PROCEDURES FOR THE DETERMINATION OF THE STATIC AND DYNAMIC FRACTURE BEHAVIOUR USING THREE-POINT BEND SPECIMENS

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The convenient and cheap instrumented precracked Charpy impact test for determination of dynamic fracture toughness suffers many disadvantages and limitations.

In this paper several testing procedures and equipment to determine the dynamic and static fracture toughness will be considered. By means of the new impact tester some of the procedures are tentatively verified utilizing three point bend (3PB) and Charpy-type specimens. The comparison with the static results obtained from the stable J_R-Δa-curve analysis is performed.

INTRODUCTION

The Charpy impact test has for a long time been widely used as a screening test in quality control. It is easy and fast to perform and the specimens are cheap to manufacture. The test has, however, some limitations. The ordinary Charpy specimen has a blunt notch, making the specimen difficult to use for determination of fracture mechanics parameters. The quantity measured in the test is the total fracture energy, giving no information about the amount of energy needed for crack initiation. Inertia effects on the specimen often have a large influence on the measured fracture energy. Some of the limitations can be to overcome, e.g. the specimen can be equipped with a fatigue precrack and the hammer can be instrumented to give a forces time signal. This in some cases makes dynamic initiation fracture thoughness determination possible. Many limitations, however, remain. The use of a fatigue precracked specimen limits the ligament length to typically 5 mm. This strongly limits the measuring capacity of the specimen. Initiation values are still hard to obtain. The inertia effects are still prevailing and it is impossible to directly determine the specimen COD during a test.

To increase the applicability of the impact test a new pendulum type of instrumented test apparatus (patented in Finland, Europe and US) has been designed and constructed /1/ at the Technical Research Centre of Finland (VTT).

This tester based on the inverted test geometry is equipped with a fully computerized data acquisition system and an optical crack opening displacement device e.g. to define the crack initiation stage. Further, the available initial impact energy is doubled compared to the conventional

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standard (300 J) impact tester making it possible to use larger (110 x 20 x 10) than the normal Charpy-size (55 x 10 x 10) specimens.

In this paper testing procedures and equipment to determine the dynamic fracture toughness, in addition to the static one, are discussed. To verify the dynamic test procedures some preliminary experimental tests have been performed using the new impact tester utilizing three point bend (3 PB) and Charpy-type specimens. The results have been compared with results on similar tests conducted with the fully computerized servohydraulic testing system for stable J_R-Δa-curve analysis.

DESCRIPTION OF TESTING PROCEDURES

Static testing

Equipment. The computer interactive testing system used for static fracture toughness measurements utilizes the unloading compliance method on single specimens to determine crack growth resistance curves based on the J-integral concept (J_R-Δa curves) for ductile materials /2, 3/. By means of the J_R-Δa curve, values of J_{IC}, the elastic plastic fracture toughness, and T_{MAT}, the tearing modulus are routinely determined. Alternatively, similar parameters based on crack tip opening displacement (CTOD) can be determined as well. For specimens behaving in a nearly linear manner a check for critical stress intensity (K_{IC}) is made.

The system consists of a microcomputer, a 250 kN servohydraulic testing machine, a data acquisition/control unit, a digital voltmeter and several auxiliary devices for real time data acquisition as well as for data storage. The block diagram of the system hardware is shown in Fig. 1. The system as a whole meets the requirements of ASTM standard E813-81 for determining elastic-plastic fracture toughness J_{IC}.

The test piece geometries for which the software is available are compact tension- (CT-), round compact tension- (RCT-), three point bend- (3PB-) and Charpy-sized three point bend -geometries. Using an environmental chamber CT-type specimens up to 2T and bend specimens up to 1T can be tested at temperatures between -120 °C and +300 °C. Also testing of irradiated specimens up to 1T is possible using a parallell system installed in a hot cell.

Dynamic testing

Equipment. The inverted test geometry of the new impact test machine consists of a specimen resting on the tup and a hammer having two impact points. Description of the new tester equipped with an optical COD measurement device is given in Fig. 2. The new tester contains several novel features which help to avoid the drawbacks of the normal designs and which make the impact testing more reliable and appropriate from the fracture mechanics point of view. These features include e.g. a larger amount of available impact energy (500 J with 5 m/s) to decrease the velocity retardation, an inverted test geometry to suppress the vibration effects and to avoid the striking tup interfering with the crack initiation. More detailed description of the special features has been presented by Rintamaa et al. /1, 4/.

