MEASUREMENT OF DYNAMIC STRESS INTENSITY FACTOR UNDER IMPACT LOADING

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The dynamic stress intensity factor is evaluated on the basis of crack opening displacement measurement using optical method with photoelectric sensing. In the paper a comparison of results with those of numerically calculated by the boundary element method is done. A good agreement was achieved between experimental and numerical results.

INTRODUCTION

The mechanical behaviour of cracked body under impact loading is usually strongly influenced by the dynamic effects. In brittle fracture the stress intensity factor is the most important characteristic of the structure including a crack. Reliable determination of this value under high rates of loading is often associated with difficulties. In such cases a simplified static or quasi-static analysis may not be used and it requires the solution of the boundary value problem under the dynamic non-stationary conditions. On the other hand there is well known exacting character of the experiments for the measurements of such fast dynamic processes.

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MEASURING METHOD AND EXPERIMENT

In order to measure the value of stress intensity factor variable in time an optical method using photoelectric sensing was proposed (1). In a simple optical setup the light beam (e.g. laser beam) passes through the narrow slit and its intensity is recorded by a photosensor (Fig.1). The slit on the crack faces is defined by the sharp edges of razor blades. Because of the width of the slit is about 10^{-2}mm the light behind its plane is considerably divergent due to diffraction phenomenon (2). The total amount of light behind the slit depends proportionally on the slit opening. This is why the collection all of this light (e.g. wide open lens) onto the effective area of the photoelectric sensor is useful. In such easy way the linear relation may be obtained between the value of the crack opening displacement and the output electric signal (considering linear characteristics of the photosensor). Through the simple linear relation the crack opening displacement close to the crack tip is tied together with the stress intensity factor (we mean the linear fracture mechanics). In this manner a simple inexpensive measurement technique that displays the analog continuous signal of the stress intensity factor directly on the oscilloscope screen is available.

In our experiments as a light source the CW laser (output power 60 mW) was used but the proposed optical scheme do not require the coherent light. However, using the laser along with a direct intensity measurement the problem of high frequency noise of CW laser light has to be solved. The random noise modulation of the intensity attained ±10 % so that the differential electronic scheme for the separation of the useful signal was needed. Moreover, another characteristic feature of the laser beam is the Gaussian intensity distribution across the beam. Such non constant level of the illumination causes the sensitivity of the device to the rigid body motion of the measured object, any relative shearing slit vs. laser beam will create a false signal on the output. In order to secure the system to be invariant with regard to the rigid body motion in a wide range the photographic plate with intensity transmittance negative to Gaussian distribution is placed into the beam.

Translation of the changes of optical signal to the electric quantity was conducted by the photodiode. Its sensitivity was enough to connect the output signal directly to the oscilloscope and the cut-off frequency exceeds the value of 1 GHz.

For calibration of the experimental measuring setup with regard to stress intensity factor value a simple static approach may be chosen, the only condition is to place the measuring slit sufficiently close to the crack tip. Much more complicated in the experiment was the measurement the dynamic loading force. For this purpose the special miniature dynamometer was developed with resonant frequency about 80 kHz. The ring shaped sensor uses the same "slit principle" with photoelectric sensing. It was calibrated statically as well as dynamically.

NUMERICAL COMPUTATION OF THE STRESS INTENSITY FACTOR

The stress intensity factor can be evaluated directly from its definition, i.e. from the asymptotic distribution of the stress field or displacements in the near vicinity of the crack tip (3). Thus, K_I is given by

$$K_I(t) = \lim_{\varepsilon \to 0} \frac{\mu\sqrt{2\pi}}{4(1-\nu)} \frac{\Delta u_2(\vec{\eta}_\varepsilon, t)}{\sqrt{\varepsilon}} \quad (1)$$

where μ and ν are the shear modulus and Poisson´s number, respectively, and $\Delta u_2(\vec{\eta}_\varepsilon, t)$ is the crack opening displacement at the point $\vec{\eta}_\varepsilon$ whose distance from the crack tip is equal to ε . This crack opening displacement can be measured as in the previous experimental part of paper or calculated numerically.

In order to compute the crack opening displacement, one has to solve the boundary value problem. Since it is not necessary to know the solution at internal points, the boundary element method (BEM) seems to be more efficient that any domain discretisation method. There are various approaches to the solution of elastodynamic problems using boundary element formulations (4). From the point of view of computer time saving the so called alternative BEM formulation (4-6) is the most appropriate one.

