FRACTURE PROCESS VOLUME: MECHANICAL-AND-PHYSICAL VIEWPOINT

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ABSTRACT

Theory of Fracture Process Volume (FPV) based on the "first principles", i.e. on analysis of elementary events of polycrystal fracture, has been discussed. On the basis of direct computer simulation of both the crack nucleus formation and propagation it has been established that the FPV is a part of material's volume ahead of notch or main crack, where forming crack nucleus are non-equilibrium. Peculiar feature of fracture of metals and alloys consists in both plastic strain and it gradient effect on FPV value ahead of notch or sharp crack. It is demonstrated that the value of gradient of relative plastic strain intensity, G ($G = \mathrm{grad}(\bar{e})/\bar{e}$), may be exploited as generalized parameter that characterizes above effect. In turn, G value is pre-determined by the notch radius and the value of relative loading σ_{NF}/σ_Y (where σ_{NF} is nominal fracture stress; σ_Y is yield stress).
Within the scope of these ideas both local fracture stress dependence on the notch radius and it steep increase at transition from notch to crack is exhibited to be display of scale effect inside of extremely small regions. Specific feature of this effect manifestation lies in it value dependence on plastic strain value within FPV. Sensitivity of cleavage stress value to change in FPV grows as plastic strain decreases.
Volumes of fracture zone and yielding are compared. They are shown to be coincident solely at low temperatures at small-scale yielding. At cleavage fracture under general yielding FPV may be several times less than the volume of local yielding region. This result is needed to be accounted when applying Local Approach for prediction of fracture toughness value over the region of ductile-to-brittle transition.
Computer code for calculation of the value of FPV using data of mechanical tests of both notched and pre-cracked specimens has been proposed.

1 INTRODUCTION

Description of the crack unstable equilibrium in metal requires solving of two problems: to calculate stress field ahead of a crack, and to predict fracture initiation of metal in this field. This problem is interdisciplinary, and it exploits both mechanics and solid state physics methods.

At present, the second problem solving turned to be the most complicated. Fracture process volume (FPV) concept is one of the ways to solve this problem This concept may be interpreted both deterministically (Pisarenko and Krasowsky [1]; Ritchie, Knott and Rice [2]; Pluvinage and Dhiab[3])) and stochastically (Beremin [4]; Tsan, Evance and Ritchie [5]; Dlouhy et al. [6]; Strnadel and Dlouhy [7]; The latter approach usually exploits Weibull distribution to describe fracture probability.

Essentially different approach has been suggested in Kotrechko and Meshkov [8], Kotrechko [9]. This approach may be regarded as First Principal Local Approach to fracture, because it is based on the quantitative analysis of **elementary** fracture processes, i.e. the crack nuclei (CN) formation and further propagation in polycrystalline metal.

The aim of this report is to demonstrate possibility of use of this first-principle approach as a tool for development of physical nature of FPV.

2 MODEL DESCRIPTION

Up-to-date physical theory of fracture is grounded on the CN ideas. These defects are of the same importance in fracture process as dislocations at plastic deformation. In [10] the concept of description of brittle fracture on the basis of statistical analysis of the CN formation and fast growth in polycrystalline aggregate has been realised. Specific feature of this model is that it accounts for both real micro-structure of polycrystalline metal where the CN grow, and quantitative analysis of it macro- and micro-stress state. This enables application of the model offered for both prediction of steel micro-structure effect (sizes and orientations of ferrite and pearlite grains, martensitic and bainitic packets, carbide particles) on the value of cleavage stress and description of fracture initiation ahead of a crack (accounting for strongly non-uniform stress and plastic strain field, multiaxial tension).

The CN in polycrystal form due to plastic strain incompatibility near the grain boundaries or phase boundaries. Two kinds of the CN arise in steels at plastic deformation, namely, the CN appearing, as a result of carbide particle cleave, and the CN emerging by dislocation micro-mechanism. In the first case the CN length, a, is specified by the carbide particle thickness, in the second case it size is pre-determined by real grain size d_g:

$$a = \frac{p}{\gamma}\left(\frac{\delta\tau_c}{\beta}\right)^2 \frac{d_g}{\bar{\varepsilon}} \tag{1}$$

where p, δ and β are the constants; γ is the specific energy of lattice fracture at the nucleus crack tip dependent on the lattice parameters; d is grain size; $\bar{\varepsilon}$ is equivalent micro-plastic strain value in the grain of size d.

The CN are of submicroscopic size. As a rule, its length doesn't exceed $0.05 - 1\mu\text{m}$. Therefore, micro-stresses influence greatly the unstable equilibrium of such cracks and their growth. Unfortunately, this problem is not studied until now. As it has been shown in [10], micro-stresses ξ_{ij}^{el} induced by elastic deformations of grains and micro-stresses ξ_{ij}^{pl} created by dislocations should be differentiated depending on their effect on the CN. In the first approximation, micro-stresses ξ_{ij}^{el} are uniform within the grain and change from one grain to another. Gauss law may be used as the first approximation of distribution of these stresses. The value of their variance may be expressed by linear function of macroscopic principal stresses σ_1, σ_2, σ_3.