Other advantages of importance are the possibility to quite easily apply an optic device for crack opening measurement because of the stationary instrumented tup and because of the relatively stationary rotation axis of the specimen, as well as the possibility to use larger than normal Charpy-size specimens.

The instrumentation and data acquisition applicable for the impact tester is shown in Fig. 3. For the COD and load signal storage a two channel transient recorder with 10 bit resolution, 300 kHz attenuation and 4096 byte storage has been installed. In the data processing the recorded force/COD time diagrams are transformed into an estimate of load displacement and COD displacement diagrams by means of a microcomputer and a flexible disc unit. For hard copy output of the results the test system is equipped with a printer and digital plotter.

Procedure for dynamic fracture mechanics characterization

The method generally used for the determination of dynamic critical J-integral values is based on the measurement of the stored potential energy $E_{\Delta a}$ up to the crack initiation on the load-deflection curve in the instrumented impact test. The J_{Icd} can be estimated by the following equation presented by Rice et al. /5/

$$J_{Icd} = 2E_{\Delta a}/B(W-a). \qquad (1)$$

The main and most difficult problem in evaluating the critical J-value is to detect the exact crack initiation point on the load-displacement curve. Wullaert & Server /6/ have pointed out that in a cleavage initiated fracture the fracture toughness up to some specific limit can be measured fairly reliably by merely using maximum load (i.e. cleavage load drop) as a point of fracture initiation. In most cases, however, ductile crack growth starts prior to the limit load. Consequently, the fracture toughness based on the limit load criteria can be too unconservative.

The methods (e.g. potential drop), which are widely used in a static test, are difficult to calibrate under dynamic loading and in addition, they require the instrumentation of each specimen which makes these methods unconvenient to carry out.

However, there are some test procedures based on either multi or single specimen technique where the specimen instrumentation can be avoided. In the following, the procedures applied in using the new tester are briefly presented:

Multi specimen low blow test (MLBT) technique. In this method the crack initiation and propagation processes are investigated by choosing several small blow angles in order to keep the pendulum energy small to avoid completely breaking the specimen ligament. In this way different amount of crack tip blunting and stable crack growth is produced on each specimen. The Δa including stretch zone width (SZW) can easily be obtained from the fracture surface of each specimen and the corresponding energy dissipation $E_{\Delta a}$ by integrating the real load-deflection curve. Thus, the J-value can be calculated according to Eq. 1. The critical J_{IC}-value is determined by the intersection of the J versus Δa straight line fit with the blunting line. Another alternative is to determine the critical Δa_c from the Δa versus SZW plot. Here the Δa_c is defined as the maximum value above which the Δa is independent of the SZW.

Single specimen low blow test (SLBT) techique. This method /7/ originally developed for static J_{IC} determining by means of a single 3PB-specimen can also be applied in dynamic testing. The method is based on the assumption that during subcritical crack growth the load versus plastic displacment (the P-Δ-curve) obeys the power law relationship (a key-curve). The critical load and plastic displacement at the crack initiation point can be determined from the following simultaneous equations:

$$\Delta_c^P = C' \cdot \left[P_c / \left(B(W-a)^2\right)\right]^m \tag{2}$$

$$\Delta a = \frac{\Delta_s^P - \Delta_c^P - \dfrac{m\Delta_c^P\,(P_s - P_c)}{}}{\dfrac{2m\,\Delta_c^P}{W-a} + \dfrac{32P_c}{EBW}\,(1-\upsilon^2)f^2(\frac{a}{W})} \tag{3}$$

All symbols are explained at the end of this paper. The only unknowns in Eqs (2) and (3) are critical plastic displacement Δ_c^P and load P_c. Values for the m, C', P_s, Δ_s^P and Δa are known or determined from experimental data and from the fracture surface of the specimen. These equations are also valid when considering the plastic crack opening displacement instead of the load displacement or deflection. The method is applicable when the amount of crack growth Δa is fairly small. More detailed information on this and also the above presented formula is described in the papers by Lai et al. /7, 8/.

