CYCLIC ELASTO-PLASTIC FRACTURE DIAGRAM FOR A SPECIMEN WITH A CRACK AND ITS ANALYSIS

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ABSTRACT

Plotting methods of the cyclic elastoplastic fracture diagram for a specimen with a crack(CEPF - diagram) are given. Plotting of two types CEPF - diagram: D - diagram and Q - diagram are proposed. These diagrams are plotted according to the cyclic crack resistance tests of compact specimens made of 45 carbon steel with the thickness of 0.01, 0.02 and 0.04 m; characteristics of the material crack resistance straining and rupture are analysed and presented in this paper. The similarity transformations are proposed and generalized CEPF - diagram for three size-type specimens tested is plotted as a result of.

KEYWORDS

Crack resistance, stress intensity factor, transvers~~ive~~ component of plastic strain, compact specimen, CEPF-diagram, Q - dia gram, D - diagram.

GENERAL DISCRIPTION OF THE CEPF-DIAGRAM

In general case CEPF-diagram is a dependence between the stress intensity factor (SIF) K^F_{Imax} and transversive component of plastic strain φ taken in a dangerous section of a specimen. (Sosnovskiy, 1990; Sosnovskiy et el., 1990) plotted, for example, according to the results of compact specimens standard cyclic crack resistance tests. The φ value is determined as the residual of t_o nominal value and t_φ current value of the specimen's thikness, i.e. $\varphi=t_o-t_\varphi$ (Fig.1,a). K^F_{Imax} value is calculated due to the formulas of linear elastic fracture mechanics, but with the extent of ductility correction. For the compact specimen (Fig.1,a) there is

$$K^F_{Imax}=(P_{max}\sqrt{a}/t_o B)\,Y(F_a/F_o)\,,$$

Correction function $Y(F_a/F_o)$ is calculated taking into consideration actual transverse section F_a occupied by a crack with length of a; F_o - nominal transverse section. The F_a/F_o value equals to ω_o and is the value of extent damage, and function Y, thus, takes into consideration not only the loading scheme and geometry of the specimen, but also (integrally) the value of plastic strain in specimen's dangerous section.

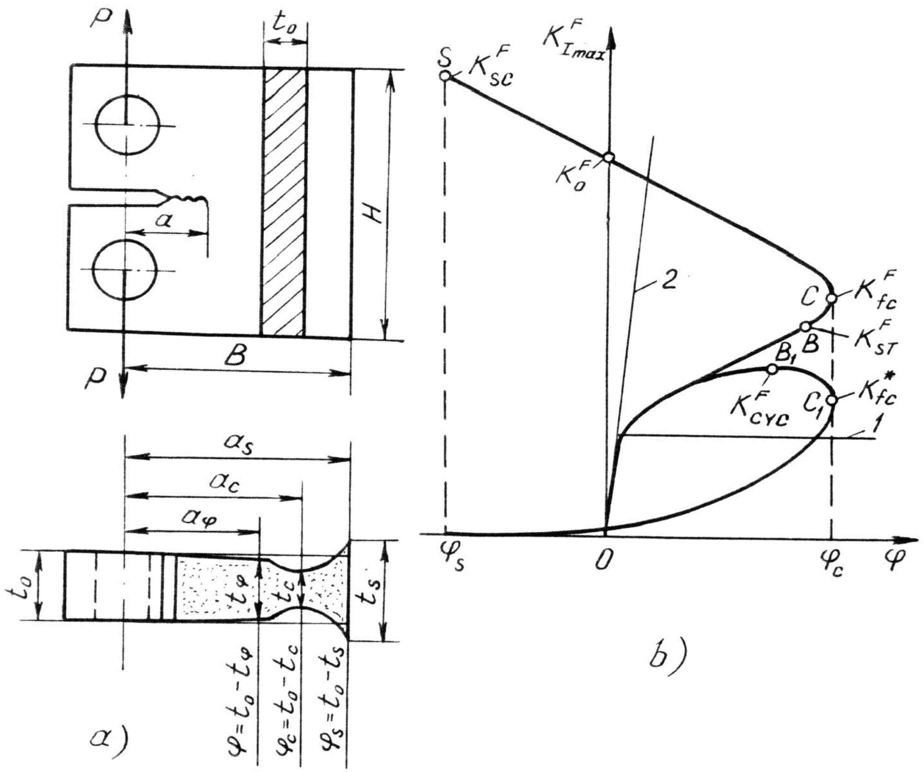

Fig.1. Specimen (a) and CEPF-diagram (b) schems.

