УДК 669.0
ББК 34.2

THE METHOD FOR LIFETIME ESTIMATION THROUGH THE MECHANICAL PROPERTIES IN TENSION

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Abstract. The method for prediction of Paris' curve shape through the results of tensile test is suggested. For this purpose the author developed non-direct method for determination of ΔK_{th} and ΔK_{fc} and corresponding to them *da/dN* values. The relationship between ΔK_{th} and σ_b/σ_y ratio was found. The correlation $\Delta K_{fc}(K_{Ic})$ was also shown. It makes possible to estimate lifetime of different structures with cracks under cyclic loading.

Key words: Paris' curve, cyclic loading, lifetime, non-direct method, tensile test.

Introduction

For many years attempts have been made to understand the crack growth mechanism and predict lifetime under conditions of cyclic loading. Cracks exist in many structural components. The crack growth resistance is an important property of the material which controls the lifetime of the component. Studies on the growth of cracks have led to the observation that fatigue life of many engineering materials is primarily dependent on micro-structural features, such as inclusion particles, voids, slip-bands or manufacturing defects. Thus, knowledge of the crack rate makes possible the prediction of residual lifetime of a component. Due to that cracked component may be kept in service for an extended useful time. Applying the fracture mechanics principles makes possible to predict the number of cycles spent for crack growth to some specified length or to final failure.

Determining the critical cyclic loading conditions is commonly performed by using a Paris' curve. The Paris' curve is dependence of crack growth rate, *da/dN* on the stress intensity range $\Delta K = K_{max} - K_{min}$.

This curve may be divided into three regions (fig. 1). At low stress intensities, Region I, cracking behavior is associated with threshold, ΔK_{th}, effects. By considering the term ΔK_{th} the designer can ensure that no crack growth will occur. ΔK_{th} is the "fatigue crack growth threshold", and signifies the critical value of ΔK below which crack growth will not occur. It is calculated using the Paris' curve, and is the value of ΔK corresponding to $da/dN = 0$. In the Region III, at high ΔK values, crack growth rates are extremely high and little fatigue life is involved. Finally, in the mid-region, Region II, the curve is essentially linear and can be described by the Paris' equation

$$da / dN = C(\Delta K)^n, \qquad (1)$$

where C and n are material constants and ΔK is the stress intensity: $\Delta K = K_{max} - K_{min}$.

However, the procedure for Paris' curve determination by means of direct testing is enough complicated and expensive. Sometimes, it is just impossible, for example in cases when structures or equipment are under exploitation conditions.

Therefore many investigators made large efforts to develop models for Paris' curve shape predicting. The relationship between fracture toughness, ΔK_{fc} and K_{Ic}, ΔK_{fc} and K_{Id} was shown in paper [4; 6]. The correlation between constants C and n in the Paris' equation is known [3; 7]. But up to date there is no model for ΔK_{th} and constants n and C in Paris' equation predicting.

Our approach to this problem is presented below.

Analysis

The simplified shape of a Paris' curve is presented on fig. 1.

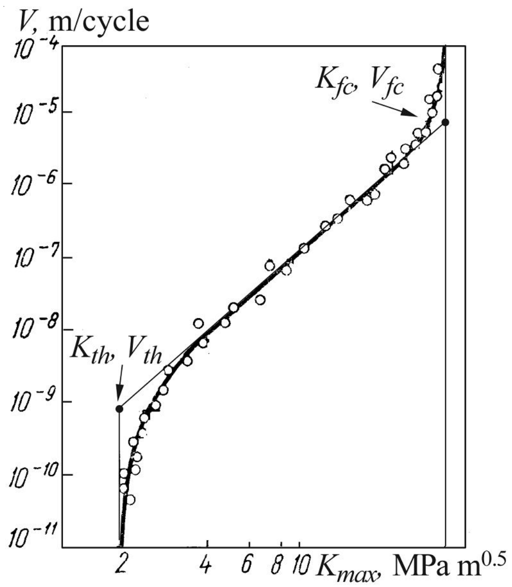

Fig. 1. The simplification of Paris' curve

As can be seen from this figure, the reconstruction of a curve linear Region II may be done if the ΔK_{th}, ΔK_{fc}, and corresponding to them da/dN values are known. It makes possible to calculate constant n in Paris' equation as:

$$n = \left(\lg v_{fc} - \lg v_{th}\right) / \left(\lg \Delta K_{fc} - \lg \Delta K_{th}\right), \qquad (2)$$

where v_{th} and v_{fc} – the crack propagation rates corresponding to ΔK_{th} and ΔK_{fc}.

