SOME FEATURES AND MICROMECHANISMS OF MATERIALS FRACTURE IN THE BRITTLE-TO-DUCTILE TRANSITION REGION

A.J. KRASOWSKY

Institute for Problems of Strength, Academy of Sciences of Ukraine
2 Timiryazevskaya Str., 252014, Kiev, Ukraine

ABSTRACT

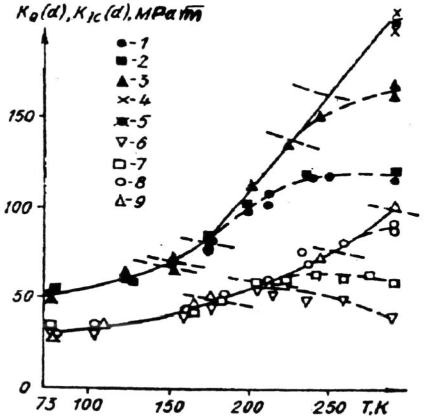
Basic laws of the influence of temperature, loading rate,specimen size, stress state mode on the structural materials fracture toughness and the relationship between the observed effects and material structure features are considered. Crack growth micromechanisms in the regions of brittle, combined and ductile fractures remain similar for materials of different classes, which allows their modelling from a unified standpoint of the nonlinearity zone evolution at the crack tip. A new generalized conception of the brittle-to-ductile transition phenomenon in materials and the developed on its basis procedures for predicting the influence of different factors on the brittleness temperature are presented. Further evolution of this conception on the basis of the two-criteria approach includes consideration of brittle-to-quasi-brittle and quasi-brittle-to-ductile transition temperatures and analytical description of their dependence on the specimen or part geometry and size, loading rate, material structure.

KEYWORDS

Materials, fracture, fracture toughness, temperature, brittle-to-ductile transition, transition temperature, prediction.

INTRODUCTION

Many engineering materials revealing low-temperature brittle-to-ductile transition phenomenon demonstrate similar behaviour during their strength and fracture toughness testings. External manifestations of this similarity are characterized by: similar behaviour of the fracture toughness temperature dependence, namely, the existence of a low temperature plateau, brittle-to-ductile transition, typical increase in fracture toughness with a temperature rise up to brittle-to-ductile transition, a fracture toughness peak and its subsequent reduction with an increase in testing temperature; a similar character of the loading rate effect on fracture toughness temperature dependence, i.e. a shift of the fracture toughness temperature dependence curves and the critical transition temperatures towards higher temperatures; an opposite character of the loading rate effect on the fracture toughness below and above the transition temperature; a change of the fracture micromechanisms in the brittle-to-ductile transition region. The results of active study of the brittle-to-ductile transition phenomenon in metals for the last decades allow to conclude that the majority of effects observed at the above transition, such as the influence of specimen size, the stress-state mode, the loading rate, the material structure, etc., and the transition temperature itself are in a direct quantitative relation to the temperature dependences of two characteristics: yield strength and fracture toughness of the material (Krasowsky, 1980; Francois and Krasowsky, 1986). Typical temperature dependences of the steel fracture toughness for specimens of different size are given in Fig.1. The figure illustrates the main of the above effects and the principal tendency of the phenomenon. In fact, the explanation of the brittle-to-ductile transition in materials is exhausted by the description of changes in the stress state at fracture initiation from plane strain to plane stress with the temperature increase. However, with its apparent simplicity the brittle-to-ductile transition phenomenon is, in fact, proved to be a complex one and dependent on many factors, it is difficult to give its analytical description and up to now it has not been obtained in a closed form.



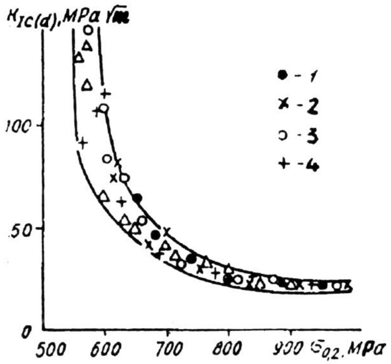


Fig.1. Temperature dependences of static (dark circles) and dynamic (light circles) fracture toughness of 15Kh2NMFA steel for large pressure vessels with specimen thicknesses, mm: 1-20; 2-24; 3-40; 4-100; 5-150; 6-5; 7-10; 8-20; 9-40. The dashed lines indicate the upper temperature limits of the plane strain condition for each value of the specimen thickness (indicated by numbers along each curve).