Two types of CEPF-diagram are distinguished (Sosnovskiy and Bogdanovich, 1992). If calculating $K^F_{I max}$ value by convention maximum rapture load is constant, then OBCD diagram is obtained (Fig.1,b). This diagram together with the Y-axis looks as letter D and that is why it is called D-diagram. If calculating $K^F_{I max}$ the actual value of rapture load is taken into consideration, then $OB_1\ C_1 S_1$ diagram is obtained (see Fig.1,b). This diagram resembles letter Q and that is why it is called Q-diagram.

In common case, CEPF-diagram consists of two curves (see Fig. 1,b): cyclic elasto-plastic fracture curve (line segments OBC on D-diagram and OB_1C_1 on Q-diagram respectively) and quasi-static fracture (rupture) curve line segments CS on D-diagram and $C_1\ S_1$ on Q-diagram respectively). In points C and C_1 the crack reaches its critical length a_c corresponding to the limit value of narrowing plastic strain and to the SIF limit value - cyclic fracture toughness (K^F_{fc} value on D-diagram and K^*_{fc} on Q-diagram). In points S, S_1 accordingly, the specimen is divided into two parts and simultaneously maximum widening φ_s of its dangerous section takes place. That is the base for determination of another SIF limit value - quasi-static fracture taughness (K^F_{sc} value on D-diagram, on Q diagram $K^F_{I max} = 0$ in this point). Crossing point of CS curve and Y-axis gives one more parameter K^F_o of the crack resistance (see Fig.1,b). Max of Q-diagram on SIF axis (point B_1) corresponds with the beginning of the cyclic rapture and characterized by parameter K^F_{cyc} ; parameter K^F_{ST} on Q-diagram corresponds to the beginning of quasi--static rapture and is not a characteristic point of this diagram, but accords with the beginning of sharp lift of the OBC curve (point B on D-diagram). In case of the "ideal plastic fracture", the cyclic elasto-plastic fracture curve transforms into direct line 1. In case of "ideal brittle fracture" (φ =0), this curve coinsides with the Y-axis. The line 2 divides areas of quasi-brittle and elasto-plastic fracture. Thus, with the help of the CEPF-diagram it is possible to analize ductile-brittle transition under, for example, the change of the test temperatures or specimen sizes.

THE CEPF-DIAGRAM OF 45 CARBON STEEL

D- diagram. Compact specimens made of 45 carbon steel with the thickness of 0.01, 0.02 and 0.04 m has been tested for cyclic crack resistance with the excentric tension, loading frequency ~20 Hz and dessymetry of cycle $R_\sigma \approx 0{,}1$ under ambient conditions. D-diagram (Fig.2) for the specimen with the thickness 0.01 m (curve 1), 0.02 m (curve 2) and 0.04 m (curve 3) has been plotted due to the test results of dangerous sections transverse dimensions in consideration of the measurements accuracy to m. The relative strain $\psi = \varphi / t_o$ is the X-axis here.

Table gives numerical values of crack resistance characteristics for 45 carbon steel.

The treshold values of SIF K_{th}; limit values of SIF K^f_Q that identisy to the K_{fc} value only in case of plain strain conditions; parameters C and n of the Paris's equation are determined by usual kinetic diagrams of fatigue failure. The characteristics K^F_{fc}, K^F_o, K^F_{sc} are determined by D-diagrams accordingly. Thus, from the Fig.2 and table, value K^F_{fc} = const, i.e. it doesn't depend on the specimen thickness, that supports experemental data obtained previously. (Sosnovskiy et el., 1990) for carbon steel 20. The values $K^f_Q < K^*_{I max} = \sqrt{t_o \sigma^2_{0,2} / 2{,}5}$, thus plain strain conditions were not fulfiled under these tests. ($\sigma_{0,2}$ is yeld strength for 45 steel).

Two approaches may be proposed for analitical description of the OBC curve on every D-diagram. The first approach - this curve is described by equation

$$K^F_{I max} = K_w \left[(\psi - \psi_t) / (\psi_c - \psi) \right]^m , \quad \psi_t = 0{,}0006 < \psi < \psi_c ,$$

where m - parameter of the strengthening, K_w - SIF value corresponding to $\psi = (\psi_c + \psi_t)/2 \approx \psi_c/2$ value.

