MODEL OF THE FAILURE OF STEEL UNDER CONDITIONS OF STRESS CONCENTRATION

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The article explains notions concerning the nature of the brittleness of steel connected with the action of stress raisers. It shows that the embrittling effect of stress raisers is connected with their bringing about a three-dimensional state of stress and strain concentration. It substantiates the advantage of using as measure of ductility of metal the coefficient of ductility K_d determined as the ratio of the "brittle" strength of the metal (resistance to microcleavage R_{mc}) to the yield strength σ_y. This approach is applied to the cold brittleness of a product containing constructional stress raisers. It was established that this phenomenon takes place when the ductility of the metal lies below some limiting K_{dc} whose magnitude is determined by the parameters of the state of stress and strain and by the proneness of the metal to strain-hardening. On the example of α-iron of carbon steels it is shown that the suggested approach can be used for predicting the temperature of cold brittleness under conditions of stress concentration.

Introduction. Regardless of the well-known achievements of fracture mechanics, so far the problem of failure of steel products containing constructional stress raisers (holes for fastening, fillets, recesses, etc.) has not been solved. In stress analysis it is current practice to regard stress raisers as factors of overstress or as sources of local deformations. Such an approach is unsuitable for adequately describing the process of failure under conditions of stress concentration because it is known from experience that notches bring about a change of the state of stress, and in addition they enhance proneness to brittle failure. Metal that is ductile under uniaxial tension becomes brittle when there is a stress raiser, and that manifests itself in a change of the micromechanism and the kinetics of failure.

One way of solving this problem is the application of local criteria of failure [1-3]. According to these criteria, the limit state is connected with the maximal principal stress attaining the magnitude of local strength (R_σ after [1], S_{OT} after [2], σ_F after [3]) which in the cited publications is regarded as some constant of the material. With such an approach the notion of the physical nature of the introduced constant of the metal is problematical, and in addition it is not always clear how to determine this characteristic with the simplest uniaxial tensile tests.

The aim of the present work is to find out on the basis of an analysis of the process of brittle failure in the region of stress concentration with which factors of the state of stress and strain the embrittling effect of stress raisers is connected, and which mechanical properties of the metal are responsible for the level of "brittle" strength and ductility of the metal under these conditions.

Principal Postulates of the Model. It was shown in [4] that local stress of brittle failure is not a constant of the material, but its minimal value is almost the same as the resistance to microcleavage R_{mc} which, in accordance with [5, 6], is the fundamental characteristic of the metal and can be determined from the results of mechanical uniaxial tensile tests (Fig. 1). For describing failure at the tip of the notch we can therefore use in the first approximation the dependence [6]

$$\sigma_1 = R_{mc}; \quad \sigma_i = \sigma_y, \tag{1}$$

where σ_1 is the maximal principal tensile stress; σ_i is the stress intensity; σ_y is the yield strength.

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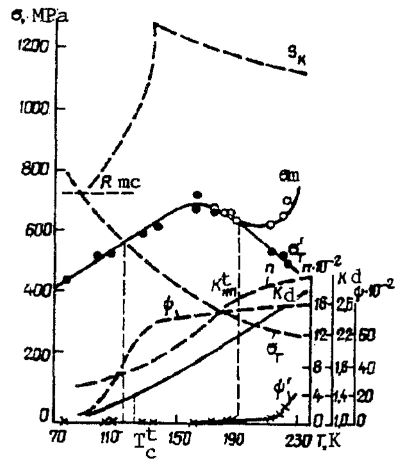

Fig. 1. Temperature dependences of the characteristics of failure of technically pure iron under uniaxial tension (dashed lines) and when there is a circular notch (radius at the tip R = 0.48 mm, depth t = 2.5 mm, maximal diameter ∅ = 14 mm) (solid lines). (σ_n) nominal rupture stress; σ_y') total yield stress; ψ') reduction of area in the effective section of notched specimens; T_c^e and T_c^t) experimental and theoretical temperature of cold brittleness, respectively.)

It should be emphasized that plastic deformation (even at the level of the yield strength e_y) is an indispensable prerequisite of failure by the model of microcleaveage since nucleating submicrocracks, which are the cause of brittle failure, are the result of dislocational rearrangements in the metal that accompany the process of plastic deformation.

In deformations deliberately exceeding e_y this requirement is ensured to a greater extent but the criterion of microcleavage (1) is somewhat modified in view of the influence of plastic deformation on the critical dimension of the submicrocrack and correspondingly on the brittle rupture stress [6]:

$$\sigma_1 = R_{mc} \ ; \qquad \sigma_i = \sigma_e \ , \tag{2}$$

where R_{mce} and σ_e are, respectively, the resistance to microcleavage and the yield stress of plastically deformed metal. According to the experimental data of [6, 7] plastic deformation raises the level of brittle strength R_{mce}. To α-Fe and low-carbon steels the following dependence applies:

$$R \quad = \beta R_{mc} \ , \tag{3}$$

where $\beta = 1 + 1.51 e_i - 0.86 e_i^2$.

