# CRITICAL CLEAVAGE STRESS $\sigma_F$ AND PROBLEM OF "BRITTLE" STRENGTH OF METALS

S.A. KOTRECHKO, Y.Y. MESHKOV and G.S. METTUS
*Department of Fracture Physics, Institute for Metal Physics,*
*Academy of Sciences of the Ukraine*
*Ukraine, 252680, GSP, Kiev-142, pr. Vernadskogo, 36*

## ABSTRACT

This paper critically analyzes modern concepts of nature of the critical cleavage stress $\sigma_F$, claimed to be a constant of a metal, characterizing its "brittle" strength. Issues discussed: dependence of $\sigma_F$ determination accuracy on specimen geometry and yielding criteria used in FEM solutions; cleavage stress $\sigma_F$ and microstructure; effect of plastic deformation on the $\sigma_F$ value. It is shown that the "brittle" strength cannot be a constant of metal. The $\sigma_F$ is substantially dependent on the plastic strain and its nonuniformity degree. Strain gradients have been ascertained to be the main factor responsible for the difference between $\sigma_F$ of smooth and notched specimens as well as for the $\sigma_F$ dependence on the notch tip radius. Special consideration is given to the characteristic of the "brittle" strength of smooth specimens, named by Meshkov (1976) the microcleavage resistance $R_{mc}$. It is shown that $R_{mc}$ is the lower limit for $\sigma_F$ of notched specimens and, furthermore, the $R_{mc}$ value is uniquely determined by linear dimensions of metal microstructure parameters.

## KEYWORDS

Cleavage, microcleavage, nucleus cracks, notches, microstructure, critical cleavage stress, microcleavage resistance, brittle strength, strain gradients, finite element method.

## INTRODUCTION

One of priority problems of the fracture science is the search for a characteristic of the "brittle" strength of metal, which in its meaning would be a measure of the metal strength in a brittle state and correspond to a brittle fracture. The concept of "brittle" strength of a solid was first suggested by Joffe (1924), who,based on experimental evidence on fracture of rock salt single crystals, concluded that the "brittle" strength is temperature-independent and is a constant, whose value is determined by the internal structure of a solid. This concept was advanced by Ludwik (1927) and Davidenkov (1937) and was used to account for the effect of a triaxial state of stress and of the loading rate on the ductile-brittle transition temperature.

It is at present adopted to use as the characteristic of the brittle strength of metals and alloys the critical cleavage stress $\sigma_F$, defined as the maximum tensile stress at the notch tip at the moment of brittle fracture. The $\sigma_F$ value cannot be directly determined by experiment, and therefore capacities of calculation methods are the bottleneck of such an approach. As shown by the history of evolution of concepts of strength, just this factor has been responsible for many delusions about properties of the critical cleavage stress $\sigma_F$ of metals. Thus, Knott (1973) calculated $\sigma_F$ with the use of the theory of slip lines, which allowed the critical cleavage stress to be determined only in a single point: at fracture at the moment of realization of the general yielding $T_{GY}$. This point was displaced along the temperature axis by varying the notch angle. As a result, it was concluded that $\sigma_F$ does not depend on the temperature and notch geometry and is determined solely by metal microstructure parameters; this was in a good accord with the Joffe's concept, which treated the "brittle" strength as a constant of a material.

The use of the finite element method (FEM) to calculate stress and strain fields at the notch tip allowed $\sigma_F$ to be determined over a broad range of loads, with the result that variation of its value at departure from the general yielding temperature $T_{GY}$ has been found. Moreover, the critical cleavage stress turned out to depend on the notch tip radius (Kuhne and Dahl, 1983). The use of the characteristic distance $X_c$ (Ritchie et al.,1973) should be regarded as an attempt to "smoothen out" this dependence and to bring $\sigma_F$ to one level. Further studies demonstrated such a technique to be effective only at very acute notches and fatigue cracks. The physical meaning of the characteristic distance $X_c$ consists in that a necessary condition for fracture of a polycrystal is fulfilment of the force conditions for formation and propagation of nucleus cracks in a finite volume rather that in a mathematical point. This effect is most pronounced at great gradients of stresses, when their variations at distances on the order of the grain size cannot be neglected. At smaller stress gradients, however, $X_c$ loses the meaning. For these reasons the influence of the notch acuteness on $\sigma_F$ value cannot be accounted for by the effect of the "characteristic distance" alone. Such a conclusion is supported by a considerable, up to 50%, excess of $\sigma_F(X_c)$ of a notched specimen over the corresponding brittle fracture stress of smooth specimens, found by Kuhne (1982). Tetelman (1968) attempted to ascribe the notch radius influence on $\sigma_F$ to a statistical effect stemming from the difference between volumes of plastically deformed metal at tips of notched and smooth specimens. In the opinion of Riedel (1979), only a third of this difference can be associated with the statistics. Kuhne (1982), analyzing results of his own studies, came to a similar conclusion. Thus, statistics plays a certain, but far from principal, part in the effect under consideration. Such an ambiguity and dependence of the $\sigma_F$ value on its determination method creates great difficulties for a physical interpretation of the "brittle" strength of metals and the use of this characteristic to predict the fracture toughness.