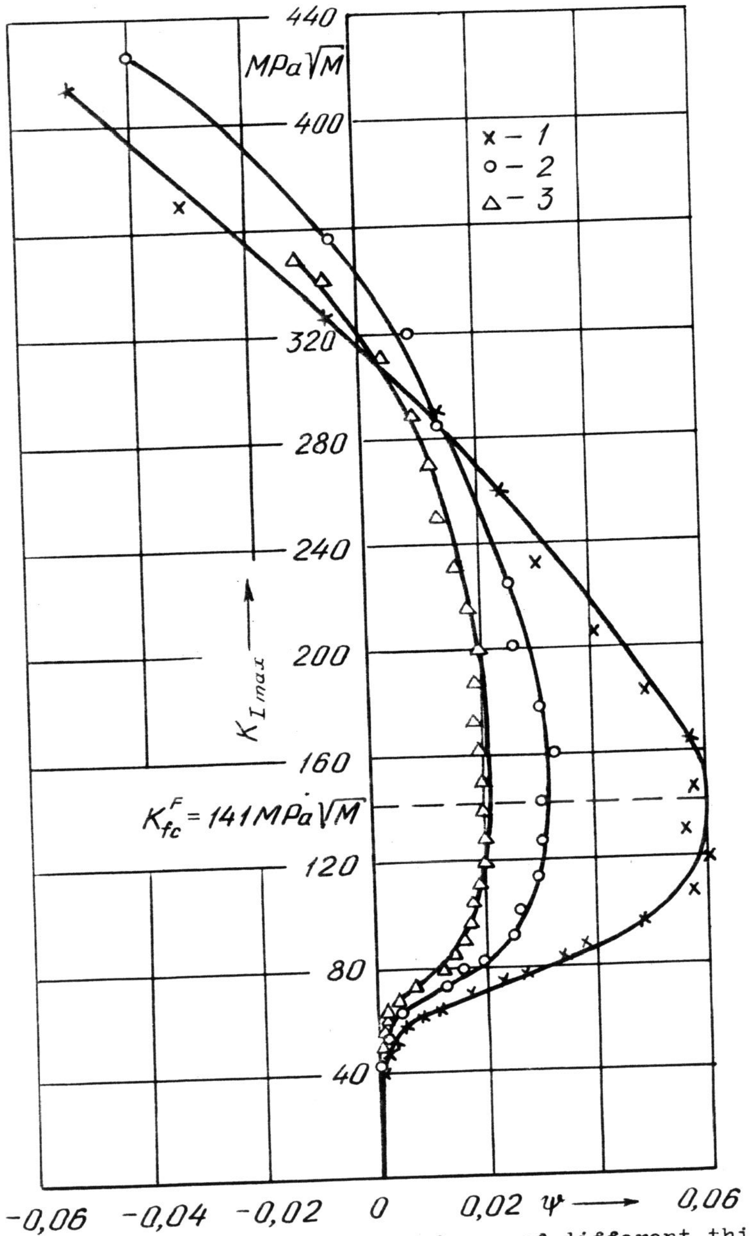

Fig.2. D-diagrams for specimens of different thickness made of 45 steel.

As a second approach – the right branch of the OBC curve is the direct line in the accordant double logarithm coordinates, hence

$$K^F_{Imax} = K_t(\psi/\psi_t)^{m'},$$

where K_t is determined as intersection point of the direct line under consideration and the Y-axis. Values m, K_w, m', K_t for 45 steel are given in Table.

D-diagrams shown on Fig.2 are individual for every specimen of given material having determined cracking resistance (ref. Table).

