Physical Fundamental of Local Approach to Cleavage Fracture of Metals and Alloys

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Abstract: *A quantitative investigation of the peculiarities of fracture of the metal ahead of notch and sharp crack has been performed on a basis of the statistical model of microcrack nucleation and growth in polycrystalline metal developed by author. These peculiarities are associated with scale effect, influence of local plastic strain on fracture probability and effect of triaxial tension on the value of the local fracture stress. It is shown that the influence of local small plastic strain on the susceptibility of the fracture stress to a "process zone" volume is a specific feature of the scale effect in metal. The results show that there is a need to predict brittle fracture of notched specimens over a wide temperature region (from small-scale yielding to general yielding) to incorporate the effect of small plastic strain. All these effects have been expressed in terms of Weibull parameters. It is shown that these parameters aren't material constants, and they depend on the plastic strain and stress state ahead of a notch.*

INTRODUCTION

Today, "Local Approach to Fracture" is one of the most strongly developing directions in fracture mechanics. It uses methods of micromechanics and is an attempt of mechanics to explain fracture physically. Three scientific areas where the use of such approach is effective may be indicated:

1. Fracture mechanics (prediction of fracture toughness temperature dependence according to the results of tests of small specimens; relation between impact toughness and fracture toughness).
2. Materials science (effect of microstructure on structural integrity).
3. Fracture physics (peculiarities of fracture initiation and propagation mechanism under the conditions of high stress and strain gradients as well as at multiaxial stress state).

The first direction is the most intensively developing one. Two others are the task of the near future.

A statistic criterion for fracture of separate cell ahead of notch is the key problem of “Local Approach”. In up-to-date version of “Local Approach” statistic criterion is applied [1-3]. For cracked bodies or for sharply notched specimens exhibiting steep stress-strain gradient, the stressed region is divided into cells V_j. Each cell is subjected to a quasi-homogeneous stress-strain state.

Determination of probability function for fracture of cell V_j is the main task of such approach. Now, Weibull distribution is employed to this end:

$$F_{V_j}(\sigma) = 1 - exp\left[-\frac{V_j}{V_0} \left(\frac{\sigma - \sigma_{th}}{\sigma_u} \right)^m \right]$$

where σ_{th} is threshold stress (low limit of strength), m is parameter that determines the shape of probability function (shape factor), σ_u scale stress (parameter); V_0 is a reference unit volume.

This approach postulates that Weibull parameters are metal's constants i.e. they are independent on stress-strain state of metal ahead of notch.

In spite of the fact that Weibull distribution is widely adopted for prediction of fracture of notched specimens, great number of experimental data exists that aren't in accord with assumption concerning independence of Weibull parameters on stress-strain state of metal ahead of notch. This appears vividly at change in stress and strain gradients ahead of notch over a wide range i.e. when comparing data on fracture of notched and on unnotched specimens. [4-6].

Statistical model of the brittle fracture of polycrystalline metals was offered in [7, 8]. Possibility of its application for prediction of a fracture based on the "first principles" i.e. analysing the crack nucleus formation and propagation was demonstrated. This model allows to develop physical fundamental of local fracture criteria.

The aim of this paper is both to analyse basic factors affecting unstable equilibrium of the crack nucleus ahead of notch and to ascertain regularities of influence of microstructure and stress-strain state of metal on the values of Weibull parameters.

