
MPK – Mechanical Testing of Plastics



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Testing of Plastics

Instrumented Charpy Impact Test (ICIT)

Procedure for Determining the Crack Resistance Behaviour Using the Instrumented Impact Test



Accredited test laboratory according DIN EN ISO/IEC 17025

MPK-Procedure

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Part I and Part II

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Procedure for Determining the Crack Resistance Behaviour Using the Instrumented Impact Test

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1 Scope

The instrumented Charpy impact test is used for determining properties related to the impact strength of plastics. It is an addition to the conventional pendulum impact test described in ISO 179 [1]; it is carried out on metal-blade-notched specimens [2, 3]. The plastics on which it can be used range from brittle thermosets to high-impact polymer blends. Both the load and the deflection signals are recorded, and the impact energy is divided into elastic and plastic part. If the requirements on the specimen size and on the notch are satisfied, geometry-independent material parameters can be calculated. These parameters can be used for control and for quality assurance as well as for research and development.

2 Short description of the procedure

The testing of tough polymers is carried out by a pendulum Charpy impact tester of type PSW 4 according to ISO 13802 [4], with 4 J work capacity at maximum fall height. A single-edge-notched square specimen is broken by the impact of the pendulum hammer. The striker, which has an edge on its impact side, is fastened to a tubular pendulum arm. After release, it moves in a circle and transfers part of its kinetic energy to the specimen at the lowest point of its trajectory.

The registration of the load signal is carried out by strain gauges positioned directly on the striker edge and arranged as a Wheatstone bridge. The output is amplified by a two-stage amplifier.

The measuring device is able to register either load–time ($F-t$) diagrams or load–deflection ($F-f$) diagrams. In the case of load–time diagrams, the deflection can be calculated from Newton's second law. In a first integration step (1), the velocity can be determined, and in a second integration step (2), the deflection f of the specimen as a function of time:

$$v(t) = v_0 - \frac{1}{m} \int_0^t F(\tau) d\tau \quad (1)$$

$$f(t) = \int_0^t v(\tau) d\tau \quad (2)$$

An optical device is used for the measurement of the deflection. A diaphragm fastened to the pendulum hammer, in the path of a beam of light, moves with the motion of the pendulum. Depending on the movement, a greater or lesser intensity of light reaches a phototransistor. The resulting signal is amplified for further analysis.

Both the load signal and the deflection signal are transferred to a storage oscilloscope. The oscilloscope is used as an analogue to digital converter and as a monitor for an initial visual interpretation of the load–time and load–deflection curves. For further analysis, the digital signals are transferred to a personal computer. The characteristic values F_{\max} , F_{gy} , f_{\max} , and f_{gy} , as shown in **Fig. 1**, are used for interpretation.

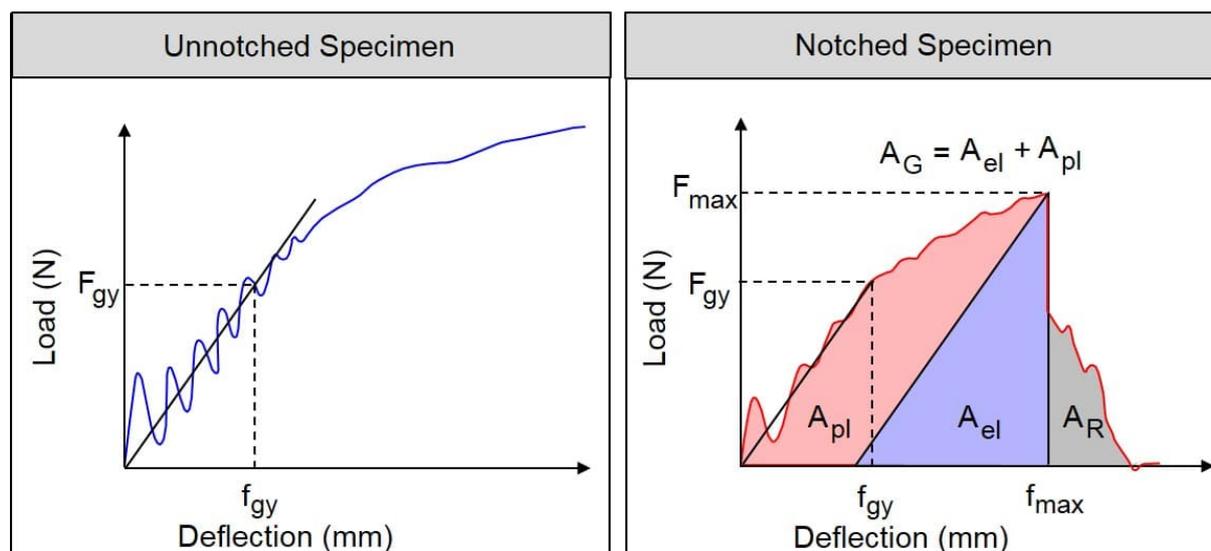


Fig. 1. Characteristic load–deflection diagram with crack propagation energy

Part I:

3 Determination of Characteristic Fracture Mechanics Parameters for Resistance against Unstable Crack Propagation

3.1 Summary of the Testing Method

The aim of this testing method is to determine characteristic fracture mechanics parameters which quantify the resistance of the material to unstable crack propagation. This method is only valid for single-edge-notched bend (SENB) specimens of polymers with a sharp crack. Starting from load–deflection diagrams, stress intensity factors K_{Id} , J values J_{Id} and critical crack-tip-opening displacement values δ_{Id} can be calculated.

