Physical Nature of Brittle Strength Anisotropy of Deformed Metal

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ABSTRACT: Elementary processes of the crack nucleation and growth in textured polycrystal are considered. It is shown that crystallographic texture results in non-uniform distribution of the crack nucleus orientations. This is the main cause for anisotropy of brittle fracture stress of deformed metal. It is ascertained that effect of "oriented" microstresses gives rise to increase in brittle strength anisotropy of polycrystal. Based on above mentioned, influence of small plastic strains preceding fracture on the value of anisotropy of fracture stress of metals and alloys is analysed.

INTRODUCTION

It is known that the value of cleavage fracture stress of single crystals depends on their orientation, i.e. anisotropy of brittle strength of crystals takes place. Such anisotropy in polycrystalline metals and alloys appears as a result of crystallographic texture formation owing to such technological processes as rolling or drawing, and it influences essentially structural integrity. In spite of this, today physical theory of brittle strength anisotropy of metals is insufficiently developed, and also there is no quantitative measure of this metal property.

BACKGROUND

Today, physical nature of anisotropy of elastic and plastic properties of metals and alloys (yield stress, yield strength) is investigated quite enough. However, microscopic factors causing influence of orientation of an applied stress on ability of textured metal to resist brittle fracture aren't investigated. There is no uniqueness in a choice of mechanical characteristics for a quantitative evaluation of this property. Usually, reduction in area, impact toughness, fracture toughness is applied to this end. However, values of these characteristics can vary by the orders at change of the fracture mechanism from ductile to brittle, therefore, it is too difficult to indicate their contribution to change in proper anisotropy. At the best, the characteristic mentioned can be used as the indicator of presence of an anisotropy. By virtue of this reason, recently, the ratio of magnitudes of local brittle fracture stress ahead of a notch, σ_F, determined in different directions is used to estimate brittle strength anisotropy of metals and alloys [1, 2]. Dependence of σ_F magnitude on specimen cutoff direction is usually explained by geometric texture due to non-equiaxiality of grains in deformed metal. Such interpretation of examined effect does not enable to explain the reasons for an anisotropy of most of structural steels fracturing by an initiation of a cleavage of carbide particles. In this case, the σ_F magnitude is determined by the size of carbide particles and does not depend on a grain diameter and shape. In such case, change in both the shape and the size of grains does not result in an anisotropy of a local fracture stress.

THE OBJECTIVE OF RESEARCH

To develop a physical model of brittle strength anisotropy of polycrystalline metal that is based on examination of elementary acts of brittle fracture initiation in polycrystal**.**

THEORY

According to modern ideas, the origin of brittle (quasi-brittle) fracture of metals and alloys is the crack nucleus formation and propagation. In statistical model of brittle fracture of polycrystalline metals [3] it is shown, that orientational distribution of the crack nucleus can influence significantly magnitude of a fracture stress. It is because the critical stress of crack unstable equilibrium depends on an angle between a crack plane and direction of an applied stress.

It is clear, that the orientational distribution of crack nucleus depends on plane orientations of a crystal lattice, in which these cracks are opened. The parameters of such distribution can be got based on the analysis of crack nucleation.

Critical Stress of Unstable Equilibrium of an Arbitrary Oriented Crack Nucleus

The model proposed assumes that microcrack opens in slip plane (Figure 1). To analyse unstable equilibrium of the arbitrary oriented crack nucleus a method of configurational force can be used [4].

For the selected co-ordinate system (Figure 1), in which the plane of a crack nucleus is normal to a basis vector $\vec{n}$, one can obtain expression for the crack nucleus unstable equilibrium:

$$\left(l_{n1}^2 \xi_{11} + \bar{\xi}\right)^2 + \left(l_{n1} l_{s1} \xi_{11} - \bar{\tau}\right)^2 \geq \xi_C^2 \qquad (1)$$

where ξ_{11} is the value of tensile microstress acting in laboratory (global) co-ordinate system; ξ_C is Griffith stress for the crack nucleus; l_{n1} and l_{s1} are directional cosines specifying orientation of local basis relatively to a direction of tensile microstresses ξ_{11}. The third direction cosine is equal to zero; i.e. one of basis vectors lies in a crack plane (Figure 1).