Table. Characteristics of 45 carbon steel cyclic crack resistance

Characteristics	Thickness of the specimen, m		
	0.01	0.02	0.04
K_{th}, MPa$\sqrt{m}$	1,3	1,9	6,9
K^*_{Imax}, MPa$\sqrt{m}$	26,6	37,6	53,1
K_t, MPa$\sqrt{m}$	42,6	45,7	52,5
K^f_Q, MPa$\sqrt{m}$	38,9	50,2	66,7
K_w, MPa$\sqrt{m}$	78,0	79,0	81,3
K^F_{fc}, MPa$\sqrt{m}$	141,0	142,5	140,0
K^F_o, MPa$\sqrt{m}$	317,0	344,0	320,0
K^F_{sc}, MPa$\sqrt{m}$	415,0	426,0	349,0
K^F_{cyc}, MPa$\sqrt{m}$	64,0	76,0	72,5
K^F_{ST}, MPa$\sqrt{m}$	63,0	73,0	72,0
K^*_{fc}, MPa$\sqrt{m}$	33,0	50,0	48,5
φ_c, m	$0,58 \cdot 10^{-3}$	$0,62 \cdot 10^{-3}$	$0,80 \cdot 10^{-3}$
φ_s, m	$-0,48 \cdot 10^{-3}$	$-0,82 \cdot 10^{-3}$	$-0,45 \cdot 10^{-3}$
ψ_c	0,060	0,031	0,020
ψ_s	-0,050	-0,041	-0,011
C	$4,3 \cdot 10^{-11}$	$5,4 \cdot 10^{-11}$	$1,36 \cdot 10^{-13}$
n	3,0	2,72	4,28
a_K	4,27	2,85	2,89
m'	0,103	0,120	0,133
m	0,133	0,142	0,150

For a given steel by similarity transformations it is possible to plot generalized D-diagram that represents uniform curve for all size- type specimens. For 45 carbon steel such diagram is given on Fig.3. (1,2,3 – specimens with the thickness

0,01, 0,02 and 0,04 m respectively).

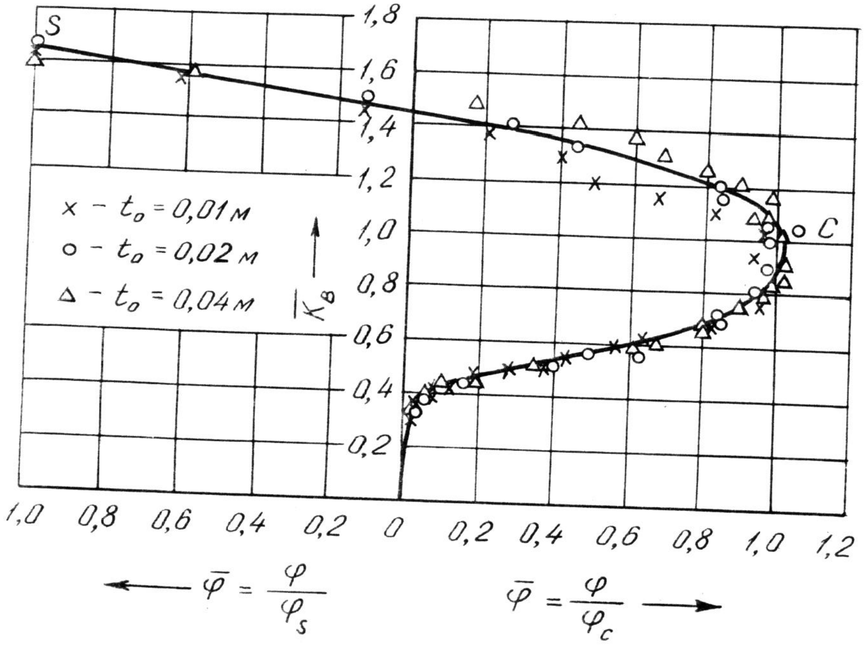

Fig.3. The generalized D-diagram for 45 steel.

To plot generalized D-diagram it is necessary to perfom coordinate transformations $K^F_{I\max}$ and ψ into $\overline{K}_B$ and $\overline{\varphi}$ respectively, where $\overline{K}_B = K^F_{I\max}/K^F_{fc}$ at $K^F_{I\max} \leq K^F_{fc}$ and $\overline{K}_B = 1 + (K^F_{I\max} - K^F_{fc})/K^F_{sc}$ at $K^F_{I\max} > K^F_{fc}$, and also $\overline{\varphi} = \varphi/\varphi_c$ (or φ/φ_s). With the help of generalized D-diagram it is not difficult to plot individual D-diagram for every size-type specimen using four parameters ($\varphi_c, \varphi_s, K^F_{fc}, K^F_{sc}$), and to restore the most important OBC branch of D-diagram only two parameters are sufficient (φ_c, K^F_{fc}). Then current value φ and SIF are determined as follows: $K^F_{I\max} = \overline{K}_B K^F_{fc}$ for the OBC branch, $K^F_{I\max} = K^F_{fc} + K^F_{sc}(\overline{K}_B - 1)$ for the CS branch (see Fig.1,b) and $\varphi = \overline{\varphi}\varphi_c$ (or $\varphi = \overline{\varphi}\varphi_s$).

