RESULTS OF A EUROPEAN ROUND ROBIN ON THE IMPACT FRACTURE TOUGHNESS OF PLASTICS AT HIGH RATES OF LOADING

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ABSTRACT

Within the ESIS TC4 committee on Polymers and Composites a round robin exercise on the determination of the impact fracture toughness K_{Id} of plastics at high rates of loading with impact velocities "> 1m/s" was performed. During this exercise a tough, strain rate sensitive material, a modified PVC, and the more brittle epoxy Araldite B was investigated. Impact tests with Charpy-sized precracked specimens were carried out at impact speeds of several metres per second. At these loading rates the times–to-fracture are very short and inertia effects are dominant. In this time range external force measurements could be completely misleading due to the missing quasistatic equilibrium of forces. Therefore, an evaluation based on the method of "Dynamic Key Curves" (DKC) was performed, which takes into account inertia and wave propagation phenomena. For this low effort engineering method the time-to-fracture is the essential quantity to be measured. In addition some reference data were produced by direct measurements with near crack tip strain gages. The results and advantages and disadvantages of different experimental techniques are discussed.

INTRODUCTION

Based on the procedure to determine the static fracture toughness K_c (ASTM E399-90) a procedure for plastics was developed by ESIS TC4 and is going to be standardized (ASTM D5045-99 and ISO-FDIS 13586-1). This procedure is based on fracture mechanics tests, e.g., with precracked three point bend specimens, SENB, and K_c is evaluated from the measured load at fracture. In principle, this procedure also applies to impact loaded SENB-specimens at moderate velocities $v_o < 1$ m/s, especially if damping pads between the striker and specimen are used to reduce dynamic effects. So-called "instrumented" impact tests (see Fig. 1 and [1-4]) enable the measurement of the applied force. According to Ireland [5], the applicability of such quasi-static procedures is limited to times-to-fracture, t_f, which are larger than the duration of three times the period of oscillation, ô, of the force-signal $P_H(t)$. In practice, this restriction t_f > 3ô is similar to the restriction $v_o < 1$ m/s.

But existing standards for impact tests are often related to impact speeds of several metres per second (e.g.: 2.9 m/s for plastics or 5 m/s for steels). Considering the crashworthiness of vehicles then even higher speeds with very short times-to-fracture, t_f, can be important. For brittle materials and high impact velocities fracture is usually observed in the very beginning of an impact test, where dynamic effects such as propagating elastic waves and, consequently, vibrations of the test sample, are dominant and indicated by oscillating load-signals, and loss of contact and bouncing can be observed (e.g. [6-9]). In this time range the striker-forces differ significantly from the actual crack-tip loading and, therefore, local measurements are recommended [6-9].

The crack tip loading history and the fracture initiation toughness at high loading rates can be measured directly, for example by near crack tip strain gauge instrumentation (Fig. 1) in combination with fast amplifiers

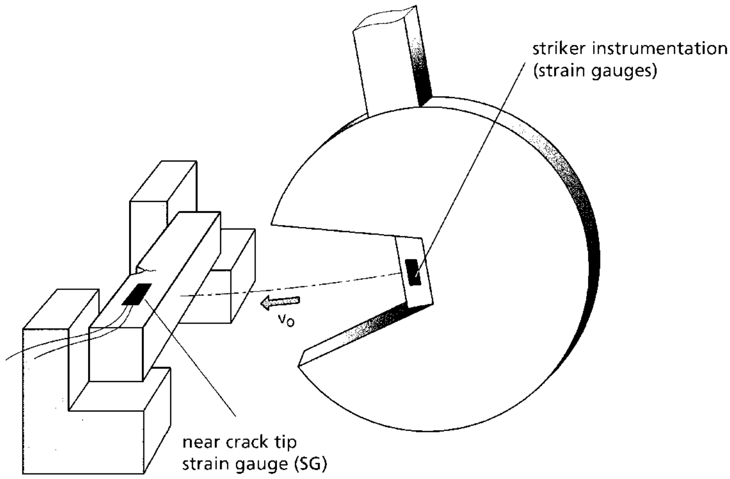

Figure 1: Instrumented impact test

(bandwidth > 100KHz). Also inertia-free optical methods such as the method of caustics in combination with high speed photography are applicable [6-9]. The involved effort in these direct measuring techniques is relatively high, and hence indirect methods with lower effort have been developed to predict the crack tip loading history of high rate tests. One such scheme is to treat the specimen and machine compliance as a spring-mass model and thus correct the striker load to determine the load in the specimen [10]. Similar analyses have been proposed using various approximations and numerical schemes (see e.g. [11, 12]).