3.2 Specimens

As stated in ISO 179 [1], specimens of thickness $B = 4$ mm, width $W = 10$ mm and length $L = 80$ mm are preferred. The notching is carried out preferably with metal blades by a pneumatic notching device on the narrow side of the specimen up to an initial crack length of 2 mm. The support distance is $s = 40$ mm. The specimens must not be twisted and both pairs of vertical surfaces should be parallel. The surfaces must be free of scratches, craters, depressions and flashes.

Before testing the specimens, the thickness and width must be measured with a precision of 0.01 mm. The results must be recorded.

At least 10 specimens should be tested, after storage in the testing room for 12 h.

3.3 Testing

The test should be carried out under standard conditions; if deviations occur or if variation from the standard conditions is necessary, this must be reported. The specimen must be arranged on the supports so that the striker edge hits the middle of the specimen. The notch must lie in the plane in which the pendulum swings, on the opposite

side of the specimen from the striker edge. The arrangement is shown in **Fig. 2**. The pendulum velocity should be 1.0 or 1.5 m/s.

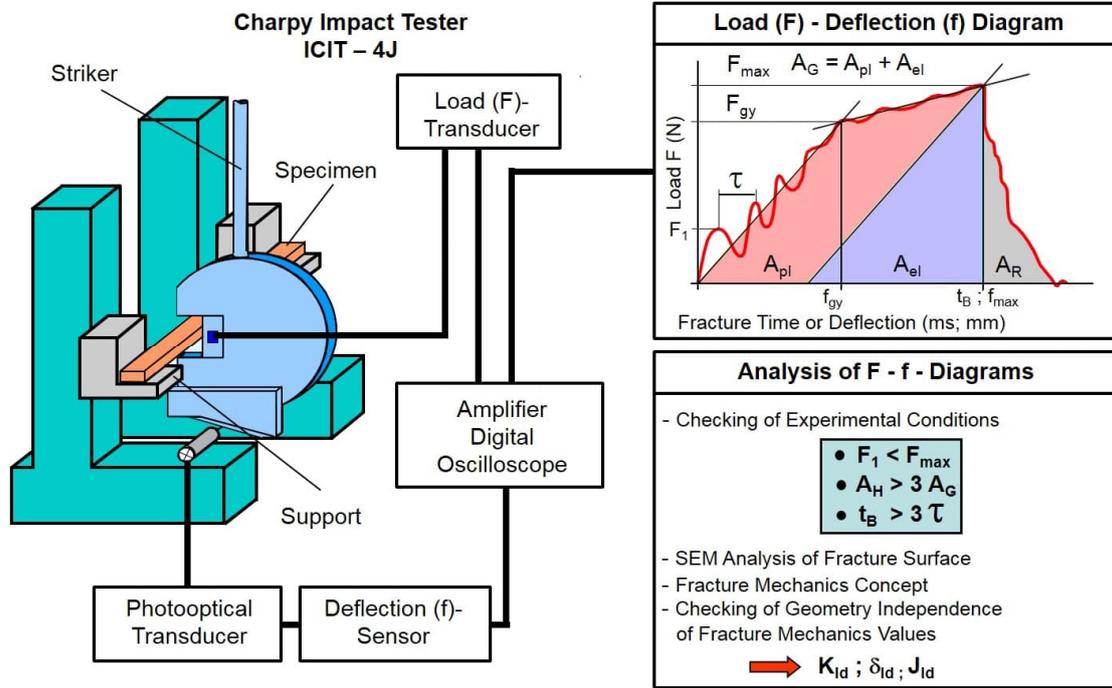


Fig. 2. Fracture mechanics testing device for the instrumented impact test

The recording of the load–deflection curves is carried out as described in the operating instructions.

The determination of the dynamic flexural modulus E_d and the dynamic yield stress σ_d are carried out on at least five unnotched specimens. For this purpose, the linear part of the load–deflection diagram is used, i.e., after finding the yield point, E_d and σ_d can be calculated from (3) and (4).

$$E_d = \frac{F_{gy} s^3}{4BW^3 f_{gy}} \quad (3)$$

$$\sigma_y = \frac{3F_{gy} s}{2BW^2} \quad (4)$$

3.4 Utilization

3.4.1 General

For utilization of the test data, the loads and deflections shown in **Fig. 1** are determined using the ‘Instrumented Charpy Impact Test’ software. In principle, the energy, i.e. both A_G and A_R and also $(A_G + A_R)$, can be determined. After inputting the geometrical details of the specimens, including the initial crack length a , the physical crack length augmented to account for crack tip plastic deformation (the fracture mirror length) a_{BS} , the dynamic yield stress σ_y and the dynamic flexural modulus E_d , the fracture mechanics parameters K_{Qd} , J_{Qd} and δ_{Qd} can be calculated. Both the input values and the calculated values are printed and added to the testing protocol; the F – f diagrams can also be plotted.

