THE TEMPERATURE DEPENDENCE OF FRACTURE TOUGHNESS OF MATERIALS UNDERGOING A BRITTLE-DUCTILE TRANSITION

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Polycrystalline materials show various fracture mechanisms during the brittle-ductile transition under uniaxial tension. The change of fracture mechanisms is determined by processes being energetically favourable at the given temperature and loading rates. The temperature dependence of the fracture toughness can be represented by a curve having maximum at the upper limit of the brittle-ductile transition.

INTRODUCTION

Various fracture mechanisms are identified in different materials under loading over a wide temperature range by scanning electron microscopy.

The data published, e.g., fracture mechanism maps for various materials proposed by Ashby (1) and a number of publications on fractography done, e.g., by Vasilev (2), Trefilov et al (3) and etc., allow the nature of the change of the fracture mechanisms to be discussed.

The purpose of the work reported here, was to carry out such an analysis for various materials over a wide temperature range by comparing the energies necessary for fracture with those required for certain mechanisms.

Let us now consider the influence of the temperature on the fracture toughness of different BCC metals for certain fracture mechanisms.

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MECHANISMS OF FRACTURE

Under uniaxial tension the following sequence of fracture mechanisms is generally observed by different authors with increasing temperature: cleavage; brittle intergranular fracture, if the grain boundaries are weak; cleavage or intergranular fracture with plastic relaxation at the crack tip; dimple fracture. Other processes observed are dimple fracture along grain boundaries, delamination combined with cleavage or dimple fracture, and at sufficiently high temperatures, high-temperature intergranular fracture, that is the most typical process in ceramics.

Cleavage. As shown by Vasilev et al (4), Lung and Gao (5), the temperature dependence of the fracture toughness by cleavage γ_{cl} (Fig. 1, curve 1), can be described by the dependence of the following type:

$$\gamma_{cl} = \gamma_0 + A/\sigma_y^2. \tag{1}$$

It should be pointed out that the fracture toughness significantly increases with the temperature dependence of the yield stress considerably decreasing as was shown by Knott (6), Romaniv (7) and Vasilev et al (4) (Fig. 1, curves 1 and 7). May be seen that $K_{1c}^{cl}\sigma_y$ = const.

Low-temperature intergranular fracture. Following Romaniv (7) et al the toughness, relative to the low-temperature intergranular fracture, increases with increasing testing temperature. The intergranular fracture toughness was determined as

$$K_{1c}^{ig} = K_{ig}^{0} + B \times \sigma_{ig} \quad . \tag{2}$$

It was proven that σ_{ig} = const, but $x \sim \sigma_y^{-1}$.

Thus, like the cleavage fracture toughness, the temperature dependence of the intergranular fracture toughness is determined by the temperature dependence of the yield stress, and can be expressed in a generalized form by a dependence which is inversely proportional to the yield strength (Fig. 1, curve 2). $K_{1c}^{ig}\sigma_y$ = const.

Thermomechanical treatment influences the extent of the fracture toughness and its temperature dependence [7, 9]. The reasons of this difference are primarily associated with different values of the intergranular strength, which is considerably controlled by the segregation of impurities as Danilenko et al (8) show.

Dimple fracture. The temperature dependence of the dimple fracture toughness γ_d may be derived from the following, similar Stuwe (9), model. The work of formation of a dimple fracture is the work done by external force σ, which moves away the crack surfaces by a distance equal to the dimple depth h_d. Then,

$$\gamma_d = 1/2\, \sigma \cdot h_d \ . \tag{3}$$

Precise values of stresses at the crack tip are still unknown. Since the plastic relaxation at the crack tip limits the stresses to a level which is proportional to the yield strength σ_y, we can assume that $\sigma \approx \sigma_y$. Experiments show that $h_d \approx$ const.

Thus,

$$\gamma_d = 1/2\, \sigma_y \cdot h_d \ . \tag{4}$$

γ_d is mainly determined by the temperature dependence of the yield stress and decreases with increasing temperature (Fig.1, curve 4). This phenomenon is observed in certain steels by Krasovsky (10) and in aluminium alloys by Kishkina (11).

High-temperature intergtanular fracture. The high-temperature intergranular fracture is usually caused by intergranular sliding. In this case, the fracture toughness can be described according to Mikin and Petch (12), as

$$\gamma_{ht} = \sigma^2 \pi d / 12 G \ . \tag{5}$$

Using the data obtained by Grabsky (13) we can find that

$$\gamma_{ht} = C T \dot{\varepsilon} \exp(U_{ig}/kT) \ . \tag{6}$$

γ_{ht} decreases with increasing temperature (Fig. 1, curve 5).

A state of grain boundaries determines strongly the high-temperature fracture toughness. Fig. 2 shows temperature dependencies of the fracture toughness of two different ceramics with clean (curve 1) and dirty (curve 2) grain boundaries. It is seen that a workability of ceramic with glass-like grain boundary phases is less than a workability of ceramic with clean boundaries. Besides in a dirty ceramic, a high-temperature increase is absent.

