STATISTICAL GEOMETRICAL EFFECT OF INTERGRANULAR CRACK BRANCHING

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The computer model of stable intergranular crack branching is based on the maximum-energy-release-rate criterion (mixed mode I + II) and the log-normal grain size distribution. All possible intergranular crack paths are generated within the crack tip region comparable with the plastic zone. When the average grain size approaches that of the plastic zone, the shielding effect of crack branching reaches its maximum. The result is in agreement with previously published experimental works concerning the beneficial effect of increasing austenitization temperature on the fracture toughness K_{Ic} of UHSLA steels.

INTRODUCTION

Increase of fracture toughness K_{Ic} with increasing average austenite grain size in the case of ultra-high strength low alloyed (UHSLA) steels was experimentally observed by many authors (e.g., Guimaraes and Savedra (1), Datta and Wood (2), Lee et al (3), Tomita (4)). This behaviour follows approximately the reverse Hall-Petch relation and is, of course, inconsistent with the simultaneously indicated drop in Charpy impact toughness. Omitting interpretations based on structural changes, geometrical aspects like subcritical crack tip branching were also mentioned to be factors of second order. It is well known, however, that particularly these processes can lead to substantial reduction of crack-extension force.

The simple analytical model of intergranular subcritical crack growth during the K_{Ic}-test (Pokluda et al (7), Zeman et al (9)) have shown that this retardative effect increases with increasing grain size. This

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result shows that conditions of reversed Hall-Petch relation are satisfied provided that n is small enough ($n < 2$). However, the simple model exhibits a physically unacceptable singularity for $n \rightarrow 0$. Thus, it seems to be useful to find a comprehensive quantitative estimation of the crack branching effect in order to understand generally the real contributions of individual structural microprocesses to the increase of K_{Ic} value.

DESCRIPTION OF THE MODEL

A subcritical intergranular crack growth during the K_{Ic}-test is to be simulated. For this purpose following assumptions are accepted:
(i) starting conditions are characterized by an original fatigue crack perpendicular to the external load direction;
(ii) intergranular crack growth takes place at the crack tip inside the zone of size r_p ($r_p \ll a_0$).
Evaluation of crack growth is done in one arbitrary selected cross section perpendicular to the plane of the precrack. Grain boundaries are approximated by the hexagonal network and the shape of the zone by a simple geometrical figure like square (r_p), rectangle (r_p, $3r_p$) and circle (r_p). The y-axis intersecting the crack tip parallel to the external load direction defines 10 percent of the zone area - see Fig. 1. Real three-dimensionality of the problem is taken into account using average values calculated with respect to all possible configurations in various arbitrary sections.

A possible crack path between two grains is explicitly determined by a grain boundary. At a boundary of more than two grains, selection of further crack growth direction is made according to the well-known energy-release-rate criterion. When an infinitesimal kink advances under conditions of plane strain, the crack-extension force can be expressed in the form

$$G = \frac{1 - \nu^2}{E} k_{eff}^2 = \frac{1 - \nu^2}{E} \cos^4(\gamma/2) K_I^2 \qquad (1)$$

A direct proportionality between the driving force G and probability $p(\gamma)$ can be accepted. The point $A(x_k, y_k)$ determinates the mean inclination angle α_k of the crack; $\alpha_k = \arctan(y_k / x_k)$. The probability of realization of a selected crack path equals to the product of individual partial probabilities $p_i(\gamma_i)$ of the gradual selection processes at the three-boundary points. Then, the probability of realization of an arbitrary crack ending at the point $A(x_k, y_k)$ equals to

$$q(\alpha_k) = \sum_j \prod_i p_i(\gamma_i) \qquad (2)$$

In eq. (2), the summation is made for all possible crack paths having the same angle α_k. The branched crack front is formed by a set of end points of various crack paths with different probabilities $q(\alpha_k)$. Average kink angle $\bar{\alpha}$ and its standard deviation $s(\alpha)$ can be introduced as characteristics of a zone which, in the direction of the precrack track, contains $n = r_p / d$ grains. However, an arbitrary orientation in a macroscopically isotropic polycrystalline aggregate consisting of grains of different sizes is to be assumed. According to Saltykov (8), the grain size distribution is of log-normal type. Then, the zone defined in this way can be characterized by an average kink angle

$$\langle\bar{\alpha}\rangle = \int_0^{2\pi} \int_0^{\infty} \Gamma(\varphi, n)\, \bar{\alpha}(\varphi, n)\, dn\, d\varphi \qquad (3)$$

