Evaluation of Dynamic Fracture Toughness and Weibull Master Curves of Polymethyl Methacrylate

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In this paper, a methodology to evaluate the dynamic fracture toughness of polymethyl methacrylate (PMMA) is presented. The proposed methodology is based on a hybrid-numerical formulation and requires the evaluation of the dynamic stress intensity factor along the experimentally measured dynamic crack fronts, and the three-parameter Weibull stress model for brittle fracture. The apparent fracture toughness master curves are determined for Double Cantilever Beam (DCB) specimens of PMMA with different thickness.

Keywords: dynamic fracture toughness, polymethyl methacrylate, Weibull master curve

In brittle polymeric materials, fracture occurs well below the materials yield stress, displays little or no macroscopically visible plastic deformation, and requires less energy to form. Thus, for brittle polymeric materials, current fracture assessment methodology relies on plain strain conditions around the crack tip which are not affected by plastic deformations, and on the assumption that the fracture toughness is not related to the specimen size.

Linear Elastic Fracture Mechanics is one of the most used methods to characterize the fracture of polymers. Within the LEFM the fracture toughness which expresses the ability to resist the fracture in the presence of cracks, may be represented in terms of the stress intensity factor, or the energy release rate. Within the static fracture mechanics, conditions based on the energy release rate or critical stress intensity factors have gained practical value [1]. Moreover, from the work on crack waves and taking into account the recently developed mechanism for crack propagation inside the solids by Nishioka and Stan [2, 3] it appears that the ultimate answer to the quasi-static fracture criterion lies in essentially dynamic phenomena.

Several experimental studies have been carried out on the dynamic fracture of brittle of polymers to determine the fracture parameters which govern rapid crack propagation [4-9]. The state of the dynamic stress field around a propagating crack, dynamic stress intensity factor K_{ID}, has been evaluated using optical methods such as the dynamic photoelasticity, the method of caustics, and the coherent gradient sensor [9, 10]. Numerous attempts have been made to relate K_{ID} and the instantaneous crack tip velocity [9, 11]. Arakawa and Takahashi [11] measured K_{ID} values during crack propagation which included both acceleration and deceleration in one fracture event. Also, Arakawa et al [12] carried out a research to study dynamic crack propagations in single-edge cracked tensile specimens of epoxy, PMMA and Homalite-100 by using method of caustics. Specimens were fractured under pin-loading conditions so that cracks were subjected to acceleration and deceleration stages in a single fracture event. Dynamic crack propagations were photographed with a modified Cranz-Schardin camera which provided bifocal photographs. Caustic patterns at the loading points were also recorded. The stress intensity factor was evaluated from the equation of Manogg which relates the stress intensity factor to the caustic pattern.

Due to the difficulties related to experimental evaluation of the dynamic fracture toughness, the definition of a standard experiment to measure the dynamic toughness has not been straightforward. Moreover, all measurements are carried out only at the surface of the specimen, so that the moment of advance of a submerged crack tip, and thus the stress state at the crack front at the critical instant, is difficult to know.

In the absence of experimental measurements, one possible way to estimate the dynamic fracture toughness is to adopt a hybrid experimental-numerical approach [2, 3], which makes use of numerical simulations using data from three-dimensional fracture experiments.

In this paper, a hybrid experimental numerical approach to evaluate the dynamic fracture toughness of polymethyl methacrylate materials is presented. The dynamic fracture toughness is represented in terms of the stress intensity factor. The component separation method of the dynamic J integral is used to evaluate the dynamic stress intensity factor along the naturally and dynamically propagating crack fronts. The results from finite element calculations are used to estimate the dynamic fracture toughness and the Weibull failure probability.

Methodology to evaluate the fracture toughness

The methodology to evaluate the critical dynamic fracture toughness of polymethyl methacrylate is illustrated in figure 1. The methodology consists of four stages:

(i) dynamic fracture experiments;
(ii) generation-phase simulation analysis;
(iii) fracture statistics;
(iv) application –phase simulation analysis.

Dynamic fracture experiments

In the fracture experiments high speed photographs of dynamically propagating crack fronts are recorded using high-speed camera. Precise measurements of the curved crack front shapes in high speed photographs are made by using image processing and data modeling.

