TWO-STAGE MODEL OF INTERGRANULAR CRACK TIP BRANCHING

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Intergranular subcritical crack tip branching observed in ultra-high-strength, low-alloy steels during the K_{Ic}-test is simulated by a computer procedure. Crack-branching-zone shapes according to the von Mises-, Tresca- and Vogt criterions are used. In all cases, practically identical decrease in the effective stress intensity factor with the increasing grain size is obtained. Using a simplified two-stage model of crack branching process, the beneficial effect of the increasing austenitization temperature on the fracture toughness of UHSLA steels can be understood.

INTRODUCTION

The crack branching can be considered to be one of the most important shielding processes - see e.g., Ritchie (1). This effect is commonly used for the fracture toughness improvement of ceramics (e.g.,Claussen et al (2)). Zeman et al (3) and Pokluda et al (4) reported the increase in the K_{Ic}-values due to the intergranular subcritical crack branching also in the case of AISI 4340 steels. The contribution of the crack branching to the fracture toughness improvement was estimated by Pokluda et al (5) by means of a computer simulation. The model has shown that this contribution represents more than 50% of the whole effect. Nevertheless, some important features remained still open in this approach - the great variety of the possible shapes of the crack-tip zone inside of which the crack branching could take place and the development stages of the subcritical branching during the K_{Ic}-test. In this paper, a two-stage model of the branching process is proposed considering the zone shapes given by the well-known von Mises-, Tresca- and Vogt elastic-plastic boundary conditions.

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PRINCIPLES OF THE MODEL CONSTRUCTION

Basic physical principles and mathematical construction of the model can be found in reference (5) in detail. Therefore, we focus our attention to the new conception giving only a brief description of the original assumptions.

A subcritical intergranular crack growth in a standard CT-specimen during the K_{Ic}-test is to be simulated. For this purpose we accept following assumptions:

(i) subcritical crack grows along the prior austenite grain boundaries inside the small crack-tip zone. Shape and size of this zone are determined by the fatigue precrack with respect to the elastic--plastic boundary conditions, the applied K_I-factor and the yield strength σ_y, respectively;

(ii) in various arbitrary cross sections perpendicular to the plane of the fatigue precrack, the grain boundaries are approximated by a regular hexagonal network of the grain size d (defined according to the number of grains in the unit area);

(iii) the real three-dimensionality of the problem is taken into account by using average values calculated with respect to all possible configurations given by an arbitrary orientation angle φ towards the precrack-track line and by the grain size distribution of the log-normal type;

(iv) selection of a possible crack path between a boundary of more than two grains is made according to the energy-release-rate criterion;

(v) the intergranular precrack front is determined by the local arrests associated with the boundaries of more than two grains followed by the intergranular facets having a greater local deflection angle towards the precrack plane;

(vi) there is no relation between the zone size and the grain size.

The size of crack-tip zone lies nearly between the process zone and the plastic zone - further we consider 1/4 of the latter one. In the material consisting of equal grains, the branched crack front is formed by a set of end points of various crack paths inclined at an angle α from the precrack plane with different probabilities. Than we can introduce both the kink angle $\bar{\alpha}(\varphi, K_I/\sigma_y, d)$ (as the weighted mean of the abs(α)-values) and its standard deviation $s_\alpha(\varphi, K_I/\sigma_y, d)$ within this zone.

Relationships $\bar{\alpha}$ vs. φ for constant values of K_I, σ_y and several values of d are shown in Figure 1 using polar coordinates. It is clearly seen that the $\bar{\alpha}$-values decrease monotonously with the decreasing grain size.