3.4.2 Determination of Fracture Mechanics Parameters

For the impact toughness evaluation of polymers by this procedure, the following values are preferred:

1. Dynamic Stress Intensity Factor K_{Qd} [5].

$$K_{Qd} = \frac{F_{\max} s}{BW^{3/2}} f\left(\frac{a}{W}\right), \quad (5)$$

where

$$f\left(\frac{a}{W}\right) = \frac{3}{2} \left(\frac{a}{W}\right)^{1/2} \left[\frac{1.99 - \frac{a}{W} \left(1 - \frac{a}{W}\right) \left(2.15 - 3.93 \frac{a}{W} + 2.7 \left(\frac{a}{W}\right)^2\right)}{\left(1 + 2 \frac{a}{W}\right) \left(1 - \frac{a}{W}\right)^{3/2}} \right] \quad (6)$$

and

$$f\left(\frac{a}{W}\right) = 2.9 \left(\frac{a}{W}\right)^{1/2} - 4.6 \left(\frac{a}{W}\right)^{3/2} + 21.8 \left(\frac{a}{W}\right)^{5/2} - 37.6 \left(\frac{a}{W}\right)^{7/2} + 38.7 \left(\frac{a}{W}\right)^{9/2}. \quad (7)$$

2. J Value J_{Qd} .

Following this procedure, J values can be evaluated by two methods.

- Evaluation method of Sumpter and Turner – J^{ST} [6]:

$$J_{Qd}^{ST} = \eta_{el} \frac{A_{el}}{B(W-a)} + \eta_{pl} \frac{A_{pl}}{B(W-a)} \frac{W - a_{eff}}{W - a}, \quad (8)$$

where

$$\eta_{el} = \frac{2F_{gy} s^2 (W - a)}{f_{gy} E_d B W^3} f^2\left(\frac{a}{W}\right) (1 - \nu^2) \quad (9)$$

and

$$\eta_{pl} = 2 - \frac{\left(1 - \frac{a}{W}\right) \left(0.892 - 4.476 \frac{a}{W}\right)}{1.125 + 0.892 \frac{a}{W} - 2.238 \left(\frac{a}{W}\right)^2}. \quad (10)$$

- Evaluation method of *Merkle and Corten* – J^{MC} [7]:

$$J_{Qd}^{MC} = G_1 + \frac{2}{B(W-a)} [D_1 A_G + D_2 A_K - (D_1 + D_2) A_{el}] \quad (11)$$

where

$$G_1 = \frac{K_{I0}^2}{E} (1 - \nu^2) \text{ for plane strain state,} \quad (12)$$

$$D_1 = \frac{1 + \gamma}{1 + \gamma^2}, \quad (13)$$

$$D_2 = \frac{\gamma(1 - 2\gamma - \gamma^2)}{(1 + \gamma^2)^2}, \quad (14)$$

$$\gamma = \frac{1.456(W - a)}{s}, \quad (15)$$

$$A_K = F_{\max} f_{\max} - A_G. \quad (16)$$

3. Critical Crack-Opening Displacement δ_{Qd} [8, 9].

$$\delta_{Qd} = \frac{1}{n}(W - a) \frac{4f_{\max}}{s} \quad (17)$$

and

$$\delta_{Qdk} = \frac{1}{n}(W - a) \frac{4f_k}{s}, \quad (18)$$

where

$$f_k = f_{\max} - f_b. \quad (19)$$

The determination of further characteristic values depends on technical requirements. These values must be reported in the testing protocol.

3.4.3 Validity Check of the Characteristic Fracture Mechanics Parameters

3.4.3.1 Check of the Experimental Conditions

For the determination of characteristic fracture mechanics parameters using the Charpy impact test, the following experimental conditions must be checked [10–14].

- Time to fracture t_B .

The time to fracture t_B must be greater than or equal to 2.3 to 3 times the inertial oscillation period τ of the specimen to ensure a quasi-static state:

$$t_B \geq 2.3 \dots 3\tau \quad (20)$$

Any further decrease in t_B causes problems in evaluation and must be avoided.

- Energy absorption ($A_G + A_R$).

The checking of the energy absorption is carried out in accordance with (21), according to which the maximum energy of the pendulum must be greater than three times the absorbed energy of the specimen:

$$A_H > 3(A_G + A_R) \quad (21)$$

- Inertial peak.

The inertial load F_1 must be smaller than the maximum impact load F_{\max} :

$$F_1 < F_{\max} \quad (22)$$

3.4.3.2 Requirements on the Specimen Geometry

For the determination of geometry-independent characteristic fracture mechanics parameters, a plane strain state must be ensured, i.e. the geometrical values of thickness

B , notch depth a and ligament length $(W - a)$ must be bigger than a certain value. For this to be the case, the following relationships must be fulfilled.