PHYSICAL MODEL OF BRITTLE FRACTURE OF POLYCRYSTALLINE METAL

Crack Nucleation

According to physical ideas, the crack nucleus triggering is due to microplastic inhomogeneity in polycrystal. This conception allows to derive the expression for a crack nucleus length a. Maximum length of the crack nucleus in a single-phase polycrystalline materials or steels with fine carbide particles is two orders less than grain size. In steels with coarse carbide particles the particle diameter or thickness determines the crack nucleus size. Microstresses influence significantly unstable equilibrium of such cracks. Unfortunately, this problem isn't studied till now. As it has been shown in [8], microstresses ξ_{ij} induced by elastic deformations of grains and microstresses ξ_{ij}^{p} created by dislocations should be differentiated depending on their effect on the crack nucleus. In the first approximation, microstresses ξ_{ij} are uniform within the grain and change from one grain to another. The value of their variance is predetermined by macroscopic stress state of polycrystalline aggregate i.e. it depends on macroscopic principal stresses σ_1, σ_2, σ_3. Peculiarity of these microstresses is that at *uniaxial* tension of polycrystal, $(\sigma_1 > 0, \sigma_2 = \sigma_3 = 0)$, the *multiaxial* stress state exists in grains ($\xi_{11} \neq 0, \xi_{22} \neq 0, \xi_{33} \neq 0$). Essential fluctuations occur at that. For example, at uniaxial tension of iron the magnitude of ξ_{11} changes over the $0.6\sigma_1 \ldots 1.4\sigma_1$ range. Magnitudes of ξ_{22} and ξ_{33} change within the range from $-0.24\sigma_1$ to $+0.24\sigma_1$.

Solely dislocation stresses acting inside the region where the crack nucleus forms (and solely at the moment of their nucleation) affect the microcrack unstable equilibrium. In addition, it may be kept in mind that dislocation structure characteristics in the region where crack nucleates (for example, in boundary region) may be essentially different from those for initial one. Pile-ups of the same sign are main peculiarity of dislocation structure in the region where cracks nucleate. Microstresses created by such dislocation structures have non-homogeneous spatial distribution; so, their influence on the crack nucleus unstable equilibrium is determined by the value of effective tensile microstresses $\bar{\xi}$. Its magnitude is proportional to the plastic strain $\bar{\varepsilon}$ ($\bar{\xi} \sim \sqrt{\bar{\varepsilon}/d_g}$) over the interval of strains that are typical for quasi-brittle fracture, namely, from 0.005 to 0.05-0.10. This effect is the cause for decrease in fracture stress with growth of plastic strain preceding fracture. This effect is observed experimentally at small plastic strains that don't exceed 0.05-0.10 [9].

The crack nuclei don't exist in metal initially. They arise from plastic deformation. It means that crack nucleus density isn't a constant, as it is assumed in conventional models, but depends also on the plastic strain value [7].

Ideas concerning mechanism of brittle fracture of polycrystalline metal considered above enable to point out the most important factors that influence brittle strength of metal:

- the crack nucleus sizes that are predetermined by grain sizes (in steels contained coarse carbide particles the crack nucleus sizes are determined by carbide particle sizes);

- the crack nucleus orientation distribution that depends on grain orientation distribution;
- the crack nucleus density that is specified by the plastic strain value reached at fracture;
- the magnitude of microstresses within the region where the microcrack nucleate that depends on the plastic strain reached at fracture.

Regularities of influence of these factors on the fracture of metal at uniaxial tension and uniform microstress distribution are analysed in detail elsewhere [7].

THE BRITTLE FRACTURE OF METAL AHEAD OF NOTCH

There are three main specific features of the fracture ahead of notch, namely:

- fracture triggering is localised in extremely small region – “process zone”;
- wide range of the plastic strain values ahead of notch;
- bi - or triaxial tension ahead of notch.

“Process zone” Size

“Process zone” size influences significantly the value of local fracture stress σ_F. It is due to scale effect observed at brittle (quasi-brittle) fracture. The magnitude of this effect depends on the crack nucleus density inside “process zone” as well as on “process zone” size. As the value of plastic strain rises the crack nucleus density increases but the susceptibility of fracture stress to "process zone" volume diminishes. Scale effect dependence on the plastic strain value is one of the peculiarities of quasi-brittle fracture of metals (Figure 1) [7].