In a macroscopically isotropic polycrystalline aggregate consisting of grains of different sizes, an average kink angle can be determined as

$$< \bar{\alpha}(K_I/\sigma_y) > = \int_0^{2\pi} \int_0^{\infty} \Gamma(\varphi, d)\ \bar{\alpha}(\varphi, K_I/\sigma_y, d)\ dd\ d\varphi . \qquad (1)$$

Then, the angle $<\bar{\alpha}>$ given by equation (1) can be considered to be a function of the parameters $\xi = (K_I/\sigma_y)^2/<d>$ and χ, the latter one being a measure of the grain size scatter. In the calculation procedure, the value $\chi = 0.4$ was used since the average kink angle $<\bar{\alpha}>$ is practically independent of χ within the range of $\chi \in <0.1,\ 1>$. The average angle $<\bar{\alpha}>$ of an inclined crack can be used to express the k_{eff}-value associated with the crack branching according to, e.g., Suresh and Shih (6). The real value of k_{eff} must correspond to a configuration somewhere in between of the kinked and symmetrically forked crack. The related reduction of the crack driving force can be estimated by the ratio of $H = k_{eff}/K_I$ as function of ξ.

TWO-STAGE MODEL

The details of the real subcritical crack growth initiation during the K_{Ic}-test are not well-known at present. Therefore, a simplified two-stage model of this process is to be used. The subcritical growth is initiated by some amount of plastic strain localized in the vicinity of grain boundaries. The first stage of the crack branching corresponds to the moment when $G = G_R$, $\xi = \xi_1$ (see Figure 2). At this moment, a damage zone has been formed already and, within this zone, conditions favourable for the subcritical crack-tip branching were created. This initial branching reduces the crack driving force to the value G_{eff1} corresponding to the ratio $H_1{}^2$ given by the related parameter ξ_1. The relevant difference between the "apparent" driving force G_{I1} for the ideal crack and the effective driving force G_{eff1} for the branched crack is denoted ΔG_1 in Figure 2.

Further increase in the external loading raises the apparent driving force following the straight line. Simultaneously, the damage zone develops proportionally to the parameter ξ preparing conditions for the second stage of branching process. The actual (effective) crack driving force associated with this process follows the curve $G_{eff}(\xi)$. When the critical condition $G_{eff} = G_R$ is fulfilled, the unstable fracture takes place. At this moment, the parameter ξ reaches its critical value ξ_c. The difference ΔG_ξ between the critical apparent driving force G_{Ic} ($\sim K_{Ic}^2$) and the critical effective driving force G_{effc}($= G_R \sim k_{effc}^2$) represents the improvement in the experimentally determined fracture toughness due to the crack branching. The G_R-value can be determined experimentally as the G_{Ic}-value of a very fine-grained material. In this case, the branching effect can be neglected ($\langle\bar{\alpha}\rangle \to 0 \Rightarrow k_{effc}/K_{Ic} \to 1 \Rightarrow \Delta G_1 \to 0$) and the equality $G_R \equiv G_{Ic}$ can be accepted.

COMPARISON BETWEEN MODEL AND EXPERIMENT

The experimental K_{Ic}-values of AISI 4340 steels obtained by various authors are shown in Figure 3. Simultaneously, the theoretical curve is marked by the full line according to the two-stage model using the value $\sigma_y \approx 1400$ MPa for all the investigated steels. The value of G_R corresponding to the $K_{Ic} = 51$ MPa$\sqrt{m}$ was used as the fine-grain limit. The dashed line in Figure 3 demarcates the upper scatter band of the calculation.

All experimental points in Figure 3 lie within the theoretical scatter area. It means that the beneficial effect of increasing austenitization temperature on the fracture toughness of UHSLA steels can be explained by the subcritical intergranular crack branching almost completely.

SYMBOLS USED

$\Gamma(\varphi, d)$ = probability density of random orientation and log-normal grain size distribution;

μ, χ = parameters of the log-normal distribution;

$\langle d\rangle$ = $\exp(\mu + \chi^2/2)$ mean grain size (m).