Equations of motion are given by (3)

$$\mu u_{i,kk} + (\lambda+\mu) u_{k,ki} + X_i = \rho \ddot{u}_i \quad (2)$$

Expressing the inertia term $\rho \ddot{u}_i$ at internal point in a separate form

$$\ddot{u}_i(\vec{x}, t) = \sum_{b=1}^{m} \ddot{\alpha}_i^b(t) f^b(\vec{x}) \quad (3)$$

and making use of the elastostatical fundamental solutions as well as the boundary element discretisation, the solution of the hyperbolic partial differential equation (2) can be recast into the solution of the system of ordinary differential equations (4):

$$\sum_{c=1}^{m} \ddot{u}_i(\vec{\xi}^c, t) M_{ik}^{cb} + \sum_{q=1}^{M} \{ u_i(\vec{\xi}^b, t) C_{ik}^{bq} + \sum_{a=1}^{3} [u_i(\vec{\eta}^{aq}, t) T_{ik}^{baq} -$$

$$- t_i(\vec{\eta}^{aq}, t) U_{ik}^{baq}]\} = 0, \quad (b = 1,2,\dots m) \qquad (4)$$

where $\vec{\xi}^b$ denotes the b^{th} nodal point, while $\vec{\eta}^{aq}$ (a = 1,2,3) stands for the a^{th} node of the q^{th} element. The explicit expressions for the matrix coefficients M_{ik}^{cb}, C_{ik}^{bq}, T_{ik}^{baq} and U_{ik}^{baq} together with a detail description of the numerical procedure can be found elsewhere (4).

The system of ordinary differential equations for unknowns at nodal points was solved by using the single step algorithm by Zienkiewicz et al. (7).

Due to the symetry of the problem it is sufficient to discretize the boundary of a half of the bar. The BEM mesh shown in Fig.2 was employed with 22 quadratic elements. The total time interval 350 μs was divided into 70 steps with quadratic approximation within each of them.

RESULTS AND CONCLUSIONS

The experimental results as well as the numerical calculations are summarized graphically in Figures 3 and 4. Both the relationships of the load P(t) and the corresponding dimensionless stress intensity factor $f_I(t)$ values vs. time are shown. The dimensionless stress intensity factor is referred to the static value corresponding to the maximum of the dynamic loading. Thus the influence of the dynamical effects can be evaluated by comparison of the dynamic stress intensity factor values with its equivalent under static conditions. The loading impulses shown here are very short, so the differencies between the static and dynamic approaches are qualitative. This implies also that for such conditions there is no possibility to use some static or quasi-static approximation.

In the Figures there is visible the main tendency of the stress intensity factor time traces. Due to the vibration of the notched bend specimen with its main resonant frequency (~3 kHz) notch opening roughly follows these oscillations (note that the notch has finite width so that no closure effect is present).

This main mode of oscillations is then modulated by the stress waves reflected from the free edges of the specimen. Using known speed of stress waves in a specimen material (steel $c_1 = 6000\ ms^{-1}$) it can be decoded that the maximum influence comes from the ends of the bend specimen. Namely the narrow peaks of loading force comparing the lenght of period of the natural frequency vibrations are responsible for such significant influence of the stress waves reflections on the response curve. It can be seen also from the comparison of Fig.3 and Fig.4 - the longer duration of the loading force leads to the curve smoothing.

As regard to the relation between the results obtained by the experimental measurement and on the other hand calculated by the numerical boundary element method we may state the very good coincidence of results. It is necessary to note that for such complicated dynamic processes any unimportant deviations in prescribed boundary conditions may influence the final result. It includes e.g. the influences from the differencies in mode of attaching of the specimen, sliding frictions at the anvils and the real material properties.

A good coincidence was achieved also in the local peaks positions on the time traces created as a response to the stress waves reflections.

The most serious deviation comparing the data experiment vs. calculation is seeing in the periods of first mode oscillations of the beam. It is caused namely by the differencies in prescribed boundary conditions for numerical calculation with regard to practical realization of the ideal clamping of the specimen edges. At the numerical calculation the assumption taking into account unmoveability of the support planes was made. However, there is no possibility to performe this condition idealy at experiment and that is why the oscillations of the beam passed with shorter period at the model under mathematical assumptions. It confirm also the other measurements of the free supported beam specimens. These specimens were oscillating with a period of first mode oscillations more longer than at the clamped beam.

From the graphical dependencies in Fig.3 and Fig.4 follows another finding - along with prolongation of the loading pulse the dimensionless stress intensity factor is growing. This may be explained simply by the fact that for such case an amount of the energie supplied to the specimen is growing,too. So, we can say that short duration loading pulses are less dangerous from the point of view of fracture mechanics.

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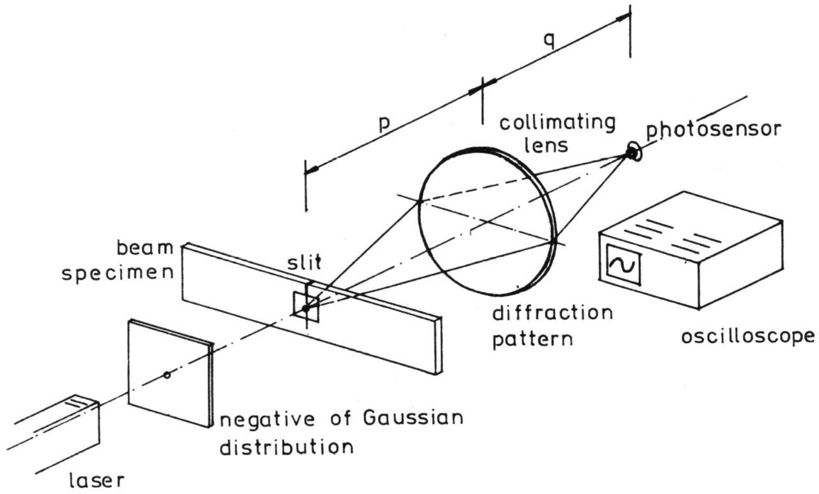