Respectively, expression for the critical tensile stress ξ_{11}^C in laboratory co-ordinate system is the following:

$$\xi_{11}^C \geq f\, \xi_C \qquad (2)$$

$$f = \frac{\beta\left[L_{sn1}\chi - 1\right] + \sqrt{\beta^2\left[L_{sn1}\chi - 1\right]^2 - \left[1 + L_{sn1}^2\right]\left[\beta^2(1+\chi) - 1\right]}}{l_{n1}^2 (1 + L_{ns1}^2)} \qquad (3)$$

where $L_{sn1} = l_{s1}/l_{n1}$;

The relations $\chi = \bar{\tau}/\bar{\xi}$ and $\beta = \bar{\xi}/\xi_C$ determine relative values of normal and shear components of tensor of the “oriented” microstresses. Level of these microstresses depends, in general case, on the value of a plastic strain reached to quasi-brittle fracture.

According to (2) and (3), parameter f characterises influence of orientation of a crack nucleus on a critical level of a tensile stress ξ_{11}^C, required for its growth. It should be noted that the magnitude of this effect depends on a level of the “oriented” microstresses acting on a crack nucleus.

DISCUSSION

In the case of ideal texture, the first approximation for coefficient of a brittle strength anisotropy γ_R can be expressed by such formula:

$$\gamma_R = \frac{f_I}{f_{II}} \tag{4}$$

where "I" and "II" characterise directions, in which the values of critical stress ξ_{11}^C are determined.

From this dependence it follows, that a main factor, that determines brittle strength anisotropy of the textured polycrystal is the orientation of a plane of a crack nucleus opening relatively to directions of acting of tensile stresses. A type of a texture and its parameters predetermines this orientation. It should be emphasised that the value of γ_R does not depend on elastic and plastic properties of metal as much as these properties don’t affect the texture. The value of the "oriented" microstresses, which depends, first of all, on a degree of a plastic strain preceding quasi-brittle fracture has an additional influence on γ_R.

