FRACTURE MECHANISMS OF MATERIALS WITH A BRITTLE-DUCTILE TRANSITION

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ABSTRACT

The fracture mechanisms of metallic and ceramic materials with a brittle-ductile transition revealed by scanning electron microscopy are discussed with respect to the fracture toughness and its temperature dependence.

Under transition from a brittle state into a ductile one due to temperature, the next sequence of fracture mechanisms may be seen: cleavage, or brittle intergranular fracture if grain boundaries are weak; cleavage or brittle intergranular fracture with a periodic relaxation; intergranular fracture due to plastic deformation of grain bodies; ductile fracture including intergranular one, by pores coalescence.The temperature dependencies of fracture toughness for a number of fracture mechanisms are analyzed and analytical expressions are given.

KEY WORDS

Fracture mechanisms, fracture toughness, influence of temperature, brittle-ductile transition, cleavage, intergranular fracture, pores coalescence, sub-critical growth, metals, ceramics.

INTRODUCTION

A lot of materials such as ceramics, the bcc-metals with a strong temperature dependence of yield strength (tungsten, molybdenum, chromium, and others) are materials with a pronounced brittle-ductile transition under loading over a wide temperature range. Using the modern methods of fractographic analysis based on scanning electron microscopy of fracture surfaces and related techniques it was possible to find a number of features which are fundamental to understand the influence of structure of materials and loading conditions on their failure. Thus, for example, it was found that the named materials fail with not a single but a few mechanisms. A wide region of loading conditions exists also where the mechanism of a crack growth is changed as the crack length increases.

At the same time, the measurement of fracture toughness shows also that practically every group of materials requires its own parameter to estimate the fracture toughness (K_{1c}, COD, J-integral, and others) in spite of that fracture toughness is energy required to create the unit of fracture surface.

A number of papers concerning the temperature dependencies of fracture toughness of materials is not enough yet. The first direct determinations of fracture energy in a rather wide temperature interval appearently were done by the Patriarch of Science on Fracture Dr. Alan A.Griffith (1920) in his famous work on phenomena of rupture. Having tried to determine the surface tension as a analog of the surface energy of glass he had to measure the surface tension at a number of high temperatures and deduce its value at room temperature by extrapolation. Griffith has found "that the surface tension of glass is approximately a linear function of temperature" decreasing from 0,0031 lb. per inch at 15 °C to 0,0023 lb per inch at 1110 °C. In the more recent works, e.g., with Zn done by Gilman (1967), with W and Mo done by Hall et al (1965) and Vasilev et al (1981), with steels done by Knott (1978) and Romaniv (1979) the fracture toughness (surface energy, stress intensity factor) has increased exponentially with increasing temperature. In another works, e.g., done by Krasovsky (1980) has been found non-monotonous dependencies of the fracture toughness on the temperature. Fracture toughness of aluminum alloys have decreased with increasing temperature. These data cited points out the discrepant influence the temperature on the fracture toughness.

The numerous data on the fracture mechanisms study of different materials under the different loading conditions summarized by Ashby (1983), Vasilev (1986, 1991) and anothers shows that the fracture mechanisms change one another with increasing temperature. Thus, for example, the polycrystalline bcc-metals and alloys, under uniaxial tension over wide temperature range, reveal the greatest number of the fracture mechanisms. When the temperature of loading grows, the next sequence of fracture mechanisms may be observed: cleavage (brittle intergranular fracture when grain boundaries are weak), cleavage or intergranular fracture with plastic relaxation, dimple fracture with pores coalescence. In addition, sometimes the dimple fracture along grain boundaries as well as the delamination together with cleavage or dimple fracture, and high-temperature intergranular fracture realize themselves.

SEM appearances of surfaces formed with some of the above enumerated mechanisms may be seen anywhere, e.g., Vasilev (1986).

