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Relationship between crack resistance and the main mechanical properties of structural steels of low and medium strength

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Abstract

The article establishes a connection between the crack resistance of low and medium-strength steels and the grain structure of the material, its strain hardening, temperature and strain rate. A method is proposed for determining the temperature dependence of the static and dynamic crack resistance of these steels by testing a cylindrical sample at one (room) temperature.

This work solves one of the key problems in the field of fracture mechanics, namely, the determination of the crack resistance of the most widely used structural steels, in which the determination of this characteristic according to the existing standard requires testing samples with a crack weighing more than a ton, and according to the method used in this work, testing smooth cylindrical samples without a crack in uniaxial tension.

Keywords: Steels of low and medium strength, crack resistance, temperature, work hardening, grain structure

Introduction

In the total volume of metal consumption, steels of low and medium strength (hypo-eutectoid, ferritic-pearlitic structure, with a bcc lattice) occupy a predominant position. Nuclear and chemical reactors, pressure vessels, turbine rotors, hulls of surface vessels and underwater vehicles, parts and assemblies of rolling stock, building structures, etc., with a wall thickness of (40...50).10^{-3} m are made from these steels. up to (200...400).10^{-3} m and more.

A feature of these steels is the change in the yield strength and other mechanical properties with temperature.

Practical calculations of crack resistance (K_{1c}) of critical structures are carried out in compliance with the strength conditions of linear fracture mechanics.

Materials and methods of research

For steels of low and medium strength, the determination of K_{1c}, according to the ASTM E-399 standard [1], requires testing samples of very large sizes, powerful testing equipment and sophisticated metrological equipment. For example, to establish the temperature dependence of K_{1c} for steel made in the USA, grade A533B (chemical composition, table 1), samples with a crack for off-center tension were used, the dimensions and weight of these compact tensile samples are presented in table 2.

Table 1: Chemical composition of steel A533B

C	Mn	Si	Ni	Mo	P	S
0,25	1,15-1,50	0,15-0,30	0,40-0,70	0,45-0,60	0,035	0,035

Table 2: Dimensions and weight of compact samples with a crack for steel A533B

T	T	Sample	Thickness	Height	Width	The weight
K	°C	-	mm	mm	mm	kg
148	-283	1TCT	25	61	64	0,761
198	-75	2TCT	50	122	127	6,04
248	-25	4TCT	100	244	254	48,4
268	-5	10TCT	250	610	635	755,3
283	10	12TCT	300	732	762	1305,2

In this article, we present a method for establishing the temperature dependence of static and dynamic crack resistance based on the results of testing a cylindrical sample for uniaxial tension at one (room) temperature with recording the strain diagram. For power-law hardened steels, which also include low- and medium-strength steels, the relationship between true stress σ_i and true strain ε_i has the form

$$\sigma_i = B\varepsilon_i^n \ (\ln \sigma_i = \ln B + n \ln \varepsilon_i) \qquad (1)$$

Based on the solution of the elastic-plastic problem, in [2-7] between Kıc and the yield strength $\tau_т$ (tangential stresses) at the moment of failure, a relationship was established in the form (normal stresses)

$$K_{Ic} / K_\mu = (\sigma_c / \sigma_т)^{1-n/2n} \text{ or } \ln(K_{Ic}/K_\mu) = \chi \ln(\sigma_c / \sigma_т), \qquad (2)$$

This connection is dictated by the stressed and deformed state of the material within the plastic zone at the moment when the crack becomes unstable, the condition for which is the equality of the local stress τ at a distance ρ_c from the crack tip to the value τ_c. In formula (2)

$$K_\mu = \sigma_c \sqrt{\pi\rho} \quad \chi = (1-n / 2n) \qquad (3)$$

n - is the degree of strain hardening.

If formula (2) is compared with the expressions obtained in [8-10]

$$\ln (K_{1c}/K^{O}_{1c}) = \alpha m T, \text{ then} \quad (4)$$

$$\alpha m = \chi \ln(\sigma_c / \sigma_T); \ K\mu = K^{O}_{1c} \quad (5)$$

here K^{O}_{1c} - is the value of K_{1c} at T= 0 K;
α and m are the temperature-speed sensitivity of the yield strength and K_{1c}, respectively.
Considering that equality (2) refers to normal (T*=293K) temperature, then

$$\alpha m = \chi^* \ln(\sigma_c / \sigma^*_T); \ \chi^*=(1-n^*) / 2n^*; \quad (6)$$

here, n* and σ^*_T are the values of the degree of strain hardening and the yield strength at a temperature T* = 293 K.
Thus, if in the coordinate system ln (K_{1c}/K^{O}_{1c}) – T the value of K_{1c} at a temperature T* = 293 K is taken equal to

$$\ln (K_{1c}/K^{O}_{1c}) = \chi^* \ln(\sigma_c / \sigma_T^*), \quad (7)$$

then when setting T= T* from expression (4) we have

$$\alpha m = \ln (K_{1c}/K^{O}_{1c}) / T^*, \quad (8)$$

Substituting (8) into (4) gives

$$\ln (K_{1c}/K^{O}_{1c}) = [\chi^* \ln(\sigma_c/\sigma_T^*)] \, T / T^* \quad (9)$$