Crack propagation rates in eqn. (2) are not known.

For this reason the assumption is accepted that the crack propagation rate is proportional to the small scale yielding zone width. In this case it makes possible to rewrite the eqn. (2) in the following form (3):

$$n = \left(\lg r_{fc} - \lg r_{th}\right) / \left(\lg \Delta K_{fc} - \lg \Delta K_{th}\right), \qquad (3)$$

where r_{th} and r_{fc} are the small scale yielding zones corresponding to ΔK_{th} and ΔK_{fc}. The r_{fc} and r_{th} values are determined as:

$$r_{fc} = \frac{(1-2\mu)^2}{2\pi} \left(\frac{\Delta K_{fc}}{\sigma_y} \right)^2, \qquad (4)$$

$$r_{th} = \frac{(1-2\mu)^2}{2\pi} \left(\frac{\Delta K_{th}}{S_k} \right)^2, \qquad (5)$$

where μ – Poisson's ratio, S_k – fracture stress.

In the eqn. (5), the substitution of an S_k value instead of σ_y is accounted for by the following reason. The ΔK_{th} determination procedure is carried out under conditions of a load decreasing. Thus, the crack propagation in this region is accomplished in the extremely hardened material.

It can be seen from eqns (3–5) that for the purposes of further analysis it is necessary to develop the non-direct methods for ΔK_{th} and ΔK_{fc} determination.

Discussion

We have proved the existence of a linear correlation between fracture toughness, K_{Ic}, and ΔK_{fc} values for more than 40 different steels [5]. This relationship is shown on fig. 2 and is described by the following equation:

$$\Delta K_{fc} = 0.8611 \cdot K_{Ic} - 26.387. \qquad (6)$$

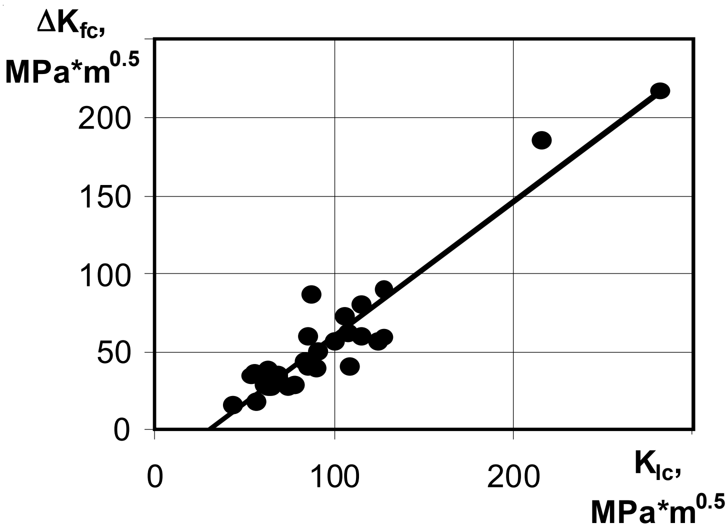

Fig. 2. The relationship between K_{Ic} and ΔK_{fc}

Previously [1; 2; 8] the practical methods for fracture toughness K_{Ic} prediction through mechanical properties in tension and hardness values of materials were developed. The predicted K_{Ic} value may be used for ΔK_{fc} calculation through the eqn. (6).

The results of calculation ΔK_{fc} are presented in table 1.

In this work also the relationship between ΔK_{th} and σ_b/σ_y was proposed (fig. 3).

It is valid for many different steels [4–6] and may be described by linear function:

$$\Delta K_{th} = 36.906 \cdot \sigma_b / \sigma_y - 34.04, \qquad (7)$$

where σ_b is an ultimate tensile strength, σ_y is a yield stress.