Dislocation stresses are distributed non-uniformly inside of the grain, so, to estimate effective dislocation stresses $\bar{\xi}$ forcing on the CN, certain procedure of averaging of these stresses over the micro-crack length is needed [10]. The effect of dislocation micro-stresses $\bar{\xi}$ on the CN unstable equilibrium gives rise to the value of critical stress being dependent on the value of plastic strain e preceding fracture. This is main discrepancy of cleavage fracture of metals and alloys from fracture of brittle solids (ceramics, glasses, etc.). As a result, expression for critical microscopic stress of the CN unstable equilibrium, ξ_C, is the following:

$$\xi_C = \frac{K}{\sqrt{a}}\phi(\theta,\eta) - \bar{\xi}(e) \tag{2}$$

where η is stress state mode parameter ($\eta = \xi_{22}/\xi_{11}$, ξ_{11} and ξ_{22} are the principal tensile micro-stresses), θ is angle between the crack plane and direction where principal tensile micro-stresses act; K is the coefficient that characterises resistance of the crystal to the micro-crack propagation; $\phi(\theta,\eta)$ is the function that describes the influence of micro-stress state η and orientation of the crack θ on the critical stress.

Based on these ideas, expression for the fracture probability of reference volume at certain value of **macroscopic** stress σ_F :

$$\mathrm{F}_{\mathrm{V}_0}(\sigma_F) = 0.5 \int\limits_{\xi_c^{\min}}^{\xi_c^{\max}} \mathrm{f}_1(\xi_c) \left[1 - \mathrm{erf}\left(\frac{\xi_c - \sigma_F}{\sqrt{2} I_\xi \sigma_F} \right) \right] \mathrm{d}\,\xi_{\tilde{n}} \tag{3}$$

where I_ξ is coefficient of variation of maximum tensile micro-stress ξ_{11}; $\xi_c^{\min}$ and $\xi_c^{\max}$ are minimum and maximum values of **micro-stress** of unstable equilibrium of the CN of an random orientation and length; $\mathrm{f}_1(\xi_c)$ is the density distribution function for this stress.

Probability of fracture of metal ahead of crack tip or notch in the volume V_i limited by the i th finite element $\mathrm{F}_{\mathrm{V}_\mathrm{i}}(\sigma_F)$, is estimated based on the well-known “weakest link” principle:

$$\mathrm{F}_{\mathrm{V}_\mathrm{i}}(\sigma_F) = 1 - [1 - \mathrm{F}_{\mathrm{V}_0}(\sigma_F)]^{V_i \rho_i} \tag{4}$$

As distinct from conventional dependences, exponent in (4) is not constant. It magnitude depend on the plastic strain value. It is due to the fact that the CN density in metals, ρ_i is plastic strain function.

3 THE FPV EFFECT ON THE REGULARITIES OF FRACTURE OF NOTCHED AND PRE-CRACKED SPECIMENS

According to above ideas, Fracture process volume may be specified as a volume of metal ahead of a crack or notch, inside of which the value of elementary fracture probability (probability of the CN unstable equilibrium), F_{V_i} , is greater than zero (Fig.1).

Executed examinations have shown that FPV coincides with plastic zone volume solely at low temperatures within the small-scale yielding region (Fig.2). In general case, fracture process zone size, X_{FPV} , is comparably smaller than size X_Y of local plastic area. Besides, plastic strain heterogeneity ahead of notch or crack influences significantly FPV value. Absolute value of relative gradient of plastic strain intensity, G ($G = \mathrm{grad}(\bar{e})/\bar{e}$), may be applied as the first approximation of this effect (Fig.3).

In turn, heterogeneity of the local plastic strain ahead of the notch, G , is specified by both the notch radius and the relative loading value σ_{NF}/σ_Y (σ_{NF} is nominal fracture stress of the specimen with notch, σ_Y is yield stress of metal).

Absolute value of Fracture process volume governs a value of the local fracture stress ahead of notch or sharp crack. It is related with scale effect at the cleavage fracture. Executed investigations have enabled ascertainment of two main peculiarities of scale effect appearance at cleavage fracture of metals and alloys. The first is scale effect dependence on the value of plastic strain preceding fracture. It is obtained that fracture stress sensitivity to volume change grows with plastic strain decrease. It is due to the effect of plastic strain value on the density of CN forming at plastic deformation. The second is

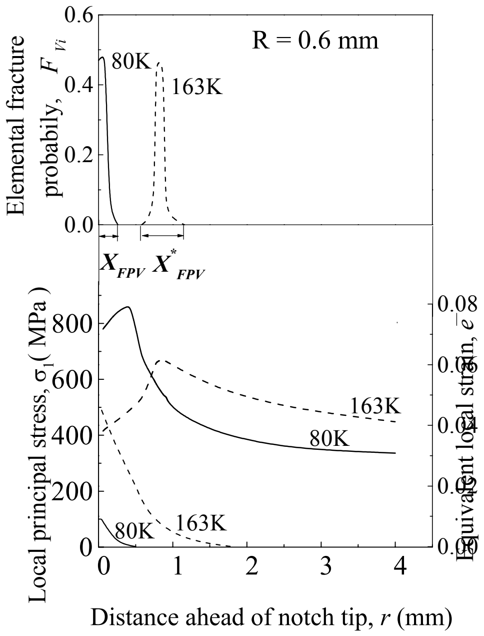

Figure 1: Distribution of principal tensile stresses σ_1 equivalent plastic strains $\overline{e}$ and probability F_{V_i} of fracture ahead of notch R = 0.6 mm for cylindrical specimen of diameter $D = 14\text{mm}$: X_{FPV} is fracture process zone length in minimum cross-section of specimen.