The study being reported was aimed at finding out what is to be meant by the "brittle" strength of metal, what are properties of this characteristic, how its value is affected by non-uniformity of the strain field at the notch tip. Gaining insight into the role of microstructure at brittle fracture of metals and alloys is of a substantial interest.

## "BRITTLE STRENGTH OF METALS AT UNIAXIAL TENSION

*Role of Microstructure*. Meshkov (1976) proposed to use the microcleavage resistance $R_{mc}$ as a measure of the "brittle" strength. It is defined as the minimum brittle fracture stress over the ductile-brittle transition temperature range (Fig. 1). Experimental studies demonstrated an unambigous relation between the value of microcleavage resistance $R_{mc}$ and metal microstructure parameters (sizes of ferrite or pearlite grain, bainitic packet, thickness of cementite platelet or size of carbide particle) (Fig. 2). Such a structural determinancy of the microcleavage resistance $R_{mc}$ is due to that linear dimensions of the above-listed microstructure elements determine the length of submicrocracks forming in the elements at a plastic deformation, and the microcleavage resistance is a macroscopic stress required for their catastrophic propagation. At least two submicrocrack sources exist in steels: grains (ferrite, pearlite, bainitic packets) and carbide particles. Due to this, the level of the "brittle" strength $R_{mc}$ of steels will be governed by that structural component where a largersize crack will appear. This component is selected with the use of critical relations of linear dimensions of microstructure parameters (Fig. 2). For example, for steel with spheroidal cementite, $R_{mc} =180d_f^{-1/2}$ ($d_f$ is the ferrite grain size) at $d_f/d_c \geqslant 52$ (d is the cementite globule diameter); otherwise, $R_{mc}= 2\ 5d_c^{-1/2}$.

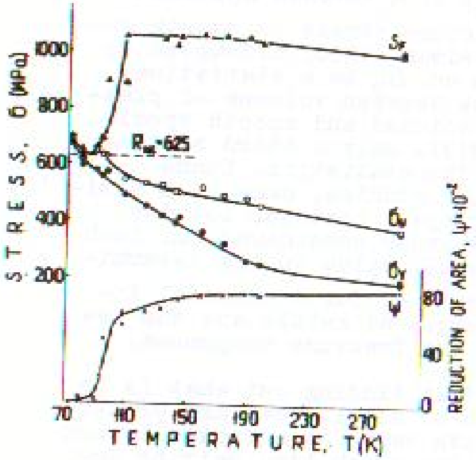


Fig. 1. Temperature dependence of mechanical properties of Armco iron: $\sigma_y$ - lower yield strength; $S_F$ - true fracture stress; $\psi$ - reduction of area; $R_{mc}$ - microcleavage resistance

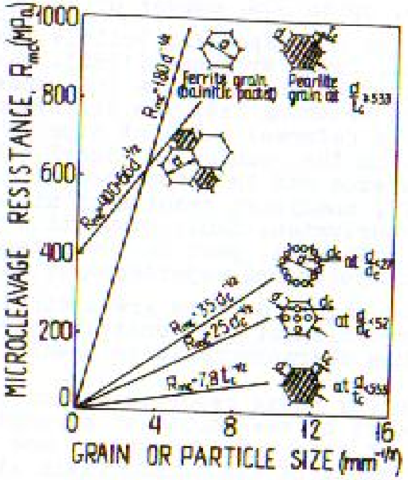


Fig. 2. Effect of microstructure parameters on microcleavage resistance: d - ferrite grain or bainitic packet size; $d_c$ - carbide size; $t_c$ - cementite platelet thickness

<u>Effect of Plastic Deformation</u>. Plastic deformation is a necessary condition for brittle fracture of metals. At the same time the brittle fracture stress $\sigma_F$ depends on the degree of plastic deformation. Figure 3 shows such a dependence for Armco iron (smooth and notched specimens) at uniaxial tension and under stress concentration conditions. It was experimentally ascertained that the "brittle" strength of smooth specimens ($R_{mc}$) will vary in a similar manner if metal has been deformed beforehand to the same degree $\varepsilon$ at room temperature and then, after lowering the temperature, fractured in the ductile- brittle transition region. This means that variation of the brittle fracture stress in the ductile-brittle transition region (Fig. 1) is due not to temperature, but to the effect of the amount of plastic deformation preceding the fracture.