Fig.2. Relation between 10G2FB steel fracture toughness and yield strength over the temperature range of brittle fractures. Strain rates when determining the yield strength (sec^{-1}): 1-$8\cdot10^{-4}$; 2-$8\cdot10^{-3}$; 3-$8\cdot10^{-2}$; 4-$8\cdot10^{-1}$ correspond to the loading rate when determining fracture toughness.

Laying aside complex and important methodology of the material fracture toughness evaluation in the brittle-to- ductile transition region, we concentrate in this paper on such problems as modelling of the brittle-to-ductile transition process and prediction of the above factors effects; the study of the physics of the crack initiation, propagation and arrest processes in the brittle-to-ductile transition temperature region; phenomenological description of the brittle-to-ductile transition and important consequences from it; finally, a generalization of the brittle-to-ductile transition concept based on the two-criteria fracture assessment diagram.

FRACTURE MODEL

Typical fracture micromechanisms in the transition region are cleavage (below the transition temperature) and ductile "dimple" fracture (above the transition temperature). The so-called "river patterns" existing on the cleavage facet surfaces make it possible to have an unambiguous identification of the local direction of fracture. As is shown by the extensive statistic investigations (Krasowsky, 1980), there is no correlation between the direction of the main crack growth and the fracture propagation direction in each individual facet. This fact can be considered as a direct experimental evidence of the main crack propagation through the nucleation of the microcrack at its tip and their subsequent coalescence. The parameters of this process are the characteristic distance, X_c, from the crack tip where the microcrack initiates, and the local microcleavage stress, σ_f^*, resulting in the microcrack initiation of a length X_c. These prerequisites have been used as the basis for the K_μ-model of fracture proposed in the work of Pisarenko and Krasowsky, (1972). The known RKR-model (Ritchie et al., 1973) proposed later is based on the same principles. The initial statements of the K_μ-model differ essentially by the classical concept of fracture as a process of a successive "stage-by-stage" interatomic bonds decohesion at the crack tip, so it is possible to say (Krasowsky and Pluvinage, 1993) about a new conception of "coalescence" fracture due to microcrack initiation and its coalescence with the main crack. The evaluation of the minimum possible fracture toughness of the material has shown that the "decohesion" mechanism of the fracture evolution corresponds to cleavage at the stage of microcrack initiation within the grain, while the "coalescence" fracture mechanism requires much more energy consumption and characterizes transcrystalline fracture of polycrystalline or multiphase material. The main relationship of the K_μ-model relates fracture toughness, K_{Ic}, with the yield strength, σ_Y, and the strain hardening exponent, n:

$$\frac{K_{Ic}}{K_\mu} = \left(\frac{\sigma_f^*}{\sigma_Y}\right)^{\frac{1-n}{2n}}, \qquad (1)$$

where $K_\mu = \sigma_f^* \sqrt{\pi X_c}$. When deriving this relation there was no need to make any assumptions about the character of X_c and σ_f^* values. However, in the calculation within the framework of the proposed model for the dependence of fracture toughness, K_{Ic}, on temperature, T, and the loading rate, $\dot{K}_I$, the independence of both X_c and σ_f^* of temperature and strain rate was accepted unambiguously in the work by Pisarenko and

Krasowsky, (1972) and from the very beginning the X_c and σ_f^* parameters in the K_μ-model were related to the material structure. Relation (1) predicts the natural character of K_{Ic} dependence on temperature and loading rate (Fig.1) as can be also judged by Fig.2 used as an example. Such a relation between fracture toughness and yield strength was repeatedly confirmed by experiment but only in those cases when a change of yield strength was not connected with changes in the parameters of the fracture micromechanism, X_c and σ_f^* (for example, with temperature and strain rate change). The formula

$$K_{Ic} = A\sigma_Y^{n'} , \tag{2}$$

which follows from relation (1), where A is the factor including the parameters X_c and σ_f^* , $n' = -\frac{1-n}{2n}$ was verified experimentally by other authors as well (Krafft and Sullivan, 1963; Silva and Brook, 1971; Pandey et al., 1974; Hahn et al., 1971) for several values of the exponent n' corresponding to the interval of the strain hardening exponent $0,2 \leq n \leq 0,3$.