Method based on the optical COD device. The signal from the optical COD measuring device installed to the new impact tester depends almost linearly on the impact time up to a certain stage of the test. At the onset of crack initiation some deviation from the linearity occurs. In a brittle material the deviation is distinct indicating the cleavage fracture initiation as schematically shown in Fig. 4. In ductile fracture mode the COD signal first increases monotonically with time. At a certain point a small deviation from a straight line occurs in the slope. This point of time is proposed to indicate the onset of crack initiation (Fig. 4). After transforming the time to displacement the corresponding point can be located on the load displacement curve. And again by means of the corresponding energy value (E_I) and the Rice's equation, the J-integral at the crack initiation can be evaluated (Fig. 5).

EXPERIMENTAL STUDIES AND DISCUSSION

Some preliminary tests were performed with the 3PB-geometry using a thickness of 15 mm (static testing) and of 10 mm (dynamic testing), and also with the Charpy V specimen geometry. The ratio of the span width (S) to the specimen width (W) in both specimen geometries was 4. The material used was a bainitic pressure vessel steel A533B Cl.1. Specimens were tested at room temperature in the L-T orientation. In dynamic testing the initial impact velocities from 0.2 to 4.2 m/s were used.

In Figs 6 and 7 the static J_R-Δa-curves are shown. The critical J-values determined according to the ASTM standard E813-81 and the power law data fit are given Table 1. The J-values from multi specimen low blow tests are also presented in Figs 6 and 7. For both specimen geometries the dynamic values were quite close to the blunting line and lay somewhat above it.

Dynamic fracture toughness was evaluated using single specimen low blow test technique (i.e. Eqs (2) and (3)). The load displacement data used for the analytical method is presented in Figs 8 and 9. According to the SLBT analysis the critical plastic load point displacements Δ_c^P are 0.774 and 1.159 mm, and the corresponding crack initiation energy values 4.6 and 17.0 J, respectively. The J-values solved from Eq. (1) and presented in Table 1 are considerably lower than the static ones and those obtained using multi specimen technique. The explanation of a very low value of the Charpy specimen requires more test data and more basic verification of the test procedures used. The low value of the 3PB specimen can be explained due to the partly brittle fracture mode. In Fig. 10 the load displacement curve of the test (3PB specimen) with the impact velocity of 4.2 m/s is given. However, before the initiation of cleavage fracture some stable crack growth (Δa = 0.122 mm) had occured. The unstable cleavage crack was arrested yielding the final portion of brittle fracture surface as approximately 20 percent. Assuming the cleavage fracture initiation to be the point of fracture initiation the critical J-integral can be calculated to 376 kJ/m^2, which coincides with the value determined by the SLBT-procedure, Table 1.

The main reason for the low dynamic J-values compared to the static ones seems to be a shift of transition temperature due to the effect of dynamic loading and specimen size. Higher test temperature should have been used to assure the stay in the upper self region. The dynamic J_{IC}-values of 338 and 376 kJ/m^2 are consistent with the values for the same steel presented by Kobayashi /9/.

CONCLUSIONS

In this work testing procedures and equipment to determine the dynamic fracture toughness have been considered. Some preliminary experimental tests have been made for the reactor pressure vessel steel A533B Cl.1 using a new impact tester (based on the inverted test geometry and equipped with an optic COD-device) utilizing three point bend (3PB) and Charpy type specimens. The results have been compared to those from static testing. The following conclusions can be made:

- The new impact tester is more applicable than the conventional one for dynamic elastic-plastic characterization of metallic materials because of the utilization of larger than normal Charpy type specimen and the installation of the optic COD measuring device. The application of the optic device for the determination of crack initiation and the measurement of crack opening displacement will be more thoroughly verified in the near future.

- The test procedure based on the "key curve" and single specimen data is also applicable for the determination of the J_{IC}-value in the dynamic loading.

- In dynamic testing the estimated J_{IC}-values for the steel A533B Cl.1 at room temperature were lower than found for static loading.

- Changing the Charpy specimen to the larger 3PB specimen some cleavage initiated fractures occured; the portion of the brittle fracture surface area increased with impact velocity.

