COLD BRITTLENESS CRITERION FOR NOTCHED STEELS

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ABSTRACT

The problem of cold brittleness of steels with notches is discussed. New toughness characteristics - toughness index K_T and toughness margin index K_{TM} - are proposed within the scope of the concept of critical cleavage stress σ_F. In contrast to traditional ones, the proposed toughness characteristics are quantitative measures of the tendency of metal to resist the embrittlening action of arbitrary-geometry notches, including fatigue cracks, which allows the toughness margin index K_{TM} to be used directly in calculations of load-bearing structural elements by analogy with the safety margin index. Based on the characteristics, criteria of cold brittleness of steels containing various macrodefects have been formulated. Possibilities of new approaches to estimating the quality and predicting the realiability of structural materials,illustrated by a broad class of structural steels, are demonstrated.

KEYWORDS

Fracture criterion, cold brittleness, critical cleavage stress, microcleavage resistance, impact strength, fracture toughness, notches.

INTRODUCTION

A sudden brittle fracture of structures can be in general case ascribed to an inadequate toughness of metal. A design engineer, however, has at present no such a quantitative characteristic of this property, with whose aid he could protect a product from a sudden brittle fracture by specifying an appropriate toughness margin. This is a fundamental difference from the strength calculation procedure, where the specified safety margin reliably ensures the absence of general yielding in a product.

The existence in metal of macrodefects in the form of various stress concentrators, fatigue cracks, and other damages results in that the average (nominal) fracture stress σ_{NF} may turn out to be less than the metal yield stress σ_{02}. From the engineering standpoint, such a situation is ultimately permissible, where the fracture occurs at nominal stresses σ_{NF}, equal to σ_{02}. The temperature at which this event occurs is expedient to call temperature of cold brittleness (T_c) of metal containing macrodefects. It is clear that at the cold brittleness temperature the metal toughness level becomes equal to some critical value. It is essential to find a method for determining this value.

Two toughness characteristics are generally adopted at present: CVN energy (KCV) and fracture toughness K_{Ic}. The former is employed in the physical metallurgy to evaluate the metal quality, while the latter is used by designers to predict the risk of fracture at the existence of fatigue cracks in a structure. The two parameters, however, characterize the metal toughness only as applied to that situation which is modeled at their experimental determination, and therefore cannot claim the role of universal characteristics, allowing prediction of the temperature of cold brittleness of metal, caused by a random-geometry macrodefect. Deficiencies of KCV and K_{Ic} include also absence of one-to-one correspondence between their value and microstructure parameters (Hahn, 1984), which prevents metal physicists from controlling steel properties by a purposeful action on the metal microstructure.

The objective of our study was: based on physical concepts of the nature of fracture of metal having random-geometry notches, to introduce a universal concept of metal toughness and, relying on it, to formulate the criterion of cold brittleness of steels with notches.

BRITTLE FRACTURE OF NOTCHED SPECIMENS

The metal's capacity to resist brittle fracture is characterized by the critical cleavage stress σ_F (Knott, 1973). A necessary condition for fracture of metal with a notch is the existence at the tip of the latter of a local region of plastic deformation. Due to this, the fracture condition is

$$\begin{cases} \sigma_{1max} = \sigma_F \\ \sigma_i = \sigma_Y \end{cases} \qquad (1)$$

where σ_{1max} is the maximum principal stress at the notch tip; $\sigma_i = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2}$ is the equivalent stress; σ_F is the critical cleavage stress; and σ_Y is the yield stress. As found recently (Kühne and Dahl, 1983), σ_F is not a constant of metal, but depends on the notch tip radius and temperature. The range of critical cleavage stress values, however, is limited from below by the level of "brittle" strength of smooth specimens at a uniaxial tension (Kotrechko et al., 1988; see also the paper "Critical Cleavage Stress σ_F and Problem of "Brittle" Strength of Metals" by Kotrechko et al. in this book).

The latter characteristic was named by Meshkov (1976) microcleavage resistance R_{mc}; it is determined experimentally as the minimum stress of brittle fracture of smooth specimens within the ductile-brittle transition temperature range (Fig. 1).

