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 \( \sigma_y \). 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 \( \alpha \)-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 (\( R_s \) after [1], \( S_{OT} \) after [2], \( \sigma_F \) 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 \( \sigma_1 \) is the maximal principal tensile stress; \( \sigma_I \) is the stress intensity; \( \sigma_y \) is the yield strength.
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 $\varnothing = 14$ mm) (solid lines). ($\sigma_n$) nominal rupture stress; $\sigma'_y$) total yield stress; $\chi'_y$) 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 $\varepsilon_y$) is an indispensable prerequisite of failure by the model of microcleavage 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 $\varepsilon_y$ 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]:

$$\sigma_1 = R_{mc} \quad ; \quad \sigma_i = \sigma_e,$$

(2)

where $R_{mc}$ and $\sigma_e$ 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 $R_{mc}$. To $\alpha$-Fe and low-carbon steels the following dependence applies:

$$R = \beta R_{mc},$$

(3)

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

It is expedient to represent the yield stress in the form

$$\sigma_e = \sigma_y \left( \frac{\varepsilon_i}{\varepsilon_y} \right)^n,$$

(4)

where $n$ is the index of strain-hardening; $\varepsilon_i$ is the strain intensity.

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

$$K_d = \frac{1}{\beta} \left( \frac{\varepsilon_i}{\varepsilon_y} \right)^n,$$

(5)