To further reduce the effort to determine the impact fracture toughness K_{Id} the method of “Impact Response Curves (IRC)” was introduced [13,14]. This procedure is based on a pre-determination of the crack tip loading history, $K_I^{dyn}(t)$, e.g. by the optical method of caustics or by strain gauge instrumentation close to the crack tip. This curve has to be determined each time for new impact situations with different specimen sizes or different materials. In order to extend the range of applicability to various materials, specimen sizes and testing conditions the method of “Dynamic Key Curves (DKC)” has been developed [7,15]. Based on a simple spring-mass model and basic measurements in model experiments, general rules have been developed to transfer these results to arbitrary materials and a wide range of testing conditions [7,15].

PRINCIPLE OF THE DKC-METHOD

It is the basic assumption of the DKC-method that the crack tip loading history $K_I^{dyn}(t)$ of three point bend impact tests can be separated into a quasi-static part, $K_I^{qs}(t)$, and a dynamic correction function, $k^{dyn}(t)$ as sketched in Fig. 2 and described by:

$$K_I^{dyn}(t) = K_I^{qs}(t) * k^{dyn}(t). \qquad (1)$$

The first term, $K_I^{qs}(t)$, can be easily calculated by an analytically derived equation, which results from a simple spring-mass model [7,15]. The second term, $k^{dyn}(t)$, was determined once in model experiments by the evaluation of caustics which were obtained by utilising high-speed photography [7] resulting in a set of dynamic correction functions which in a normalised form are called “Dynamic Key Curves (DKC)” [7,15].

This DKC-method describes the dynamic crack tip loading history, $K_I^{dyn}(t)$, for special types of SENB specimens and different materials, based only on the knowledge of the testing conditions. If the dynamic crack tip loading history $K_I^{dyn}(t)$ is known or predicted, respectively, then during routine testing the measured time-to-fracture t_f determines the impact fracture toughness according to [13-15]:

$$K_{Id} = K_I^{dyn}(t=t_f). \qquad (2)$$

The time-to-fracture, t_f, is the essential quantity to be determined during the tests. This time can be measured by different techniques, e.g., by strain gauges close to the crack tip [13,16], by conductive paint along the crack path [17-20], or by contactless methods such as electric emission [21].