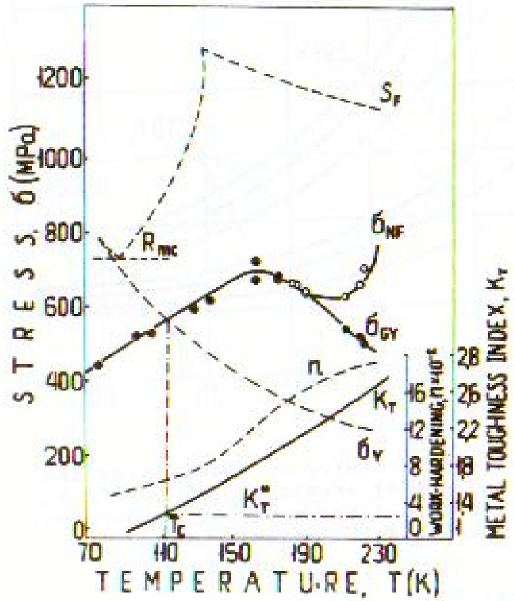

Fig. 1. Temperature dependences of fracture characteristics of smooth (broken line) and axisymmetric notched (solid line; notch radius R = 0.48 mm; depth h = 2.5 mm; maximum diameter, 14 mm) specimens of Armco iron. T_c - cold brittleness temperature; K_T^* - critical value of toughness index

Transforming (1) with account of the above yields

$$\begin{cases} \sigma_{1max} = f(\sigma) R_{mc} \\ \sigma_i = \sigma_Y \end{cases} \qquad (2)$$

or

$$j / f(\sigma) = K_T \qquad (3)$$

where $j / f(\sigma)$ is a dimensionless parameter characterizing the stressed-strained state at the notch tip ($j = \sigma_{1max}/\sigma_i$ is the overstress coefficient; $f(\sigma)$ is a function of the relative strain gradient G , interrelating σ_F and R_{mc}); and $K_T = R_{mc}/\sigma_Y$ is the toughness index (Meshkov, 1981).

In essence, K_T characterizes the yielding state of metal, defining how far it is from brittle fracture at the yielding onset moment. At uniaxial tension the easiest way for attaining the brittle state ($K_T \approx 1$) is to raise the yield stress to the R_{mc} level ($\sigma_Y \approx R_{mc}$) by lowering the temperature.

As follows from (3), the existence of notch results in that the metal can undergo brittle fracture at higher temperatures and hence at K_T values exceeding unity and equal to $j/f(G)$. This means that for any notch, according to its geometric parameters, there is a corresponding critical toughness K_T^*, at which the metal goes into the brittle state. The K_T^* value can be calculated if the j and $f(G)$ values are known or determined experimentally as the K_T value at the cold brittleness temperature (Fig. 1).

Figure 1 shows temperature dependences of main mechanical properties of Armco iron, including the toughness index K_T and parameter n , as well as fracture stresses σ_{NF} of notched specimens (R = 0.6 mm). The condition $\sigma_{NF} = \sigma_{0e}$ corresponds to the cold brittleness temperature, and the corresponding toughness index has the critical value K_T^*. Such K_T^* values were obtained by the authors for a great assortment of materials with various parameters n and for a wide range of concentrator types, from weakest ones (R = 4 mm) to fatigue cracks (Fig. 2). Thus, a simple relation $K_T = K_T^*$ can serve as a cold brittleness criterion, and the relation $K_T > K_T^*$, as a reliability condition. The whole problem reduces to finding the K_T^* value. Requirements for the level of toughness K_T^* depend on conditions of metal in a structure. The more acute a stress concentrator or defect, the higher K_T^* and the higher level of toughness K_T the metal should have so as to prevent cold brittleness of a product. It is to be pointed out that the degree of overstress at the concentrator tip is substantially affected, apart from the concentrator geometry, also by the value of the work-hardening index n in the Hollomon's expression ($\sigma_{\varepsilon}=\sigma_Y(\varepsilon/\varepsilon_Y)^{n}$). This stems from the fact that brittle fracture of metal with a notch is always preceded by a local yielding in a region at its tip, the stressed-strained state in this region depending on the metal's tendency to the work hardening. Figure 2 shows experimental dependences of K_T^* on the work-hardening index n , where it is seen that with the notch geometry unchanged the critical toughness K_T^* rises with increasing n .