Fig.1 Experimental setup for the stress intensity factor measurement by optoelectronical method

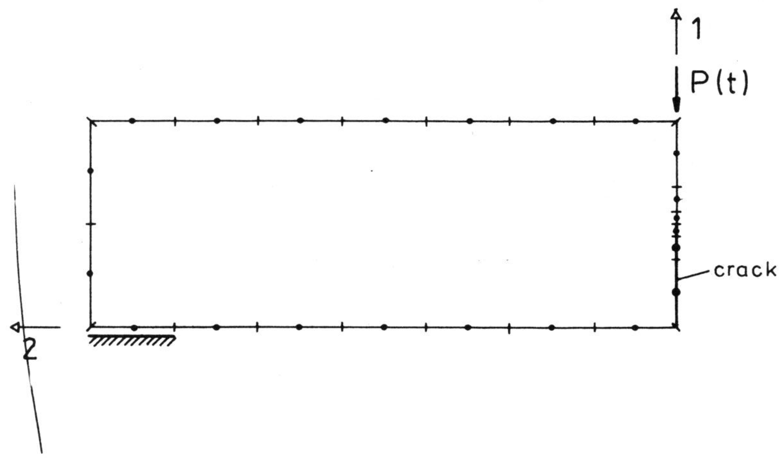

Fig.2 BEM mesh for a half of the notched bar

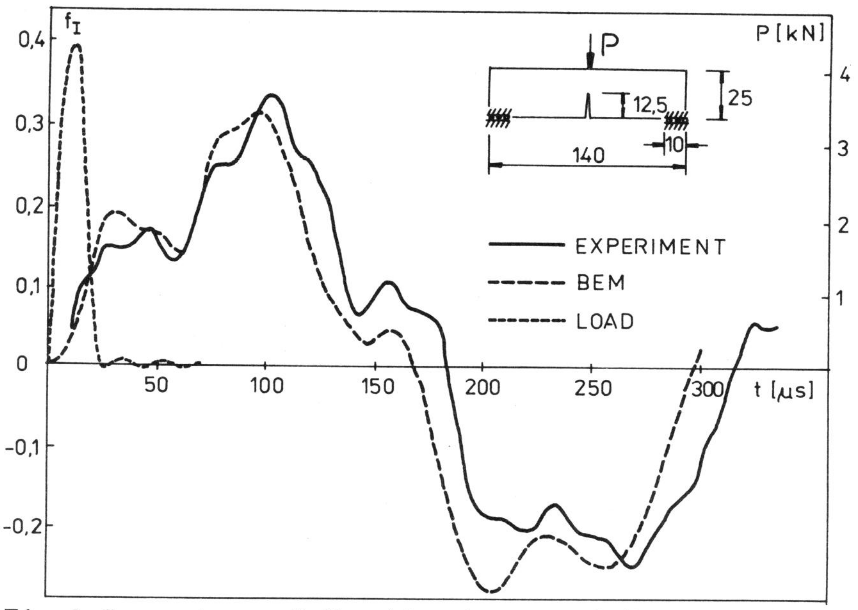

Fig.3 Comparison of the time traces of the stress intensity factor obtained experimentally and numerically

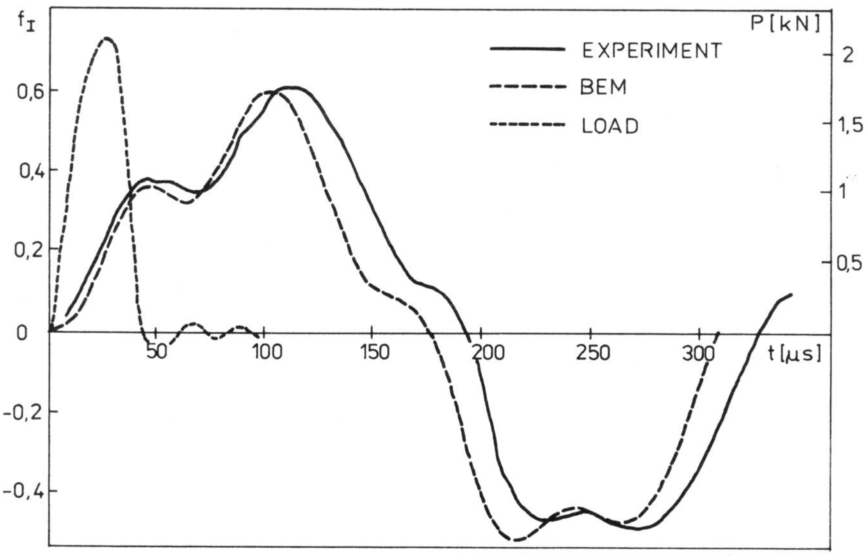

Fig.4 Stress intensity factors vs. time for a longer duration of loading