NUMERICAL EVALUATION

The average kink angle $\langle\bar{\alpha}\rangle$ determined by the numerical integration of eq. (3) and the same value extended by the standard deviation are shown in Fig. 2 as functions of $\langle n \rangle$. Angle $\langle\bar{\alpha}\rangle$ represents a mean inclination of the crack front within the zone of size r_p according to the macroscopical precrack plane. Region between the α_h-curve and the $\langle n \rangle$ axis characterizes a scatter of the inclinational angle α along the intergranular crack front. When the mean grain size becomes comparable with that of the zone ($\langle n \rangle \approx 1$), the scatter reaches its maximum. These conclusions apply to all three zone shapes under consideration.

Taking into account all observed cases of irregular crack paths in UHSLA steels it is clear that there exists a great variability of possible branching configurations. Nevertheless, real values of k_{eff} lie somewhere in between those of the kinked and symmetrically forked crack. Then, the average angle $\langle\bar{\alpha}\rangle$ of an inclined crack can be used to express the k_{eff}-value associated with both above mentioned cases. Results presented in (5) and (6) enable to calculate k_{eff}-values as functions of $\langle\bar{\alpha}\rangle$ and α_h. Reduction of G and related increase in K_{Ic} due to crack branching can be estimated by the ratio of k_{eff} / K_I. These ratios for kinked (k^k_{eff}) and forked (k^f_{eff}) crack are drawn in Fig. 3 as functions of $\langle n \rangle$.

DISCUSSION

Subcritical intergranular crack growth is evidently accompanied by some amount of plastic strain in the vicinity of grain boundaries. Therefore, it must be associated with the plastic zone at the crack tip. Since the extent of the crack branch is negligible in comparison with the length of the precrack, the plastic zone size at the onset of instable fracture can be roughly estimated by means of the well-known relation $r_p \approx 1/10(K_{Ic}/\sigma_Y)^2$. This value is practically independent of the mean austenite grain size in the case of UHSLA steels. Consequently, the physical interpretation of Fig. 3 is following:

(i) crack branching effect increases with decreasing number of grains within the plastic zone, i.e., with coarsening of grains (σ_Y = const.) or increasing strength (d = const.).

(ii) maximal effect of crack branching is reached when the mean grain size nearly approaches that of the plastic zone ($\langle n \rangle \approx 1$).

These conclusions are in a good agreement with the experimental results (1), (2), (3), (4), (9) - values of the ratio k_{effc}/K_{Ic} are marked in Fig. 3. The k_{effc}-values where replaced by the lowest K_{Ic}-value (for $\langle n \rangle \gg 1$), which is not influenced by intergranular branching. Nearly all experimental points in Fig. 3 lie within the scattering zones for kinking or forking. Thus, the geometrical effect of crack branching can be considered to be a very important factor responsible for the positive influence of the high austenitizing temperature on the fracture toughness of UHSLA steels. It is to be expected that the effect of crack-tip blunting, which was not considered in our analysis, rather enhances this beneficial shielding effect.

SYMBOLS USED

a_0 = length of the fatigue precrack (m)
d = grain size (m)
E = Young's modulus (Pa)
k_{eff} = effective stress intensity factor (Pa $m^{1/2}$)
k_{effc} = critical effective stress intensity factor (Pa $m^{1/2}$)
n = number of equal grains inside the (plastic) zone in the direction of precrack track
$\langle n \rangle$ = mean number of grains having log-normal size distribution