Let us now try to analyze the influence of temperature on fracture toughness of materials failing with some of the above mentioned mechanisms (cleavage, low-temperature intergranular, dimple, and high-temperature intergranular fracture) and give them analytical expressions.

Presented by Trefilov et al (1988) analysis of the temperature influence on fracture toughness of materials shows that the change of fracture mechanisms results from their competition under a given temperature-rate conditions of loading. The sequence of this change is determined by the structure of materials as well strength of bounds between separate structural elements. E.g., the ratio between cleavage and the low-temperature brittle intergranular mechanism is completely determined by the intergranular strength. Cleavage, in principle, may be observed in all temperature region of the brittle-ductile transition up to its upper temperature limit. At the low intergranular strength, the cleavage is not observed at all, the intergranular fracture goes directly into the dimple one.

Let us consider the influence of temperature on fracture toughness for the certain fracture mechanisms.

Cleavage. Its appearance is well-known and as shown by Vasilev et al (1981), Lung and Gao (1985), the temperature dependence of fracture toughness by cleavage, γ_{cl}, (Fig.1, curve 1), can be described by the dependence of the following type:

$$\gamma_{cl} = \gamma_o + A/\sigma_y^2 \qquad (1)$$

where γ_{cl} is the true surface energy, A is constant, and σ_y - yield strength.

It should be pointed out that the fracture toughness significantly increases as the temperature dependence of yield stress considerably decreases as was shown by Knott (1978), Romaniv (1979) and Vasilev et al (1981) (Fig. 1, curves 1 and 7). May be seen that $K^{cl}_{1c}\,\sigma_y$ = const in the brittle-ductile transition temperature interval.

One of the most remarkable features of materials with a brittle-ductile transitions is the stageness of fracture process consisting in changing of fracture mechanism as a crack length grows under active monotonous loading. During the first stage, length or other crack/notch parameters are growing up to some critical size and after that event the first stage fracture mechanism is sharply changed into cleavage and thereby the fracture goes into the second stage. By mechanisms of the first stage may be intergranular fracture, cleavage with relaxation, dimple fracture by pores coalescence. Ceramics like silicon nitride materials may show the foam-like fracture. Other ceramics, not containing glass phases, may show other kind of sub-critical growth mechanism not differing from mechanism of the catastrophic cleavage of the second stage in micro-scale. These two stages differ themselves only by the roughness of a crack relief (Fig. 2) and result from microcracking during the first stage and result in crack bridging.

The SEM fractographic study of samples tested for fracture toughness, in some cases, allows to distinguish two stages of

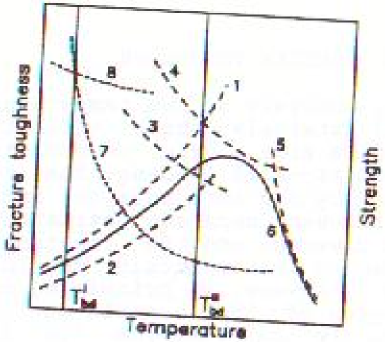

Fig. 1.

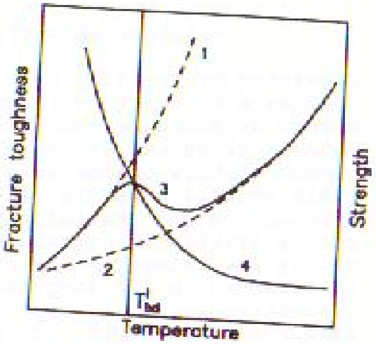

Fig. 2.

Fig.1. The scheme of temperature dependence of fracture toughness of materials with a pronounced brittle-ductile transition. 1) cleavage, 2) low-temperature intergranular fracture, 3) cleavage with relaxation, 4) pores coalescence, 5) high-temperature intergranular fracture, 6) resulting dependence, 7) yield and 8) fracture strength. T^l_{bd} and T^u_{bd} - the lower and upper temperature limits of the brittle-ductile transition respectively.