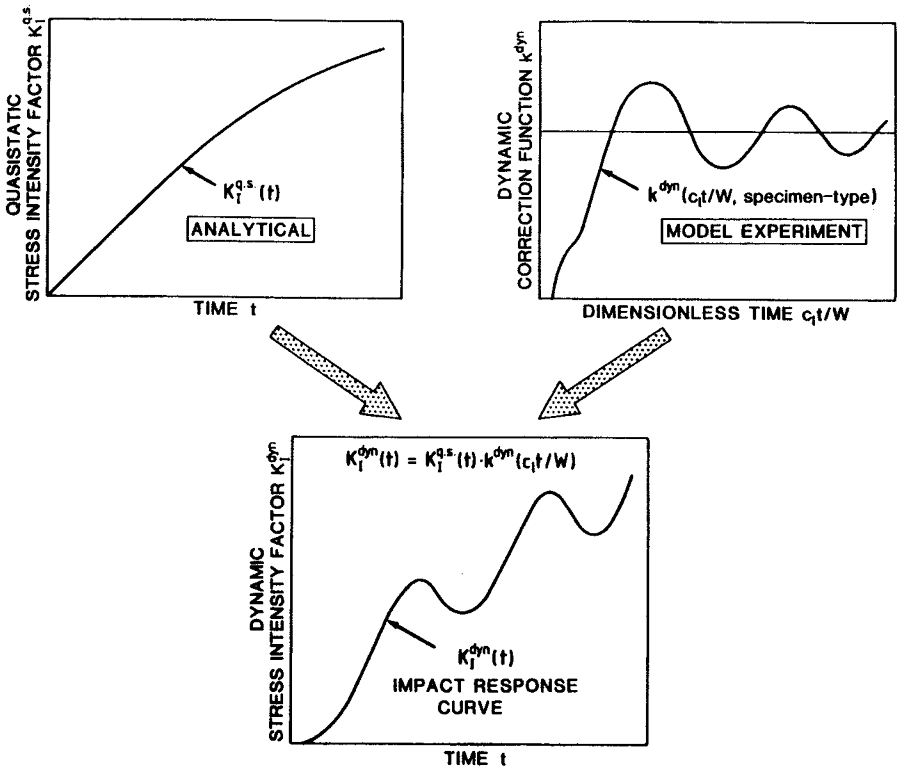

Figure 2: Principle of the DKC-method (schematic)

The DKC-method has been successfully applied to different materials such as steels [15], plastics [9] and ceramics [19,20]. However, there might be some limitations of the applicability for materials with strongly strain-rate dependent elastic moduli. The DKC-method should be considered as an engineering approach to determine the impact fracture toughness K_{Id}, even at short times-to-fracture where quasi-static procedures are no longer applicable.

Basic Equations

Provided that the impact energy is large compared to the consumed fracture energy then the impact fracture toughness can be determined from three point bend impact tests by the measured time-to-fracture, t_f, and the following simplified equation [7,9,15] where a relative support distance S/W = 4.0 – 4.2 is considered:

$$K_{Id} = \frac{E\,S\,f}{4\,W^{3/2}\,C_s^*(1+C_m/C_s)}\left(v_o t_f\right).\,k^{dyn}(t=t_f) \tag{3}$$

$k^{dyn} = k^{dyn}(c_l t/W)$ = dynamic key curve (see next section),

E = elastic modulus of the specimen (it is convenient to use a modulus determined in vibration tests or an estimated one. An uncertainty of 5% is acceptable.),

f = $f(a_o/W)$ is the well known static relationship for K_I-determination of three point bend specimens according to Srawley [24] and ASTM E 399:

$$f(\alpha) = \frac{6\,\alpha^{\frac{1}{2}}\,[1.99-\alpha\,(1-\alpha)(2.15-3.93\alpha+2.7\alpha^2]}{(1+2\alpha)(1-\alpha)^{\frac{3}{2}}} \qquad \text{with } \alpha = a_o/W = \text{relative crack length,}$$

C_s^* = $C_s^*(\alpha)$ = EBC_s is the dimensionless specimen compliance after Bucci et al. [25]:

$$C_s^*(\alpha) = 20.1 + 135\alpha^2\begin{pmatrix}1-2.11\alpha+8.76\alpha^2-19.9\alpha^3+\\ 41.4\alpha^4-67.7\alpha^5+92.1\alpha^6-76.7\alpha^7+35.6\alpha^8\end{pmatrix}.$$

C_s = C_s^*/EB = specimen compliance as calculated from C_s^*,

C_m = machine compliance (details see chapter “loading devices”),

c_1 = longitudinal wave propagation velocity for plane stress: $c_1 = \sqrt{E/[\rho(1-v^2)]}$ with ρ = mass density and ν = Poisson's ratio (c_1 = 1766 m/s for Araldite B).

Dynamic Key Curve $k^{dyn}(c_l t/W)$

For the special type of three point bend specimen with a_o/W=0.3, L/W=5.5 and S/W=4.0, which was known to have reduced dynamic effects during impact according to [7,15], the dynamic key curve k^{dyn} is shown in Fig. 7 taken from [7,15]. Three different time ranges have to be considered and the corresponding k^{dyn}-values are given by:

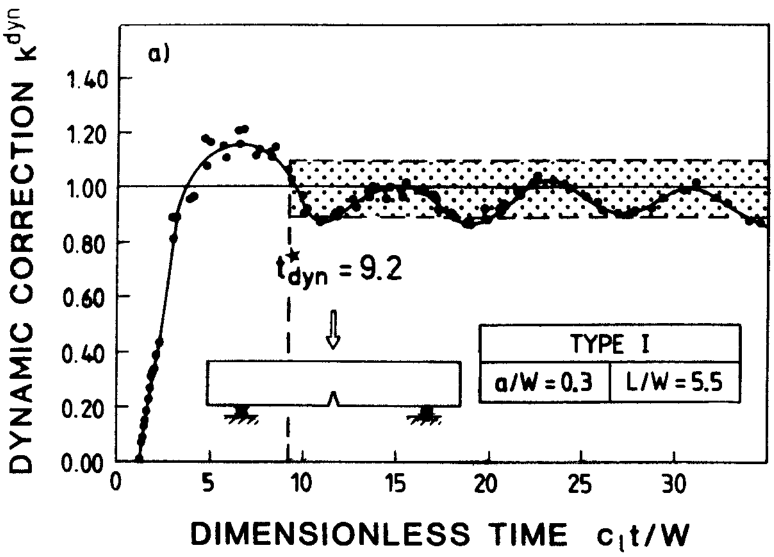

Figure 3: Dynamic Key Curve (DKC) for a bend specimen with a_o/W=0.3, S/W=4 and L/W=5.5

a) Initial time range $0 < t < 1.18\ W/c_l$:

$$k^{dyn} = 0 \tag{4a}$$

Due to wave propagation effects no crack opening will occur in this time range, but some crack closure caused by compressive waves [7,8]. Crack opening was observed only, when the first shear wave front approaches the crack tip [7,8]. The corresponding time $t_{f,min} = (W-a_o)/c_t$ (= $1.18W/c_l$ for ao/W=0,3) is a lower limit for observable times-to-fracture. For a specimen made from Araldite B (c_t=1022 m/s, W=10mm, a_o=3mm) the calculated threshold of $t_{f,min} = 7\ \mu s$ was confirmed experimentally at IWM [19].

b) Fully dynamic time range $1.18\ W/c_l < t < 9.2\ W/c_l$:

$$k^{dyn} = -0.9096 + 0.8176(c_l t/W) - 0.1005(c_l t/W)^2 + 0.003765(c_l t/W)^3 \tag{4b}$$

For the chosen type of specimen this is roughly the time range of the inertia peak. A dynamic evaluation with k^{dyn} as given by eq. (4b) has to be applied, if fracture is occurring in this time range.

c) Intermediate and quasi-static time range $t > 9.2\ W/c_l$:

$$k^{dyn} = 1 \tag{4c}$$

can be used approximately in equation (3).

EXPERIENCE WITH THE DKC-METHOD DURING AN ESIS ROUND ROBIN

During a session of ESIS TC4 in Sardinia in 1992 it was decided to investigate the applicability and accuracy of the DKC-method by a round robin exercise. This exercise focussed on the determination of the impact fracture toughness K_{Id} of plastics at high rates of loading at impact velocities "> 1m/s". For reasons of practical application a simplified version of the DKC-procedure was prepared [22]. This first draft served as a guideline for a European ESIS TC4 round robin exercise and the results are presented here. A revised version considering the experience obtained during this round robin is now available [23]. The participants who contributed to this exercise are given in Table 1.

Materials

It was agreed to investigate two materials which cover a wide range of toughnesses. Furthermore, both materials should have different strain rate sensitivity. As an example of a tough and strain rate sensitive material a

TABLE 1
PARTICIPANTS IN THE ESIS TC 4 ROUND ROBIN ">1 m/s" AND OBTAINED C_M-VALUES

Participants	Organisation	PVC: C_m (m/MN)	Araldite: C_m (m/MN)
Ph. Bèguelin	EPFL, Lausanne (CH)	0,33	0,22
W. Böhme, M.Hug, T. Gerster	IWM, Freiburg (D)	0,22	0,20
Ir. A. Cervenka	SHELL, Arnhem (NL)	---	---
Ir. J.C. Dekker	University, Delft (NL)	---	0,12
Z. Major	University, Leoben (A)	0,24	0,24
D.R. Moore	ICI, Wilton (UK)	0,24	0,20
P.E. Reed	University, Twente (NL)	0,23	---
J.G. Williams, M. Chong	Imperial College, London (UK)	0,19	0,19

modified PVC (grey) was provided by Prof. A. Pavan, Milan. The same material was investigated during a corresponding round robin at velocities of 1 m/s. As an example for a brittle and not very strain rate sensitive material the epoxy Araldite B was provided by IWM, Freiburg.