Within the framework of statistical approach the “process zone” size is a region ahead of notch where probability of fracture is greater than zero. Beremin's model supposes equality of the plastic zone size and "process zone" size. According to data obtained in [8,10], these regions coincide only at small scale yielding. In general case, “process zone” size X_{P-Z} is most of all, because of both fracture stress dependence on the plastic strain value and non-homogeneous strain distribution within local plastic area. Plastic strain and its gradient are specified by the notch radius and relative loading of notched specimen σ_{NF}/σ_Y (where σ_{NF} is nominal fracture stress of notched specimen; σ_Y is yield stress). As it is shown in [8], the effect of influence the plastic strain and its gradient on X_{P-Z} can be described, in the first approximation, by dependence of X_{P-Z} on relative gradient of equiva-

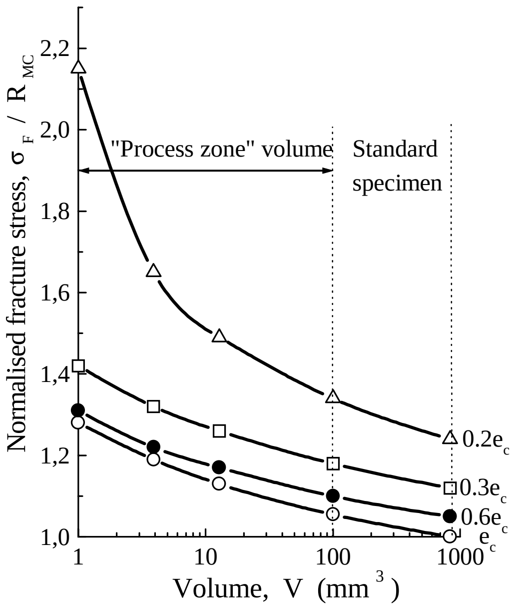

Figure 1: Quasi-brittle fracture stress dependence on the volume of specimen and the value of plastic strain for fracture.

lent local plastic strain G ($G = |\mathrm{grad}(\bar{e})| / \bar{e}$; where $\bar{e}$ is the value of local equivalent plastic strain).

Triaxial Stress State Effect on the Value of Local Fracture Stress

Multiaxial tension is important specific feature of stress state of metal ahead of notch. As consistent with experimental data, at transition from uniaxial to biaxial tension brittle fracture stress of iron and carbon steels decreases approximately 1.2-1.3 times [11]. It was shown by computer simulation in that non-uniform distribution of the crack nucleus orientations may be the cause of stress state influence on the value of fracture stress in metals [7]. Such non-uniformity is because of the crack nucleus arisen from plastic deformation and so, their plane orientations relate with shear plane orientations.

EFFECT OF METAL MICROSTRUCTURE AND STRESS STATE OF METAL ON WEIBULL PARAMETERS

All these effects may be expressed in terms of Weibull parameters. Three-parameter Weibull distribution is sufficiently "flexible" function. Therefore,

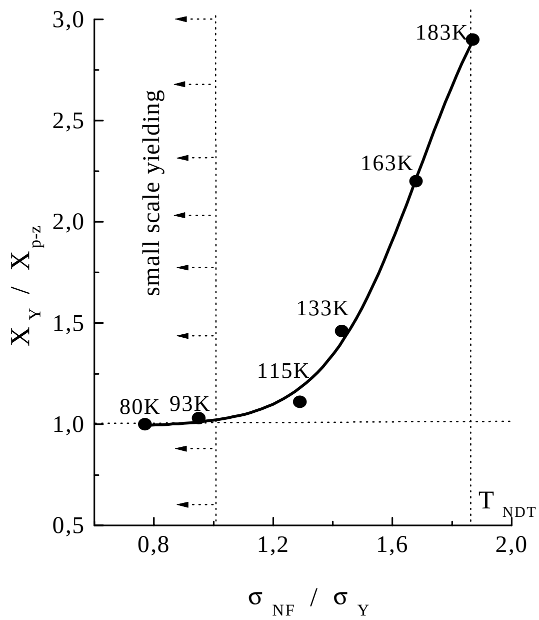

Figure 2: Influence of the relative value of nominal fracture stress σ_{NF}/σ_Y on the interrelation between lengths of local yielding region X_Y and "process zone" X_{p-z} in the minimum cross-section of notched ($\rho = 0.6$ mm) tensile specimen (iron, ferrite grain size ~ $97\mu m$).

a function of cumulative probability of failure for *reference volume* $F_{V_0}(\sigma_F)$ obtained by computer simulation was fitted by three parameter Weibull distribution [12].

