Time-changeable Fracture Mechanics Parameters for Polymers under Impact Loading

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ABSTRACT: *For further developing of a standardized crack resistance curve (R-curve) routine for thermoplastic polymer materials, the kinetics of the crack propagation under impact loading conditions must be universally clarified. Here, the instrumented Charpy impact test is used for the determination of fracture mechanics parameters. In this connection, methodical investigations have shown that only by use of the stop block method and multiple-specimen technique it is possible to determine crack resistance curves that correspond to homogenous kinetics of crack propagation. Other methods of R-curve determination such as the low-blow technique are normally not suitable for polymers due to the time-dependent mechanical properties of these materials. Typically, the crack-tip-opening displacement rate as resistance against the intrinsic rate of fracture mechanics parameters converges rapidly to a matrix-specific threshold value corresponding to (quasi) steady-state stable crack propagation (an equilibrium state) after crack initiation and non-stationary stable crack propagation. This behaviour forms a basic to describe the relationship between the loading parameters such as J-integral or CTOD and the stable crack growth theoretically.*

INTRODUCTION

Following from one of the primary objectives of fracture mechanics – the analysis of strain limits – several methods of fracture mechanics to characterize materials are stable weaved into the wide field of material testing [1]. An overview of selected methods and results of the experimental fracture mechanics for polymers is given by Grellmann and Seidler [2].

For fracture mechanical assessment of toughness behaviour three levels of knowledge can be formulated those are based on each other. Level I that corresponds to fracture mechanics concepts describing unstable crack initiation is state of the art. First applied on polymers by Blumenauer and Schroeder in 1973 [3], the concepts of this level are successfully applied to optimise 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). A first application of the concepts of this level on polymers took place already by Agarwal and Giare in 1981 [4]. However, the whole information content of this level, that is higher than that of level I, cannot 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 with concepts computing the crack toughness as resistance against the intrinsic rate of fracture mechanics parameters (Fig. 1). However, in contrast to static, fatigue or rapid loading conditions, in recent times not many basic investigations are known for that under impact loading conditions.

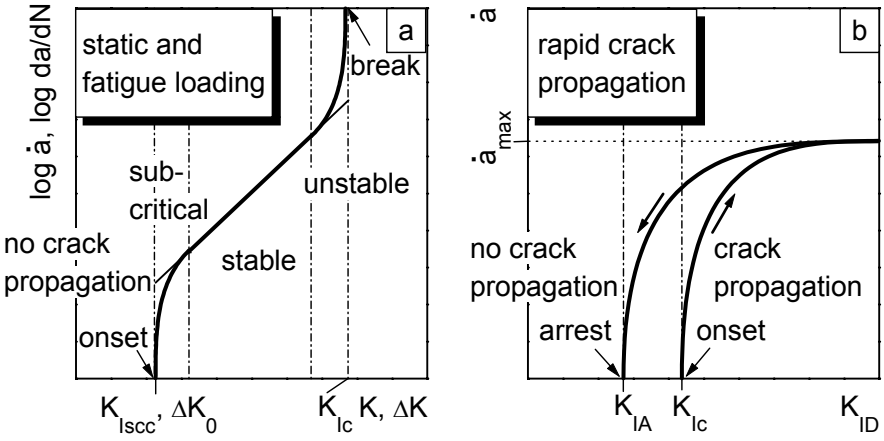

Figure 1: Crack resistance K, K_{ID} and ΔK as a function of 'crack speed' ȧ or da/dN respectively for different loading conditions; K, K_{ID}, ΔK – static, dynamic or cyclic stress intensity factors; K_{Iscc}, ΔK_0, K_{Ic} – onset values of crack propagation, K_{IA} – K-value for crack arrest

For polymers under static (creep) or fatigue loading conditions both the function ȧ = f (K) and the function da/dN = f (ΔK) show 3 sections with different magnitudes corresponding to subcritical, stable and unstable crack propagation (Fig. 1a). After subcritical crack propagation marked by an onset at K_{Iscc} or ΔK_0 the process of stable crack propagation can be described empirically using a power law (Paris law).

Also under rapid crack propagation conditions some results are known for polymers [5,6]. After an onset at K_{Ic}, the crack propagation speed ȧ as a

function of the dynamic stress intensity factor K_{ID} converges to about 0.2 – 0.4 times of the sound velocity (Fig. 1b).

R-CURVE DETERMINATION FOR POLYMERS UNDER IMPACT LOADING CONDITIONS

Polymers are typical viscoelastic-(visco)plastic materials associated with a pronounced time- and temperature-dependent mechanical behaviour, where different stages of crack kinetics such as crack formation, crack-tip blunting, stable crack initiation and propagation, and unstable crack propagation can be observed. Therefore, an adequate description of the whole fracture process of polymers implies the application of various concepts of elastic-plastic fracture mechanics. One of the more popular is the crack resistance curve (R-curve) concept that can be utilized if higher amounts of stable crack growth exist.