ACKNOWLEDGEMENTS

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LIST OF SYMBOLS

a	crack depth after fatigue precracking (mm)
a/W	crack depth to width ratio
Δa	nine-point average of stable crack growth depth (mm)
Δa_c	value of Δa at the onset of crack initiation (mm)
B	specimen thickness (mm)
C'	material constant in the "key curve" i.e. in Eq. (2) (mm^2/N)
Δ_c^P	plastic load point displacement at the onset of crack initiation in the SLBT-procedure
Δ_s^P	plastic load point displacement at the unloading point in the SLBT-procedure
E	Young's modulus (N/mm^2)
$E_{\Delta a}, E_I$	energy dissipation up to crack initiation (J, Nm)
E_M	premaximum load energy dissipation (J, Nm)
J_R	value of J-integral (kJ/m^2)
J_{IC}	static critical J-value (kJ/m^2)
J_{ICd}	dynamic critical J-value (kJ/m^2)
m	material constant in Eq. (2)
P_c	load at the onset of crack initiation in the SLBT-procedure (N)
P_s	load at the unloading point in the SLBT-procedure (N)
W	specimen width (mm)

Table 1. Summary of the J-integral values at the crack initiation determined from the results of Figs 6 to 10.

	Specimen type	Testing Stat.	Testing Dyn.	Critical J-value kJ/m^2	Procedure
Fig. 6	CVN	x		473 621	ASTM Power law fit
Fig. 7	3PB	x		563 628	ASTM Power law fit
Fig. 8	CVN		x	202	SLBT; m=6.0; $C'=2.138\cdot10^{-9}$
Fig. 9	3PB		x	338	SLBT; m=6.9; $C'=5.254\cdot10^{-8}$
Fig. 10	3PB		x	376	At the point of cleavage fracture initiation

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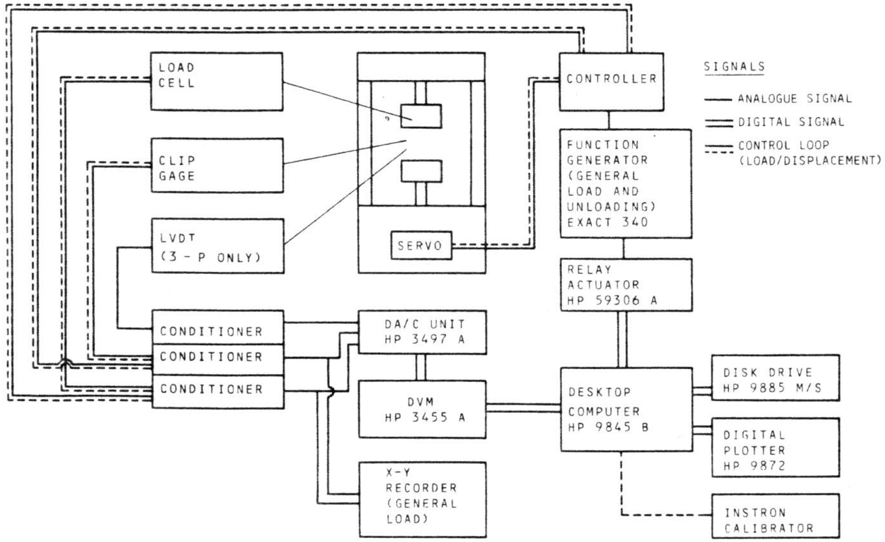

Fig. 1. Block diagram of computer interactive testing system used for static fracture toughness measurements.

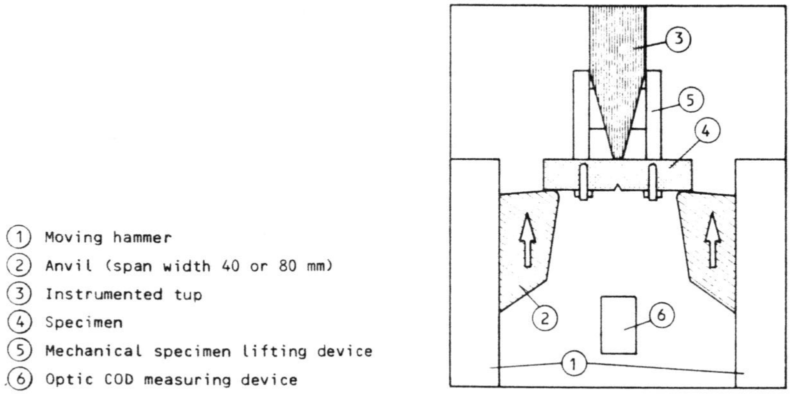

Fig. 2. Description of the new impact tester based on the inverted test geometry.