The generation-phase simulation analysis

The generation-phase simulation can be considered as one of the techniques classified into the hybrid experimental-numerical method. In the generation-phase simulation analysis, the experimental observed fracture phenomena are re-generated in the computer model using experimental conditions and experimentally measured

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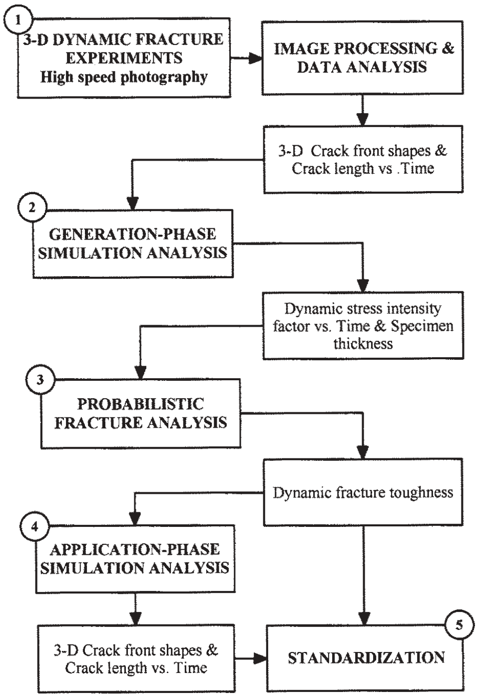


Fig. 1. Methodology to evaluate the dynamic fracture toughness

fracture data (i.e., crack front shapes). From the numerically regenerated three-dimensional fracture phenomena, the distributions of the fracture parameters such as the dynamic stress intensity factor along the actual fracture fronts are determined. The dynamic stress intensity factor along the naturally and dynamically propagating crack fronts is evaluated using the component separation method of the dynamic *J* integral [2].

Fracture Statistics

The results from finite element calculation are used to estimate the dynamic fracture toughness and the failure probability based on the three-parameter Weibull stress model for brittle fracture.

Application-phase simulation analysis

In the application-phase analysis, the crack propagation history can be determined by specifying the initial conditions and material fracture toughness as input data. Tow criteria must be postulated: i) the crack propagation criterion which must be described by a fracture parameter; ii) the propagation direction criterion or crack growth criterion. Once the dynamic fracture toughness is known prediction simulation of the formation of the crack fronts can be carried out.

Dynamic stress intensity factor

It is commonly admitted that the stress intensity factor is the relevant parameter to define the crack state. The stress intensity factor is a measure of the strength of the stress singularity at a crack tip, and is useful from a mechanics perspective as it characterizes the displacement, stress and strain in the near field around the crack tip. Additionally, the stress intensity concept is important in terms of crack extension as critical values of the stress intensity factor govern crack initiation.

The calculation of the stress intensity factor in finite solids under arbitrary loading conditions is difficult and is usually done through analytical or numerical approximation. Due to the extreme mathematical complexity of the problem, analytical solutions are able to provide only qualitatively insights for idealized situations. Among the available numerical methods for calculating stress intensity factors, the component separation method has emerged as a useful technique.

Explicit expressions for the dynamic stress intensity factors, in terms of the component separation method, can be summarized as [2]:

$$K_M = \frac{\delta_M}{A_M(C)}\overline{K}\ (M = I, II, III), \tag{1}$$

where

$$\overline{K} = \left\{ \frac{2\mu J_1'^0}{\frac{\delta_I^2}{A_I(C)} + \frac{\delta_{II}^2}{A_{II}(C)} + \frac{\delta_{III}^2}{A_{III}(C)}} \right\}^{\frac{1}{2}} = \left\{ \frac{2\mu G}{\frac{\delta_I^2}{A_I(C)} + \frac{\delta_{II}^2}{A_{II}(C)} + \frac{\delta_{III}^2}{A_{III}(C)}} \right\}^{\frac{1}{2}}. \tag{2}$$

The crack opening displacements δ_M (M=I, II, III) at a point near the crack tip can be expressed by

$$\delta_I = \left(u_2^0\right)^+ - \left(u_2^0\right)^-;\ \delta_{II} = \left(u_1^0\right)^+ - \left(u_1^0\right)^-;\ \delta_{III} = \left(u_3^0\right)^+ - \left(u_3^0\right)^-, \tag{3}$$

where $(\ )^+$ and $(\ )^-$ denote the quantities of the upper and lower surfaces of the crack. The signs of K_M correspond to the signs of δ_M ($K_1 > 0$ if $\delta_1 > 0$, and so on).

