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DETERMINATION OF STRESS INTENSITY FACTORS BY OPTICAL METHODS

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Introduction

In the development of structures the fracture mechanics principles and criteria are used in an ever greater number of applications. The stress intensity factor (SIF) provides a quantitative criterion which combines critical fracture stresses with the length of crack and the specimen geometry. The determination of the influence of geometry and loading on stress concentrations in the vicinity of the crack tip has been included to the problems which are solvable by optical methods of stress analysis. In the Institute of Construction and Architecture of the Slovak Academy of Sciences several methods in the area of holographic interferometry, speckle interferometry and some other optical techniques were developed and realized for this purpose.

1. Stress intensity factors in the generalized plane stress state cracked specimens

As one of the first applications we used the image-plane holographic technique on models of PMMA transparent material to the examination of isopachic fringes. The advantage of this procedure is in the fact, that the SIF may be determined from isopachics data without requiring troublesome separation of principal stress components. A holographic interferometer was developed in the optical arrangement of which the diffuser screen is not included. For this reason the recorded interference pattern can be photographically greatly magnified and by this the required resolved power of image details can be secured.

Stress intensity factors K_I and K_{II} were determined in cracked beams with inclined and curved edge cracks. Example of the pattern of isopachics is shown in Fig. 1.

In order to determine the quantitative values of K_I as well as K_{II} several evaluating procedures have been developed based on the description of the stress state around the crack tip by asymptotic series. It has been shown that these procedures allow reliably to calculate SIF-s generally in arbitrary geometrical and loading configurations of cracked specimens in the plane stress state with an accuracy of better than ± 5 per cent [1].

An analogous technique of the holographic record and SIF evaluating we used also in the investigation of the dynamic crack propagation. The interferometer functioned

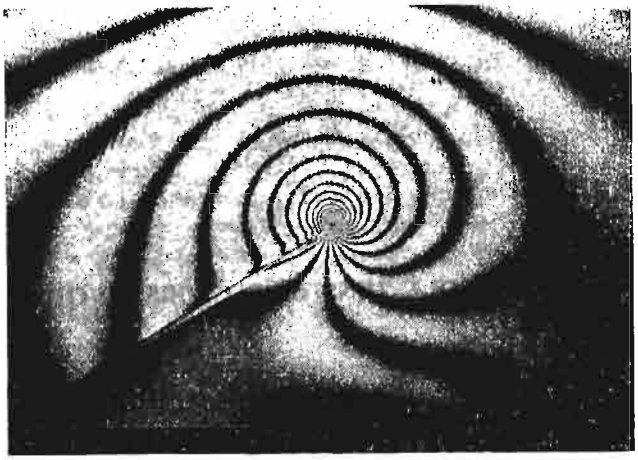

Fig. 1. Interference pattern of isopachics in the vicinity of the angled crack in a bend specimen

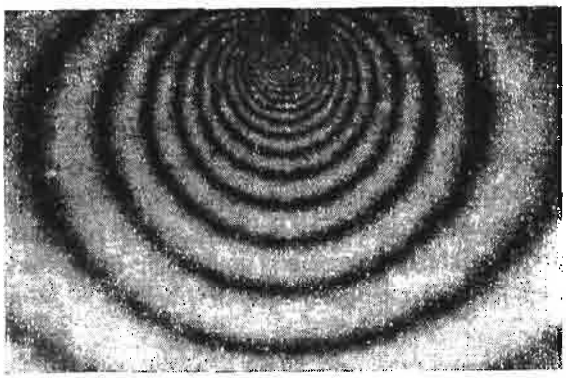

Fig. 2. Isopachic fringes of dynamic crack propagation in PMMA three-point bend specimen at crack velocity of 400 m/s

with a ruby impulse laser. Isopachics around the crack running with the speed of about 400 m/s in the bend PMMA specimen are shown in Fig. 2. For the quantitative evaluating of K_{ID} values a dynamic correction of interference constant must be performed. To do this, we can get the known dynamic dependencies of material constants and by using the graphical Fourier analysis and iterative procedure the evaluating interference fringe values may be calculated. It has been shown, that the differences between static and dynamic values in polymer materials (such as PMMA) may be 50 per cent or even more. By this procedure the relationship between the dynamic SIF and the crack tip velocity $\dot{a}$, which is the important fracture characterization, was obtained (Fig. 3).