Fig.2. The scheme of dependence of fracture toughness of Mo at cleavage on temperature. 1) for blunting notch, 2) for notch like crack of cleavage with relaxation, 3) resulting dependence, and 4) yield strength.

fracture followed by catastrophic cleavage: the stage of plastic blunting of sharp notch and following stage of cleavage with discrete steps of crack growth due to plastic relaxation of stresses in crack tip.

Such a crack behavior results in the non-monotonous dependence of fracture toughness of molybdenum vs temperature (Fig. 2) demonstrated by and Koval et al (1993) that, in its turn, is resulted from, in the first approach, blunting of notch during the first increase, sharpening of blunted crack during decrease, and the next increase caused by a new structure, in front of crack tip, allowing more long crack.

The length of sub-critical crack grows with temperature as Vasilev et al (1981) showed for molybdenum and tungsten as

$$c=C_o\exp(-u/kT), \qquad (2)$$

where C_o is constant, u is energy of activation, and k is Boltzman's constant.

Low-Temperature Intergranular Fracture. Following Romaniv et al (1979) toughness, relating to the low-temperature intergranular fracture, increases with temperature. The intergranular fracture toughness was determined as

$$K^{ig}_{1c} = K^o_{ig} + BX\sigma_{ig}, \qquad (3)$$

where K^o_{ig} is toughness of a absolutely brittle intergranular fracture, B is constant, X is size of a process zone, and σ_{ig} is the intergranular strength. It was proven that σ_{ig} =const, but X ~ σ_y^{-1}.

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

Fig.3. The SEM appearance of silicon nitride based ceramics fracture surface at 1200 °C with Vickers notch, sub-critical growth and catastrophic cleavage.

Dimple Fracture. Difference appearances of fracture by pores coalescence may be seen in Vasilev (1986) and the temperature dependence of dimple fracture toughness γ_d may be derived from the following, similar Stuwe (1980), model. The work of formation of a dimple fracture is the work being done by external force σ, which moves away the crack surfaces by a distance equal to the dimple depth h_d

$$\gamma_d = 1/2\sigma h_d . \qquad (4)$$

Precise values of stresses at the crack tip are unknown yet. But 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,

$$\gamma_d = 1/2\sigma_y h_d \qquad (5)$$

γ_d is mainly determined by the temperature dependence of the yield strength and decreases with increasing temperature (Fig. 1, curve 4). This phenomenon was observed in certain steels and aluminum alloys.

As to the mechanism of pores coalescence, the main point of it is the nucleation of pores. In materials, not containing any kind of particles of the second phases, pores nucleate inside of grain and dislocation cell boundaries by the three-dimensional field of stresses as has shown by Vasilev et al

(1986, 1991). It was found that in ceramics as well as in metals but at more high temperatures about $0,8T_{melt}$ plastic deformation forms a cellular structure with all ensuing consequences: crack initiation along cell boundaries, delamination, nucleation of pores, subsequent coalescence of which produces the specific dimple fracture. The scanty systems of sliding does not permit the walls of pores and dimples to be perfect as it is seen in stereopair and like fully them in metallic materials.

High-Temperature Intergranular Fracture. The high-temperature intergranular fracture is usually caused by intergranular sliding. In this case, the fracture toughness can by described according to Mikin and Petch (1967), as

$$\gamma_{ht} = \sigma^2 \pi d/12G, \qquad (6)$$

Using the data obtained by Grabsky (17) we can find that

$$\gamma_{ht} = CT\dot{\varepsilon}d^2 \exp(u_{ig}/kT), \qquad (7)$$

where C is constant, $\dot{\varepsilon}$ is the deformation rate, d is grain size, and u_{ig} is energy to activate diffusion along boundaries. γ_{ht} decreases with increasing temperature (Fig. 1, curve 5).