Size of Specimens and Preparation

According to the guideline three point bend specimens with reduced dynamic effects were chosen, i.e. with $a_o/W = 0.3$, $L/W = 5.5$ and $S/W = 4.0$. Furthermore, it was decided to use specimens with dimensions 10 mm $\times$ 10 mm $\times$ 55 mm corresponding to standardised Charpy specimens. The participants were told to take care on the rectangularity of the specimens to enable a perfect line-contact at both impacting tup and anvils. The PVC-specimens had to be precracked by sharpening an initial notch with a sliding razor blade and the epoxy-specimens by impact tapping up to initial cracks of a length of 3 mm.

Loading Devices

There was no restriction on the use of testing devices, except that the SENB-specimens must be loaded in three point bending. No damping pads were allowed. Common pendulums, drop-weight towers and servo-hydraulic testing machines could be used to perform the impact tests.

Since the quasi-static part of the DKC-approach is based on displacements, the compliance of the loading system has to be taken into account. According to the guideline, the participants determined the compliances by pre-experiments with un-notched specimens at reduced velocity v_o of about 0.2 - 0.5 m/s from the slope of the mean load line, dP/dt_{MLL} [23].

The machine compliance C_m was considered in an integral manner, i.e. including the contact-regions between the machine and the specimen (i.e the contact-stiffness), which for tests with plastics are usually the most compliant parts of the system apart from the specimen itself. The obtained C_m values are listed in Table 1. Besides two results these values differ not very much and are close to 0.2 m/MN (a variation of 20% would be of minor importance on the final evaluation). As expected, similar contact radii result in similar C_m-values.

Time-to-fracture determination

The time-to-fracture, t_f, is the essential quantity to be determined during the tests. This characteristic time is defined by the difference between the moment of impact, t_o, and the time at fracture initiation, t_i:

$$t_f = t_i - t_o. \qquad (5)$$

For the DKC-method the moment of impact, t_o, is defined as that time, when the load-transfer to the specimen starts, neglecting initial settling effects. The moment of fracture initiation, t_i, is that time, when the crack starts to propagate. Especially for short times-to-fracture (< 100 µs) the measured times should be corrected, e.g. due to wave propagation effects and depending on the measuring technique [23].

The participants of the round robin were free to use appropriate methods to detect these times. Four simultaneously measured signals of an experiment at IWM are presented in Fig. 4a)-d). Some participants determined t_o from the increase of the force signal measured at the striker (see Fig 4a). Other participants determined t_o from signals of conductive strips on the specimens at the region of the striking tup (see Fig. 4c). The time at initiation of fracture, t_i, was determined by several participants with strain gauges attached on the specimens near the crack tip (see Fig. 4b). Other participants used conductive paint across the crack path (see Fig. 4d).