- Dynamic fracture toughness.

$$B; a; (W - a) \geq \beta \left(\frac{K_{Id}}{\sigma_d} \right)^2, \tag{23}$$

Where-

$$\beta = 3466 K_{Id}^{-1.73} \tag{24}$$

- J value.

$$B; a; (W - a) \geq \varepsilon \frac{J_{Id}}{\sigma_d}, \tag{25}$$

where

$$\varepsilon = 224 J_{Id}^{-0.94} \tag{26}$$

- Critical crack-tip-opening displacement.

$$B; a; (W - a) \geq \xi \delta_{Idk} \tag{27}$$

and

$$B; a; (W - a) \geq \xi \delta_{Idk} \tag{28}$$

where

$$\xi = 3.6 \delta_{Idk}^{-0.83} \tag{29}$$

The functions $\beta = f(K_{Id})$, $\varepsilon = f(J_{Id})$ and $\xi = f(\delta_{Idk})$ have been determined experimentally and are shown in **Figs. 3–5**.

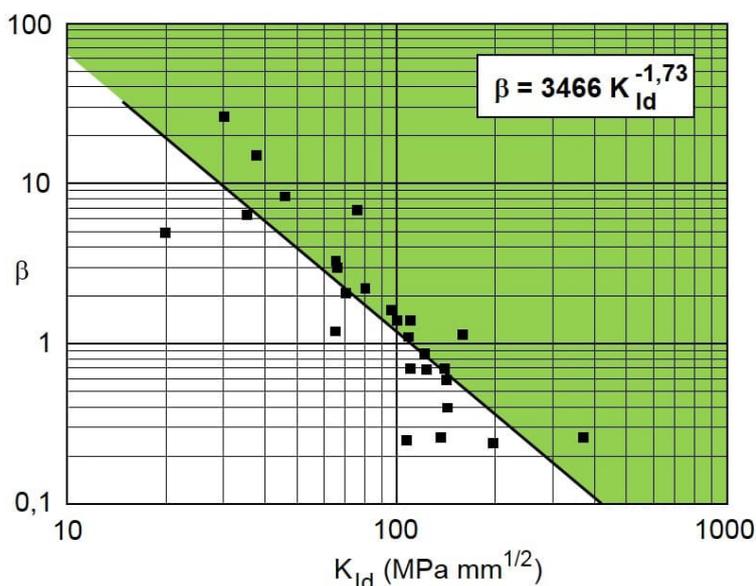


Fig. 3. Requirements on the specimen geometry for the estimation of the dynamic fracture toughness K_{Id} [12, 13]

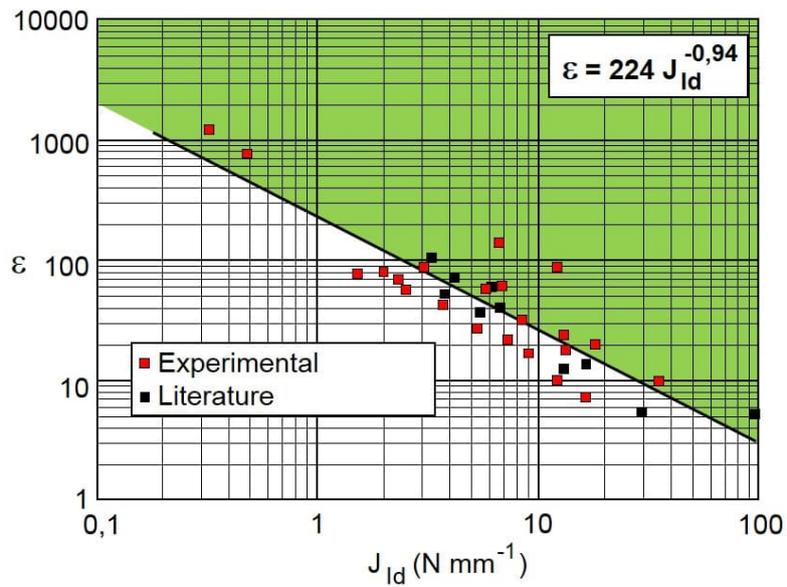


Fig. 4. Requirements on the specimen geometry for the estimation of the J value J_{Id} [12, 13]

