Opto-Electronic Measuring Methods in Dynamic Elastic–Plastic Fracture Mechanics

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ABSTRACT

Opto-electronic measuring methods offer new possibilities for fracture mechanics investigations. Primarily this is true where contact-free sensors of small dimensions, low weight and high bandwidth are needed, e.g. in the case of impact loaded specimens and components. The paper presents as examples the registration of the crack tip displacement field of impact loaded double edge notched tensile specimens and newly developed opto-electronic methods to determine the crack opening displacement (COD) resp. the crack tip opening displacement (CTOD) of impact loaded compact tension specimens.

KEYWORDS

Dynamic testing, opto-electronic measuring methods, crack tip displacement field, crack opening displacement, crack tip opening displacement.

INTRODUCTION

Investigations of the past few years (Krabiell and Dahl, 1981, Klepaczko, 1985) have shown that the load bearing capacity of impact loaded cracked ferritic components depends strongly on the loading rate. This applies especially to the transition zone of the toughness-temperature-curve. It is therefore an indispensable prerequisite for safety analyses of components with high risk potential to have reliable material characteristics obtained under impact loading on hand. For the loading rate spectrum primarily investigated up to now, with impact velocities smaller than 5 m/s, the quasi-static fracture mechanics evaluation procedures (ASTM E-399, ASTM E-813, BS 6729) are applied although there is no experimental proof in how far the prerequisites, necessary for the applicability of these concepts, are fulfilled under dynamic loading. It should be added that a numerical simulation of the behaviour of impact loaded cracked components requires material parameters for impact velocities higher than 5 m/s. Under these testing conditions stress wave and inertia effects have to be taken into account. This comprises amongst others the transit time delay of stress waves between different measuring points on the specimen and thus a strong demand in fracture mechanics for the acquisition of the measured quantities as close to the crack tip as possible using non-contacting high resolution measuring methods. For that purpose MPA Stuttgart has developed several opto-electronic measuring methods which are especially suitable when testing specimens in a high energy 33 MJ rotating disk impact machine where compact tension (CT), double-edge notched tensile (DENT) and smoothed or notched round bar tensile specimens can be tested up to an impact velocity of 100 m/s.

CRACK TIP DISPLACEMENT FIELD

The displacement field around the tip of an impact loaded crack contains all the information necessary for the characterization of the material behaviour. It is for example possible to conclude from the structure of the field the fracture mechanics parameter K with the extrapolation method (Iskander, 1981) and the parameter J with the contour integral (Rice, 1968). A procedure was developed (Demler and Klenk, 1987) using microgrid square patterns applied to the surface of the specimen around the crack tip to describe the crack tip displacement field. The deformation of the patterns during loading represents the displacement field of the specimen surface layer. To apply the square pattern, a grid is printed photographically on the surface and etched electrolytically into the surface. A grid line spacing of 50 µm has proved to be suitable for most purposes.
The photographic storage of the displacements during loading is achieved via an electronic image converter camera Imacon 790 with a front lens system based on a macroscope Wild M 400. Figure 1 shows a framing sequence of a DENT-specimen tested with an impact velocity of 5 m/s. The displacement of the notch tip in y-direction due to specimen elongation, the increasing crack opening displacement (COD) and the formation of the plastic zone are clearly perceptible.

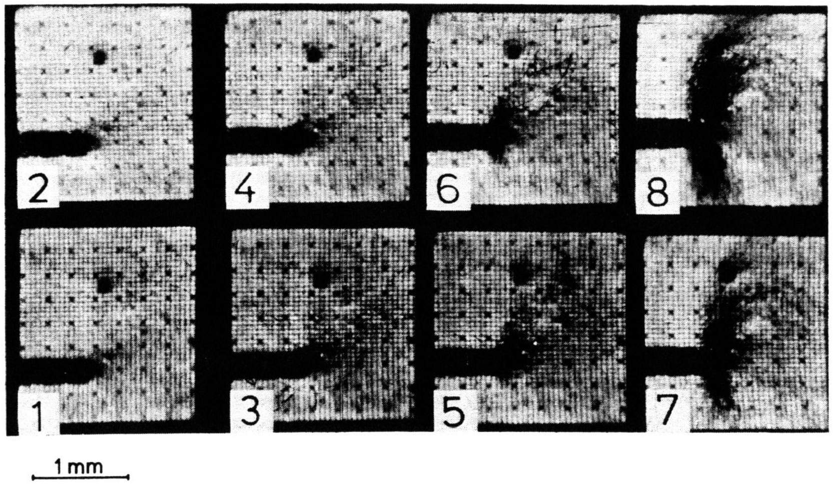

Fig. 1. Framing sequence of a DENT-specimen, impact velocity 5 m/s, f = 100 000 fps

After a hundredfold magnification the crossing points of the grid lines were digitized via a 16 bit xy-scanner with a reproducibility better than ± 2 µm with respect to the original grid. The displacements of the crossing points compared with the unloaded state were calculated and presented as contour plots, vector fields or in lines r=const., ϕ=const. or y=const. The coordinate systems r, ϕ and x, y were centred in the notch tip. Figure 2 gives a vector field for y > 0 of a test at 15 m/s impact velocity, for which a J-integral value of 112 N/mm was calculated.