Parameters X_c and σ_f^* of the K_μ-model are in a direct relation to the material structure; their physical interpretation and experimental definition are shadowed by the statistical nature of the characteristic distance X_c and the local nature of the microcleavage stress σ_f^* (Krasowsky and Pluvinage, 1993). The additional condition for the determination of numerical values of parameters X_c and σ_f^* can be obtained from relation (1) when considering the situation at the crack tip at fracture at lowering temperature. At sufficiently low temperatures the size of the critical plastic zone (at fracture initiation) could be equal to the value of X_c, i.e. the site of microcrack initiation coincides with the elastic-plastic boundary, therefore, $\sigma_f^* = \sigma_Y$ and from (1) we shall get:

$$K_{Ic\min} = K_\mu = \sigma_f^* \sqrt{\pi X_c} . \tag{3}$$

It follows herefrom that K_μ can be determined by the temperature dependence of fracture toughness at the level of the so-called low-temperature plateau $K_{Ic\min}$, and relation (3) is an additional condition for the estimation of X_c and σ_f^* parameters.

STRETCHED ZONE

The independent data on the fracture process features and micromechanisms in the brittle-to-ductile transition region were obtained by analyzing the stretched zone (Krasowsky, 1988). This analysis requires special procedure of stereoscopic measurements to be used. Being performed firstly on a single fracture surface, those measurements resulted in significant scattering of results. The development of a new measuring procedure of the stretched zone height by the superposition of mating profiles of the opposite fracture surfaces made it possible to increase the reproducibility of measurement results to a great extent, to reduce the scattering of data. The reason of the above scattering turned out to be connected with the pecularities of the crack initiation resulting

in the asymmetry of the stretched zone and in nonsimilarity of its two parts on the opposite mating fracture surfaces. The results obtained have shown that because of equal probability for a crack in each point of the front to initiate into one of the two plastic zone fans (along the trajectory of the maximum material damage by plastic strains) depending on the location of the measured profile along the crack front, the stretched zone asymmetry can be reversed, the fact which is the source of scattering in results measurements of with the use of only one fracture surface. The analysis of the stretched zone measurements data and the results of the material fracture toughness determination by standard methods in the brittle-to-ductile transition region has allowed to draw important conclusions.

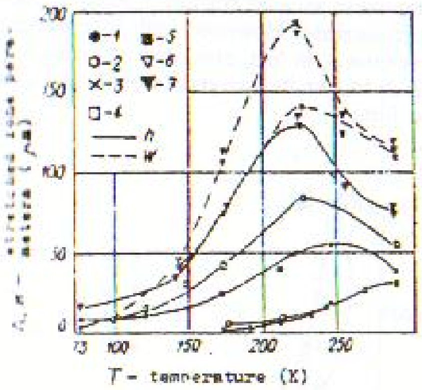


Fig.3. Temperature dependences of the stretched zone geometrical parameters. Steels: *1, 2* – 15Kh2NMFA (shell); *3* – CSN15313; *4, 5* – low-carbon; *6, 7* – 15Kh2NMFA (plate). Loading: *1, 4, 5, 6, 7* – static; *2, 3* – dynamic.

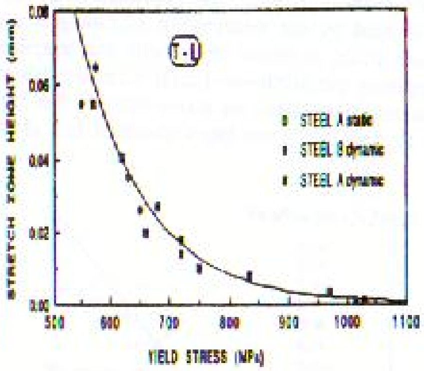


Fig.4. Relation between the stretched zone height and the yield strength for different temperatures in the temperature region of brittle-to-ductile transition and below. Steels for main pipelines: *A* – 10G2FB–U steel; *B* – X70.