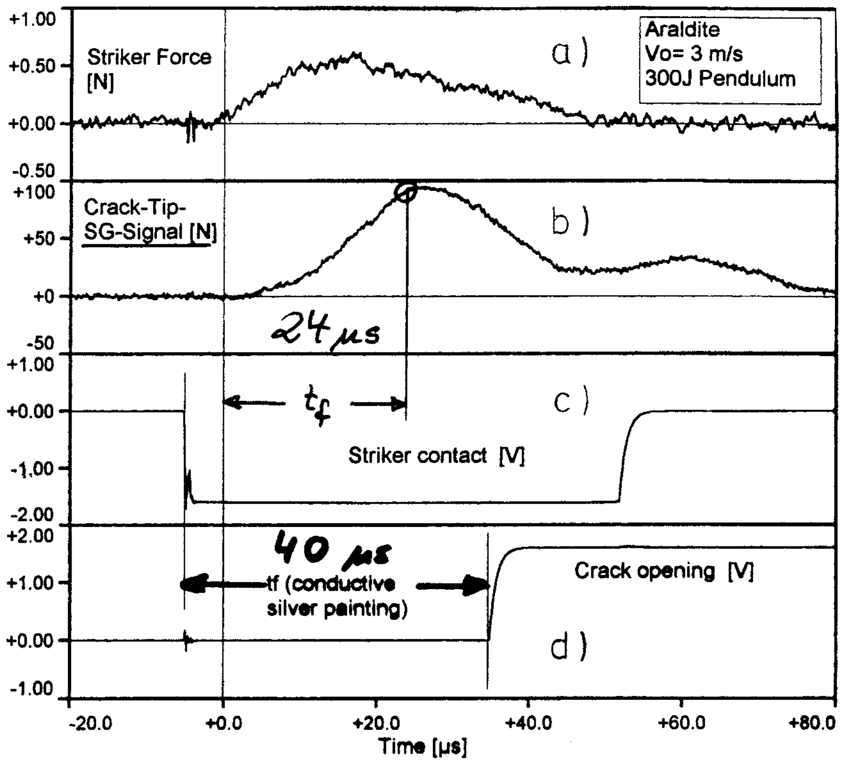

Figure 4a)-d): Example of measured signals during an impact test

Reference data

Some experiments were performed at IWM with strain gauges attached close to the crack tip in order to get reference data. A quasi-dynamic calibration-factor was determined at reduced velocity of 0.5 m/s by comparison of the strain signal with the externally measured striker force. This calibration-factor was then applied at higher rates of loading to evaluate the impact fracture toughness K_{Id} from the fracture initiation point of the strain gauge signals. The validity of this procedure has been verified several years ago by comparison with results of caustics obtained by high speed photography (see [16]).

Results of PVC

The results for impact tests with PVC are given in Fig. 5. The filled black circles are the reference data. All other data were evaluated by the IWM-program for DKC-evaluations using the input-data of the individual laboratories in order to avoid some differences of the individual evaluations. The corresponding times-to-fracture vary between about 400µs at 1 m/s down to about 30 µs at 8 m/s. The significant amount of scatter might be due to different procedures to measure the time-to-fracture. Most of the data are close to the reference data and show clearly a decreasing toughness with increasing loading rate.

Results of Araldite B

The results for impact tests with Araldite B are given in Fig. 6. Again, the filled black circles are the reference data. All other data were evaluated by the IWM-program for DKC-evaluations using the input-data of the individual laboratories. The corresponding times-to-fracture vary between about 150 µs at 1 m/s down to about 20 µs at 8 m/s. The IWM-data show a reasonable agreement with the reference data. The results of the other participants are on the average about 30% higher. Nevertheless, these results indicate, that the toughness of this epoxy is less dependent on strain rate than PVC.