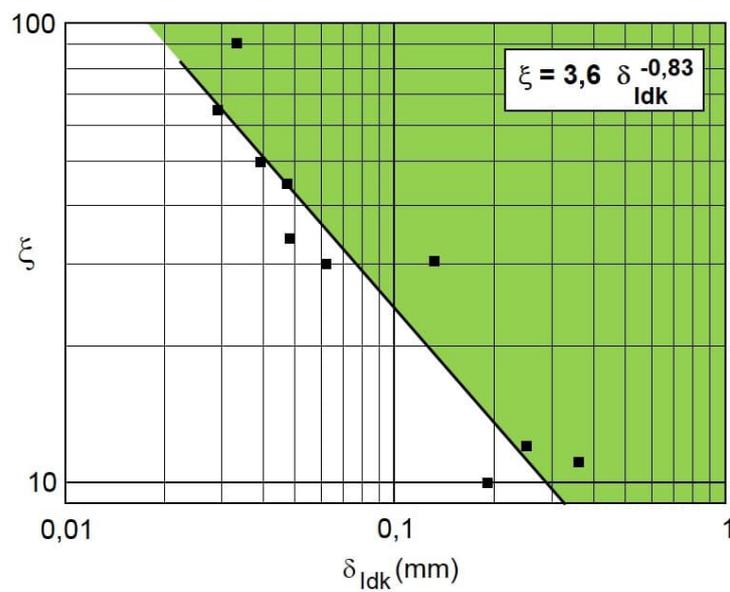


Fig. 5. Requirements on the specimen geometry for the estimation of the critical crack-opening displacement [12, 13]

Part II:

4 Determination of Characteristic Fracture Mechanics Parameters for Resistance against Stable Crack Propagation

4.1 Summary of the Testing Method

The aim of this testing procedure is the determination of fracture mechanics characteristics that quantify the initial process of crack growth and the energy dissipation of the material. This method is only valid for SENB specimens with a sharp crack, and the multiple-specimen method must be used. Starting from load–deflection curves, J and crack-tip-opening displacement values can be determined. These values are plotted versus the crack growth Δa . The data points characterize the resistance of the material against stable crack initiation and propagation [20–23]. By a suitable fitting of the data points, a crack initiation value can be determined and energy-dissipating processes can be quantified.

4.2 Specimens

For the determination of fracture mechanics parameters for resistance against stable crack propagation, the preferred specimen geometry is the same as for the determination of characteristic values for unstable crack propagation; this means the dimensions are thickness $B = 4$ mm, width $W = 10$ mm and length $L = 80$ mm.

The notch is made on the narrow side up to an initial crack length of $a = 4.5$ to 5 mm by a pneumatic device. The support distance is $s = 40$ mm, except when using the support distance method.

Before testing the specimen, the thickness and the width must be measured with a precision of 0.01 mm. The results must be recorded.

For the determination of one dynamic crack resistance curve using the multiple-specimen method, 15 to 20 identical specimens are necessary. They should have been stored for 12 h in the testing room before testing.

4.3 Testing

The test should be carried out under standard conditions; if deviations occur or if variation from the standard conditions is necessary, this must be reported.

The specimen must be arranged on the supports as described in Sect. 3.3. Before the determination of the J – Δa data points themselves, at least one load–deflection diagram must be recorded under the following conditions:

- specimen geometry:
 - $L = 80$ mm
 - $B = 4$ mm
 - $W = 10$ mm
 - $a = 4.5$ to 5.0 mm
- testing conditions:
 - $s = 40$ mm
 - $v_H = 1$ and 1.5 m/s
 - $m_H = 0.955$ kg.

This load–deflection diagram is used as a starting diagram for the actual measurements. After recording this diagram, stable crack growth is produced using one of the following methods, and load–deflection diagrams are recorded in parallel with this.

1. Energy method.

Changing the pendulum hammer energy by varying the pendulum hammer weight or velocity (low-blow technique).

2. Support distance method.

Changing the ratio of support span to specimen width.

3. Specimen length method [24].

Reducing the specimen length L to a length = support span + 0.1 to 0.2 mm oversize.

4. Stop block method [25, 26].

Changing the deflection by using hardened steel bars or by catching the pendulum hammer (Fig. 6).

