Requirements on the Specimen Geometry to Determine Intrinsic Fracture Mechanics Values of Polymer Materials

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ABSTRACT: *Specific requirements on the specimen geometry necessary for the determination of fracture mechanics parameters for polymers by using the instrumented Charpy impact test are summarized. As examples, the influences of the specimen thickness and a/W ratio are considered. For characterizing the geometry independence of fracture mechanics parameters, geometrical factors are used, which make possible an estimation of the requirements on the specimen geometry without any further experiments. For polymers, the experimentally determined geometrical factors vary in a wide range; this means that the use of constant geometrical factors must cause a pronounced under- or overevaluation of the requirements on the specimens. The relationships between geometrical factors and fracture mechanics parameters, which were found to be generally valid for polymers, are independent of the kind of loading (static, impact-like) and the crack propagation behaviour (stable, unstable).*

BASIC REMARKS

The geometry dependence of fracture mechanics parameters in terms of B, a and $(W–a)$ is characterized independently of the fracture mechanics concept (LEFM, J-integral or CTOD concept) by a transition from geometry-dependent (K_Q, J_Q and δ_Q) to geometry-independent values in terms of a universal brittle-to-tough transition (BTT). The BTT is connected with a change from a predominant plane stress state to a predominant plane strain state. The values of B, a and $(W–a)$, for which K_Q, J_Q and δ_Q are constant for the first time, are the minimum specimen thickness, minimum crack length and minimum ligament length (B_{min}, a_{min} and $(W–a)_{min}$). Furthermore, because of the low heat conductance of polymers in comparison with metallic materials, the change from isothermal to adiabatic behaviour is important,

especially for such polymers which are strongly plastically deformed under load.

For a generally valid description of the geometry dependence of fracture mechanics parameters, geometrical criteria with the factors ε, β and ξ were introduced. These factors make possible an estimation of the minimum requirements on the specimen geometry without any experimental determination of the influence of the geometry on fracture mechanics parameters. The estimation of minimum requirements on specimen size and crack length is performed according to:

$$B, a, (W - a) \geq \varepsilon \cdot \frac{J}{\sigma_y} \tag{1}$$

in the case of the *J*-integral concept with the geometrical factor ε,

$$B, a, (W - a) \geq \xi \cdot \delta \tag{2}$$

in the case of the CTOD concept with the geometrical factor ξ and

$$B, a, (W - a) \geq \beta \cdot \left(\frac{K}{\sigma_y} \right)^2 \tag{3}$$

in the case of LEFM with the geometrical factor β, where σ_y is the yield stress.

For metallic materials, the geometrical factors are fixed to $\varepsilon = 25$ [1], $\xi = 50$ [2] and $\beta = 2.5$ [3]. These values are also often used for polymers or are taken into account in standard drafts [4]. However, also for metals, these values are not universally valid. For example, experimental values of ε in the range from 25 to 200 [5,6] are known.

This fact and the fundamental differences between the mechanical behaviour of metals and polymers result in the conclusion that the requirements on minimum specimen size defined above can not be transferred self-evident to polymers, as it should be shown in the following sections.

INFLUENCE OF SPECIMEN GEOMETRY ON FRACTURE MECHANICS PARAMETERS

The influence of the geometry on fracture mechanics parameters related to both resistance against stable and unstable crack propagation can be characterized experimentally by variation of the specimen configuration (com-

pact tension (CT), single-edge-notched bending (SENB), single-edge-notched tension (SENT) specimens etc.) and the specimen size, especially the thickness B and the crack length a (a/W ratio), as well as the notch radius. Exemplary in this study, the influences of specimen thickness and a/W ratio are considered. More detailed information can be found in Ref. [7].

Fracture Mechanics Parameters as a Function of Specimen Thickness for Various Polymers

The determination of the influence of specimen thickness on the material parameters is one of the most relevant fields in fracture mechanics material characterization, because the independence of the thickness is an important criterion for the transferability of parameters determined using specimens to components. In Figure 1, various J values are summarized obtained at room temperature. Figure 1a shows the dependence of J values on specimen thickness $J_{Qd} = f(B)$ in the case of unstable crack propagation (PP, PVCC and cast PA). In Fig. 1b, the influence of the specimen thickness on the technical crack initiation values $J_{0.2} = f(B)$ is illustrated for polymers showing stable crack propagation. In any case, values of B_{min} can be determined experimentally.