The results of ΔK_{th} calculation are presented and compared to their experimental values in table 2.

It should be noted however that determining ΔK_{th} values is dependent on testing equipment.

Now, when the ΔK_{th} и ΔK_{fc} are already found, the n constant value in the eqn. (3) can be calculated. After that we have to find the C constant in eqn. (1).

The correlation between constants C and n in the Paris' equation is known [3; 7]. We have confirmed this relationship for steels investigated in present paper. It can be described as:

$$C = 0.0002 \cdot e^{-6.9048 \cdot n} \qquad (8)$$

The fair of this formula was shown for more than 200 different materials. The correlation coefficient value equals to 0.998. Thus in the linear region of a Paris' curve the crack propagation rate is controlled by the single parameter C or n. The results are presented in tables 3, 4 and fig. 4.

As can be seen from the presented analysis the non-direct method for determination of all parameters of the Paris' curve is developed. The calculated and experimental values of constants C and n are in good agreement.

Table 1

The comparison of results experimental and calculation ΔK_{fc} values

Steels	T, K	σ_{02} MPa	σ_b MPa	ΔK_{fc} MPa*m (experiment)	ΔK_{fc} MPa*m (calculation)	δ, %
15KH2MFA	293	584	700	121.3	127.5	4.8
	243	647	752	59	63.8	7.5
	213	674	783	62	72.3	14.2
15KH2NMFA	293	593	707	129.4	132.8	2.6
	243	658	756	72.46	85.7	15.4
	183	745	943	34.2	42.9	20.2

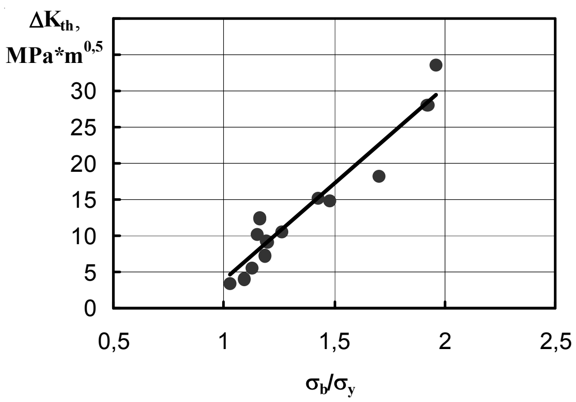

Fig. 3. The relationship between ΔK_{th} and σ_b/σ_y

Table 2

The comparison of results experimental and calculation ΔK_{th} values

Steels	T, K	$\sigma_{0.2}$ MPa	σ_b MPa	ΔK_{th} MPa*m (experiment)	ΔK_{th} MPa*m (calculation)	δ, %
15KH2MFA	293	584	700	9.1	10.19	-12
	243	647	752	12.4	8.85	28
	213	674	783	12.5	8.83	29
15KH2NMFA	293	593	707	9.2	9.96	-8.2
	243	658	756	10.2	8.36	18
	183	745	943	10.6	10.67	-19
St3sp	293	240	470	33.58	30.03	10.58
18Gsp	293	260	500	28.08	28.12	-0.13
09G2S	293	352	503	15.25	15.06	1.24

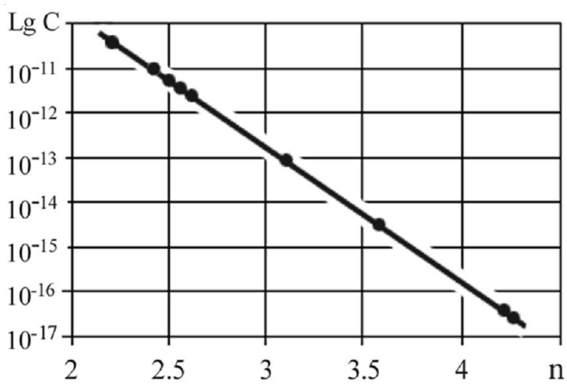

Fig. 4. The C dependence on a n value

For the lifetime prediction the Wilson' approach can be used. The number of cycles, N, necessary for crack grows from the initial size a_0 to the critical size a_{cr} can be found from the Paris' equation as