The dynamic *J* integral to be used in equation (2) is calculated via the equivalent domain integral method [13, 14] over a finite region surrounding the crack tip. This process removes the need to precisely capture the details of the singular fields near the crack tip, and the approach has been shown to be well suited for a wide range of fracture problems.

According to the equivalent domain integral method [14], the *J* integral for a small contour Γ_ε is transformed into a domain integral over an area between the small contour and an arbitrary contour Γ by introducing a special (weighting) function *s*.

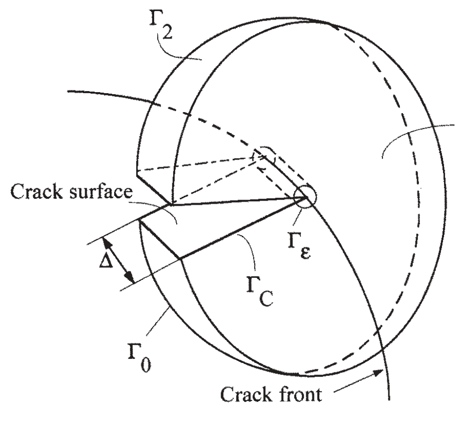


Fig. 2. Integral paths for dynamic J integral

Suppose that the curved crack front in three-dimensional body is divided into segments (fig. 2). For a layer of the segment (fig. 2), using a continuous function *s* that takes non-zero on the near-field path Γ_ε, and zero on the far-field paths $\Gamma_o + \Gamma_c$ the following equation can be written [2, 13]

$$J_k' = \frac{1}{f}\left\{ \int_{V_\Gamma}\left[\sigma_{ij} u_{i,k} s_{,j} - (W+K)s_{,k} + \left\{(\rho\ddot{u}_i - b_i)u_{i,k} - \rho\dot{u}_i\dot{u}_{i,k}\right\} s\right] dV + \int_{\Gamma_1+\Gamma_2}\left[(W+K)n_k - t_i u_{i,k}\right] s\, ds \right\} \tag{4}$$

here f is the integral value of the *s* function along the segment of the crack front under consideration.

Defining the surface $\partial(V-V_\varepsilon)=\Gamma_o + \Gamma_c - \Gamma_\varepsilon + \Gamma_1 + \Gamma_2$ as the envelope of the volume ,($V-V_\varepsilon$) the equivalent domain integral expression [13]

$$J'_k = \frac{1}{f}\left\{ \int_{V_\Gamma}\left[\sigma_{ij}u_{i,k}s_{,j} - (W+K)s_{,k} + \{(\rho\ddot{u}_i - b_i)u_{i,k} - \rho\dot{u}_i\dot{u}_{i,k}\}s\right]dV + \right.$$
$$\left. + \int_{\Gamma_1+\Gamma_2}\left[(W+K)n_k - t_i u_{i,k}\right]s\,ds\right\}. \tag{5}$$

In the finite element model of the cracked body, the dynamic J integral can be evaluated by [2]

,

$$J'_k = \frac{1}{f}\sum_{n=1}^{N_V}\sum_{q=1}^{20} R_{knq}\,s_q + \frac{1}{f}\sum_{n=1}^{N_s}\sum_{q=1}^{20} Q_{knq}\,s_q\,, \tag{6}$$

where

$$R_{knq} = \int_{V_n}\left[\sigma_{ij}u_{i,k}N_{q,j} - (W+K)N_{q,k} + (\rho\ddot{u}_i u_{i,k} - \rho\dot{u}_i\dot{u}_{i,k})N_q\right]dV \tag{7}$$

and

$$Q_{knq} = \int_{S_n}\left[(W+K)n_k - t_i u_{i,k}\right]N_q\,dS\,, \tag{8}$$

N_V and N_S are the total number of elements in V_Γ and on the $\Gamma_1+\Gamma_2$, respectively V_n and S_n are the volume and surface of the n-th element, respectively.

The features of the component separation method can be summarized as follows:

(i)it can be expressed by the explicit formulas, as expressed by equation (6);

(ii)it does not require any auxiliary solution field, which is required in the M_1 integral method that is often used to evaluate mixed-mode stress intensity factors;

(iii)it is applicable using the path independent dynamic J integral, or the dynamic energy release rate;

(iv)the signs of the stress intensity factors are automatically determined by the signs of the corresponding crack opening displacements.