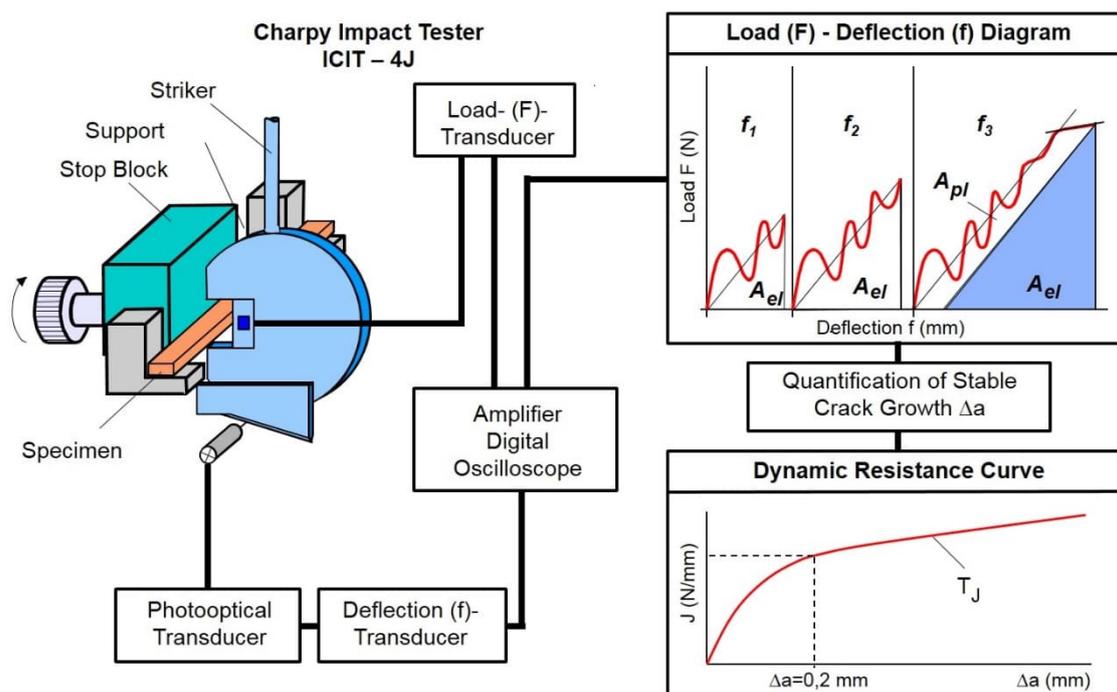


Fig. 6. Fracture mechanics testing device for the instrumented impact test with stop block device

A continuous sequence of measurements from smaller to larger crack growth Δa or in reverse order is useful. The measurements are carried out as long as $F \leq F_{\max}$ of the load–deflection diagram recorded previously.

The recording of the load–deflection curves is carried out as described in the operating instructions.

The final breaking of the specimens is carried out at low temperatures and/or at high testing velocities. After this is done, the amount of stable crack growth is measured by using a light microscope.

The determination of the dynamic flexural modulus E_d and the dynamic yield stress σ_d is carried out in accordance with (3) and (4).

4.4 Utilization

4.4.1 General

For the utilization of the test data, the loads and deflections shown in Fig. 1 are determined using the ‘Instrumented Charpy Impact Test’ software as in Sect. 3.4.1. The

energy required for the crack growth can be determined from the load–deflection diagrams.

After input of the specimen dimensions, the initial crack length a , the amount of stable crack growth Δa , the dynamic yield stress σ_y and the dynamic flexural modulus E_d , the loading parameters J_d and δ_d can be calculated. Both the input values and the calculated values are printed and added to the testing protocol; the F – f diagrams can be plotted, as well as exported as ASCII files.

4.4.2 Determination of the Loading Parameters

For the determination of the loading parameters (J , δ) of the crack resistance curve the following equations are used.

1. J Values.

$$J_d = \eta_{el} \frac{A_{el}}{B(W-a)} + \eta_{pl} \frac{A_{pl}}{B(W-a)} \left\{ 1 - \frac{(0.75\eta_{el} - 1)\Delta a}{(W-a)} \right\}, \quad (30)$$

where

$$\eta_{el} = 0.5 + 5.5 \left(\frac{a}{W} \right) - 5 \left(\frac{a}{W} \right)^2. \quad (31)$$

For the determination of η_{el} , (9) can also be used. The geometrical function η_{pl} can be determined according to (10).

2. Critical Crack-Opening Displacement.

The determination of the critical crack-opening displacements δ_d and δ_{dk} is carried out using the relations (17) and (18).

4.4.3 Determination of Valid Crack Resistance Curves

For the determination of the crack initiation values ($J_{0.2}$, $\delta_{0.2}$), the following evaluation algorithm is used in accordance with ESIS TC4, 'A Testing Protocol for Conducting J -Crack Growth Resistance Curve Tests on Plastics' [27,28].

1. Plot the functions J and $\delta = f(\Delta a)$.
2. Draw lines parallel to the J and δ axis at $\Delta a = 0.05$ mm (Δa_{min} in **Fig. 7**).
3. Determine Δa_{max} using Eq. (32):

$$\Delta a = 0.1(W - a) \quad (32)$$

4. Draw second line parallel to the J and δ axis at Δa_{max} .

5. Check the data point distribution; the data points should be spaced as shown in **Fig. 7**.

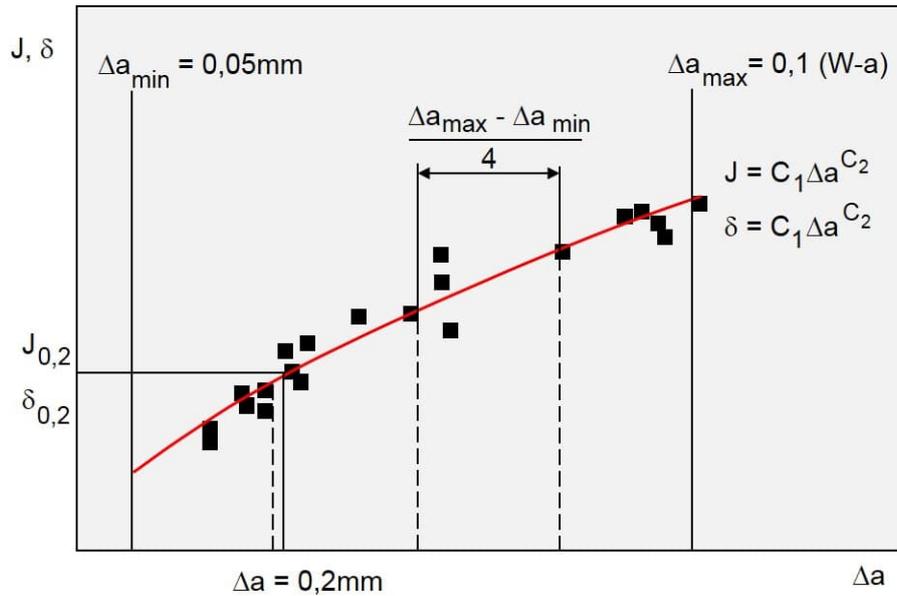


Fig. 7. Validity limits, data point distribution and determination of the crack initiation value