In a more compact form, (9) can be rewritten as

$$\ln (K_{1c}/K^{O}_{1c}) = \gamma T ; \text{ or } K_{1c} = K^{O}_{1c} \exp (\gamma T); \quad (10)$$

$$\text{where } \gamma = [\chi^* \ln(\sigma_c / \sigma^*_T)] / T^* \quad (11)$$

The value of σ_c follows from [11] $\sigma_c = [\sigma_T(0) - \sigma_o]$
σ_o is the temperature-independent (athermal) part of the yield strength,
From works [8-10]:

$$K^{O}_{1c} = \sigma_c \sqrt{\pi d} = [\sigma_T(0) - \sigma_o] \sqrt{\pi d} \quad (12)$$

d- is the average value of the grain diameter.
A change in the strain rate leads to a change in formula (9) values

$$\chi^*=(1-n^*) / 2n^* \text{ and } \sigma_T^*$$

Thus, in order to construct the temperature dependence of the crack resistance of steels of low and medium strength, according to (9), it is sufficient to test a cylindrical sample at one (room) temperature with a deformation diagram.

Results and discussion

Below is an algorithm (order) for applying the provisions of this technique to construct the temperature dependence of K_{1c} for any steel grade:

1. Production of a standard cylindrical (five or tenfold) sample from the steel under study.
2. Methods of metallography determination of the average grain size (d).
3. By testing for uniaxial tension, record the tension diagram of the sample in the coordinates force-elongation (P - ΔL) (Fig. 1).
4. Division into equal, approximately, k = 4…..5 parts, the area of uniform elongation on the tension diagram (Fig. 1) and according to the formulas

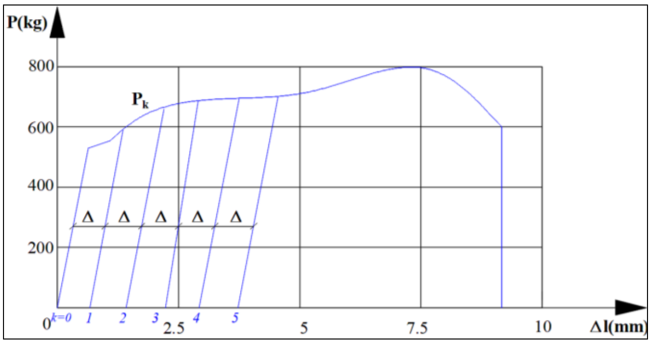

Fig 1: Tensile diagram of a cylindrical sample at room temperature.

$$\sigma_i = P_\kappa/F_o[1+(\kappa.\Delta L/L_O)], \ \varepsilon_i = \ln[1+(\kappa.\Delta L/L_O)] \quad (13)$$

Determination of the true value of stress and strain. Formulas (13) correspond to the condition of volume constancy during plastic deformation.

5. In the coordinates $\ln\sigma_i$ - $\ln\varepsilon_i$ plotting the points of the true values of stress and strain (Fig. 2) and determining from the graph $\ln\sigma_i$ - $\ln\varepsilon_i$ the value of the strain hardening index n:

$$n = \ln(\sigma_a/\sigma_c) / \ln(\varepsilon_c/\varepsilon_b)$$

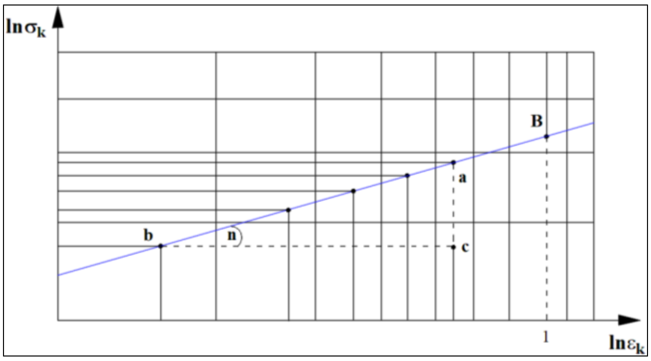

Fig 2: True tension diagram of a cylindrical sample for uniaxial tension.