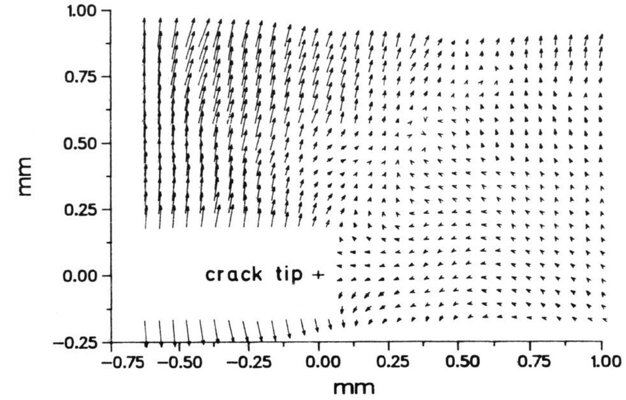

Fig. 2. Section of the crack tip displacement field of a DENT-specimen, impact velocity 15 m/s, J = 112 N/mm

As the position of the notch tip was kept constant in the evaluation, negative x-displacements can be found in the ligament.
In Fig. 3 the displacements in y-direction are compared with the plane stress and plane strain curves of the HRR-field (Hutchinson, 1968) for a line of y=250 µm.

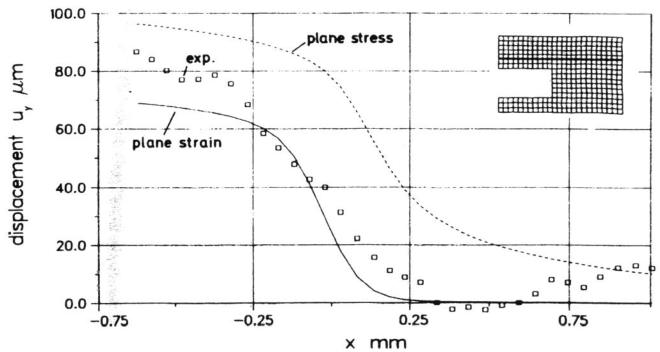

Fig. 3. Experimental and HRR-displacements in y-direction on a line y = 250 µm = const., DENT-specimen, impact velocity 15 m/s, J = 112 N/mm

The stress-strain-curves required as a function of the strain rate are available from impact tests with round bar tensile specimens. The strain rate at the elastic-plastic boundary of the DENT-specimen was calculated acc. to (Irwin, 1964). Particularly for x-coordinates <0 the experimental displacements approach plane strain conditions, which is plausible in view of the specimen geometry (B=2W, a/W=0.5). In the case of equivalent macroscopic J-integral values a comparison of the y-displacements in a line y=200 µm under quasi-static and dynamic loading (v=5m/s) gives similar, but not identical curves, Fig. 4. Compared to that the differences between the dynamic tests in the impact velocity range 5m/s≤v≤30m/s are of minor importance.

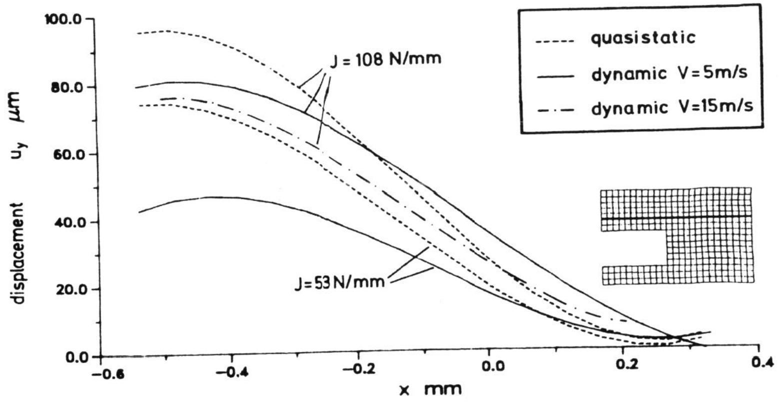

Fig. 4. Comparison of y-displacements on a line y = 200 µm = const. for quasi-static and dynamic loading, DENT-specimen

At present fatigue precracked CT-specimens with microgrid patterns applied to the fatigue crack tip are investigated. For the macroscopic calculation of the J-integral acc. to ASTM E-813 the load line displacement COD has to be known.