6. Curve fitting.

A fit curve is plotted through the data points falling between the 0.5 mm offset exclusion line and the Δa_{\max} exclusion line, using a power law ((33) or (34)):

$$J \text{ and } \delta = C_1 \Delta a^{C_2} \quad (33)$$

$$J \text{ and } \delta = C_1 (C_3 + \Delta a)^{C_2} \quad (34)$$

7. Checking of the validity of the J and the δ values.

An upper limit to the validity range (J_{\max} or J_G) within which crack growth is considered to be J -controlled must be determined. As seen in **Fig. 8**, this occurs where the fit curve from (33) or (34) intersects either the Δa exclusion line (J_G) or a line drawn parallel to the Δa axis through J_{\max} . The value of J_{\max} is the smaller of the two values in (35):

$$J_{\max} = \frac{(W-a)\sigma_d}{20} \quad \text{and} \quad J_{\max} = \frac{B\sigma_d}{20} \quad (35)$$

The way in which the δ - Δa curve is checked is analogous (Fig. 8), (36):

$$\delta_{\max} = \frac{(W-a)}{50} \quad \text{and} \quad \delta_{\max} = \frac{B}{50} \quad (36)$$

8. Finally, the checking of the slope of the J - Δa curve is carried out at the point J_{\max} or J_G (see **Fig. 8**) according to (37):

$$\omega = \left. \frac{W-a}{J} \frac{dJ}{d(\Delta a)} \right|_{J_{\max} \text{ or } G} \geq 10 \quad (37)$$

When this condition is fulfilled, the J - Δa data points represent a material-specific, geometry-independent crack resistance curve within the area delimited by Δa_{\min} ,

Δa_{\max} , J_{\max} and J_G . If $\omega < 10$ the allowed maximum crack growth Δa_{\max} reduces according to (38):

$$\Delta a_{\max} \equiv \Delta a_1 = \frac{C_2(W - a)}{10} \quad (38)$$

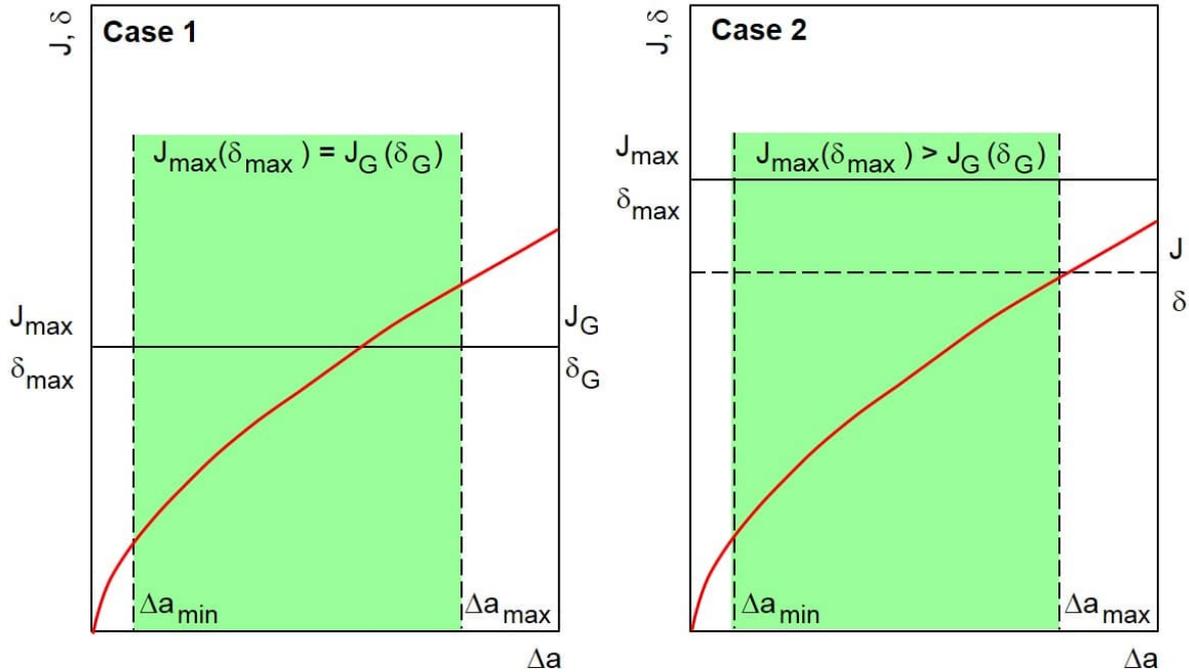


Fig. 8. Validity limits of J -controlled crack growth

The δ - Δa curve also meets all the requirements for a geometry-independent crack resistance curve within the limits Δa_{\max} , Δa_{\min} , δ_{\max} , and δ_G .