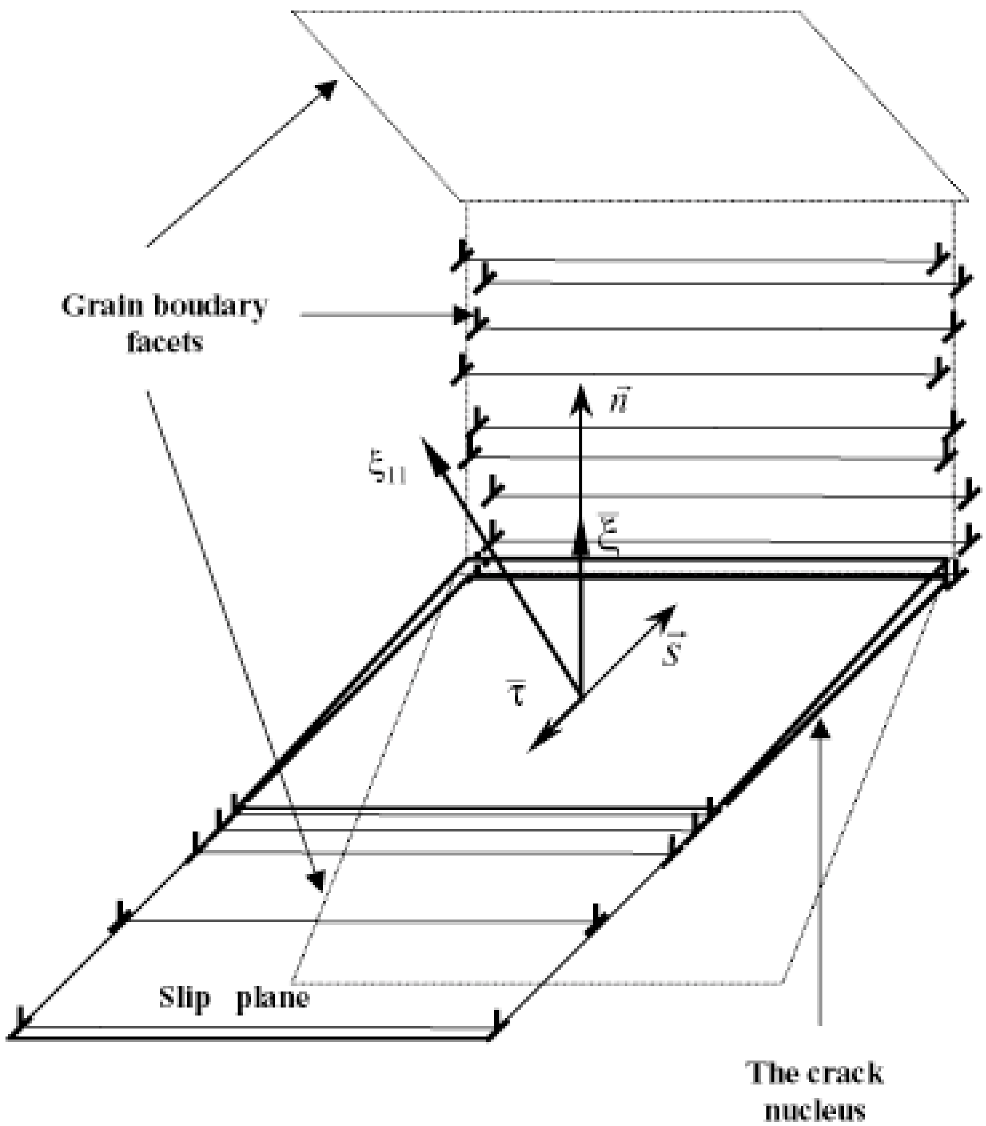

Figure 1: The microcrack nucleation in slip plane near one of the grain boundary facets ($\vec{s}$ and $\vec{n}$ are vectors of slip direction and normal to slip plane; ξ_{11} is "applied" stress; $\overline{\xi}$ and $\overline{\tau}$ are effective "oriented" microstresses).

Evaluation of a Brittle Strength Anisotropy of Polycrystalline Metal after Rolling and Drawing

Model rolling and drawing textures are convenient to consider the basic regularities of origin of the brittle strength anisotropy a crystallographic texture influence on it. For sharp rolling texture in iron (001) [110] i.e. at zero values of the "oriented" stresses ($\beta = 0, \chi = 0$ - perfectly cleavage fracture) the relationship of a fracture stress ξ_{11}^{C} along longitudinal directions to the appropriate fracture stress along through-thickness directions is equal to 1.35. The calculated value of critical stress in a transverse direction coincides with the appropriate value along rolling directions. It is because the estimations were carried out for an ideal single-component texture.

Upper bound of the coefficient of brittle strength anisotropy for ideal axial texture, γ_R, may be estimated as the ratio of critical stress at tension along direction [II0] ($\xi_{11C}^{[IIO]} = 2.08\xi_C$) to the minimum value of this stress at loading along direction normal to the texture axis. Calculations show that among directions *lying in* plane normal to the texture axis directions $[\bar{I}\,I\,\bar{2}]$ and $[I\,\bar{I}\,2]$ are those where critical stress reaches its minimum value ($\xi_{11C}^{[\bar{I}I\bar{2}]} = \xi_{11C}^{[I\bar{I}2]} = 1.17\xi_C$). Respectively, substituting these values to (4), one can obtain $\gamma_R = 1.78$.