The Weibull stress model

For brittle materials, the Weibull distribution has been found to successfully describe a large body of fracture data. Furthermore, the Weibull master curve has been recognized as an alternative approach to evaluate the fracture toughness [15, 16]. The method provides the confidence levels of fracture toughness in consideration of the statistical distribution, which is a natural property of fracture toughness.

The failure probability of the three-parameter Weibull distribution has the form [15]

$$P(\sigma) = 1 - \exp\left[-\left(\frac{\sigma-\sigma_\tau}{\sigma_0}\right)^m\right],\ \sigma > \sigma_\tau \tag{9}$$

where σ denotes the applied failure stress, σ_τ is the threshold stress underneath the cumulative probability of failure is zero, σ_0 is a normalized material strength, and m is the Weibull modulus which is also called the shape factor.

Then, the probability density function of the three-parameter Weibull distribution is given by

$$f(\sigma) = \frac{m}{\sigma_0}\left(\frac{\sigma-\sigma_\tau}{\sigma_0}\right)^{m-1}\exp\left[-\left(\frac{\sigma-\sigma_\tau}{\sigma_0}\right)^m\right]. \tag{10}$$

The specimen size-independent Weibull master curves can be obtained for every $m > 0$ as follows [15]

$$I(y,m) = 1 - \exp\left[\left(\frac{1-m}{m}\right)^m y^m\right], \tag{11}$$

in which y is the scaled stress defined by

$$y = \frac{\sigma-\sigma_\tau}{\sigma_{th}-\sigma_\tau}, \tag{12}$$

where σ_{th} is the alternative scaling parameter for the material defined by [15]

$$\sigma_{th} = \sigma_0\left(\frac{m-1}{m}\right)^{1/m} + \sigma_\tau\,. \tag{13}$$

By scaling the cumulative Weibull failure probability distribution function $P(\sigma)$ with the mean stress, one can get the alternative Weibull master curve [15]

$$T(y,m) = 1 - \exp\left\{-\left[\Gamma\left(1+\frac{1}{m}\right)\right]^m y^m\right\}, \tag{14}$$

in which y is the scaled stress defined by

$$y = \frac{\sigma-\sigma_\tau}{\bar{\sigma}-\sigma_\tau}, \tag{15}$$

where the alternative scaling parameter $\bar{\sigma}$ is defined by

$$\bar{\sigma} = \sigma_0\Gamma\left(1+\frac{1}{m}\right) + \sigma_\tau\,, \tag{16}$$

whereby Γ is the complete Gamma function.

Based on the equation (11), one can derive the Weibull curve in terms of the stress intensity factor, which can be applied to every type of brittle material under all circumstances [15].

The theoretical, alternative apparent fracture toughness master curve is formally equal to T(y,m=4)and is defined as follows [15]

$$P(K_I) = T(y) = 1 - \exp\left\{-\left[\Gamma\left(1+\frac{1}{4}\right)^4\right]y^4\right\}, \tag{17}$$

with the variable y defined by

$$y = \frac{K_I - K_{\min}}{\bar{K} - K_{\min}}, \tag{18}$$

where K_{min} is threshold stress intensity factor underneath the cumulative failure probability is zero, $\bar{K}$ is the scaling parameter.

Numerical example

In this paper, in order to demonstrate de applicability of the proposed methodology, the experimentally measured fracture data [2, 3, 17] regenerated in the computer model were used [Nishioka and Stan]. The specimens for evaluating the dynamic fracture toughness were made by Polymethyl Methacrylate (PMMA).

PMMA is a polymer regarded as inert and nontoxic, hard, rigid, but brittle polymer. However, as well as being very resistant to degradation and well tolerated by tissues, it does possess two distinct advantages: (i) firstly, it is an amorphous polymer with high surface gloss, high brilliance, and crystal-cleat transparency. (ii) secondly, it can be

Table 1
MECHANICAL PROPERTIES OF PMMA

Young's modulus (GPa)	Poisson's ratio	Mass density	Refractive index	Dilatational wave velocity (m/s)	Shear wave velocity (m/s)	Rayleigh wave velocity (m/s)
2.94	0.39	1190	1.49	2220	943	886

produced and fabricated under ambient conditions [18]. The main disadvantages of PMMA are: the release of heat associated with polymerization process, the toxicity of the volatile methylmethacylate, and the poor fracture toughness.