Influence of Temperature on the Requirements on Specimen Dimensions

Figure 2 shows the influence of the temperature on J_{Qd} in dependence on thickness for PC under impact loading conditions. With increasing temperature, the minimum specimen thickness increases from $B_{min} = 1.5$ mm at 0 °C and $B_{min} = 2$ mm at 20 °C to $B_{min} = 3$ mm at 40 °C [8]. This change in requirements on specimen thickness in a relatively small temperature range ($\Delta T = 40$ °C), which approximately corresponds to the temperature range of application of PC, is a polymer-specific phenomenon that can be clarified by the assumption of a generalized brittle-to-tough transition (BTT). It is assumed that the BTT's corresponding to the loading conditions (temperature, speed etc.), the material behaviour (mechanism of deformation, concentration, particle size and distance etc.) and the geometry (specimen thickness, notch radius etc.) are interdependent due to the polymer-specific viscoelastic–viscoplastic behaviour. As a consequence, a variation of the loading conditions leads to a change in the BTT, as it is shown in Figure 2 using the variation of the temperature as an example. Here, the change of the BTT is due to a change of the deformation mechanisms. Thus, the minimum specimen thickness increases. Therefore, if limits of application should be fixed and the transferability of parameters to components should be evaluated, these changes must be taken into account.

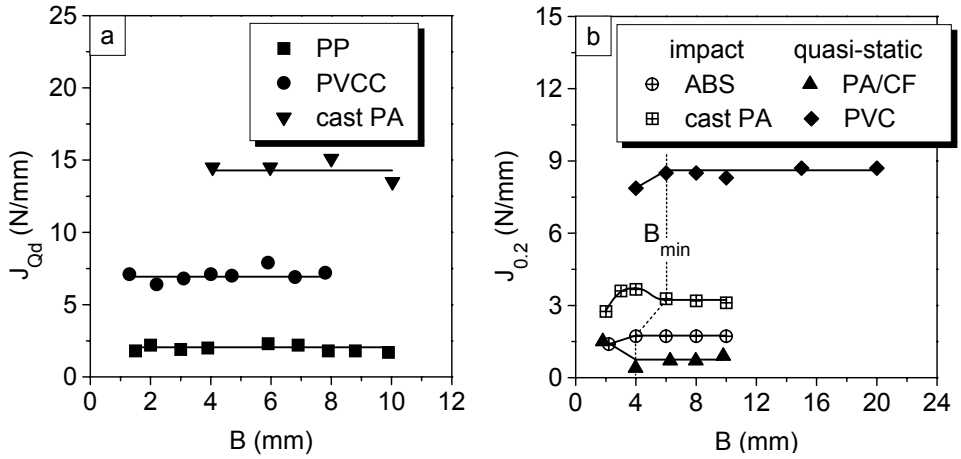

Figure 1: J_{Qd} values related to resistance against unstable crack propagation (a) and $J_{0.2}$ values related to resistance against stable crack initiation (b) as a function of the specimen thickness and the material

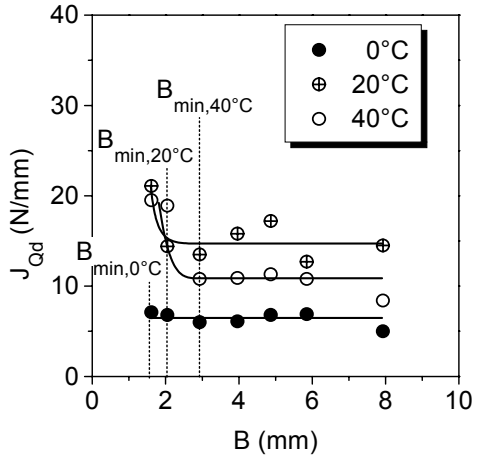

Figure 2: Influence of the temperature and the specimen thickness on the J_{Qd} values for polycarbonate

Experimental Determination of Maximum Stable Crack Growth

For predominantly unstable crack propagation, a variation of the a/W ratio, i.e. the initial crack length in the case of a constant specimen geometry, leads to relationships that are qualitatively comparable to that from a variation of specimen thickness. If stable crack propagation occurs, for example during R-curve measurements, the a/W ratio continuously changes. On the

one hand, because the *J*-integral is – strictly speaking – only defined for a stationary crack, the amount of stable crack growth must be limited by definition of a maximum valid amount of stable crack growth Δa_{max} ensuring *J*-controlled crack propagation. Guidelines for it were formulated for example in the standard draft of ESIS TC4 [4]. On the other hand, as it was shown in Ref. [9], no limiting of the amount of stable crack growth is necessary, if *J* values are corrected regarding the finite stable crack growth Δa and the influence of the instationary stress field ahead of the crack tip. *J* values calculated using an iterative procedure and *J* values determined using an approximative method for R-curve determination suggested by Seidler, including a correction of the crack growth, are in very good agreement [9,10].