It appeared that over the temperature range where subcritical crack growth is not observed prior to catastrophic fracture, there exists a linear correlation between the stretched zone height and the critical crack tip opening displacement. Since the stretched zone height is, in fact, the residual crack opening displacement, its occurrence is possible only above some minimum load corresponding to the elastic crack tip opening displacement at the stress intensity factor level being equal approximately to $K_{Ic\min}$ determined, as it has already been mentioned, by the low-temperature plateau of fracture toughness. Over the temperature range above the brittle-to-ductile transition, where a stable subcritical crack growth precedes catastrophic fracture, the correlation between the stretched zone height and the critical crack opening displacement calculated using the K_{Ic} value is not observed. The actual crack initiation occurs much earlier than that predicted by the standard J_{Ic}-estimation procedure or by the *R*-curve method but essentially later than the crack initiation predicted by the standard K_Q estimation according to the 5%-secant rule. Consequently, over this temperature range the measurements of the stretched zone give a conservative estimate of fracture toughness. Meanwhile, at room temperatures when subcritical crack growth precedes catastrophic crack growth, the stretched zone height appeared not to be dependent on the specimen thickness over the interval of thicknesses from 10 to 300 mm.

As seen from Fig.3, the character of temperature dependences of the half height, h, and width, w, of the stretched zone is identical to the character of temperature dependences of the fracture toughness standard characteristics (Fig.1). Similarly, the relation between the stretched zone height and the yield strength is observed (Fig.4 and Fig.2).

TRANSITION TEMPERATURE

The above peculiarities of the materials fracture in the brittle-to-ductile transition region can be generalized as a new concept according to which the critical temperature of brittle-to-ductile transition is determined as an upper temperature boundary of existence of plane strain conditions (or in a more general formulation, conditions of applicability of the linear fracture mechanics criteria) for a cracked body of the given geometry at the defect tip at the moment of fracture onset. According to this, the brittle-to-ductile transition temperature can be determined as the abscissa of the cross point of the fracture toughness temperature dependence with the line reflecting the dimension requirements to specimens for fracture toughness testing at plane strain (Francois and Krasowsky, 1986):

$$T_c = \frac{T_0}{2} \ln(B\sigma_Y^2/\beta K_0^2)\,, \qquad (4)$$

where B is the thickness, β is the coefficient equal to 2.5 for steels, for example; T_c is the transition temperature, the other values are the material constants approximating the fracture toughness temperature dependence according to the formula:

$$K_{Ic} = K_0 \exp(T/T_0)\,. \qquad (5)$$

From relation (4) a number of practically important consequences result which show, in particular, proportionality of the transition temperature to the natural logarithm of the specimen thickness, the fact which is confirmed by the experiment and gives the possibility of: predicting the transition temperatures for large cross sections by using the test results for small laboratory specimens; predicting the material fracture toughness temperature dependence according to the results of its transition temperature determination; estimating the loading rate influence on fracture toughness and transition temperature; using the transition temperature value in calculations of structural parts for brittle fracture resistance. In the latter case the use of the two-criteria approach (the so-called fracture assessment diagrams) is rather promising.

Generalization of the above brittle-to-ductile transition conception was performed on the basis of the two-criteria fracture assessment diagram in dimensionless coordinates $K_r = K_I/K_{Ic}$ and $S_r = P/P_u$, where P and P_u are the current value of a generalized load and its limit value for the completely ductile fracture, respectively. The fracture assessment diagram consists of a horizontal ($K_r = 1$) and a vertical ($S_r = 1$) straight lines connected by some arc., while the beams starting from the origin of coordinates correspond to the loading lines for cracked bodies. Two points of conjugation between the straight lines and the curvilinear arc can be interpreted as corresponding to two temperatures of transition from brittle to quasi-brittle and from quasi-brittle to completely ductile fractures. A family of beams crossing only the straight line $K_r = 1$ is described by the condition

$$\frac{K_I}{K_{Ic}} \geq \frac{P}{\alpha P_Y}\left(= \frac{P_u}{\alpha P_Y}\cdot\frac{P}{P_u}\right), \qquad (6)$$