The material properties as well as the dilatational, shear and Rayleigh wave velocities in PMMA are listed in table 1. Since the refractive index is greater than $\sqrt{2}$, PMMA has mirror-like fracture surfaces [18], which make it possible to visualize the instantaneous shapes of dynamically propagating crack fronts.

The geometry of the Double Cantilever Beam (DCB) specimen and the loading system are schematically illustrated in figure 3. The specimens have a precut edge notch of 84 mm along the symmetry plane. The blunt crack tip allows a substantially higher energy density to be imposed in the system prior to fracture than that allowed by a "sharp" crack.

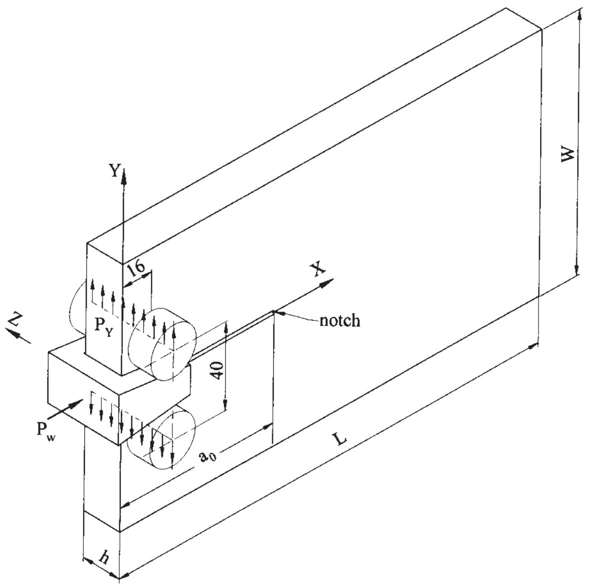


Fig. 3. Specimen geometry

The variations of the crack front shapes during the crack propagation and arrest are presented in figure 4. It can be seen that in the thinner specimen the crack propagated with almost straight crack front, while in the thicket specimens, the crack stared to propagate from the off-centered initiation point along the initial notch front, and the curvatures of the dynamically propagating crack fronts increase with increasing thickness of the plate.

Finite element analysis

A computer code which incorporates the methodology presented in section 2 has been developed. The numerical analyses are performed using a fracture mechanics finite element code which incorporates the three-dimensional moving finite element method together with an automatic element control method. The Newmark method is used for the time integration of the finite element equations. Furthermore, to make it possible to evaluate the dynamic

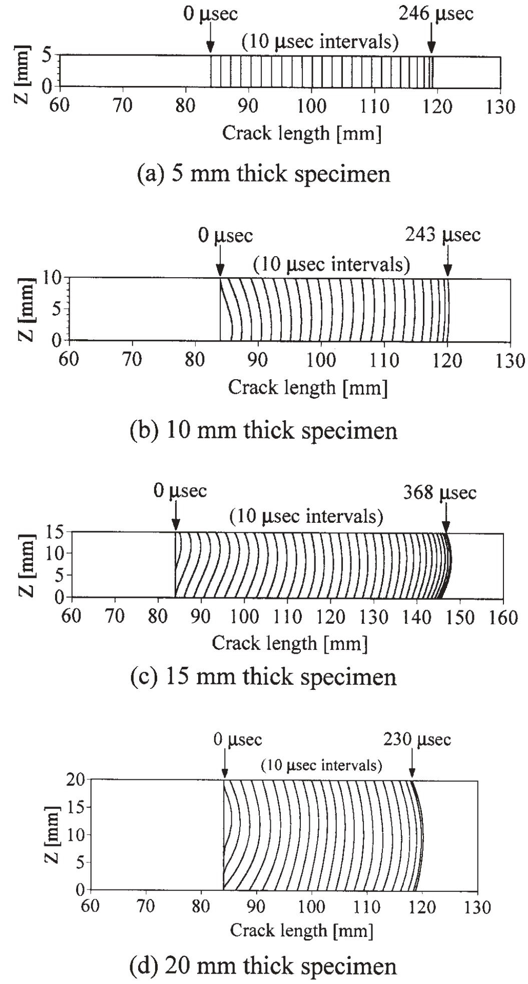


Fig. 4.Variation of crack-front shapes during dynamic crack propagation and arrest

J integral (equivalently the energy release rate) along the dynamically propagating crack front, the equivalent domain integral method of the path independent integral is used [2, 3]. The code can be executed in its generation-phase or application-phase simulation modes to yield results which are unobtainable when only one of the techniques is used.