Nevertheless, the influence of specimen geometry on *J* and CTOD values remains. With increasing amount of stable crack growth, the external energy cannot be dissipated any longer into a large region of the specimen by an increasing plastic-zone size because of interactions between the plastic zone and the specimen boundary. Furthermore, the crack propagates into the pressure zone of the specimen. This leads to an increase of the energy density and the local deformation in the spatially finite plastic zone. As a result, a strong increase of the crack resistance at a certain amount of stable crack growth, the maximum valid amount of stable crack growth Δa_{max}, occurs, which corresponds to the transition from a plane strain to a plane stress state (Fig. 3). Thus, valid *J* values can only be determined if $\Delta a \leq \Delta a_{max}$.

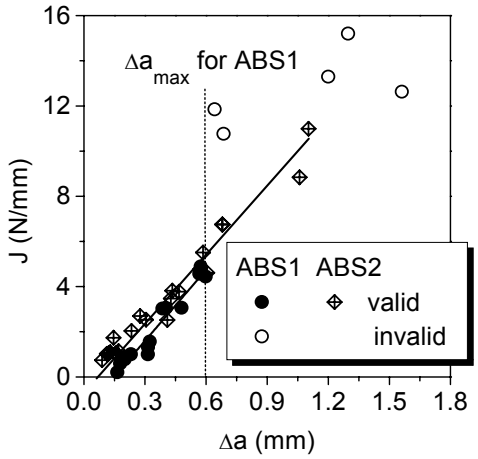

Figure 3: Experimental determination of the maximum valid amount of stable crack growth under impact loading using ABS as an example

REQUIREMENTS ON SPECIMEN GEOMETRY FOR POLYMERS

In order to consider the influence of the material on the geometrical criterions (equations 1–3), the experimental determination of the geometrical factors on the basis of the dependence of thickness or a/W ratio (Figs. 1–3) was found to be suitable. From such measuring data, correlations of the geometrical factors ε, β and ξ, and the related fracture mechanics parameters can be determined (Figs. 4 and 5) which are generally valid for polymers, because of their independence of the kind of loading (quasi-static/impact-like) and the material behaviour (stable/unstable) [9,11].

From the double-logarithmic plot of the geometrical factor ε versus the 'critical' J values (J_{Ic}, J_{Id}, $J_{0.2}$ and J_{max}) in Fig. 4, a general connection can be derived:

$$\varepsilon = A_1 \cdot J^{A_2} \tag{4}$$

Analogously, for ξ as a function of the 'critical' δ values (δ_{Id} and $\delta_{0.2}$) and for β as a function of 'critical' K values (K_{Ic} and K_{Id}) (Fig. 5), following equations result:

$$\xi = B_1 \cdot \delta^{B_2}, \tag{5}$$

$$\beta = C_1 \cdot K^{C_2} \tag{6}$$

By fitting of A_1, B_1 and C_1, and A_2, B_2 and C_2, the following empirical connections can be derived:

$$\varepsilon = 224 \cdot J^{-0.94} \quad (J \text{ in Nmm}^{-1}), \tag{7}$$

$$\xi = 3.6 \cdot \delta^{-0.83} \quad (\delta \text{ in mm}) \text{ and} \tag{8}$$

$$\beta = 3466 \cdot K^{-1.73} \quad (K \text{ in MPamm}^{1/2}). \tag{9}$$

These equations represent the essential basis for the estimation of the minimum specimen size. Owing to the wide range of experimentally determined geometrical factors (ε = 5.2–1220, ξ = 10–139 and β = 0.24–26), the assumption of constant values of ε = 25 [1], ξ = 50 [2] and β = 2.5 [3] would lead to a pronounced under- or overvaluation of the requirements on the specimen geometry. In principle, equations (7–9) make possible a material-specific estimation of the requirements on specimen geometry within the complete toughness range ranging from linear elastic behaviour with unstable crack propagation to elastic–plastic behaviour with stable crack propagation.

