surface of the specimen was provided with special marks, I mm spaced apart. The length of the crack was measured visually by means of an optical microscope of tenfold magnification. The fatigue crack growth rate (da/dN) was determined by graphical differentiation of the relationship between the length of the crack and the number of the loading cycles. The stress intensity factor ΔK was derived by the formula:

$$\Delta K = \frac{F \cdot \sqrt{\lambda}}{t \cdot \sqrt{W}} \, y \qquad (4)$$

where $y = (\sqrt{\pi}/2) \cdot \sec(\pi\lambda/2) \cdot (I - 0.025\lambda^2 + 0.06\lambda^4)$; F is the range of the applied load; t is the thickness of the specimen; W is the width of the specimen; $\lambda = 2a/W$ is the relative length of the crack; a is the half-length of the crack.

EXPERIMENTAL DATA AND DISCUSSION

Aluminium alloys. Fig. I shows the kinetic diagrams of aluminium alloys DI6T and AM 6H2. Stage II of the fatigue crack growth is divided (using parameters K_{IS} or K_a) by vertical dotted lines into a stage of quasi-elastic growth (IIa) and a stage of elastic-plastic growth (IIb) of the fatigue crack. Each stage is controlled by the respective main mechanism of failure (Gurevich, I98I). The value of K_{IS} was calculated with the use of equation (2), while the quantity K_a was determined by the point of intersection of relations lg V = f (lg (ΔK)) and lg S = = f (lg (Δ K)), where S is the pitch of the striation spaced.

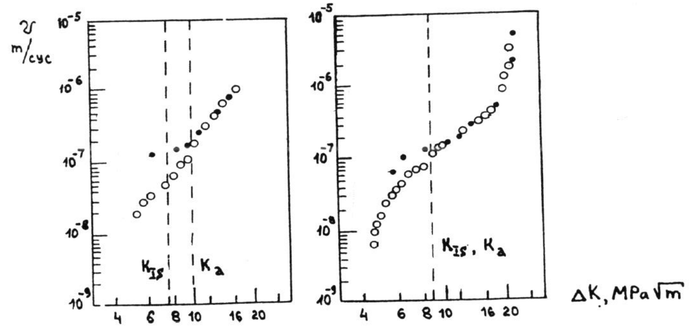

Fig. I. Kinetic Diagrams of Fatigue Failure of Aluminium Alloys. a - alloy AMr6H2; b - alloy DI6T; • for S, o for V;

The fractographic research shows that at stage IIa the microrelief of the fatigue failure surface corresponds to the weak dependence of the striation spaced on the length of the crack. This is indicative of quasi-elastic behaviour of a fatigue crack. Transition to stage IIb is accompanied with an increase of the spaced of the striation with rise of the crack length crack propagation, and also as a trend toward equalization of the rates of the crack growth (determined macro- and microscopically).

Consequently, the moment when the macroscopic and microscopic rates of the crack growth is achieved stands for the time of local plastic instability, that is characterized with the threshold coefficient of stress intensity K_a equal to K_{IS} under maximum PCF. Table 5 presents the experimental data of K_a, as well as the data of K_{IS} calculated by the use of equation (2) and experimental values of n. The same table contains the particulars indicating the values of coefficient μ_L^*.

It will be obvious that whenever the self-similar conditions of the crack growth are provided the parameters K_{IS} and K_a are approximate, i.e. a maximum PCF ($\mu_L^* = 1$) at the elastic-plastic transition takes place. These conditions ($\mu_L^* = 1$)

can be realized in testing small-sized specimens, respectively selecting the loading conditions, so as to provide determination of the parameter n in the self-similar conditions.

Titanium alloys. The kinetic diagrams of fatigue failure of small-sized specimens with a central crack are shown in Fig. 2. Indicated by dotted lines are the stages of the quasi-elastic and elastoplastic growth of the cracks with the use of K_{IS} calculated on the basis of the parameter n and K_a determined against a sharp change of acceleration of the crack propagation. The value of K_a was determined in the following way. The value of N_a was first found by the kink point on the curve acc = f (N) Then taking into account this value the respective values of the stress intensity factor K_a were determined by means of the dependence acc = f (N) and log V = f (lgΔK).