Effect of "Oriented" Microstresses

Above mentioned estimations are calculated on the assumption of perfectly cleavage fracture i.e. effect of microstresses due to plastic deformation on the crack nucleus isn't accounted. As consistent with up-to-date fracture physics, plastic deformation is necessary condition for cleavage (brittle) fracture of metals because of the crack nucleus arisen as a result of plastic deformation. Moreover, "oriented" tensile microstresses arise from plastic deformation in grains, and they influence the crack nucleus propagation. By [5], the level of such stresses increases with growth of the magnitude of brittle fracture stress up to its minimum value R_{MC} that is reached at critical plastic strain value e_C (for iron and steels $e_C \approx 0.01...0.0\ 8$). Regularities of influence of "oriented" microstresses on the values of both critical stresses of fast crack nucleus growth and its anisotropy for ideal axial rolling texture are presented on Figures 2 and 3. Principal trend is that the magnitude of critical fracture stress ξ_{11}^{C} decreases with rise in "oriented" stresses, but rate of ξ_{11}^{C} decrease along the direction normal to axial texture axis is less then decrease along the direction of axis. The same regularities in ξ_{11}^{C} change take place for rolling texture.

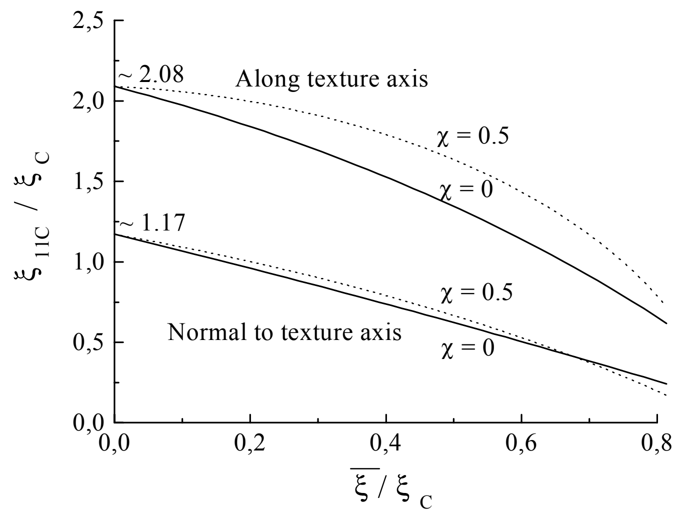

Figure 2: Dependence of critical stress of the crack nucleus fast growth, ξ_{11}^{C}/ξ_C , on the level of normal, $\beta = \bar{\xi}/\xi_C$, and shear, $\chi = \bar{\tau}/\bar{\xi}$, "oriented" microstresses at tension along and transverse to the axial texture axis.

CONCLUSIONS:

1. The origin of brittle strength anisotropy of polycrystalline metals is non-uniform distribution of the crack nucleus orientations predetermined by distribution of slip plane orientations and dependent on kind and parameters of crystallographic texture.

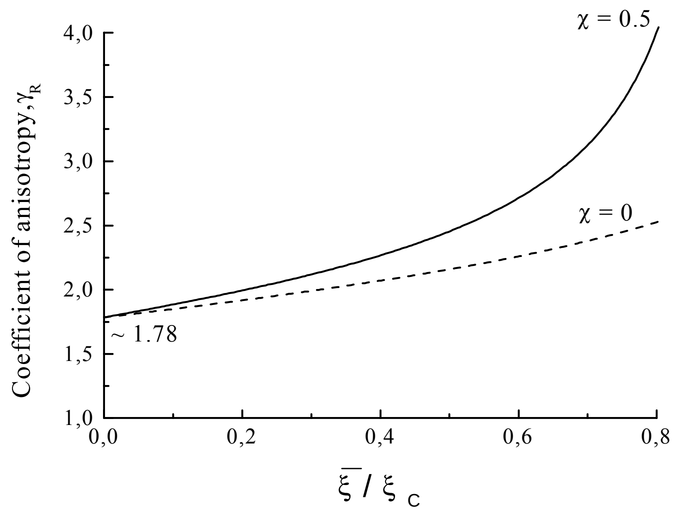

Figure 3: Effect of normal and shear "oriented" microstresses on the value of the coefficient of brittle strength anisotropy of polycrystal with axial texture γ_R

2. "Oriented" microstresses also influences the level of brittle strength anisotropy. Effect of these microstresses gives rise to increase in the coefficient of brittle strength anisotropy.

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