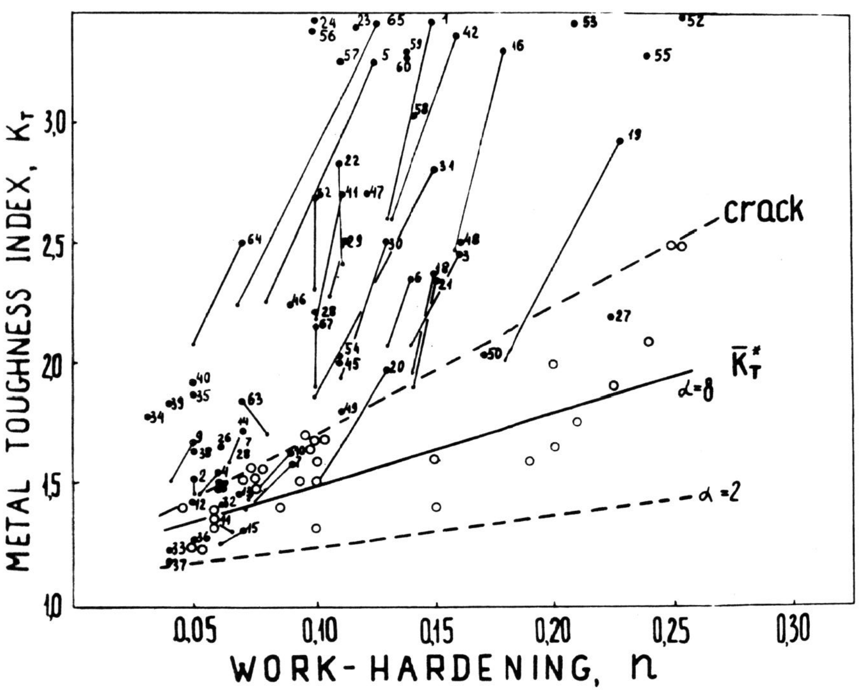

Fig. 2. Effect of work-hardening index n on critical toughness K_T^* for various notches: α - Neuber's elastic stress concentration factor; $\bar{K}_T^*$ - average critical toughness; ●, • - K_T^* values at T = +20 °C and T = -60 °C.

Steel grades corresponding to numerals in the figure are given in book by Meshkov and Serditova (1989)

COMPLEX CHARACTERISTIC OF METAL TOUGHNESS

Having available the value of the ultimately permissible metal toughness level K_T^*, we may introduce the concept of the "toughness margin index", defined as the ratio of the toughness of the metal proper, K_T, to its required level K_T^* at the presence in the metal of a macrodefect of a certain geometry:

$$K_{TM} = K_T / K_T^* . \tag{4}$$

While K_T characterizes the metal toughness level at uniaxial tension, K_{TM} characterizes the metal toughness margin at the presence of a stress concentrator. At $K_{TM} < 1$ a metal with a stress concentrator exhibits cold brittleness, i.e., its fracture occurs at average stresses σ_{av} below the yield stress, which evidences an inadequate metal toughness level for the concentrator under consideration. Values $K_{TM} \geqslant 1$ indicate that the metal toughness level is adequate for a safe performance of the metal with a defect at average stresses not over $\sigma_{0.2}$.

The value of the limiting toughness K_T^* in (4) depends on the stress concentration geometry, and therefore for a practical use of K_T^* it is expedient to select a reference concentrator, with respect to which the metal toughness margin could be normalized. From Fig. 2 it follows that it is reasonable to take a macrodefect with the stress concentration value $\alpha = 8$ as the reference one. For this concentrator the ultimately permissible toughness is described by the following empirical relation:

$$K_T^* = 1.2 + 3n \, . \qquad (5)$$

With account of (5) the normalized toughness margin index is:

$$K_{TM} = \frac{K_T}{1.2 + 3n} \, . \qquad (6)$$

The K_{TM} value given by (4) has the meaning of a quantitative measure of the metal toughness margin with respect to the situation of a sudden fracture of metal with a concentrator ($\alpha = 8$) at a nominal stress not over the yield stress. From (6) it follows that K_{TM}, describing the metal's capacity to resist brittle fracture, depends on a set of mechanical characteristics - microcleavage resistance R_{mc}, yield stress $\sigma_{0.2}$, and work-hardening index n , and therefore may be named complex toughness index (CTI).