9. Determination of crack initiation.

According to this procedure, the crack initiation value is defined as that value of that J or δ which is obtained from the point of intersection between the crack resistance curve and a line parallel to the J or δ axis, respectively, at $\Delta a = 0.2$ mm. These values of $J_{0.2}$ and $\delta_{0.2}$ are valid J and δ values under the following conditions:

- There must be at least one J - Δa or δ - Δa data point between 0.2 and 0.4 mm crack growth.
- $J_{0.2}$ must be smaller than or equal to J_{\max} ; $\delta_{0.2}$ must be smaller than or equal to δ_{\max} .
- The $J_{0.2}$ value must meet the size criterion for validity of the concept of the J -integral (39):

$$B; a; (W - a) > \frac{25J_{0.2}}{\sigma_d} \quad (39)$$

- The $\delta_{0.2}$ value must meet the size criterion for validity of the concept of the CTOD (40):

$$B; a; (W - a) > 25\delta_{0.2} \quad (40)$$

- The slope of the J - Δa curve at $\Delta a = 0.2$ mm must be smaller than the yield stress σ_y of the material ($\sigma_y = \sigma_d$ is used).
- None of the specimens should exhibit brittle cleavage fracture before maximum load.

4.4.4 Determination of JT_J

The quantification of the energy dissipation processes is carried out on the basis of the JT_J concept of Will and Michel [29–32] using the following formalism:

1. Plotting the data points.
2. Fitting the J - Δa data points to a function like the following one:

$$J = \sqrt{C_4 + C_5 \Delta a} \quad (41)$$

3. Checking the validity of the crack resistance curve:

- (a) Checking of the slope criterion at the maximum amount of stable crack growth determined experimentally Δa_{exp} (42):

$$\omega = \frac{W - a}{J} \frac{dJ}{d(\Delta a)} \Big|_{\Delta a_{\text{exp}}} \gg 1 \quad (42)$$

- (b) If there are differences between the data points and the regression function determined at higher values of crack growth, Δa_{max} and ω_{exp} must be determined with the help of a J^2 - Δa diagram (**Fig. 9**). After doing this, a new fitting of the data points must be carried out for $\Delta a \leq \Delta a_{\text{max}}$ according to (41).

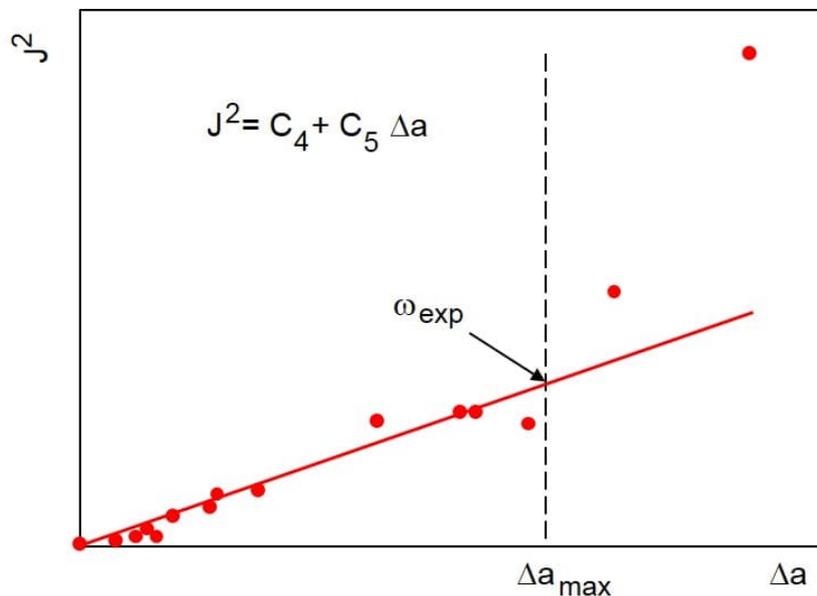


Fig. 9. Experimental determination of ω

4. Determination of the value of JT_J .

The determination of the JT_J value follows (43). This parameter is a geometry-independent fracture mechanics parameter which allows a direct comparison of crack resistance curves in relation to the resistance of the material against crack growth, presupposing that the resistance curve is valid according to (42):

$$JT_J = \frac{1}{2} C_5 \frac{E_d}{\sigma_d^2} \quad (43)$$

The tearing modulus T_J [33] is calculated in accordance with (44), and $J = f(\Delta a)$ according to (41):

$$T_J = \frac{dJ}{d(\Delta a)} \frac{E_d}{\sigma_d^2} \quad (44)$$

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