R-curves as functions of loading parameters (such as J-integral and crack-tip-opening displacement) versus stable crack growth Δa can be measured at impact loading conditions (instrumented Charpy impact test) by the use of different experimental procedures, whereby the stop block method (variation of Δa by a component that limits the maximum deflection) and the low-blow technique (variation of Δa by different testing velocities) are the most common. The tests can be performed with the (quasi)single-specimen technique (one specimen is loaded some times corresponding to complete unloading after each loading cycle) and the multiple-specimen technique (each of some specimens is loaded one time).

On basis of earlier investigations [2] the loading parameters, J-integral and crack-tip-opening displacement (CTOD) δ, 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.

The analysis of the measured R-curves can been realized by different procedures whereas two standards are especially developed for polymers (ASTM D 6068 and a Standard Draft of ESIS TC4). However, a sufficiently workable, standardized R-curve routine, that is material-physically motivated and considers the energy- as well as the deformation-determined toughness behaviour, must been still generated in future. Up to now, the kinetics of the crack propagation are not universally clarified, particularly the processes of blunting of a sharp initial crack and those of initiation of stable crack growth. For this reason in many R-curve standards, the blunting region is not analysed. Thus instead of physical crack initiation values, engineering

crack initiation values are used often to quantify the stable initiation process, such as $J_{0.2}$ at $\Delta a = 0.2$ mm.

MATERIAL EXAMPLES

TPU/ABS blends

Generally, polymer materials with new properties are created by blending or copolymerisation of well-known materials. Both methods are used to improve impact toughness of polymers and for an adequate fracture mechanics characterization the crack resistance concept must be used.

Blends made from thermoplastic polyurethane (TPU) and an acrylonitrile-butadiene-styrene copolymer (ABS) are an example for such materials. On example of these TPU/ABS blends (Fig. 2) and other polymers [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. the crack-tip-opening displacement rate $\dot{\delta}$ defined as $d\delta/dt$ is constant excepting small Δa values.

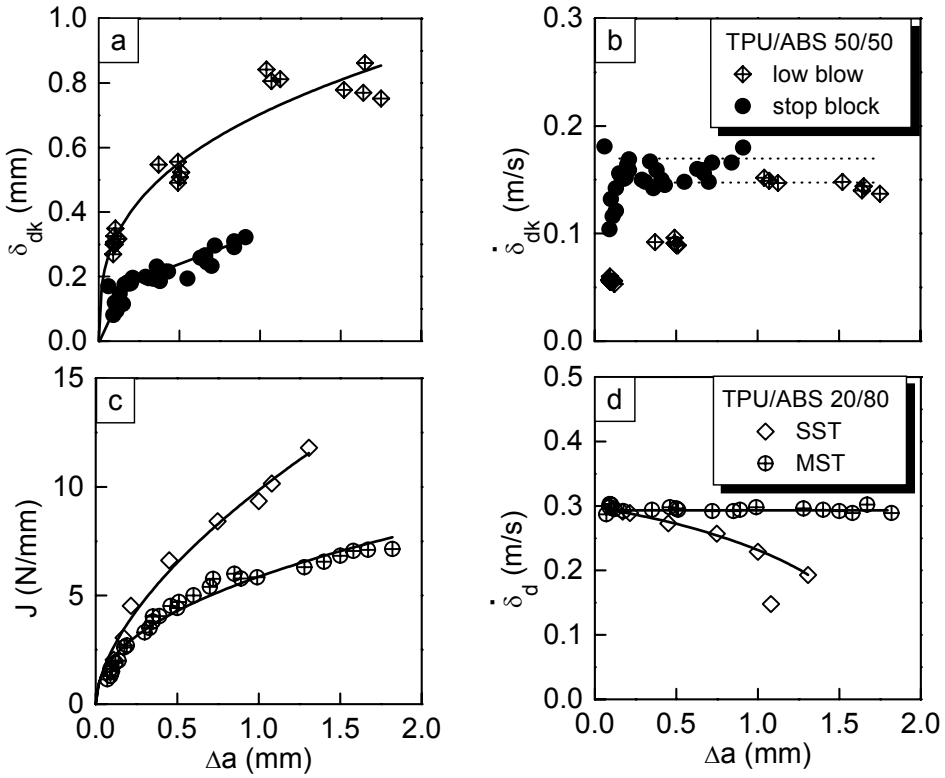

Figure 2: δ_{dk}-R (a) and J-R curves (c) measured using various methods (SST – single-specimen technique, MST – multiple-specimen technique) corresponding to crack-tip-opening displacement rate for TPU/ABS blends (b,d)

Compared to the stop block technique, $\dot{\delta}_{dk}$ -values determined by using the low-blow method increase with increasing Δa-values (i.e. with increasing pendulum hammer speed v_H) (Fig. 2b), because the ratio $\dot{\delta} / v_H$ is material specific as noted below. The increasing crack-tip blunting area observed by using the (quasi)single-specimen technique leads to an decreasing crack-tip-opening displacement rate $\dot{\delta}_d$ (Fig. 2d), that is a measure for the local strain rate ahead the crack tip. Comparing to the multiple-specimen technique, this behaviour is combined with higher energy dissipation as a function of Δa (Fig. 2c).