In the finite element analysis, the DCB specimens were modelled with moving 20-noded isoparametric elements. Since the fracture paths were straight along the *X*-axis, only Mode I crack propagation is considered. Due to the symmetry of the geometry and the loading conditions, only the upper part of the specimen was modelled in the present analyses. The finite element mesh pattern for the initial configuration as well as the far-field paths for the dynamic *J* integral is shown in figure 5.

For each crack-front segment, the dynamic *J* integral values were evaluated for three far-field paths by using equation (6). The dynamic stress intensity factors were obtained directly by the component separation method as described in equation (1). The variations of the dynamic stress intensity factor values at the mid-thickness of the plates against the time are summarized in figure 6. Details

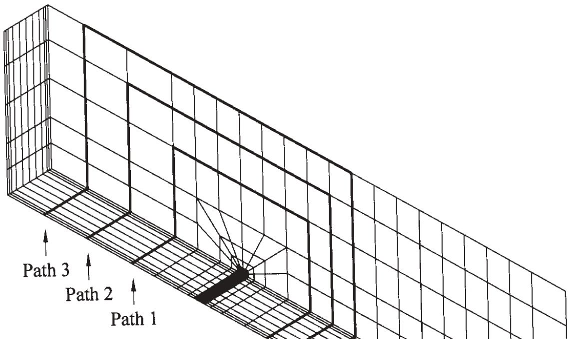


Fig. 5. Far-field paths for dynamic J integral

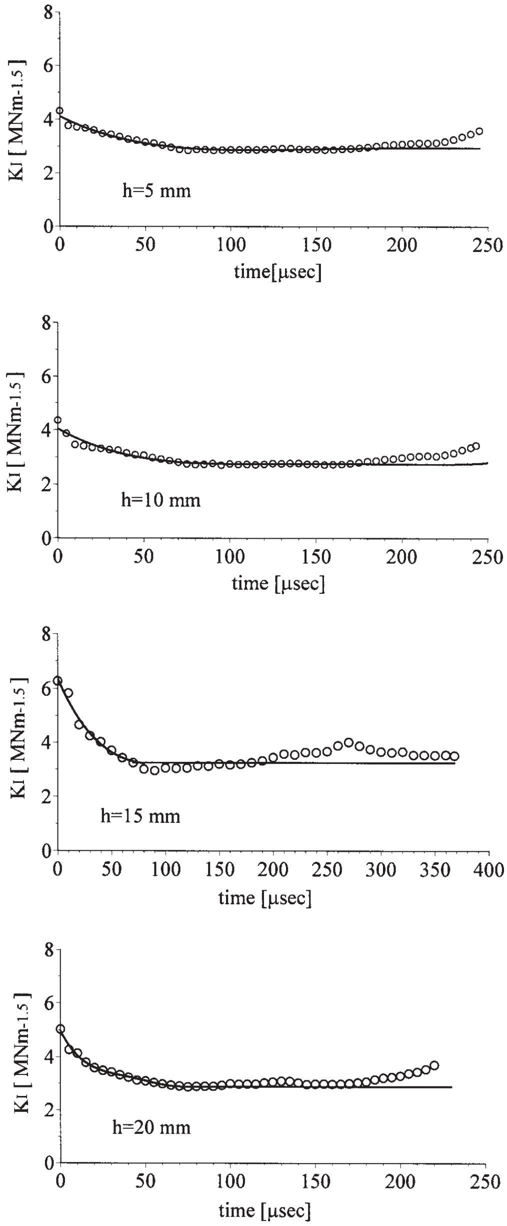


Fig. 6. History of the dynamic stress intensity factor at the mid-thickness of the plate. The solid line represents the dynamic fracture toughness

on dynamic stress intensity factor distribution have been specified in [3] and shall not be repeated here, but examining the conditions leading to dynamic crack growth along the experimentally measured crack fronts, it can be seen that, in each specimen, after initiation the dynamic stress intensity factor decreases up to a value which stays approximately constant during the propagation stage. Moreover, the crack attempts to form curved crack fronts to make uniform distribution of the dynamic stress intensity factor.