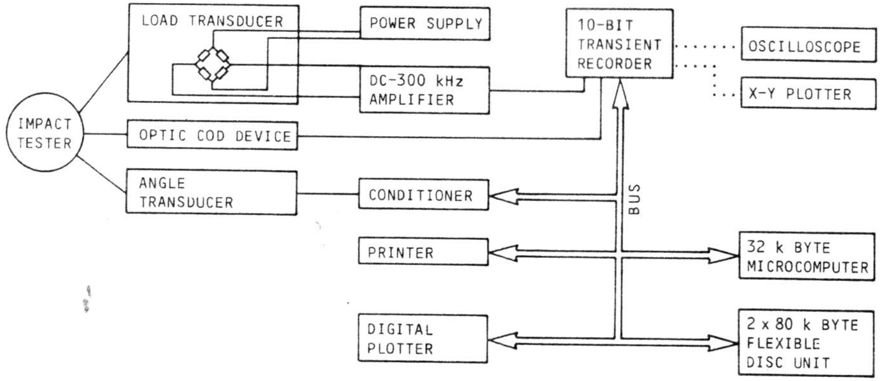

Fig. 3. Block diagram of the instrumentation and data acquisition of the new impact tester used for dynamic characterization of materials.

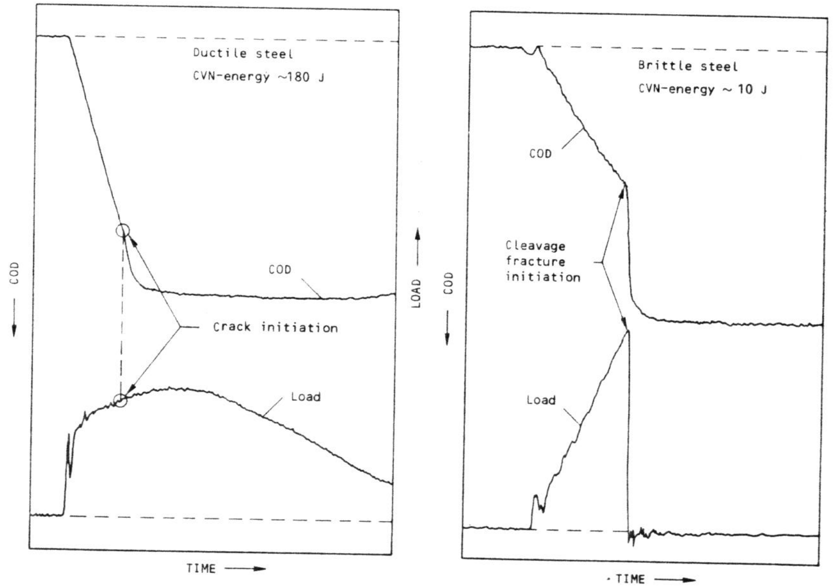

Fig. 4. Operation of the optic COD measurement device schematically shown for brittle and ductile material.

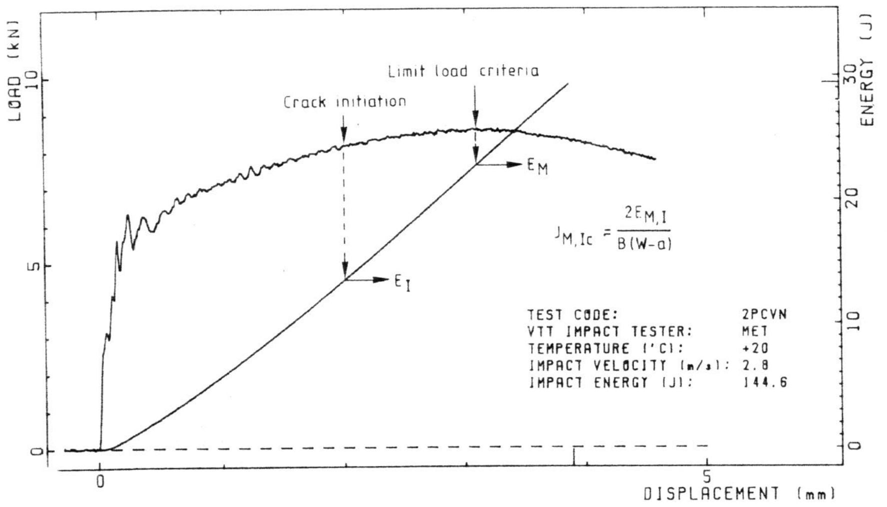

Fig. 5. Determination of the dynamic fracture tougness parameters based on the detection of crack initiation point (J_{IC}) and limit load (J_m) on the load displacement curve.