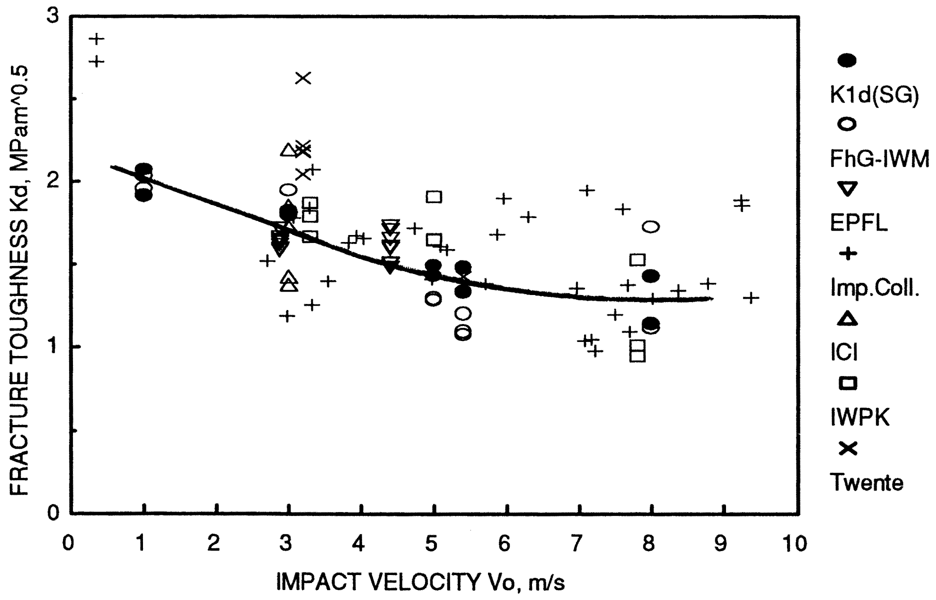

Figure 5: Impact fracture toughness data of PVC(grey)

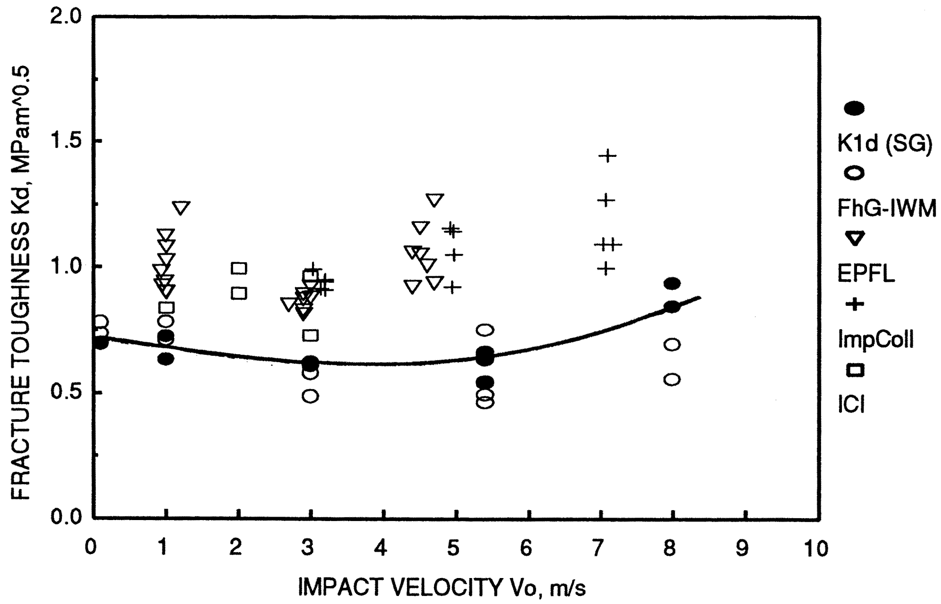

Figure 6: Impact fracture toughness data of Araldite B

DISCUSSION AND CONCLUSION

For the investigated high loading rates and impact velocities > 1 m/s the evaluated toughness values are more meaningful than misleading quasi-static evaluations of externally measured striker forces, especially for PVC. For the epoxy most of the obtained values are systematically 30% too high compared to more precise direct measurements. Two possible reasons were considered:

- One reason for the systematic deviations could be the pre-cracking procedure: lower bound toughness values will be observable only with natural sharp cracks. Especially for an epoxy it is sometimes very difficult to produce a natural crack, even by impact tapping. An improvement and less scatter is expected from an improved precracking procedure.

- Another systematic deviation could be caused by different time-to-fracture measurements and specific time-corrections were not included in the first draft of the guideline. More precise definitions to measure the time-to-fracture t_f are given in the new version and time-corrections are now included [23].

The round robin exercise demonstrated in principle the application of the DKC-method on the determination of the impact fracture toughness K_{Id} of plastics at high rates of loading. In detail the following conclusions can be drawn:

- The equations to determine K_{Id} are meaningful.
- The determination of the machine compliance is sufficiently accurate.
- The DKC-method applies well for plastics such as PVC,
- at different loading rates, and
- at different levels of toughness.

The method of Dynamic Key Curves (DKC) has to be considered as an engineering approach. The accuracy of this approach is estimated by current experience to be about 10 %. This is often acceptable, especially at high impact velocities, where external force-measurements are completely misleading. More complicated local measurements close to the events of interest would be necessary to achieve higher precision, but the effort will be greatly increased.

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