According to the above considerations, the wide temperature range dependence of fracture toughness may be composed of the temperature dependencies of separate 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), (3), (5) or (7). The resulting temperature dependence of fracture toughness is represented by curve 6 in Fig. 1. The left-hand half of the curve is determined by cleavage and mechanisms of sub-critical growth, but its right-hand half is controlled by mechanisms of coalescence of pores and high-temperature types of fracture.

FRACTURE MECHANISMS AND FRACTURE TOUGHNESS OF CERAMICS

The temperature dependence of fracture toughness of ceramic materials may be schematically represented as shown in Fig. 4 by (1989). In the region of comparatively low temperature, up to $0,6T_{melt}$, the fracture toughness decreases slightly. In materials with pure strong boundaries, this decrease is probably proportional to the decrease of elastic modulus. The basic fracture mechanisms is cleavage. The fracture originates from defects of the samples. With activation of sliding, at temperatures above $0,6T_{melt}$, there arise intergranular cracks preceding cleavage, SEM fractographs of ceramics may be seen in Vasilev et al (1991).

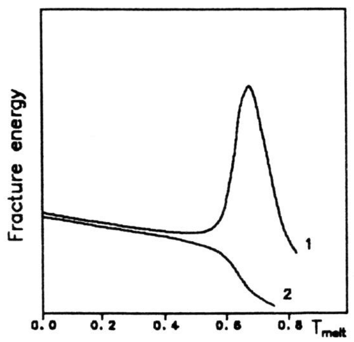

Fig.4. The scheme of fracture toughness of ceramics vs temperature for materials with 1) "clean", and 2) "dirty" grain boundaries.

The fracture toughness of pure materials increases in the temperature range of $0,6T_{melt}$ as seen from the scheme in Fig. 4, curve 1. The temperature dependence of fracture toughness of ceramics is perhaps inversely proportional to the yield strength as in metals, if it would be measurable here.

Strength and fracture toughness dependencies on the grain size in this temperature range like the Hall-Petch's type. Further temperature increase, above $0,8T_{melt}$ produces a notable growth of ductile properties. For some ceramics the phenomenon of superplasticity is typical here. Yield strength becomes measurable, fracture toughness drops sharply. A transition to the high temperature intergranular fracture by intergranular sliding is observed. It caused by intensification of diffusion processes along the grain boundaries. Then, materials with larger grain size should possess more high fracture toughness.

The materials with "dirty" weak boundaries fail intergranularly and reveal a considerable decreasing of fracture toughness (Fig. 4, curve 2) and strength due to "softening" of low melting intergranular phases. Unlike the pure materials with strong grain boundaries, where the intergranular sliding becomes only possible after nucleation of intergranular cracks resulting from plastic deformation of grain bodies, intergranular fracture and sliding in these materials occur bypassing the stage of plastic initiation of crack, and this accounts for the observed decrease of properties.

CONCLUSIONS

1. Under uniaxial tension over a wide temperature region when materials transit from the brittle state into the ductile one, the fracture occurs by a few mechanisms changing consecutively one another as the temperature is increased: cleavage or brittle intergranular fracture, cleavage with relaxation, low-temperature intergranular fracture resulted from yielding of grain bodies, dimple fracture, and high-temperature intergranular fracture resulted from grain boundary sliding. There exists also a wide region of loading conditions where the crack growth mechanisms are changed as the crack length has been increased, e.g., cleavage with relaxation transits into cleavage. Other pairs: low-temperature intergranular fracture - cleavage, or dimple fracture - cleavage may exist too.

2. This replacement of fracture mechanisms is determined by competition in respect of energy consumption under the given temperature-rate or other conditions of loading. The sequence and quantity of replacements depend on structure of materials as well as strength of bounds between separate structural elements.

3. The temperature dependence of fracture resistance of materials depends on fracture mechanisms. Full temperature dependence, covering the all temperature region of a brittle-ductile transition, consists of the partial dependencies typical for intervals of the existence of certain fracture mechanisms.

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