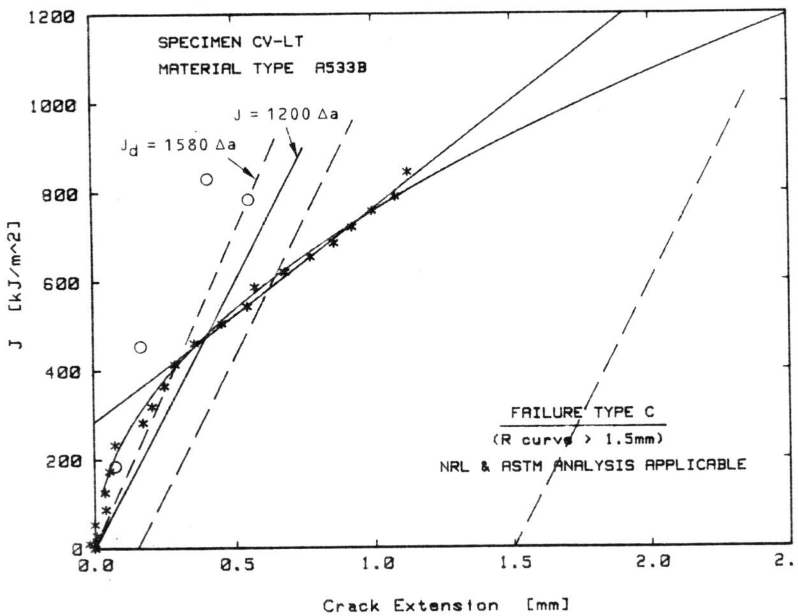

Fig. 6. Static J_R-Δa-curve determined using the precracked Charpy V-notch (PCVN) specimen with sidegrooving of 20 percent (a/W=0.558; B=15 mm). Open circles indicate the J_R-Δa-values from the multispecimen low blow tests (a/W=0.5; B=10 mm).

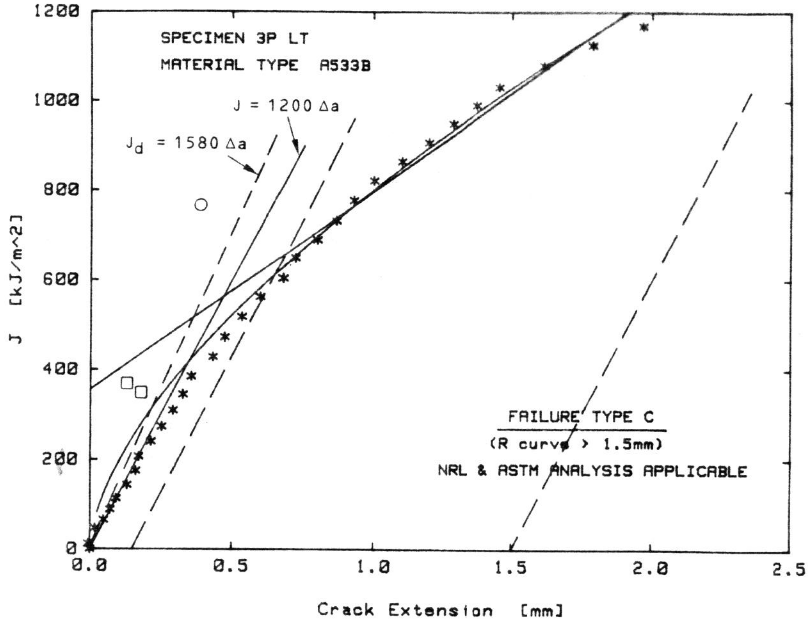

Fig. 7. Static J_R-Δa-curve determined using the precracked three point bend (3PB)-specimen with sidegrooving of 20 percent (a/W=0.584; B=15 mm). Open circles indicate the J_R-Δa-values from the multispecimen low blow tests (a/W=0.5; B=10 mm) and open squares values at the onset of cleavage initiated fracture (e.g. Fig. 10).