Q-diagram. Q-diagrams has been plotted taking into account the actual value of rapture load of 45 steel specimens with the thickness of 0.01 curve (1), 0.02 (2) and 0.04 m (3) (Fig.4). The values of crack resistance K^*_{fc}, K^F_{cyc} and K^F_{ST} obtained with the help of these Q-diagrams are given in Table. It is important to note, that cyclic fracture toughness $K^*_{fc} < K^F_{fc}$

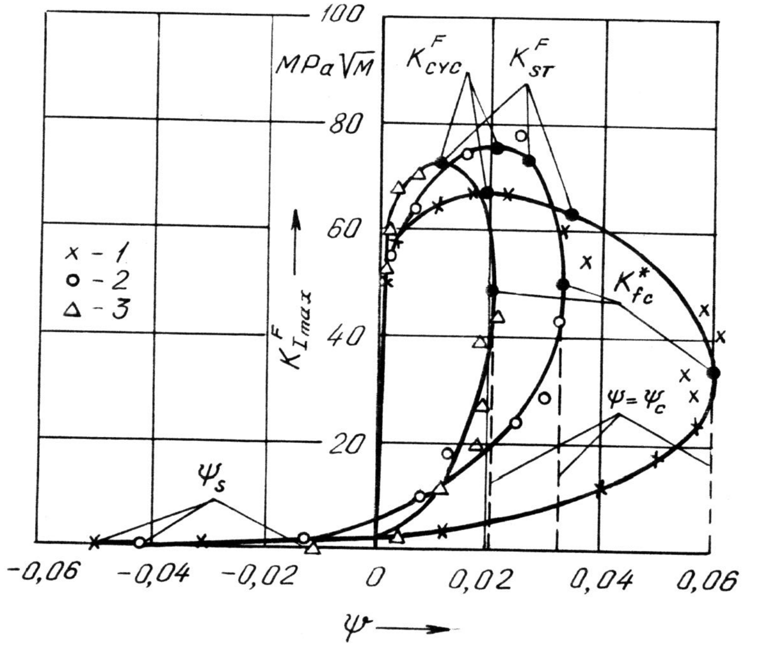

Fig. 4. Q-diagrams for specimens of different thickness made of 45 steel

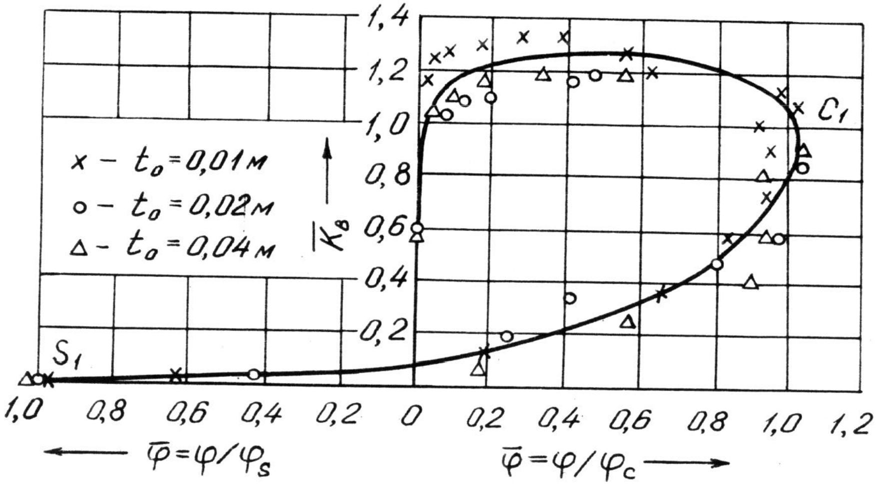

Fig.5. The generalized Q-diagram for 45 steel.

and relationship $K^F_{fc}/K^*_{fc} = a_K$ is practically constant for 45 stell at $t_0 \geqslant 0.02$ m (see Table).

