Physical Aspect of Plasticity in Linear Fracture Mechanics.

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Formation of the plastic zone at the crack tip determines in many respects the behavior of materials at fracture. The latest developments in the linear fracture mechanics make it possible for the case of small scale yielding to describe a stress field beyond the plastic zone with an elastic singularity, as well as fields of stress and strain within the plastic zone using Rice's J-integrals. Basing on these assumptions the authors obtained expressions for the strain rate $\dot{\gamma}_e$ on outlines of the plastic zone

$$\dot{\gamma}_e = \frac{2(1-2\nu)}{G}\frac{\tau_s}{K_I}\left(\dot{K}_I + \frac{2\pi\tau_s^2 W}{K_I}\right) \qquad (1)$$

and for fracture at the crack tip

$$\frac{\tau_c}{\tau}\left(\frac{\tau_s}{\tau}\right)^{\frac{1-n}{2n}} = \frac{K_\mu}{K_I} \qquad (2)$$

In these equations ν is Poisson's ratio, G-shear modulus, τ_s-yield stress on outlines of the plastic zone, K_I and $\dot{K}_I$ stress intensity factor and rate of its variation, respectively, W-crack velocity, τ-local shear stress at a distance ρ_c ahead the crack tip where a microcrack is nucleated, τ_c-value of the stress τ at the crack instability onset, $K_\mu = 2\tau_c\sqrt{\pi\rho_c}$, n-strain hardening exponent.

Relations (1) and (2) enable us to link up both physical mechanism of yielding on outlines of the plastic zone and that of fracture at the crack tip with external parameters of loading and material structure.

To analyse the brittle-ductile transition three series of experiments were conducted on specimens made of the same heat of iron containing 0.05% C.

1. Solid cylindric specimens of 4 mm diameter with three different grain sizes of 0.03, 0.06, and 1.0 mm were tested at various temperatures ($78 < T, °K < 800$) and with different strain rates ($3.5 \times 10^{-6} < \dot{\mathcal{E}}, s^{-1} < 1.75 \times 10^{-3}$).

2. Thin-walled tubular specimens (wall thickness of 0.8 mm and internal diameter of 24 mm) with the average grain size of 0.03 and 1.7 mm were tested with 5 modes of the plane stress state ($K = \frac{\sigma_2}{\sigma_1} = 0, 0.667, 1, -0.25$ and -0.55) at low temperatures ($100 < T, °K < 273$).

3. Plane specimens (of 2.5 mm thickness and 80 mm width) with double symmetrical edge-notches were tested in tension with two rates of loading ($\dot{K} = 0.5$, 10 kg/mm$^{3/2}$s) at low temperatures ($78 < T, °K < 293$). The average grain size was 0.06 mm. The length of each notch was about 15 mm, the blunt radius at the notch root about 0.03 mm.

These experiments enabled us to establish both temperature and strain rate conditions for a crack to transit into the instability state, and to relate these with physical properties of the material.

Fig.1 shows temperature dependences of fracture stress for smooth cylindric (curve 3), tubular (curves 1, 2) and plane notched (curves 4,5) specimens, as well as similar dependences of yield stress on outlines of the plastic zone (curves 6,7). Fig.2 presents temperature dependences of deformational characteristics of fracture, i.e. elongation $\mathcal{E}_1$ at fracture for tubular specimens

(curves 1,2,3,5), critical crack opening displacement δ_c and cross-section area reduction ψ for plane notched specimens (curves 4 and 6). Comparing Fig.1 and Fig.2 suggests that for the material tested the ductile-brittle transition due to lowering the temperature is determined by conditions of formation of the plastic zone (see curves 3,4,6 in Fig.2) while conditions for fracture initiation are attained owing to increase in applied stresses (see curves 3,4,5 in Fig.1).