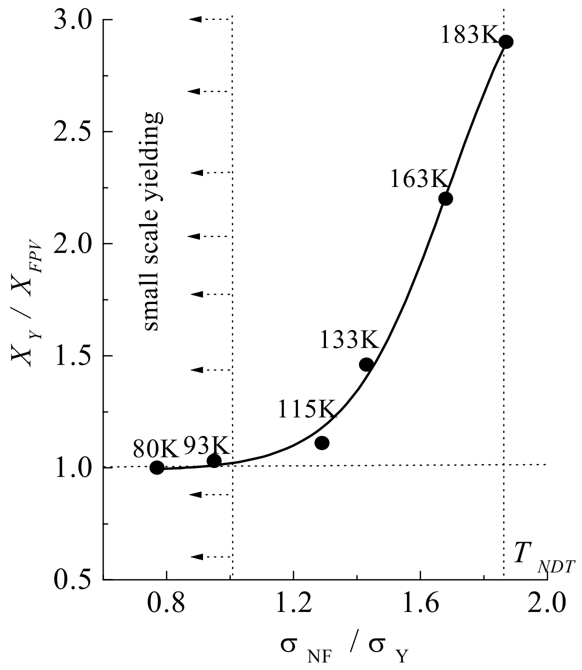

Figure 2: The influence of the relative value of nominal fracture stress σ_{NF}/σ_Y on the interrelation between lengths of local yielding region X_Y and process zone X_{FPV} in the minimum cross-section of notched ($R = 0.6\text{mm}$) tensile specimen; T_{NDT} is nil ductility temperature.

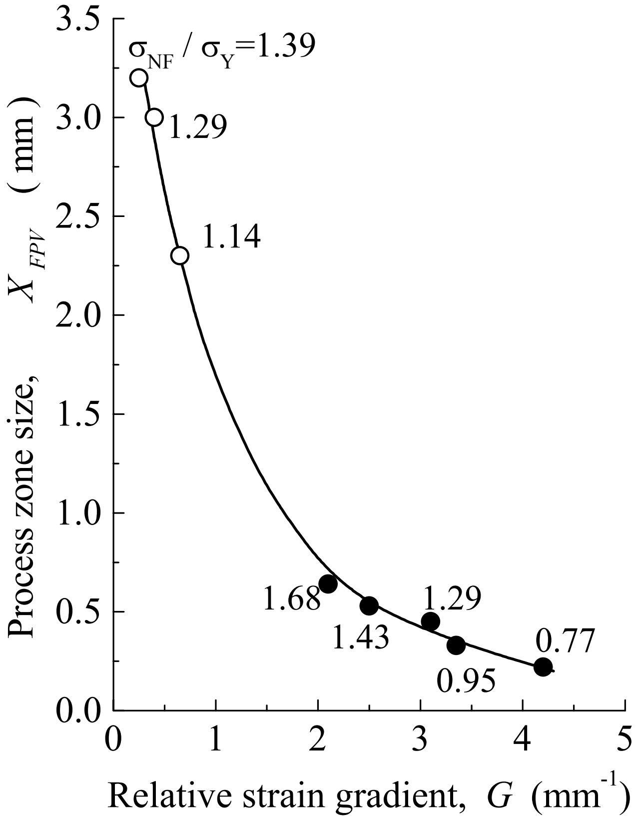

Figure 3: Dependence of process zone length X_{FPV} on the absolute value of relative strain gradient G; solid circles represent data from specimen with notch radius 0.6 mm; open circles represent data from specimen with notch radius 4 mm.

that scale effect in metals, unlike ceramics and other brittle materials, is significant only within extremely small volumes ($V<100\text{mm}^3$).

4 CONCLUSIONS

1. From the physical viewpoint, Fracture Process Volume (FPV) should be understood as region ahead of notch or main crack, where probability of the crack nuclei unstable equilibrium is greater than zero.
2. Specific feature of fracture of metals and alloys is the effect of both plastic strain value

and its gradient ahead of notch or sharp crack on the value of FPV.

3. The value of Fracture Process Volume coincides with Yield Volume solely at low temperatures at small-scale yielding. At cleavage fracture under general yielding FPV may be several times less than volume of local yielding region.

4. Local cleavage stress dependence on the notch radius and it stress steep increases at transition from notch to sharp crack are due to scale effect at cleavage fracture. Peculiarity of this effect appearance in metals consists in dependence of it value on the plastic strain gradient in FPV. Sensitivity of cleavage stress value to FPV change grows with decrease in plastic strain.

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