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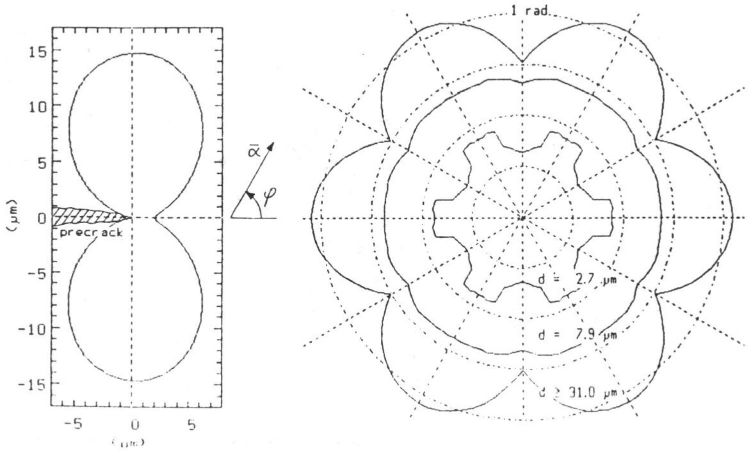

Figure 1. Von Mises-damage zone and polar diagram of the average kink angle $\bar{\alpha}$ as function of the orientation angle φ (K_I = 30 MPa$\sqrt{m}$, σ_Y = 1400 MPa).

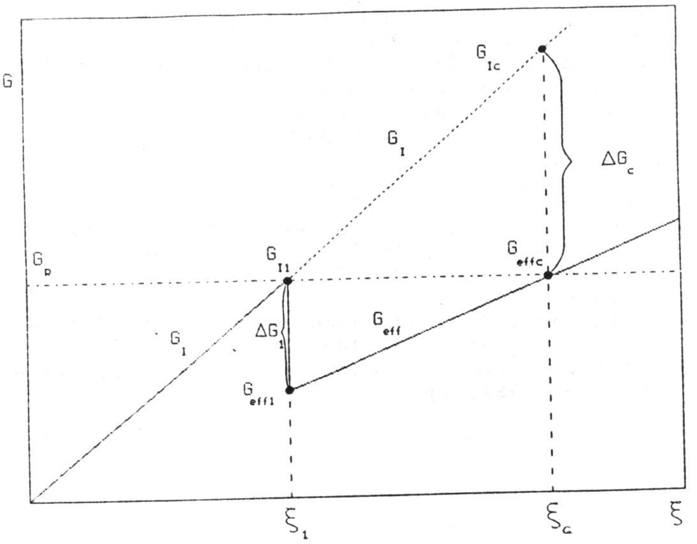

Figure 2. Scheme of the two-stage model of crack branching.

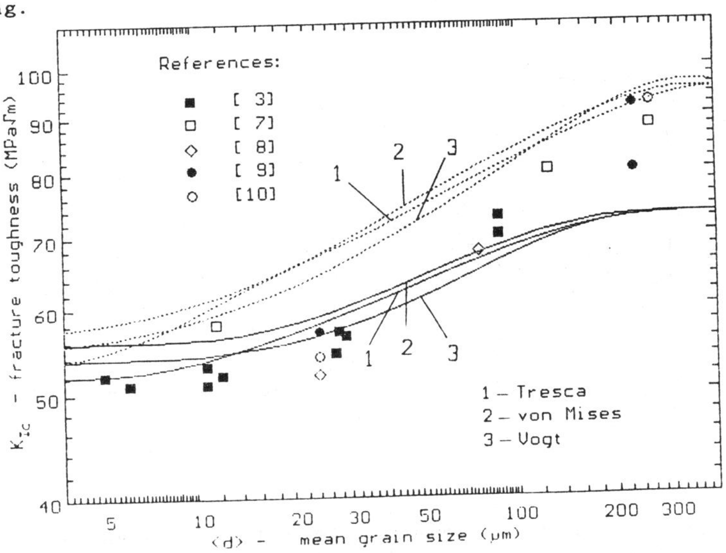

Figure 3. Comparison between the theoretical effect of crack branching and experimental data.