It is expedient to represent the yield stress in the form

$$\sigma_e = \sigma_y \left(\frac{e_i}{e_y} \right)^n , \tag{4}$$

where n is the index of strain-hardening; e_i is the strain intensity.

Transforming (2) with (3) and (4) taken into account, we obtain the criterion of brittle failure in the following form:

$$K_d = \frac{j}{\beta} \left(\frac{e_i}{e_y} \right)^n , \tag{5}$$

TABLE 1. Calculated Values of the Critical Level of Ductility K_{dc} and of the Temperature of Cold Brittleness T_c of α-Iron and Carbon Steels

Material	R_{mc}, MPa	$n(T_c)$	K_{dc} (exp.)	K_{dc} (calc.)	δK_{dc}, %	T_c, K (exp.)	T_c, K (calc.)	ΔT_c	Parameters of notch, mm	
									t	R
α – Fe* anneal.	730	0,066	1,28	1,33	3,9	115	121	+6	2,5	0,48
α – Fe* anneal.	730	0,050	1,11	1,26	13,5	95	115	+20	2,5	0,71
α – Fe** anneal.	625	0,045	1,15	1,27	10,4	96	113	+17	2	0,60
St. U8 anneal.	865	0,100	1,11	1,23	10,8	113	133	+40	3	3,90
St. 45 anneal.	920	0,050	1,15	1,28	11,3	108	143	+35	2,8	0,50
St. 20GFTL	970	0,040	1,10	1,25	13,6	133	161	+28	2,5	0,48
St. 50	1470	0,080	1,41	1,37	2,8	138	128	-10	2,5	0,48
St. 70	1580	0,100	1,35	1,45	7,4	173	195	+22	2,5	0,48

*The size of ferrite grain is $d_f = 70\ \mu m$, **$d_f = 90\ \mu m$.

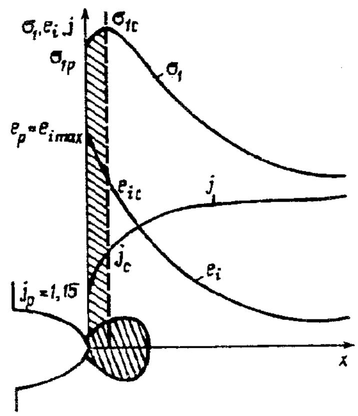

Fig. 2. Diagram of the stress and strain distribution in the region affected by the stress raiser: σ_1) maximal principal stress; e_i) local strain intensity; j) rigidity of the state of stress; σ_{1c}, e_{ic}, j_c) critical value of the respective parameters; σ_{1p}, e_p, j_p) their theoretical values.

where j is the rigidity parameter of the state of stress, $j = \sigma_1/\sigma_i$ [2, 6]; K_d is the ductility coefficient of the metal, $K_d = R_{mc}/\sigma_y$ [6, 7].

The obtained criterion makes it possible to predict failure if we know the properties of the metal (K_d, n) and the parameters of the state of stress and strain (j, e_i) in the region affected by the stress raiser.

At present there do not exist any accurate solutions of nonlinear boundary-value problems of stress concentration except for stress raisers with the simplest configurations, therefore, to determine j and e_i it is necessary in an actual case to solve this problem approximately by analytical or numerical methods. However, for the analysis of the common regularities of the embrittling effect of constructional stress raisers it is expedient to transform (5) by proceeding from simplifying assumptions. It follows from data of [8] that with constructional stress raisers ($\alpha_\sigma \leq 2 \ldots 3$) with nominal loads not exceeding the yield strength ($\sigma_n \leq \sigma_y$) plastic deformation is localized at the contour of the notch. This makes it possible to take it in the first approximation that the condition of failure (5) is fulfilled on the contour of the stress raiser (Fig. 2). Then

$$e_i \approx e_1 = K_e e_n \,, \tag{6}$$

where e_1 is the maximal deformation on the contour; K_e is the strain concentration factor; e_n is the nominal (mean) deformation.

According to [8] the following applies to constructional stress raisers with $\sigma_n \le \sigma_y$

$$K_e = \alpha_\sigma^2 \frac{\sigma_n}{\sigma_y}, \tag{7}$$

where σ_n is the nominal (mean) stress; α_σ is the elastic stress concentration factor.

Substituting (7) and (6) into (5) we obtain

$$K_d = \frac{1}{\beta} \left(\alpha_\sigma^2 \frac{\sigma_n e_n}{\sigma_y e_y}\right)^n . \tag{8}$$

An analysis of the temperature dependences of the mechanical properties of specimens with stress raisers shows that the most dangerous situation arises when the mean stress in the effective section at the instant of failure σ_n is smaller than the yield stress of the metal σ_y. It is reasonable to bring this situation into connection with cold brittleness and to denote the temperature at which the conditions $\sigma_n = \sigma_y$ and $e_n \approx e_y$ are fulfilled by T_c.