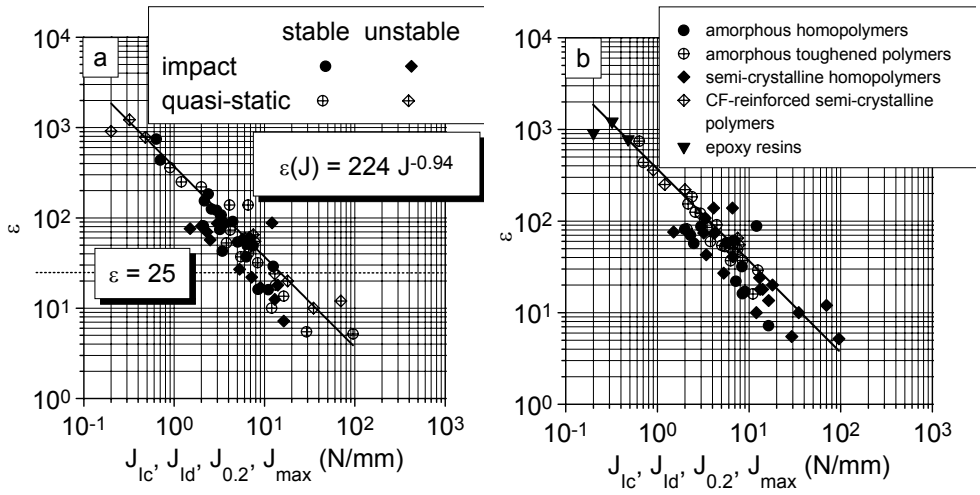

Figure 4: Geometrical factor ε versus J values for different loading conditions and crack propagation behaviour (a), and for various materials (b)

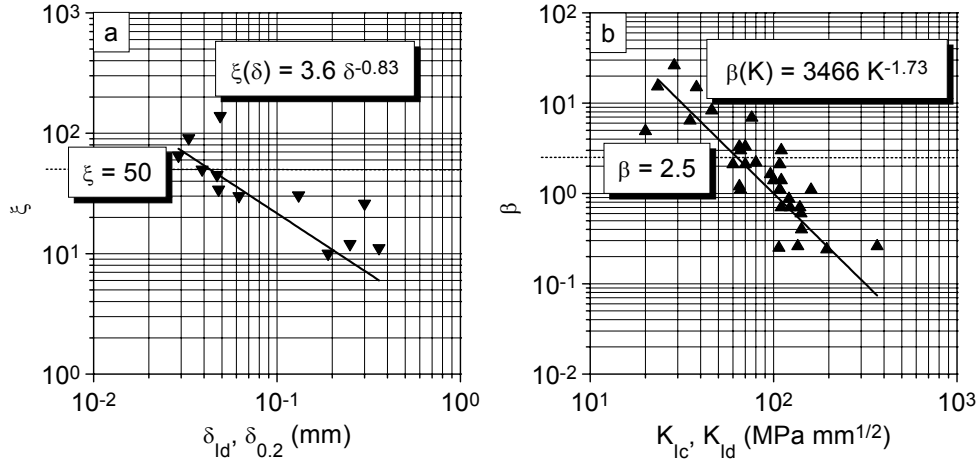

Figure 5: Geometrical factor ξ as a function of the CTOD values δ_{Id}, $\delta_{0.2}$ (a) and geometrical factor β as a function of the stress intensity factor K_{Ic}, K_{Id} (b) for polymers

Strictly speaking, the use of such empirical relationships is limited to the range of values considered. Therefore, a noticeable generalization is necessary. Assuming that A_1 and A_2 are independent of J and B_1 and B_2 are independent of δ, i.e. $A_2 = -1$ and $B_2 = -1$, it follows:

$$\varepsilon = 370\,\mathrm{Nmm}^{-1} \cdot J^{-1} \text{ and} \tag{10}$$

$$\xi = 2.2\ \mathrm{mm}^{-1} \cdot \delta^{-1}. \tag{11}$$

By replacing the initial with the effective crack length $a_{\mathrm{eff}} = a + \Delta a$ and using equations (1), (2), (10) and (11), following requirements on the maximum valid amount of stable crack growth for J–R and δ–R curves can be derived:

$$\Delta a \le (W - a) - \frac{370\,\mathrm{N mm}^{-1}}{\sigma_{\mathrm{y}}} \text{ and} \tag{12}$$

$$\Delta a \le (W - a) - 2.2\,\mathrm{mm}. \tag{13}$$

Thus, the basis of a material-specific criterion of valuation for fixing the maximum valid amount of crack growth values is established.

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