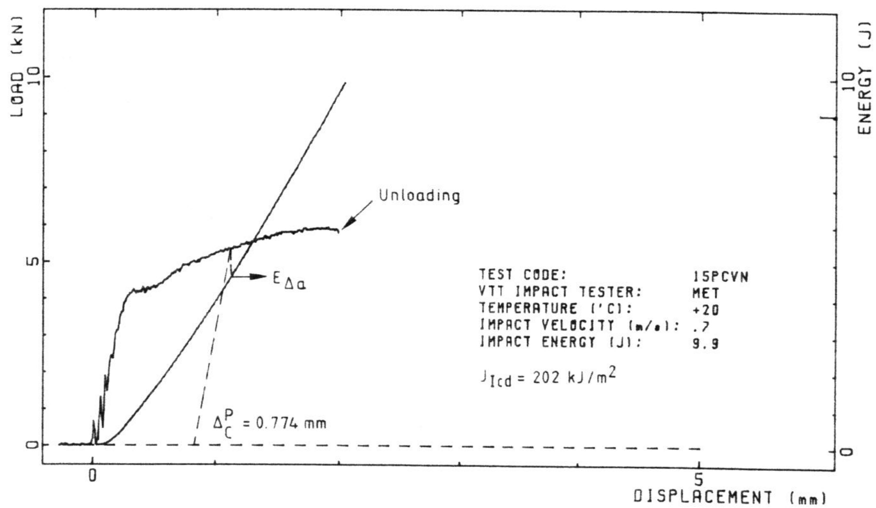

Fig. 8. Evaluation of the dynamic fracture toughness by means of the single specimen low blow test (SLBT) technique utilizing the precracked Charpy specimen without sidegrooving (a/W=0.552).

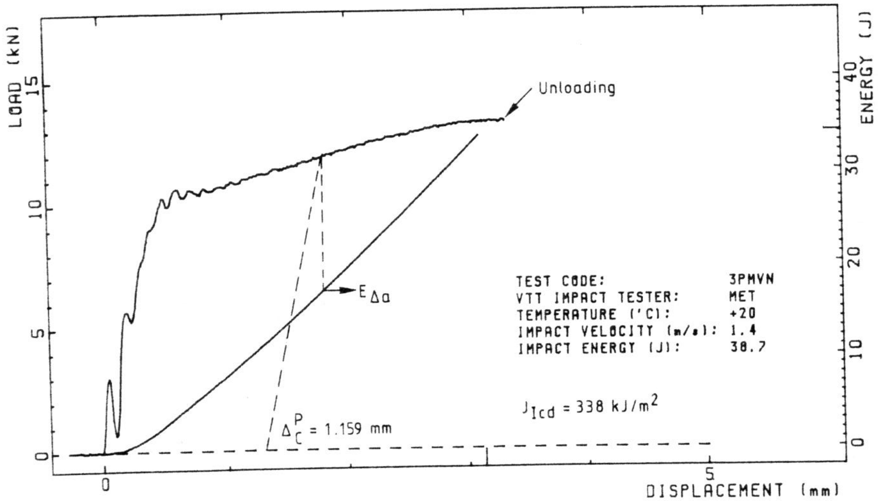

Fig. 9. SLBT-technique with 3PB specimen (a/W=0.496; B=10 mm), no sidegrooves.

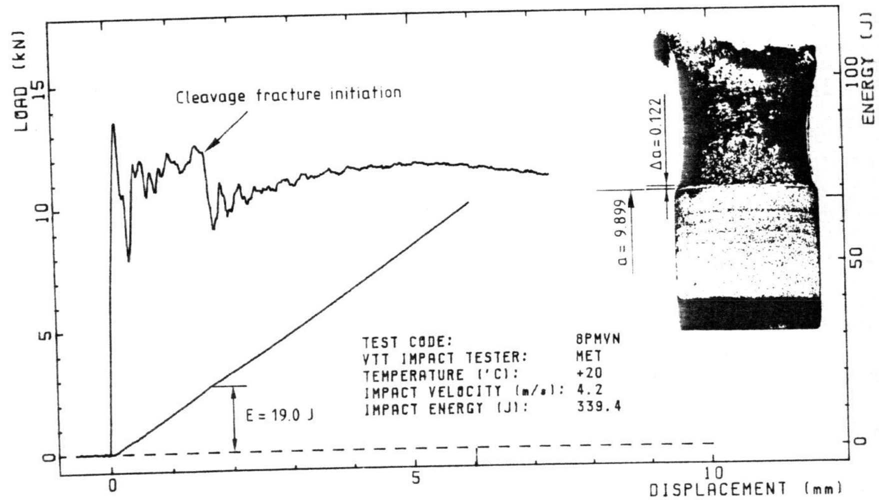

Fig. 10. Determination of the dynamic J_{IC}-value at cleavage fracture-initiation assumed to be the onset of crack initiation.