PP/EPR/PE copolymers

Based on these methodical investigations, R-curves (Fig. 3a) are determined for ethylene/propylene copolymers (PP/EPR/PE copolymers) with various particle centre distances CD ranging from CD = 2.0–4.1 µm.

It can be observed that the values of the crack-tip-opening displacement rate converge rapidly to a matrix-specific threshold value ((quasi)steady-state stable crack propagation, i.e. an equilibrium state) after crack initiation and non-stationary stable crack propagation (Fig. 3b) that is independent of the particle distance.

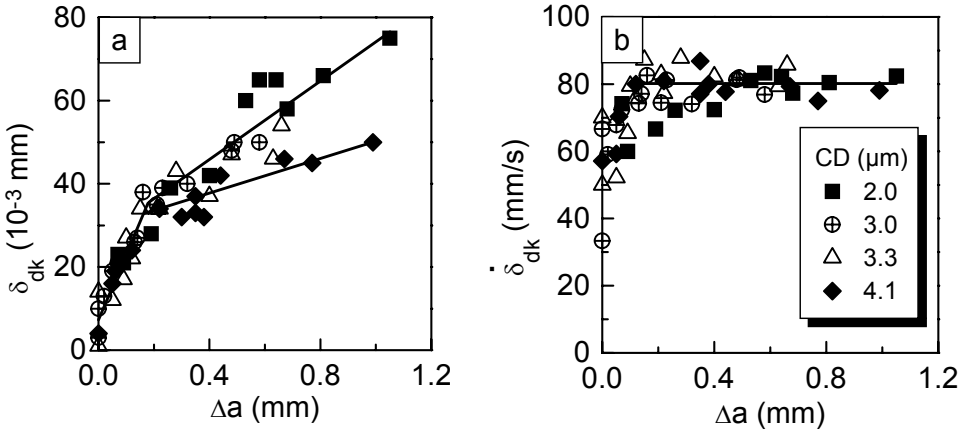

Figure 3: δ_{dk}-R curves (a) and CTOD rate values $\dot{\delta}_{dk}$ in dependence on stable crack growth Δa (b) for PP/EPR/PE

Binary block copolymer blends based on PS and PB

In addition to heterophase polymers such as TPU/ABS or PP/EPR/PE with particle-matrix structure and heterogeneities lying in the order of micrometers, new classes of self-assembled nanostructured polymer materials such

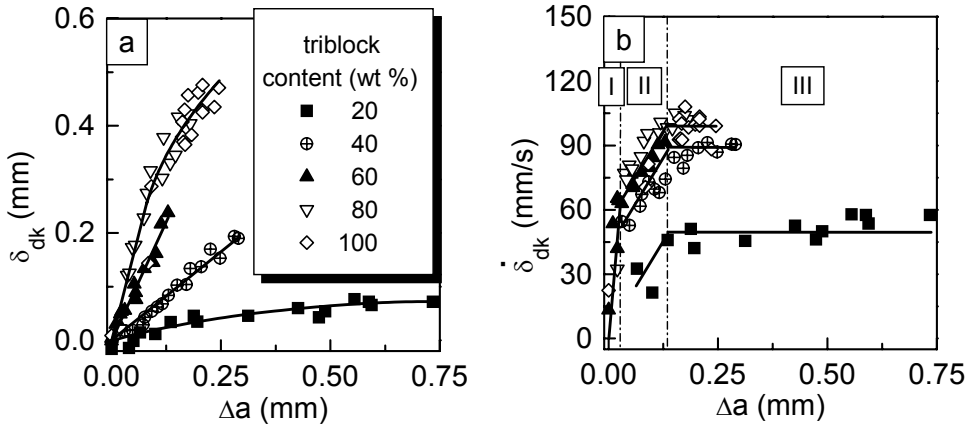

Figure 4: δ_{dk}-R curves (a) and CTOD rate $\dot{\delta}_{dk}$ (b) as a function of the stable crack length Δa for SB-based binary block copolymer blends

as binary block copolymer blends are utilized increasingly. As example for these materials, blends made from a relatively brittle star block copolymer and a triblock copolymer (thermoplastic elastomer) [7], both based on styrene and butadiene are used in this study.