where $P_u/\alpha P_Y$ is the slope of the beam crossing the limiting curve at the point of conjugation of the horizontal straight line with the curvilinear part of the fracture assessment diagram (i.e. at the point of transition from brittle to quasi-brittle fractures). Inequality (6) as applied to laboratory specimens testings can be interpreted as the requirement of correct definition of the material fracture toughness characteristic K_{Ic} (or K_{Id}), i.e. as the necessary condition of the applicability of linear fracture mechanics criteria and also as the condition for determination of the brittle-to-ductile transition temperature. In the former case, taking into consideration a specific geometry of the specimen we can get the condition

$$w \geq \frac{1}{\Gamma_i(a/w)}\left(\frac{K_{Ic}}{\alpha\sigma_Y}\right)^2, \qquad (7)$$

where $\Gamma_i(a/w)$ is the dimensionless function depending on the relative crack length a/w. This condition can be used for determining the minimum necessary characteristic size of the specimen for fracture toughness testing.

Similarly, the expression for the transition temperature T_c is obtainable when making use of formulas (5) and (6):

$$T_c = T_0\left[\ln\left(\frac{\sigma_Y}{K_0}L^{1/2}\right) + \ln\alpha\Gamma_i(a/w)\right], \qquad (8)$$

where L is the characteristic size of the cracked body. According to formula (8) the critical transition temperature depends not only on the body dimensions and the material mechanical properties but also on the body geometry which makes it possible to use the results of laboratory specimens testing for estimation of the structural part transition temperature.

REFERENCES

Francois D. and Krasowsky A.J. (1986) Relation between various transition temperatures and K_{Ic} fracture toughness transition curve. Eng.Fract.Mech., 23, N.2, pp. 455-465.

Hahn G.T., Hoagland G.R. and Rosenfield A.R. (1971). The variation of K_{Ic} with temperature and loading rate. Met. Trans., 2, N.2, pp.537-541.

Krafft J. and Sullivan A.M. (1963) Effect of speed and temperature on crack toughness and yield strength in mild steel. Trans.ASM, 56, N.1, pp. 160-175.

Krasowsky A.J. (1980) Brittleness of Metals at Low Temperatures. Naukova Dumka, Kiev.

Krasowsky A.J. (1988). Stretched zone stereoscopic measurements as an independent control of material fracture toughness. In: Failure Analysis - Theory and Practice. Proc. 7th European Conf.Fracture, Budapest (Ed.E.Czoboly), vol.1, pp. 796-804. EMAS, Warley, U.K.

Krasowsky A.J. and Krassiko V.N. (1990). Fracture Toughness of Pipe-Line Steels (in Russian). Naukova Dumka, Kiev.

Krasowsky A.J. and Pluvinage G. (1993) Structure parameters governing fracture toughness of engineering materials. Physico-Chemical Mechanics of Materials, vol. 29, N.3, pp. (to be published).

Pandey R.K., Haridas J.D. and Banerjee S. (1974) Fracture behavior of dynamically loaded shipbuilding plate materials. Eng.Fract.Mech., 6, N.1, pp. 105-118.

Pisarenko G.S. and Krasowsky A.J. (1972) Analysis of kinetics of quasi-brittle fracture of crystallyne materials. - In: Mechanical Behavior of Materials. Proc.Int.Conf.Mech.Behav. Mat., Kyoto 1971 (Ed.S.Taira), vol.1, pp. 421-432. JSMS, Kyoto, Japan.

Pluvinage G., Krasowsky A.J. and Krassiko V.N. (1992) Dynaic fracture toughness at crack initiation, propagation and arrest for two pipeline steels. - Eng.Fract.Mech., vol.43, N.6, pp. 1063-1084.

Ritchie R.O., Knott J.F. and Rice J.R. (1973) On the relation between critical tensile stress and fracture toughness in mild steel. J.Mech.Phys.Solids, vol.21, N.6, pp. 395-410.

Silva da P.S.P. and Brook R. (1972) Fracture toughness of martensitic steels. In: Mechanical Behavior of Materials. Proc.Int.Conf.Mech.Behav.Mat., Kyoto 1971 (Ed.Taira), vol.1, pp. 513-524. JSMS, Kyoto, Japan.