EXPRESSIVENESS OF CRACK TOUGHNESS AS RESISTANCE AGAINST THE INTRINSIC RATE OF FRACTURE MECHANICS PARAMETERS FOR POLYMERIC MATERIALS

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INTRODUCTION

For fracture mechanical assessment of toughness behaviour three levels of knowledge exist that are based on each other [1]. Level I that corresponds to fracture mechanics concepts describing unstable crack initiation is state of the art. The concepts of this level are successfully applied to optimize material properties and for quality management of products. Level II contains fracture mechanics concepts to determine the material resistance against stable crack initiation and propagation, especially in form of the crack resistance curve concept (R-curve concept). However, the whole information content of this level, that is higher than that of level I, cannot be used completely because a method to describe the non-linear time-dependent crack propagation behaviour of polymers theoretically does not exist. Additional information to characterize materials can be expected from level III that corresponds to concepts computing the crack toughness as resistance against the intrinsic rate of fracture mechanics parameters, like the crack-tip opening displacement rate \( \dot{\delta} \) (Fig. 1). However, in recent times not many basic investigations are known for that under impact loading conditions.

THEORETICAL BACKGROUND

The crack-tip opening displacement rate \( \dot{\delta} \) is defined from the left site of Eq. (1)

\[
\dot{\delta} = \frac{d\delta}{dt} = \left( \frac{\delta}{a} \right) \left( \frac{da}{dt} \right) = \frac{C_{\delta_1} C_{\delta_2}}{C_{11} C_{12}} \Delta a (C_{a_2} - C_{a_1})
\]

where \( \delta \) is the crack-tip opening displacement (CTOD), \( a \) the crack length, and \( t \) the crack propagation time. The right site of this equation is calculated assuming a power law of the form of

\[
J, \dot{\delta}, t = C_{11} \Delta a^C_{11} + J_0, C_{\delta_1} \Delta a^C_{\delta_1} + \delta_0, C_{11} \Delta a^C_{11} + t_0
\]

for \( J = f(\Delta a) \), \( \delta = g(\Delta a) \), and \( t = h(\Delta a) \) those are functions of the stable crack growth \( \Delta a \). The parameters \( C_{11, \delta_1, \delta_2} \), \( C_{12, \delta_2, \delta_1} \) and \( J_0, \delta_0, t_0 \) are dependent on the material, the loading conditions and are valid for a limited range of \( \Delta a \).

The main condition for stationary stable crack propagation can be derived from the right site of Eq. (1) and the inverse function of \( h(\Delta a) \) in the form of:

\[
\lim_{t \to \infty} C_{\delta_2} = \lim_{t \to \infty} C_{12} = 1
\]

That means, that the slope of the R-curve \( g(\Delta a) \) should be converged to a straight line. In this case threshold values \( a_{\text{lim}} \) and \( \dot{\delta}_{\text{lim}} \) (for the crack speed \( a \) and \( \dot{\delta} \)) exist that are determined using

\[
\dot{a}_{\text{lim}} = \lim_{t \to \infty} \left[ \frac{d(\Delta a)}{dt} \right] = \lim_{t \to \infty} \left[ \frac{\Delta a}{t} \right] = \text{const.}
\]
\[
\dot{\delta}_{\text{lim}} = \lim_{t \to \infty} \left[ \frac{d\delta}{dt} \right] = \lim_{t \to \infty} \left[ \frac{\delta}{t} \right] = \text{const.}
\]

In practise it is often possible to change \( t \to \infty \) by \( t \to t_{\text{lim}} \).

Figure 1. Crack resistance \( K_{\text{stat, dyn}}, \Delta K \), and \( J \) as a function of ‘crack speed’ \( \dot{\delta} \) or \( da/dN \) and crack-tip opening displacement rate \( \dot{\delta} \) respectively in dependence on loading conditions
R-CURVE DETERMINATION

R-curves as functions of loading parameters versus stable crack growth $\Delta a$ can be measured at impact loading conditions by use of different experimental procedures, for example by means of a (quasi) single-specimen technique (one specimen is loaded some times corresponding to complete unloading after each loading cycle) or a multiple-specimen technique (each of some specimens is loaded one time), and using the stop-block method (variation of $\Delta a$ by a component that limits the maximum deflection) or the low-blow method (variation of $\Delta a$ by different testing velocities, i.e. different initial impact energies) respectively. On basis of earlier investigations the loading parameters, $J$-integral and crack tip opening displacement $d$, are determined using an evaluation method which considers the amount of stable crack growth adequately and by means of a modified plastic hinge model respectively.

On example of TPU/ABS-blends (Fig. 2) it has been shown that only by use of the stop-block method in multiple-specimen technique it is possible to determine R-curves those correspond to homogenous kinetics of crack propagation, i.e. $\delta$ is constant excepting small $\Delta a$-values [2].