6. According to the formula [14]

$$\sigma_T = \sigma_{To} \exp [\beta_T(1/T - 1/To)] \quad (14)$$

plotting the temperature dependence of the yield strength.
In formula (14): σ_{To} - is the value of the yield strength at temperature T_o = 293 K.
β_T - material characteristic determined from the graph β_T - σ_{To} (Fig. 3).
The value of σ_T at T = 0, T is defined as the effective value of the yield strength $[\sigma_T(0) - \sigma_o]$. The method for determining the values of σ_o and $[\sigma_T(0) - \sigma_o]$ is given in [12, 13].
Below is a numerical example of calculating K_{1C} for steel, in which the value of the yield strength at To = 293 K, $\sigma^*_T = \sigma_{To} = 700$ MPa, for which from Fig. 3, the value of $\beta_T = 50$. The necessary parameters for the calculation, as well as the values of σt and K_{1C} are presented in tables 3 and 4.

From the tensile diagram, for this steel, according to paragraph 5 and fig. 2 strain hardening index at temperature $T^* = 293$ K $n^* = 0{,}25$ and accordingly $\chi^*=(1-n^*)/2n^* = 1.5$. $T\to\infty$) can be determined from formula (14) as $\sigma_{\text{т}} - \sigma_o = \sigma_{\text{т}o} \exp[-\beta_{\text{т}}/T_o)] = 700 \exp[-(50 / 293)] = 590$ MPa.

The average grain size for this steel is d = 22, 4μм (grain grade number 9). The value of $[\sigma_{\text{т}}(0) - \sigma_o]$ is determined according to fig. 4.

Then the value of K_{1C} at T= 0 K according to (12):

$$K^O_{IC} = \sigma_c \sqrt{\pi d} = [\sigma_{\text{т}}(0) - \sigma_o]\,(\pi \cdot 22{,}4.10^{-6})^{1/2} = 1800.8{,}389.10^{-3}\ \text{MPa}\sqrt{\text{м}} = 15{,}1\text{MPa}\sqrt{\text{M}}\ ; \tag{15}$$

$\gamma = \chi^* \ln[\sigma_{\text{т}}(0) - \sigma_o) / \sigma^*_{\text{т}}] / T^* = [1{,}5\ln(1800/700)] / 293 = 4{,}835.10^{-3}$

Thus

$$K_{IC} = K^O_{IC} \exp(\gamma T) = 15{,}1\exp(4{,}835.10^{-3}.T) \tag{16}$$

Table 3: Numerical values of the parameters, for this steel, in the above formulas

$T^* = T_o$	$\sigma^*_{\text{т}} = \sigma_{\text{т}o}$	n*	χ*	$\beta_{\text{т}}$	d	σ_o	$\sigma_{\text{т}}(0)-\sigma_o]$	K^O_{IC}
К	MPa	-	-	-	µm	MPa	MPa	$\text{MPa}\sqrt{\text{м}}$
293	700	0,25	1,5	50	22,4	590	1800	15,1

Table 4: Numerical values of K_{IC} according to formula (16)

T, К	1/T-1/293-	exp50.(2)-	$\sigma_{\text{т}}$=700.(3) MPa	$\sigma_{\text{т}} - \sigma_o$, MPa	K_{IC}, $\text{MPa}\sqrt{\text{м}}$
1	2	3	4	5	6
0	-	-	-	-	15,1
50	0,01658	2,29	1604	1014	19,3
100	$6{,}587.10^{-3}$	1,39	973	383	24,5
150	$3{,}25.\ 10^{-3}$	1,1766	824	234	31,2
200	$1{,}587.10^{-3}$	1,083	758	168	39,7
250	$5{,}87.10^{-4}$	1,03	721	131	50,6
293	0	1	700	110	62,3

Most often, cracks appear at the tops of dislocation clusters near any barriers. Modern ideas about destruction proceed from the fact that this is a process that goes on in time in parallel with deformation (elastic or plastic). The peculiarity of destruction lies in the fact that it is much more local and structurally sensitive.

In metals with a lattice crack can form according to the well-known model proposed by Cottrell.

Conclusion

The technique presented in the work, along with the establishment of a connection between crack resistance and the main mechanical properties ($\sigma_{\text{т}}$, n, σ_c,) and grain structure (d) of structural steels with lattice, allows you to determine the crack resistance of steels in any research or factory laboratory with minimal material costs.

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