OPTO-ELECTRONIC COD-MEASUREMENT

For the measurement of the crack opening displacement in the load line of impact loaded CT-specimens clip gauges or other conventional inductive or capacitive displacement gauges cannot be used because of their low natural frequency and lack of geometric compatibility. Therefore the load line displacement is measured using an opto-electronic sensor which offers as main advantages small dimensions, low weight, high bandwidth and an absolute insensitivity to electromagnetic high-frequency noise fields. The principle is represented in Fig. 5.

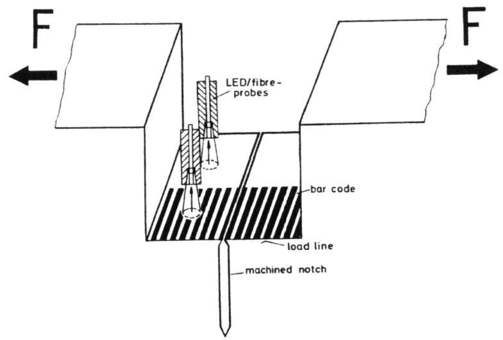

Fig. 5. Sketch of the opto-electronic COD-meter

A barcode is attached to the load line using paper or glass as backing and showing a line spacing between 100 µm and 300 µm. The sensor, which is mounted at a distance of 0.3 mm in the unloaded state, contains a GaAlAs luminescence diode with a maximal spectral emission at 660 nm which works as a Lambert emitter and illuminates the barcode. A certain part of the light reflected is coupled into a step index multimode fibre which is led through the LED besides the chip and transfers the retroreflected light to a photodiode placed outside the test rig in the amplifier casing. Because of the small distance between sensor and amplifier and the optimal balance of fibre and LED the attenuation is insignificant. At the amplifier output a continuous series of maxima and minima is available during the displacement of the load line, the wavelength of which corresponds to the line spacing. Interstages of the amplifier output can be correlated with displacements via quasi-static calibration. A second LED/fibre probe is integrated into the sensor to compensate changes in intensity due to the superposition of the translation and rotation of the specimen halves. The second probe illuminates an object of similar grey scale value without code. Calculating the difference of the two output signals of the parallel transmission lines a signal of constant mean voltage is achieved, which can be registered in a 10 MHz, 12 bit transient recorder and analysed with a microcomputer.

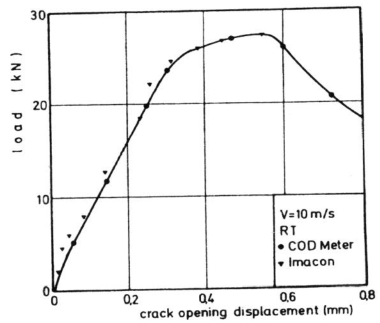

Fig. 6. Load-displacement-diagram of a CT-specimen

Figure 6 shows a load-displacement-diagram received with the test method presented and valid for a CT-specimen of thickness B=15mm made of a fine-grained structural steel and tested at an impact velocity of 25 m/s.

Parallel to the opto-electronic sensor application the load line displacement was also registered at discrete time steps via an electronic image converter camera Imacon 790. Depending on the framing rate and delay time further check points of the COD could be provided in certain time intervals. These points are marked in Figure 6. The acquisition of critical parameters for crack initiation can be established via strain gauges attached to the side faces in the crack tip near field (Giovanola, 1985). Figure 7 presents a comparison of quasi-static and dynamic initiation parameters of a lower bound melt of the nuclear reactor pressure vessel steel 22NiMoCr37.

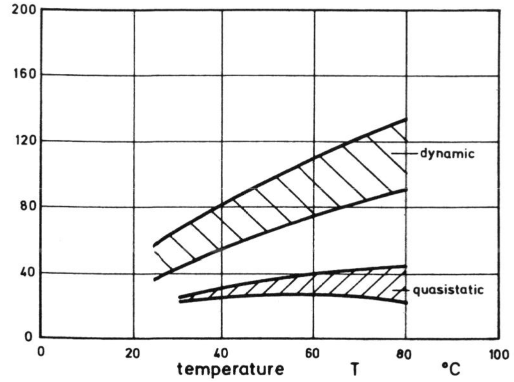

Fig. 7. Quasi-static and dynamic J initiation values of the pressure vessel steel 22 NiMoCr 37

The measuring principle of hte high frequency barcode scanner presented here can also be used for other fast acting hodometry, mainly of translational nature, in dynamic materials testing, if barcode and amplifier are adjusted to the specific problem. An example is the displacement measurement of the piston rod of the 12 MN high speed testing machine of MPA Stuttgart which is driven by a propellant charge.