Figure 3 shows K_{TM} dependences on strength and limiting K_{TM}^* values for various concentrators for most widely used structural steels.

These dependences make it possible to predict the risk of brittle fracture at stress concentration. If the metal's toughness margin K_{TM} exceeds its limiting value K_{TM}^* for a given defect, then such a defect is not dangerous. At $K_{TM} = K_{TM}^*$ the defect under consideration can cause cold brittleness, i.e., fracture at average stresses equal to $\sigma_{0.2}$; this is a second formulation of the cold brittleness criterion, more general than $K_T = K_T^*$.

Thus, the proposed complex toughness index (CTI) in the form of K_{TM} is a quantitative measure of the degree of risk of

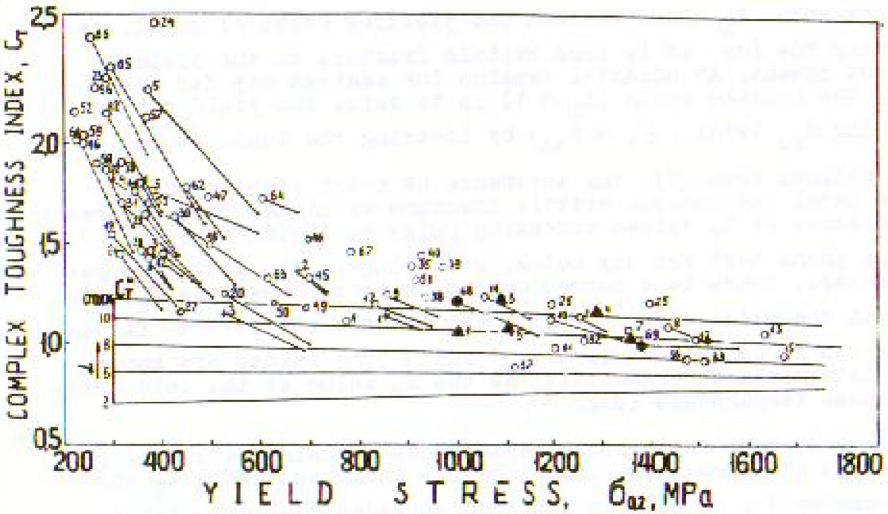

Fig. 3. Variation of toughness margin index with yield stress $\sigma_{0.2}$:

K_{TM}^* - limiting K_{TM} levels for various notches (fatigue crack and concentrators with $\alpha = 10$; 8; 6; and 2)

brittle fracture at loading below the metal's yield stress when the product has a defect, crack, or another stress concentrator. Advantages of this index lie in that the K_{TM} value in combination with the yield stress can serve as a tool for ranking steels when selecting process techniques or melting blends, optimal in terms of economy, reliability, etc. (Fig.3). Compare, e.g., items 3 (manganese-silicon steel 15GS) and 5 (quality structural carbon steel 45): at the same strength ($\sigma_{0.2} = 380$ MPa) item 5 has a much higher K_{TM}, which ensures a higher resistance of a product against a possible embrittlement because of presence of stress concentrators not taken into account. When, however, also a lower alloying of steel 45 is taken into consideration, advantages of the new metal toughness index for a production engineer and a designer become still more obvious.

CONCLUSIONS

The metal's capacity to resist the embrittlening effect of stress concentrators is determined by a set of such characteristics as the microcleavage resistance R_{mc}, yield stress σ_{02}, and work-hardening index n; used as a complex index of toughness (CTI) of structural steels can be the toughness margin index K_{TM}, defined as the ratio of toughness of the metal proper, K_T, to its critical level K_T^* determined by normalization to a definite concentrator (e.g., $\alpha = 8$).

The condition $K_{TM} \leqslant K_{TM}^*$ or, which is the same, $K_{TM} \leqslant 1.2 + 3n$ (for a typical concentrator $\alpha = 8$) can serve as the cold brittleness criterion in the general case of a product with a stress concentrator.

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