From the expression (2) it follows that at the crack instability onset ($\tau = \tau_c$) the relation between K_{Ic} and τ_s may be given by

$$K_{Ic} = K_\mu \tau_c^{\frac{1-n}{2n}} \tau_s^{-\frac{1-n}{2n}} \tag{3}$$

which reveals a complex nature of temperature effect on this relation. On the other hand, a number of studies where τ_s varied due to changes in temperature or strain rate without any variation of material structure indicate a simplier relationship between K_{Ic} and τ_s

$$K_{Ic} = a\tau_s^{-1,5} \tag{4}$$

As seen from Fig.3, a similar relation is found in our tests. The equation (4) represents a particular case of the expression (3) when $\frac{1-n}{2n} = 1.5$, i.e. $n = 0.25$. Using Irwin's formula for small scale yielding and expressions (3) and (4) we derive the following relations, respectively:

$$2r_{pc} = \frac{K_\mu \tau_c^{\frac{1-n}{n}}}{4\pi} \tau_s^{-\frac{1+n}{n}}; \quad 2r_{pc} = \frac{a^2}{\pi} \tau_s^{-5}, \tag{5}$$

in which the yield stress may be considered as a physical quantity. The first series of experiments gave th sion for yield stress

$$\tau_S = \tau_{P_0}\left(\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)^{\frac{kT}{210 b^3}} + \tau_a \,, \qquad (6)$$

where τ_{P_0} is friction stress of the crystalline lattice at 0°K, $\dot{\gamma}$ - strain rate, $\dot{\gamma}_0$ - preexponential factor in the Arrenius' type expression, T - absolute temperature, k - Boltzmann's constant, b - Burgers' vector, τ_a - athermal component of stress yield. Combining the expressions (5) and (6) gives a relation between size of the plastic zone and various physical parameters

$$2r_{Pc} = \frac{a^2}{\pi}\left[\tau_{P_0}\left(\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)^{\frac{kT}{210 b^3}} + \tau_a\right]^{-5} \qquad (7)$$

which for a given constant value of $2r_{Pc}$ establishes a link between the ductile-brittle transition temperature T_C and the strain rate, as well as other physical parameters. This expression predicts a linear relation between T_C^{-1} and $\lg \dot{\gamma}$ which has been supported by many experiments. Fig.4 gives temperature dependences of the $8r_{Pc}^2$ quantity proportional to the strain energy within the plastic zone, as calculated for various strain rates $(\frac{\dot{\gamma}}{\dot{\gamma}_0})$.

Apart from the slip influence, the low-temperature crack growth in iron is affected by twinning. Estimation of this effect was made by an analysis of forces interacting between the crack tip and a twinning dislocation that belongs to one of the twelve systems of twinning.

The obtained results make it possible to explain fractographs of cleavage on which "tongues" are observed, and answer the question why there are only two pairs of twins on the plane of cleavage.

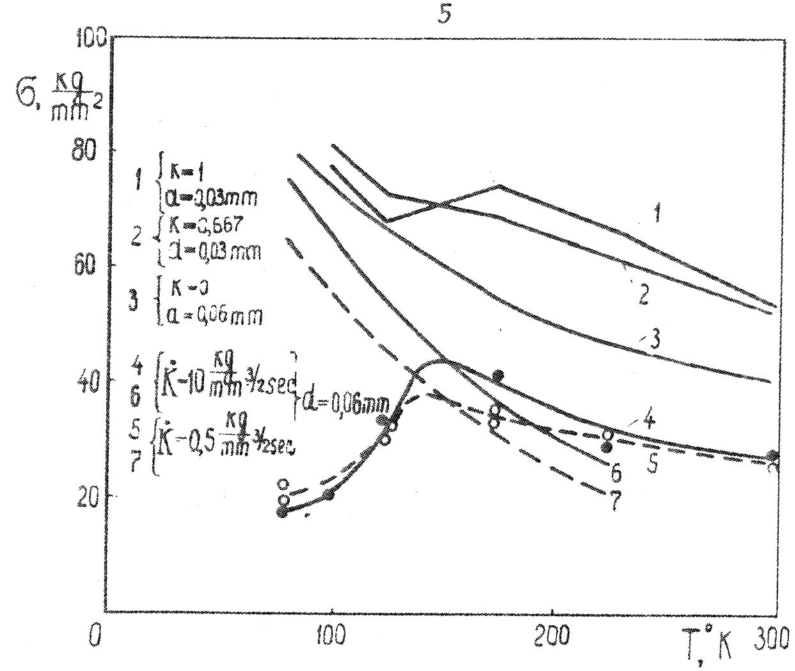

Fig.1 Stress at fracture vs. temperature.