Studies on pre-deformed and then tempered steels demonstrated that heating of deformed steels to temperatures not over the recrystallization temperature brings about no change in the fracture stress $R_{mce}$. This evidences that the "brittle" strength dependence on deformation is due not to evolution of the substructure, but to change in the state of grain boundaries.

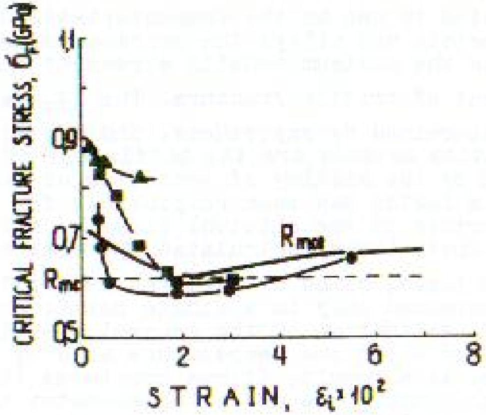


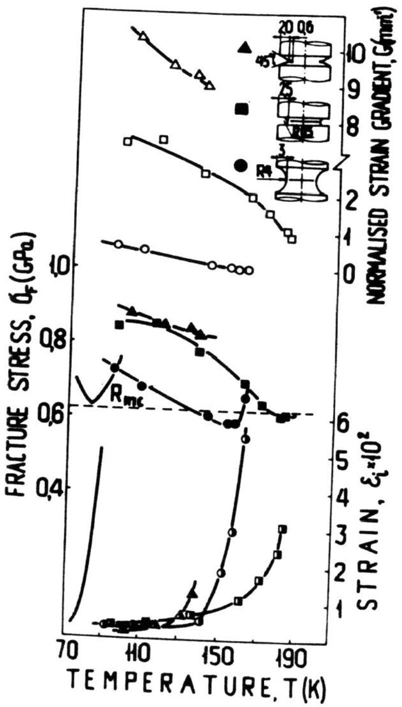
Fig. 3. Effect of plastic deformation on brittle fracture stress: brittle fracture resistance $R_{mce}$ of smooth specimens (———); $\sigma_F$ of specimens with notch of radius R=4 mm (●) and R=0.6 mm (■); and $\sigma_F$ of annular fatigue crack (▲)

## BRITTLE STRENGTH OF METAL WITH NOTCHES

<u>Factors Determining the Critical Cleavage Stress $\sigma_F$</u>. Main regularities of $\sigma_F$ variation are shown in Fig. 4 for Armco iron as an example. As seen, for all notches from R = 4 mm and up to a fatigue crack[*] the $\sigma_F$ value has a minimum at a temperature somewhat over the general yielding one; for notches with R = 4 mm and R = 0.6 mm $\sigma_F$ coincides with the "brittle" strength $R_{mc}$ of a smooth specimen. A further tempe-

---

[*] In construction of the finite element mesh for a circular fatigue crack the initial crack tip opening was assumed equal to ferrite grain size $d_f$ = 97 um. Fracture characteristics $\sigma_F$, $\varepsilon_i$, $j$, and $\sigma$ were determined by averaging throughout a region of $2d_f$.



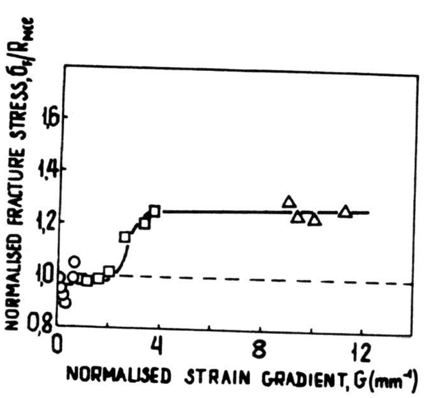


Fig. 5. Effect of relative strain gradient on normalized critical cleavage stress $\sigma_F/R_{mce}$:

○- Notch R = 4 mm;

□- R = 0,6 mm;

△- fatigue crack

Fig. 4. Temperature dependences of fracture characteristics of notched specimens ( $\alpha$-Fe):

▲, ■, ● - critical cleavage stress $\sigma_F$;

△, □, ○ - relative strain gradient ($G$ =grad ($\varepsilon_i$)/$\varepsilon_i$ );