OPTO-ELECTRONIC CTOD-MEASUREMENT

The CTOD-concept represents an advantageous instrument of fracture mechanics which has been applied predominantly in the United Kingdom. Suitable material parameters are obtained on the basis of BS 5762, calculating CTOD from easily performable COD measurements by means of an extrapolation method. Up to now, a validation of the procedure was possible by surface measurement techniques only, e.g. the moiré-method. Owing to the small sensor dimensions fibre optics offered for the first time the possibility to compare the BS 5762-procedure with CTOD-measurements from the specimen interior.
To that aim a hole of a diameter of 0.9 mm was drilled into several CT-specimens about 1 mm behind the fatigue crack tip in mid-thickness position. Through this hole optical fibres were introduced from both sides of the specimen and fixed to the fatigue crack flanks. Via the upper fibre light of a LED is emitted which partly can be coupled into the lower fibre and transferred to a photodiode, Fig. 8.

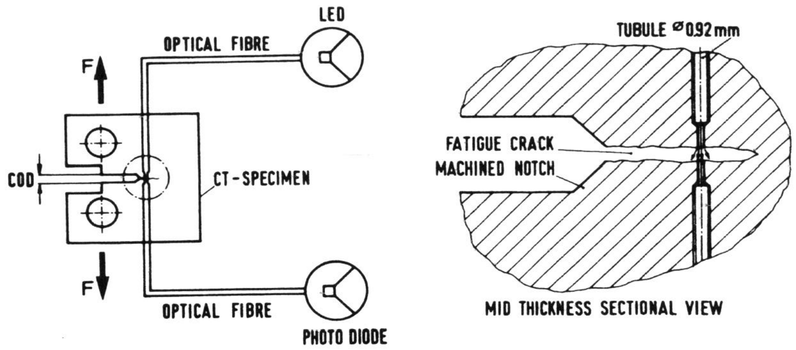

Fig. 8. Scheme of the opto-electronic CTOD-meter

Calibration tests have demonstrated that for an optimal amplifier design a linear relation exists between the distance of the optical fibre ends in the specimen interior and the amplifier output. The opening of the fatigue crack flanks during deformation of the specimen represents a reduction of the intensity transferred between both fibre ends which can be converted into a translation through calibration curves. Optimal resolution is about 2 µm. The influence of twisting during plastic deformation of the CT-specimen can be neglected because of the $\cos^2\phi$-character of the spatial intensity distribution of the fibre. This was proved experimentally too. Using this method a value in the fatigue crack area can be provided for the extrapolation of the COD-signal to the fatigue crack tip. This extrapolated value can be compared with the result of BS 5762.
For several fine-grained structural steels quasi-static investigations at the onset of the upper shelf toughness regime (ambient temperature up to 80°C) were performed. Figure 9 compares the experimental CTOD-results with values determined according to BS 5762.

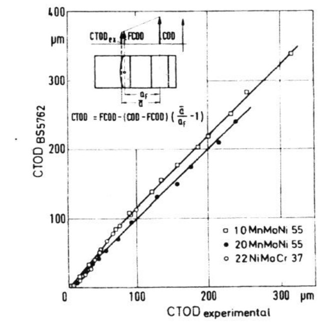

Fig. 9. Comparison of the extrapolated signal of the opto-electronic sensor with the extrapolation technique acc. to BS 5762

Under ideal conditions an identity should exist as is true for CTOD> 60 µm. For the relationship between J and CTOD acc. to Fig. 10 results a linear dependence

$$J = m \cdot R_e \cdot CTOD.$$

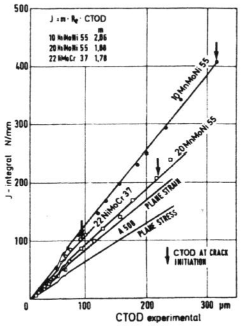

Fig. 10. J-CTOD-relationship for various reactor pressure vessel steels

The material dependent parameter m varies between 1,78 and 2,06 for the materials investigated. This linear relationship has been proposed on the basis of finite element analyses of three point bend specimens made of ASTM A508 steel (Wellman et al., 1984). At present dynamic tests with this opto-electronic device are under way.

CONCLUSIONS

The opto-electronic measuring methods presented here reflect only a small selection of possible opto-electronic devices in view of the variety of emitters (e.g. laser diodes) and optical fibres available, the insensitivity against agents and the temperatures applicable today. Together with a high bandwidth and low manufacturing costs opto-electronic devices offer most promising advantages for future materials testing applications.

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