It permits to ascertain relations between Weibull distribution parameters and such microstructural parameters as the most probable grain size and grain size variance (Figure 3). It had been exhibited that at uniaxial tension and fixed value of plastic strain the value of shape parameter m is, actually, independent on the value of the most probable grain size. The value of shape parameter m diminishes with rise in logarithmic grain size variance $D_{\ln d}$. Shape parameter m is linear function of $\sqrt{D_{\ln d}}$ at that. The threshold stress σ_{th} is proportional to $d_{mpv}^{-1/2}$ (d_{mpv} be a most probable value of grain size) and depends on grain size variance. This stress is approximately equal to $0.7R_{MC}$ (R_{MC} be a minimum brittle fracture stress of unnotched specimens over ductile-brittle temperature region). The normalised scaling stress σ_u/σ_{th} is a linear function of $D_{\ln d}$.

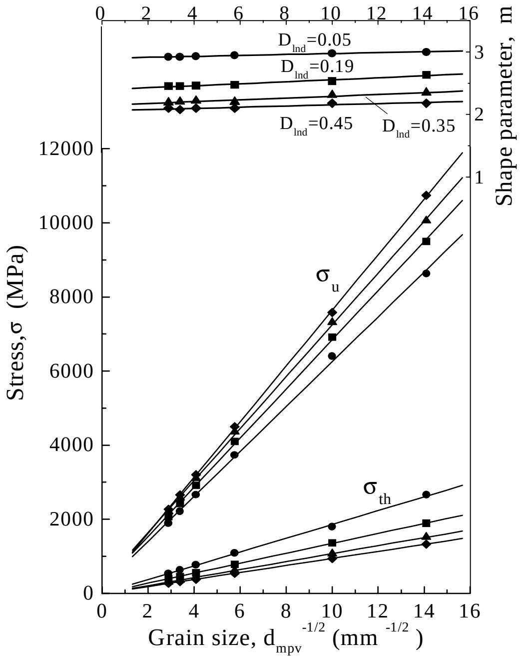

Figure 3: Effect of the most probable grain size on Weibull distribution parameters (D_{Lnd} - values of variance of grain size logarithm).

According to computer simulation findings, shape parameter m is nearly constant over the interval of small plastic strains. As strain grows, threshold stress decreases approximately by 1.3 times; vice versa, σ_u becomes 2.7 times greater. In most existing models effect of small plastic strains on Weibull parameters is not considered.

Computer simulation findings indicate, also, on influence of stress state on the value of Weibull parameters. For example, at transition from uniaxial to biaxial tension ($\sigma_1 = \sigma_2$) threshold stress σ_{th} and parameter m are approximately constant, but the value of scale parameter σ_u decreases nearly 1.6 times. Effect of plastic strain and stress state on Weibull parameters will be examined in detail in the next paper.

CONCLUSIONS:

1. Four main factors predetermine the level of brittle strength of metal:

- distribution of the crack nucleus lengths that is specified by grain sizes or carbide particle sizes;

- distribution of the crack nucleus orientations that depends on distribution of grain orientations;
- the crack nucleus density;
- the value of microstresses within the region where the crack nucleus form.

2. Specific feature of scale effect at quasi-brittle fracture consists in its value dependence on the value of plastic strain. This is because of plastic strain influence on the crack nucleus density inside of "process zone".
3. "Process zone" length X_{p-z} in the minimum cross-section of specimen is controlled by the value of relative gradient of plastic strain. The value of X_{p-z} may coincide with respective value of local yielding region size solely at small scale yielding. At quasi-brittle fracture under the conditions of general yielding the value of X_{p-z} is essentially less than local yielding region depth.
4. A susceptibility of σ_F value of metals to stress state is caused, substantially, by non-uniform distribution of the crack nucleus orientations.
5. Weibull distribution parameters aren't metal constants. Plastic strain and stress state ahead of notch influence them. Increase in plastic strain results in threshold stress decrease and scale stress increase. Transition from uniaxial to biaxial tension gives rise to scale stress fall.

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