▲, ◧, ◑ - strain intensity $\varepsilon_i$

rature increase results in some $\sigma_F$ growth. It should be emphasized that this $\sigma_F$ growth can be detected if $\sigma_F$ is determined with allowance for the geometric nonlinearity (Kotrechko et al., 1988). Such a nonmonotonic character of variation of the critical cleavage stress is due to the influence of plastic deformation rather than to temperature (Fig.4). Comparing at equal equivalent strains $\varepsilon_i$ the values of the "brittle" strength of smooth ($R_{mce}$) and notched ( $\sigma_F$) specimens, one has to take into account substantial differences in the character of the spatial distribution of strain fields. In a smooth specimen strains are macrouniform, and therefore gradients are zero, whereas at the notch tip there occur gradients $G$ . Just the existence of the gradients causes the $\sigma_F$ excess over $R_{mce}$ as well as the variation of the critical cleavage stress with the notch acuteness (Fig. 5). In Fig.5 the fracture stress is plotted in units of the cleavage stress for smooth specimens, which is convenient for analysis of the basic factors governing the level of the "brittle" strength of metal: firstly, the size of the structural element responsible for the formation of a critical-size submicrocrack and, secondly, the value of the local macrostrain $\varepsilon_i$ and its nonuniformity degree $G$ . The essence of influence of these factors on the local fracture stress value consists in that the microstructure of metal "sets" via the corresponding size of the submicrocrack some initial level of the "brittle" strength $R_{mc}$. Nucleus cracks, however, do not exist in metal intrinsically, but are formed in the course of plastic deformation, and therefore the critical size of a submicrocrack varies with the amount of the deformation and degree of its nonuniformity, with the result that the cleavage stress $\sigma_F$ deviates from its initial level $R_{mc}$. This effect gives rise to the $\sigma_F$ dependence on the notch acuteness.

The ascertained regularities make it possible to account for the temperature invariance of $\sigma_F$, found by Knott (1973).The point is that $\sigma_F$ was determined at the general yielding temperature $T_{GY}$, which was varied by changing the notch angle. This means that all $\sigma_F$ values were obtained at a constant relative strain gradient $G$, which, as known, depends on the notch tip radius rather than on the notch angle. As seen from Fig.5, at a constant $G$ value the fracture stress $\sigma_F \approx$ const.

## CONCLUSIONS

The concepts of the physical nature of fracture and experimental evidence, presented in this paper, lead to a conclusion that capacity of metals to resist the brittle fracture cannot in principle be characterized by a constant quantity.

There exists, however, a lower limit of the range of values of the critical cleavage stress $\sigma_F$. Used as the value of this limit in the first approximation can be the minimum stress of brittle fracture of smooth specimens, $R_{mc}$. The convenience of using this characteristic lies not only in that it can serve as the point of reference for $\sigma_F$ (as "brittle" strength unit), but also in that there are simple relations connecting the $R_{mc}$ value to linear dimensions of the metal microstructure.

From the above-reported study it follows also that the level of the critical cleavage stress $\sigma_p$ is substantially affected, apart from the structure and the plastic deformation degree, also by the magnitude of the relative strain gradient. The nonuniformity of strains is the basic factor causing the difference between $\sigma_p$ of a smooth specimen and notched specimens as well as the cleavage stress dependence on the notch tip radius.

## REFERENCES

Davidenkov N.N. and Wittman F. (1937), Mechanical Analysis of Impact Brittleness. Phys.-Tech. Inst., USSR, v.4, pp. 308.

Joffe A., Kirpitscheva M.W. and Lewitzky M.A. (1924), Deformation and Festigkeit der Kristalle. Z. fur Physik, v. 22, pp. 296-302.

Knott J.F. (1973), Fundamentals of Fracture Mechanics. Butterworths, London.

Kotrechko S.A., Meshkov Y.Y. and Mettus G.S. (1988), Brittle Fracture of Polycrystalline Metals at Complex State of Stress. Metallofizika, v. 10, No 6, pp. 46-55.

Kuhne K. (1982), Einfluss des Spannungszustandes und des Gefuges auf die Spaltbruchspannung von Baustahlen. (Dr.-Ing.-Diss., Techn. Hochsch. Aachen).

Kuhne K. und Dahl W. (1983), Einfluss des Spannungszustandes und des Gefuges auf die Spaltbruchspannung von Baustahlen. Arch. Eisenhuttenwes., B. 54, Nr. 11, S. 439-444.

Ludwig P. (1927), Die Bedeutung des Gleit- und Reisswiderstandes fur die Werkstoffprufung. ZVDI, B. 71, S. 1532-1538.

Meshkov Y.Y. (1976), Problems of Iron Fracture Mechanism. Metallofizika, issue 65, pp. 32-45.

Riedel H. und Kochendorfer A. (1979), Spaltbruch von Stahlen bei tiefen Temperaturen. Arch. Eisenhuttenwes., B.50, Nr.4, S. 173-178.

Ritchie R.O., Knott F.J. and Rice J.R. (1973), On the Relationship between Critical Tensile Stress and Fracture Toughness in Mild Steels. J. Mech. Phys. Solids, v.21, pp. 395-410.

Tetelman A. S., Wilshaw T.R. and Rau Jr. (1968), The Critical Tensile Stress Criterion for Cleavage. Int. J. Fract. Mech., v. 4, No. 2, pp. 144-157.