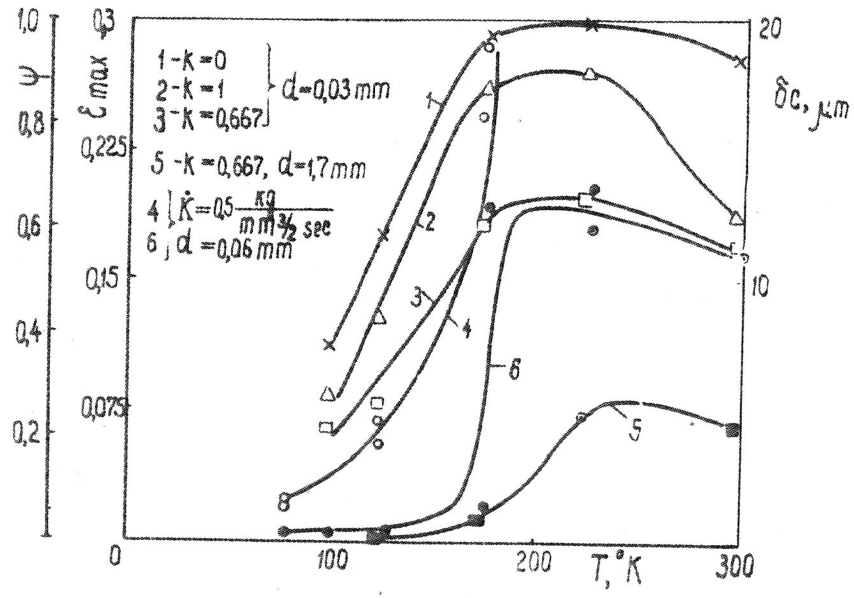

Fig.2 Deformational characteristics of fracture.

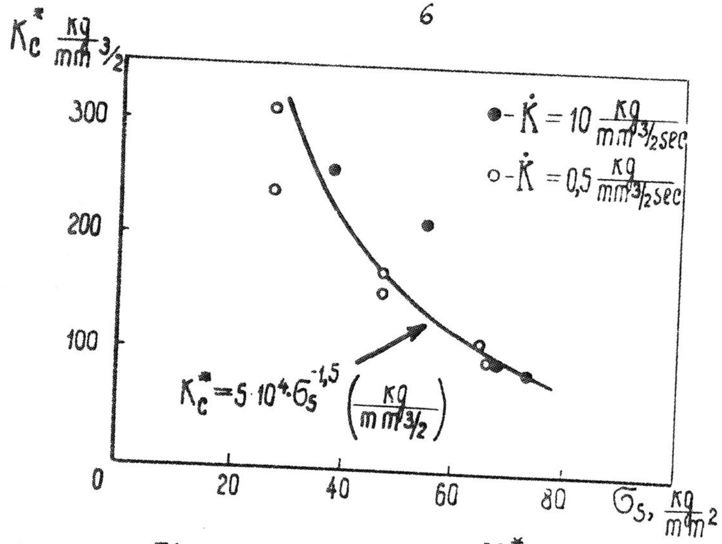

Fig.3 Relation between K_c^* and σ_s.

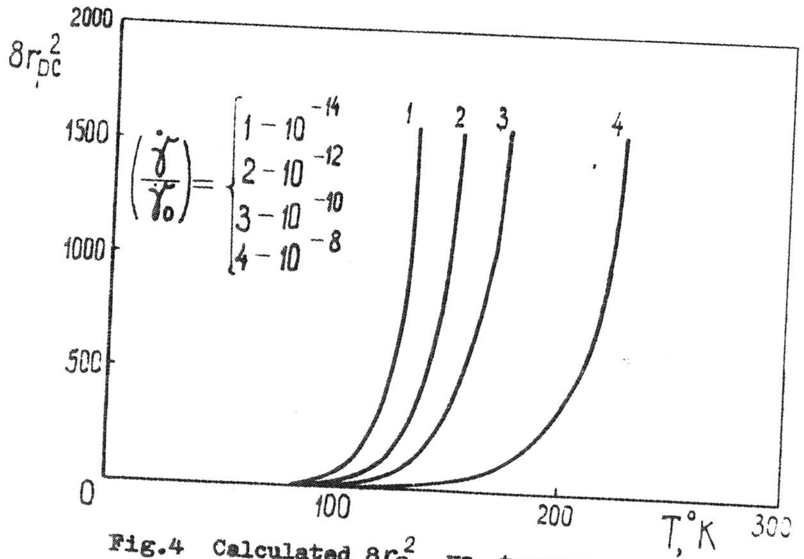

Fig.4 Calculated $8r_{pc}^2$ vs. temperature.