$p(\gamma)$ = partial probability of the crack advance along the direction given by γ
$q(\alpha_k)$ = probability of realization of an arbitrary crack path of angle α_k
r_p = size of the (plastic) zone (m)
x_k, y_k = cartesian coordinates (m)
ν = Poisson's ratio
α_k = mean inclination angle of the k-th set of paths (rad)
$\langle\bar{\alpha}\rangle$ = average kink angle in the log-normal grain network (rad)
α_h = sum of $\langle\bar{\alpha}\rangle$ and its standard deviation in the log-normal grain network (rad)
γ = angle of the partial kink (rad)
$\Gamma(\varphi, n)$ = probability density of random orientation and log-normal grain size distribution
φ = orientational angle between the hexagonal network and the precrack plane (rad)

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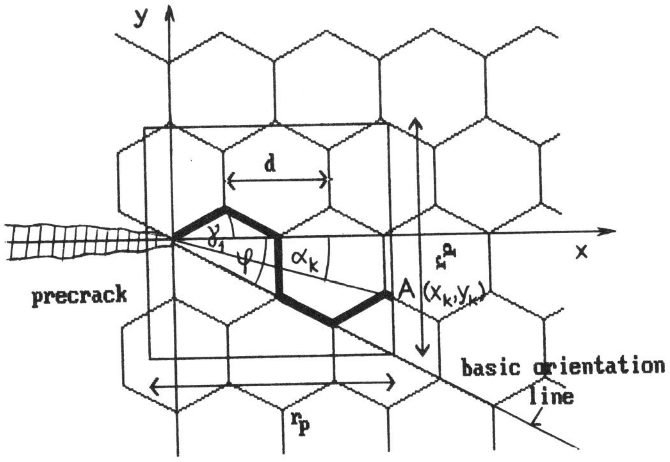

Figure 1. Basic geometrical scheme of the model (square zone).

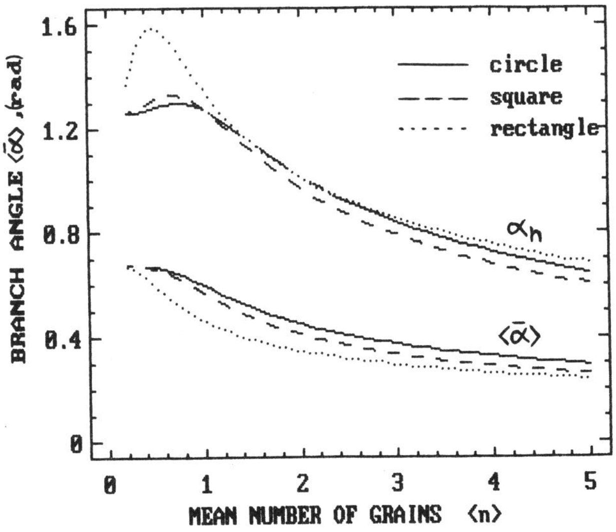

Figure 2. Dependence of the average kink angle $\langle\bar{\alpha}\rangle$ and the limit angle α_h on the mean number of grains $\langle n\rangle$.

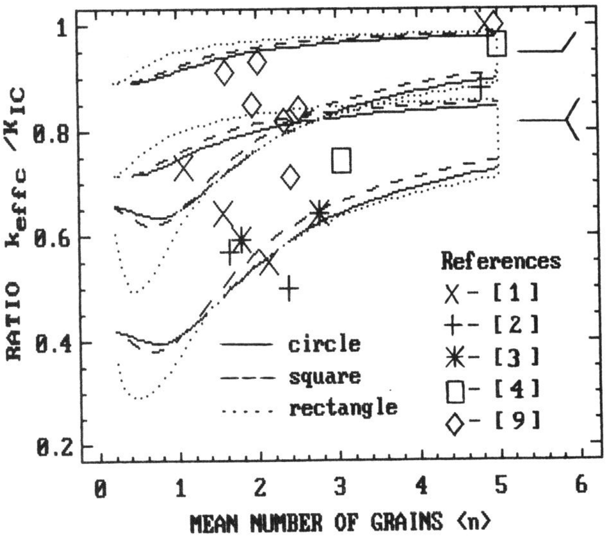

Figure 3. Theoretical k_{effc}/K_{Ic}-curves and experimental points.