RESULTS

Based on these methodical investigations, R-curves are determined for PP/EPR/PE-copolymers with various particle centre distances $CD$ ranging from $CD = 2.0 - 4.1 \mu m$ (Fig. 3) [1,2]. From the $\Delta a(t)$-plot a crack initiation time $t_i$ can be derived that corresponds to the physical crack initiation process (Fig. 4a). Thus, physical crack initiation values, $J_i$ and $d_i$, can be computed if $t = t_i$. $J_i$ is strongly dependent but $d_i$ is relatively little dependent on the morphology (Table 1).

<table>
<thead>
<tr>
<th>$CD$ (µm)</th>
<th>$J_i$ (N/mm)</th>
<th>$d_i$ (10^{-3} mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>0.68</td>
<td>16</td>
</tr>
<tr>
<td>3.0</td>
<td>0.31</td>
<td>11</td>
</tr>
<tr>
<td>3.3</td>
<td>0.30</td>
<td>12</td>
</tr>
<tr>
<td>4.1</td>
<td>0.22</td>
<td>10</td>
</tr>
</tbody>
</table>

Furthermore, it can be observed that the values of the crack-tip opening displacement rate converge rapidly to a matrix-specific threshold value (stationary stable crack propagation) after crack initiation and non-stationary stable crack propagation [2] (Fig. 5). This behaviour has also been shown as typical for other polymeric materials (Table 2) where
Table 2. Materials, activation process for plastic deformation and values of $\dot{\delta}_{\lim}/v_H$ and the (pseudo) activation enthalpy $\Delta H^*$ ($\alpha$ – glass transition, $\beta$ – secondary relaxation process)

<table>
<thead>
<tr>
<th>Number in Fig. 6</th>
<th>Material</th>
<th>$\dot{\delta}_{\lim}/v_H$</th>
<th>Process</th>
<th>$\Delta H^*$ (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>polycarbonate (PC) in the temperature range of 60−95 °C</td>
<td>0.11</td>
<td>$\beta$</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>ethylene-propylene copolymers (PP/EPR/PP) with various phase morphology</td>
<td>0.08−0.13</td>
<td>$\alpha_{PP}$</td>
<td>117</td>
</tr>
<tr>
<td>3</td>
<td>polypropylene (PP) and PP/glass-fibre compounds with various matrix materials</td>
<td>0.09</td>
<td>$\alpha_{PP}$</td>
<td>117</td>
</tr>
<tr>
<td>4</td>
<td>various commercial high-density polyethylenes (HDPE)</td>
<td>0.05−0.09</td>
<td>$\alpha$</td>
<td>108</td>
</tr>
<tr>
<td>5</td>
<td>acrylonitrile-butadiene-styrene copolymers (ABS) with rubber contents of 20−36 wt.-%</td>
<td>0.02−0.06</td>
<td>$\alpha_{rubber}$</td>
<td>216</td>
</tr>
<tr>
<td>TPU/ABS-blend</td>
<td></td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. CTOD rate values $\dot{\delta}_{dk}$ in dependence on stable crack growth $\Delta a$ for PP/EPR/PE-copolymers $\dot{\delta}_{\lim}/v_H$ ($v_H$ – pendulum hammer speed) is nearly independent on temperature and phase morphology for a given matrix material group respectively. A comparison between Fig. 3 and 5 verifies the assumption that stationary stable crack propagation can be observed if the slope of $g(\Delta a)$ converges to 1.

For polymers we assume that the process of stable crack propagation can be described in a thermodynamic sense as a thermally activated process. In cases that this assumption gives an adequate description of the fracture process, the stability of crack propagation should be the higher the higher the value of a stability parameter $s$ is:

$$s = 1 - \exp(-\Delta H^*/\Delta H_0^*)$$  \hspace{1cm} (5)

For the stable fracture process of polymers that means if $\dot{\delta}_{\lim} \to 0$ then $s \to 1$ (fully stable) and if $\dot{\delta}_{\lim} \to v_H$ (the transition from stable to unstable crack propagation) then $s \to 0$ (unstable). The parameter $s$ can be derived on basis of a two-potential model: The high and low level are separated by an energy gap $\Delta H^*$ named (pseudo) activation enthalpy; $\Delta H_0^*$ is the activation enthalpy per molecular unit. The value of $\Delta H_0^*$ can be roughly estimated to 7 kJ/mol: $\Delta H^*$ of the secondary ($\beta$-) relaxation pro-

Figure 6. $\dot{\delta}_{\lim}/v_H$ in dependence on (pseudo) activation enthalpy $\Delta H^*$ (see also Table 2); the line is calculated using Eq. (6) with $\Delta H_0^*$ = 7 kJ/mol process of polycarbonate, that is caused by co-operative motions of 7 molecular units (here: monomer units) \[3\], is equal to 50 kJ/mol. Thus, $s$ can be calculated as probability of the transition from the high to the low enthalpic level. Since no theoretical description of $\dot{\delta}_{\lim}(s)$ is known, the relationship $\dot{\delta}_{\lim}(s)$ can be simply hypothesized in view of Fig. 6 in the form of

$$\Delta H^*/\Delta H_0^* \cdot \dot{\delta}_{\lim}/v_H = 1$$  \hspace{1cm} (6) if $\dot{\delta}_{\lim} << v_H$.

REFERENCES