Based on the results presented in figure 6, for each specimen, we assume that the dynamic fracture toughness (the solid line) is nearly constant and nearly independent on the position along the crack front.

Statistics of fracture

A complete picture of dynamic stress intensity factor variability and thereby the failure probability is obtained if the values of the dynamic stress intensity factor are plotted in a histogram as shown in figure 7. The dashed lines indicate the normal distribution fit while the continuous

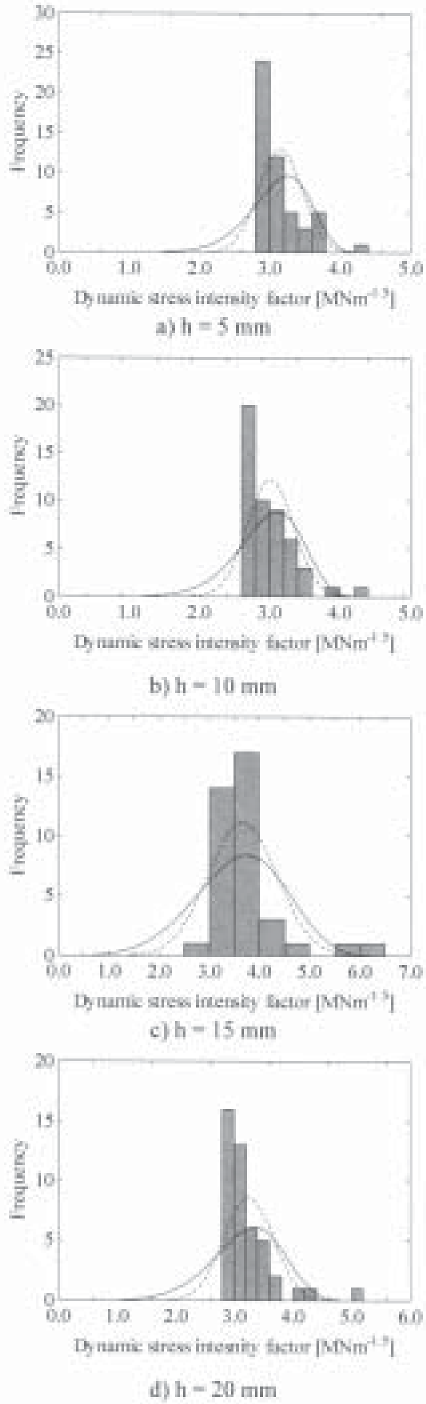
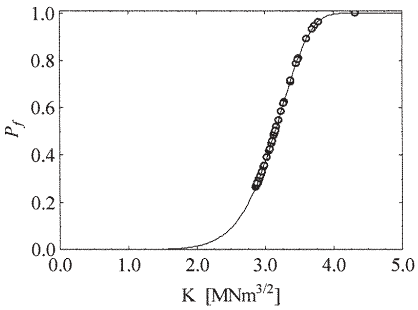
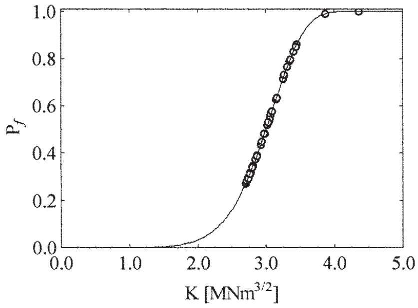


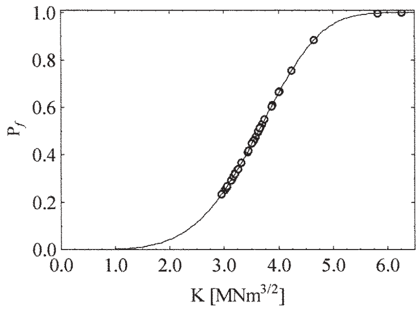
Fig. 7. Histograms of dynamic stress intensity factor at the mid thickness of the plate (dashed line: normal distribution; continuous line: Weibull distribution)