To plot generalized Q-diagram being uniform curve for all size-type specimens, it is necessary to transit to coordinates $\overline{K}_B - \varphi$, where $\overline{K}_B = 1 + (K^F_{I max} - K^*_{fc})/(K^F_{CYC} + K^*_{fc})$ at $0 \leqslant \varphi \leqslant \varphi_c$ and $\overline{K}_B = K^F_{I max}/K^*_{fc}$ at $\varphi_c \leqslant \varphi \leqslant \varphi_s$; $\overline{\varphi} = \varphi/\varphi_c$ (or φ/φ_s)(Fig.5). Individual Q-diagram for a given size-type specimen may be plotted having generalized Q-diagram and value of four parameters $(\varphi_c, \varphi_s, K^*_{fc}, K^F_{CYC})$ for this specimen. In this case current values φ and SIF are determined as: $K^F_{I max} = K^*_{fc} + (\overline{K}_B - 1)(K^F_{CYC} + K^*_{fc})$ for branch OB_1C_1, $K^F_{I max} = \overline{K}_B K^*_{fc}$ for branch C_1S_1, and also $\varphi = \overline{\varphi}\varphi_c$ (or $\overline{\varphi}\varphi_s$).

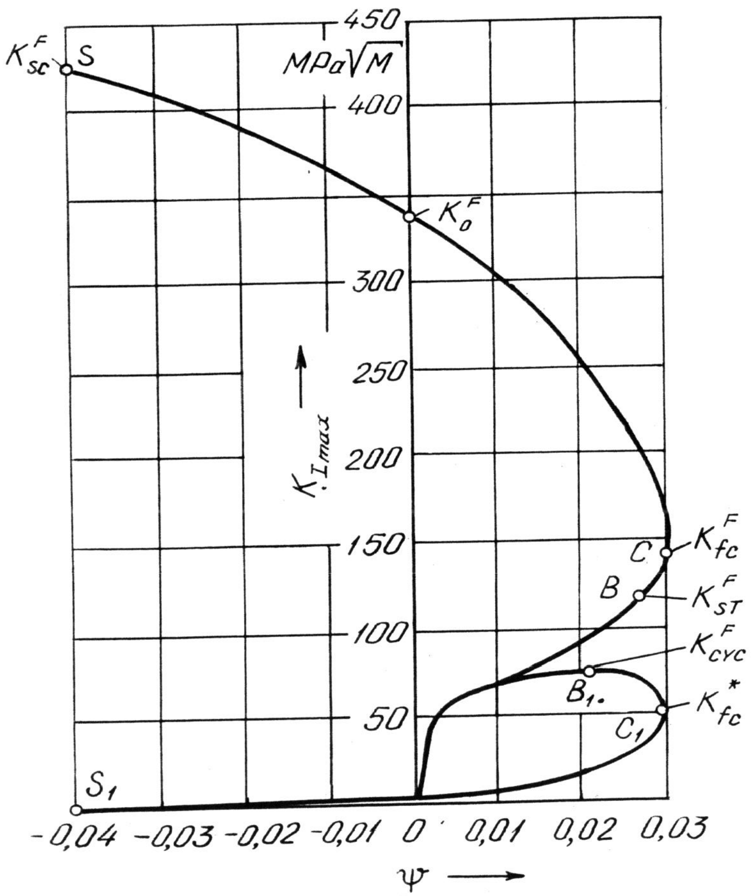

Fig.6. Aligned Q-and D-diagrams for the specimens of 0,02 m thickness made of 45 steel.

Fig.6 shows aligned Q-and D-diagrams plotted for the specimens of 0.02 m thickness made of 45 steel. As follows from Fig.6, $K^f_Q \ll K^F_{fc}$ value is characteristic point of neither the first nor the second diagram. K^F_{CYC} value being characteristic point (B) of Q-diagram, for D-diagram is not such. But K^F_{ST} value being characteristic point (B_1) of D-diagram is not Q-diagram characteristic point V.V.

Necessary to note that CEPF-diagram may be plotted in coordinates $\overline{K}_{Ie} - \psi$ (Sosnovskiy and Bogdanovich, 1992); where $\overline{K}_{Ie}$ is strain intensity factor (Makhutov, 1981).

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