Such a determination of the temperature of cold brittleness yields with the aid of (8) an expression for the critical coefficient of ductility K_{dc}:

$$K_{dc} = j\alpha_\sigma^{2n} . \tag{9}$$

In deriving this dependence we assumed that for constructional stress raisers with $\alpha_\sigma \le 2 \ldots 5$ for $\sigma_n/\sigma_y \approx 1$ the maximal deformation does not exceed a few percent, we therefore neglected the increase of R_{mce}, supposing that $\beta \approx 1$. We emphasize that K_{dc} determines the minimally permissible level of ductility K_d ($K_d = R_{mc}/\sigma_y$, the ductility limit of the system metal–stress raiser) below which the stress raiser causes cold brittleness of the product, i.e., its failure at nominal stresses not exceeding yield stress.

It follows from (9) that the embrittling effect of stress raisers has to do with the three-dimensionality of the state of stress (parameter j) and strain concentration induced by it. (According to (7) $K_e = \alpha_\sigma^2$ for $\sigma_n = \sigma_y$.)

It should be noted that this last factor is dangerous mostly because of the proneness of the metal to strain-hardening (parameter n). Metals with large values of n are more subject to the embrittling effect of stress raisers. In fact, the larger the index of strain-hardening n is, the higher is the level of normal stresses σ_1, other conditions being equal, and the closer are they to their limit value R_{mc}. In ideally plastic metal (n = 0) the embrittling effect of notches is due solely to the rigidity of the state of stress j induced by them.

Results of the Experimental Investigations. The obtained criterion of failure (5) in the simplified alternative (9) can be experimentally verified without particular difficulties. For that it is necessary to calculate K_{dc} by (9) and to compare the obtained value with the ductility of the metal K_d at the temperature of cold brittleness T_c. Besides that, Eq. (9) makes it possible to predict the temperature of cold brittleness. In fact, after some simple transformations of dependence (9) we obtain a nonlinear equation for T_c:

$$\sigma(T_c) = \frac{R_{mc}}{j\alpha_\sigma^{2n(T_c)}} . \tag{10}$$

The experimental investigations envisaged mechanical uniaxial tensile tests of cylindrical specimens at low temperatures. From the results of these tests we plotted the temperature dependences of the yield strength $\sigma(T)$ and of the index of strain-hardening $n(T)$* (Fig. 1).

The resistance to microcleavage R_{mc} was determined as the minimal rupture stress S_K in the temperature range of the viscoelastic transition (Fig. 1).

*The index of strain-hardening was calculated by the formula $n = \log(S_b/\sigma_y)/\log(e_p/e_y)$, where S_b is the true ultimate strength, e_p is uniform deformation.

As stress we used circular notches with different geometry on cylindrical specimens ($\varnothing = 14$ mm) of α-iron or carbon steels (Table 1). The elastic stress concentration factor α_σ was determined with the aid of the tables of [9].

Dependence (9) describes failure on the contour of the stress raiser where there is a state of plane stress, therefore $j \leq 1.15$. We adopted $j = 1.15$.

According to the obtained results the deviation of the theoretical values of the ductility limit K_{dc} from the experimental ones does not exceed 10-15%, and the theoretical values are consistently larger than the experimental ones (Table 1). The relation between theoretical and experimental values of the temperature of cold brittleness T_c is analogous. Such a difference is due to the adopted assumptions. Firstly, as local strength we used the lower estimate, viz., the resistance to microcleavage R_{mc}. Secondly, in deriving dependence (9) we arbitrarily transferred the focus of failure to the contour of the stress raiser, which led to larger deformation at the point of failure (Fig. 2).

Thus, the suggested model, regardless of a number of simplifying assumptions, makes it possible to understand the physical nature of the embrittling effect of constructional stress raisers and to identify the main factors of the state of stress and strain ($K_e \approx \alpha_\sigma^2$, j), and also the key mechanical characteristics ($K_d = R_{mc}/\sigma_y$, n) determining the temperature of cold brittleness.

CONCLUSIONS

1. The phenomenon of cold brittleness of a product with a constructional stress raiser at $\sigma_n \leq \sigma_y$ is connected with the drop of the level of ductility of the metal K_d to its limit value K_{dc}.

2. The limit of ductility K_{dc} is determined by the rigidity of the (bulk) state of stress (j) induced by the notch, by the plastic strain concentration ($K_e \approx \alpha_\sigma^2$), and by the proneness of the metal to strain-hardening n ($K_{dc} = j\alpha_\sigma^{2n}$).

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