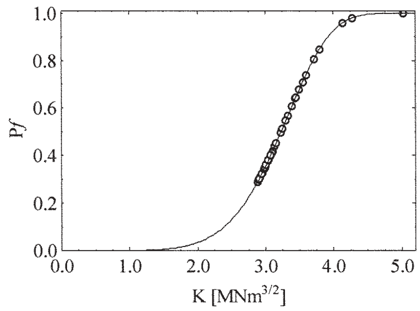
a) h = 5 mm, m = 8.5



b) h= 10 mm, m = 7.5

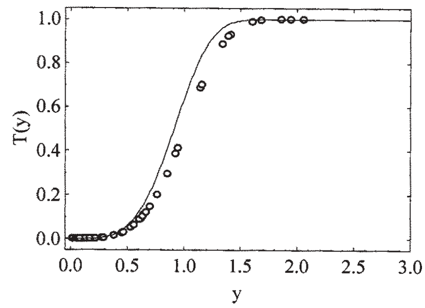


c) h = 15 mm, m = 4.6

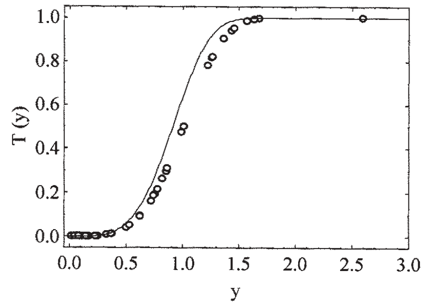


d) h = 20 mm, m = 6.2,

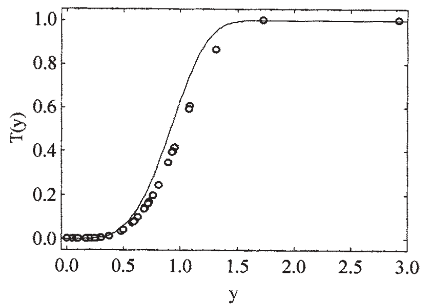
Fig. 8. Two-parameter cumulative failure probability Weibull distribution for DCB specimens



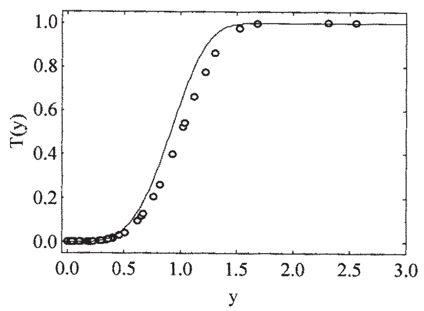
a) h = 5 mm



b) h = 10 mm



c) h = 15 mm



d) h = 20 mm

Fig. 9. Numerical, apparent fracture toughness curve T(y,m=4)

lines indicate the Weibull distribution. It can be shown that the maximum in the histogram is near the mean value of the dynamic stress intensity factor and its width is related to the standard deviation.

The Weibull master curves of the PMMA undergoing stable crack growth can be constructed by calculating the Weibull modulus and the scaling parameter. In this work, the Weibull modulus and the scaling stress intensity factor were calculated from the upper limit of the two-parameter cumulative failure probability Weibull distribution obtained based on the numerical simulation of the dynamic fracture in DCB specimen of PMMA (fig. 8). Then, the apparent fracture toughness master curves were obtained by fitting a curve to the data points (y_i, $T(y_i)$) as presented in figure 9. The threshold stress intensity factor values used in equation (16) are in reasonable agreement with the results reported in the literature (between 2 and 3 MPa$\sqrt{m}$). For reference (fig. 9) the continuous line shows the master curves constructed based on the assumption that the threshold stress intensity factor is equal to zero.

Conclusions

In this paper, a new methodology for the fracture toughness evaluation of polymethyl methacrylate (PMMA) was presented. The proposed methodology is based on a hybrid-numerical formulation and requires the evaluation of the dynamic stress intensity factor along the experimentally measured dynamic crack fronts. The dynamic stress intensity factor along the naturally and dynamically propagating crack fronts were evaluated using the dynamic *J* integral and the moving finite element method. To obtain a relevant fracture toughness and thereby the failure probability from the numerical simulation results, the three-parameter Weibull stress model for brittle fracture was used. If the fracture toughness is associated with the dynamic stress intensity factor, the methodology predicts correctly the fracture toughness probability distributions for stable crack growth. The results obtained in this paper offer some important new insights into the evaluation of the dynamic fracture toughness.

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