$$N = \int_{a_0}^{a_{cr}} \frac{da}{C(\Delta K)^n}. \quad (9)$$

Assuming that

$$\Delta K = \Delta\sigma\sqrt{Ma}, \quad (10)$$

where $\Delta\sigma = \sigma_{max} - \sigma_{min}$, M – parameter of geometry and the shape of defect, we get

$$N = \int_{a_0}^{a_{cr}} \frac{da}{C(\Delta\sigma\sqrt{Ma})^n}. \quad (11)$$

Integrating of the eqn. (11) results in Wilson' formula:

$$N = \frac{2}{(n-2)CM^{n/2}\Delta\sigma^n}\left[\frac{1}{a_0^{(n-2)/2}} - \frac{1}{a_{cr}^{(n-2)/2}}\right]. \quad (12)$$

Table 3

The comparison of results experimental and calculation *n* values

Steels	$\sigma_{0.2}$ MPa	σ_b MPa	*C* (experiment)	*C* (calculation)	δ, %
20KH13 (1)	655	775	3.12	3.15	1.0
20KH13 (2)	566	749	2.89	3.04	5.1
14KH17N2	782	943	2.56	2.76	7.4
13KH11N2V2MF	885	1 015	2.86	2.88	0.9
08KH17N6T	840	895	2.57	3.18	19.3
1KH16K4NMVFBA	980	1 163	2.56	3.51	27.1

Table 4

The comparison of results experimental and calculation *C* values

Steels	$\sigma_{0.2}$ MPa	σ_b MPa	*C* (experiment)	*C* (calculation)	δ, %
20KH13 (1)	655	775	$5.89 \cdot 10^{-9}$	$6.07 \cdot 10^{-9}$	2.9
20KH13 (2)	566	749	$1.15 \cdot 10^{-9}$	$1.27 \cdot 10^{-9}$	9.4
14KH17N2	782	943	$6.71 \cdot 10^{-9}$	$8.88 \cdot 10^{-9}$	24.4
13KH11N2V2MF	885	1 015	$3.82 \cdot 10^{-9}$	$3.79 \cdot 10^{-9}$	-0.8
08KH17N6T	840	895	$6.04 \cdot 10^{-9}$	$4.72 \cdot 10^{-9}$	-27.9
1KH16K4NMVFBA	980	1 163	$1.6 \cdot 10^{-8}$	$1.99 \cdot 10^{-8}$	19.6

The a_{cr} value is found from the condition of the pressure vessel fracture or can be taken with consideration of crack size allowed for this structure.

The verification of the suggested model has shown its applicability for express lifetime estimation of different structures.

Conclusions

1. The relationship between ΔK_{th} and σ_b/σ_y ratio was found. The correlation $\Delta K_{fc}(K_{Ic})$ was also demonstrated.

2. The non-direct method for determination of ΔK_{th} and ΔK_{fc} and corresponding to them da/dN values was developed.

3. The method for prediction of Paris' curve shape through the results of tensile test is suggested. It makes possible to estimate lifetime of different structures with cracks under cyclic loading.

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МЕТОД ОЦЕНКИ ДОЛГОВЕЧНОСТИ ПО МЕХАНИЧЕСКИМ СВОЙСТВАМ ПРИ РАСТЯЖЕНИИ

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Аннотация. Предложен метод прогнозирования формы классической кинетической диаграммы усталостного разрушения по результатам испытаний на растяжение. Для этого разработаны косвенные методы определения пороговых размахов коэффициентов интенсивности напряжений ΔK_{th} и ΔK_{fc}, а также соответствующих им значений скоростей da/dN. Установлена взаимосвязь между ΔK_{th} и отношением предела прочности к пределу текучести σ_b/σ_y. Получена корреляция $\Delta K_{fc}(K_{Ic})$. Показана возможность прогнозирования долговечности различных конструктивных элементов и деталей машин при наличии трещин в условиях циклического нагружения.

Ключевые слова: кинетическая диаграмма усталостного разрушения, циклическое нагружение, долговечность, косвенный метод, испытания на растяжение.