Under temperatures above $0{,}8T_{melt}$, the fracture mechanism of these two ceramics is the same - the intergranular sliding. But the intergranular sliding of dirty ceramics results from a softening of intergranular phases instead of a intergranular delamination which is due to plastic deformation of grains bodies. The intergranular sliding of dirty ceramics is passing by the stage of a plastic originating of intergranular cracks, that accounts for decreasing fracture toughness of such materials.

DISCUSSION

According to above considerations, the temperature dependence of fracture toughness is composed of the temperature dependences of individual mechanisms which are predominant in certain temperature intervals. This results from the change of fracture mechanisms which is determined by the energy of the processes operating under the specific loading conditions. The partial dependencies may be described by expressions (1), (2), (4) or (6). The resulting temperature dependence of fracture toughness is represented by curve 6 in Fig. 1. The left-hand side of the maximum is determined by cleavage, but the right-hand part is controlled by mechanisms of coalescence of the pores and the high-temperature types of fracture.

The course of certain curves in this diagram depends on the kind of the material and of its structure. E.g., the sequence of the fracture mechanisms in polycrystalline Cr and Mo is essentially different. While in Cr, fracture toughness is only determined by cleavage, in Mo it depends on both intergranular fracture and cleavage with periodic relaxation and delamination, that results in nonmonotony of the temperature dependence of fracture thougness in medium temperature range as Danilenko et al (8), Koval et al (14) and etc. show.

In materials having weak grain boundaries, dimple fracture is sometimes not observed, thus, curve 4 lies considerably higher than the point of intersection of the curves 2 and 5. In that case the low-temperature intergranular fracture goes directly into the high-temperature intergranular fracture. This is observed in ceramic materials, when their grain boundaries are dirty (Fig. 2, curve 2).

The relation between the fracture toughness and the yield strength is represented in a general form as $\gamma \sim \sigma_y^{-n}$. However, as follows from the data given, the sign and the value of the exponent n depend on the temperature of the loading and of the operating fracture mechanism. As examples, for cleavage n = -2 and for the coalescence of pores n = 1 have to be used.

SYMBOLS USED

A, B, C = constants

d = grain size

$\dot{\varepsilon}$ = creep rate

γ_0, γ = true and effective surface energy, respectively, J/m^2

$\gamma_{cl,d,ht}$ = fracture toughness under cleavage, dimpled and high-temperature intergranular fracture, respectively

h_d = dimple depth

K_{1c}^{cl}, K_{1c}^{ig} = fracture tougness under cleavage and low-temperature intergranular fracture, respectively

K_{ig}^{0} = toughness of a absolutely brittle intergranular fracture

σ_{ig} = intergranular strength

U_{ig} = activation energy of diffusion along boundaries

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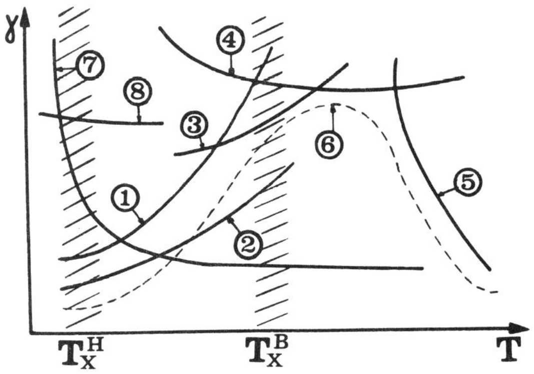
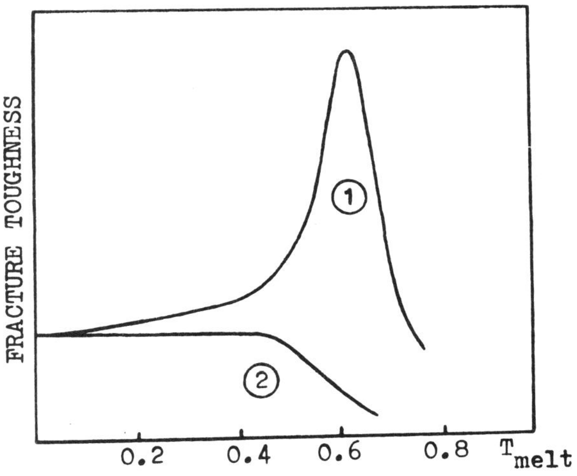


1 - cleavage; 2 - low-temperature intergranular fracture; 3 - cleavage with delamination; 4 - dimple fracture; 5 - high-temperature fracture mechanisms; 6 - resulting dependence; 7 - yield strength; 8 - ultimite tensile strength; $T_x{}^H$ and $T_x{}^B$ - lower and upper limits of the brittle-ductile transition.

Figure 1. Scheme of the temperature dependence of fracture toughness of materials.



1 - for ceramics with clean grain boundaries; 2 - with dirty ones

Figure 2. Scheme of the temperature dependence of fracture toughness of ceramics.