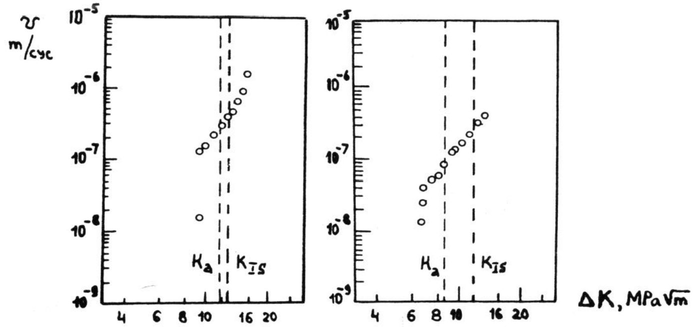

Fig. 2. Kinetic Diagram of Fatigue Failure of Titanium. a - alloy OT4-I; b - titanium BTI-O.

Table 5 contains the respective values of n, K_{IS}, K_a and μ_L^* for the tested materials. It has been apparent that the values of K_{IS} and K_a determined for the model specimens are very approximate. This means that the model specimens of titanium alloys allow determination of the boundary of transition from a quasi-elastic crack growth to an elastic-plastic crack growth when the conditions of its self-similar growth is fairly met, and, besides, the cyclic fracture toughness can also be determined. The obtained experimental data suggest that the alloy OT4-I possesses better characteristics of cyclic fracture toughness as compared to commercially pure titanium.

TABLE 5 Values of Threshold Factor Δ K complaying with Transition from quasi-elastic to elastic-plastic of Fatigue Crack Growth

Alloy	n	K_{IS}	K_a	μ_L^*
	-	MPa$\sqrt{m}$	MPa$\sqrt{m}$	-
DI6T	2	8.7	8.7	I
AM 6H2	2.8	7.7	I0.0	0.8
BTI-O	4.0	II.9	8.7	0.73
OT4-I	3.7	I2.8	I2.0	0.94
30X CA-I	3.9/3.9*	20.2	-	-
30X CA-II	2.4/2.8*	35.0	-	-

* - index n for tests in low-cycle loading area.

Steel 30XΓCA. Subjected to testing for cyclic fracture toughness was steel 30XΓCA melted by two methods; (A) by the method of ordinary melting in an open-hearth furnace (method I), and (b) by the special melting method (method 2). The kinetic diagrams of the fatigue failure plotted in the conditions of an self-similar crack growth are given in Fig. 3. The obtained data concerning the quantity n are presented in Table 5. The material was tested both for low-cycle and for high cycle fatigue. It might be well to point out that comparison of the curves for low-cycle loading and high-cycle loading indicates a slight variation of the parameter n in the expression (I). This suggested that the parameter n, i.e. the exponent in the Paris' equation seems to be more conservative to external conditions of loading as C parameter. The obtained experimental data shows that steel 30XΓCA melted by method 2 features a higher cyclic cracking resistance as compared with that melted by the ordinary method.

CONCLUSIONS

The use of the threshold value $\Delta K = K_{IS}$ complying with the transition from quasi-elastic to elastic-plastic fatigue cracks growth under maximum PCF makes it possible to compare the alloys in the conditions of similarity of local fracture stress state and to determine the PCF in the case of a elastic-plastic transition complying with a sharp change of acceleration of the crack growth, or under realization of the condition when the macroscopic rate of crack propagation determined by the macro-increment of the crack corresponds to the microscopic rate calculated by the fatigue striation spaced.

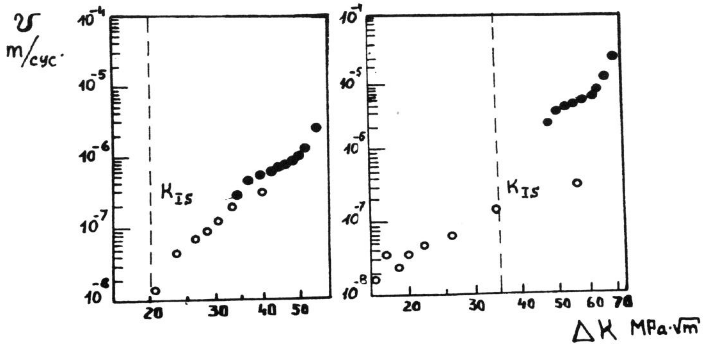

Fig. 3. Kinetic Diagram of Fatigue Failure of Steel 30XГCA. a - melting method I; b - melting method 2; ● - for low-cycle fatigue; o - for high-cycle fatigue.

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