The δ_{dk} versus Δa curves of star block/triblock copolymer blends with different contents are plotted in Fig. 4a. With increasing triblock content the slope of the R-curves increases drastically.

For this material group, the stages of crack propagation can be seen very clearly (Fig. 4b). Stage I correlates with the crack-tip blunting, which results in a strong increase in $\dot{\delta}_{dk}$-values. In the stage II, the crack moves quite stable but in a non-stationary way, the $\dot{\delta}_{dk}$-values increase. In the stage III, the non-stationary stable crack finally reaches a (quasi)steady-state (equilibrium state), the values of $\dot{\delta}_{dk}$ remain constant. The maximum value of $\dot{\delta}_{dk}$ increases with increasing triblock content up to 100 mm/s for 60 wt %.

GENERALIZING REMARKS

The observed three stages of stable crack propagation (Fig. 5) are also typical for other polymeric materials (Table 1). The ratio between the crack-tip-opening displacement rate and the external loading speed, in the case of impact loading the pendulum hammer speed, $\dot{\delta}_{lim} / v_H$ is nearly independent on temperature and phase morphology for a given matrix material group.

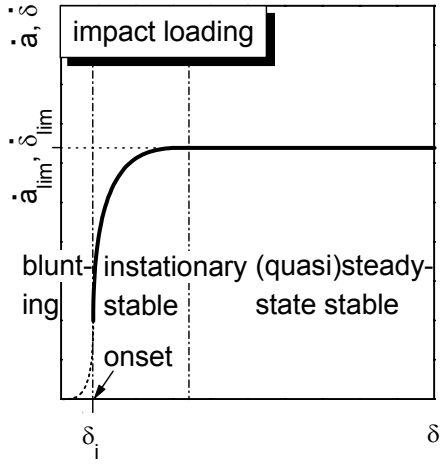

Figure 5: Generalized scheme for the crack resistance δ as a function of the crack speed $\dot{a}$ or the CTOD rate $\dot{\delta}$ respectively for impact loading conditions; δ_i – CTOD values of physical crack initiation; $\dot{a}_{lim}, \dot{\delta}_{lim}$ – threshold values of (quasi) steady-state stable crack propagation.

TABLE 2: Materials and values of $\dot{\delta}_{lim} / v_H$

Material	$\dot{\delta}_{lim} / v_H$
PC, temperature range: 60–95 °C	0.11
PP/EPR/PE, various phase morphology	0.08–0.13
PP; PP/glass-fibre, various matrix materials	0.09
HDPE, various commercial grades	0.05–0.09
ABS, rubber contents: 20–36 wt. %	0.02–0.06
TPU/ABS blend 50/50	0.16
SB block copolymer blends (blends of a thermoplastic material (SB1) and a thermoplastic elastomer (SB2))	
SB1/SB2-ratio = 80/20	0.05
SB1/SB2-ratio = 60/40–0/100	0.09–0.1

The value $\dot{\delta}_{lim} / v_H$ is a measure of the rate sensitivity of stable fracture processes. For materials those have a higher rate sensitivity, the influence of the specimens geometry and the methodology of R-curve determination on the slope of the R-curves, i.e. changes in the plastic constraint, should be higher as for such materials having a lower one. Because of the high $\dot{\delta}_{lim} / v_H$-values for the TPU/ABS blend with $\dot{\delta}_{lim} / v_H$ = 0.16, the differences in the corresponding R-curves determined in low-blow and stop block technique are highly pronounced (Fig. 2a). By way of contrast, for ABS the plastic constraint is more or less the same independent of the specimen configuration because of the small $\dot{\delta}_{lim} / v_H$-values.

The intrinsic velocities measured in the crack propagation direction, the crack speed $\dot{a}$, and perpendicular to it, the CTOD rate $\dot{\delta}$, have different physical meaning. The crack speed $\dot{a}$ indicates the stability of the whole mechanical system and, consequently, it is dependent on the stiffness of the cracked specimens, the stiffness of the testing devise and the kind of loading. But in cases in which the stability of the mechanical system is not externally influenced i.e. the loading conditions are constant – as in the present study – the crack propagation velocity should increase with increasing values of the toughness parameter, which can also be observed in reality. Comparing to $\dot{a}$, $\dot{\delta}$ should be a function of the kind of deformation and the phase predominantly deformed during the deformation process because the CTOD is a measure of the deformation capacity for the material close to the crack tip. Thus, $\dot{\delta}$ delivers also insight into the micromechanics and the activation mechanisms of the fracture process. A possible correlation is that between $\dot{\delta}_{lim} / v_H$ and the activation enthalpy of plastic deformation processes [8]. But, further investigations are necessary to give more precise predictions.

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