For the measurement of the time functions of the dynamic values of SIF-s also a new photo-electric method was developed. Based on optical observation of the deformation of a mirror like flat close to the crack tip and on optical filtration principle, changes of the light intensity are produced. These are transformed to electric quantities by means of a photosensor. In this simple way without emploing a high speed camera a continuous record directly of the stress intensity factor can be obtained immediately in time on the

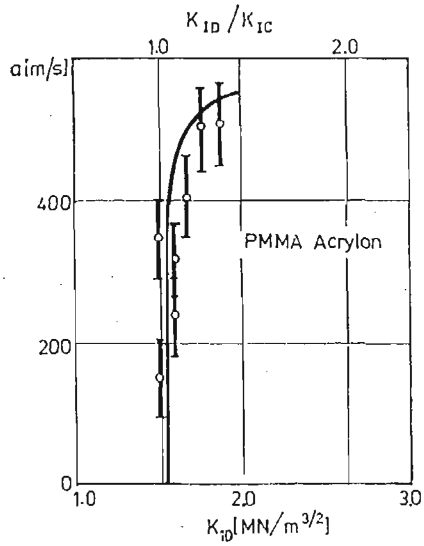

Fig. 3. The K_{ID} — a relation for PMMA Acrylon obtained from the holographic interferometry data

oscilloscope screen. Consequently, very fast non-stationary dynamic processes such as impact load may easily be solved. Moreover, the technique takes notice of the stress waves space distribution due to the fact that the deformation is watched close to the crack tip. Fig. 4 illustrates the method by the K_{ID} versus time dependence in the typical impact load process as was observed on the oscilloscope screen.

The possibility of the displacement measurements on the specimen surfaces ranks among the most important characteristics of the holographic-speckle interferometry principle. For the study of the SIF determination from displacement data we can tried on application of image optics free speckle technique when the holographic plate is fixed immediately on the measured object. The main advantage of this technique is the self compensation of large non-controlled displacements of the rigid body motion. We employed

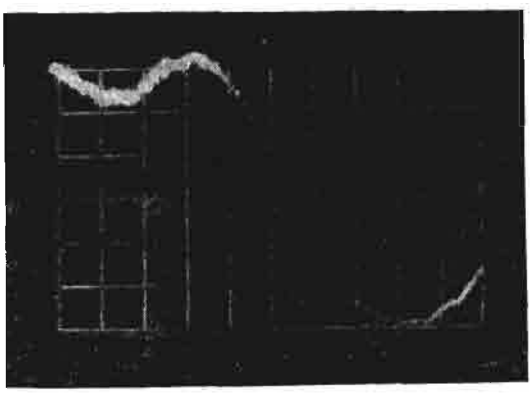

Fig. 4. Stress intensity factor in the strip with an edge stationar crack subjected to three-point impact load bending as a function of time $\left(\text{time calibration } 200\ \mu s \middle/ \text{div and } K_{ID} - 10^5\ \text{MNm}^{-\frac{3}{2}} \middle/ \text{div}\right)$

the method by means, when one of the transparent model surfaces is roughed (on the side of holographic plate emulsion). Collimated laser beam passed through the model and the groud screen surface scatter it so that the specklegram may be recorded. In the step of reconstruction we used the Fourier filtration procedure and by this in-plane orthogonal displacement components are optically obtained. As a test specimen we chosen the crack emanating from a hole in a complicated piercing bending specimen.
In evaluating of the SIF the relation displacements versus the distance from crack tip is graphically drawn. A precise interpolation of that curve to the zero distance from the tip can be done on the basis of linear fracture mechanics condition of zero value displacements at the tip (see Fig. 5). So the first term of asymptotic solution for displacements

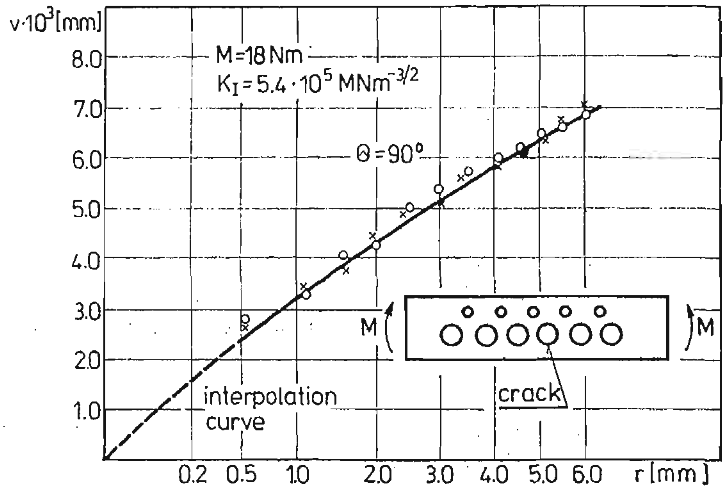

Fig. 5. Displacement data as a function of square root of radial distance r from the crack tip for the piercing cracked specimen

field around the crack may be successfully used. We believe that the displacement data with respect to the stress intensity factor determination give the most precise results of all the optical methods.

2. Application of non-destructive optical methods to study 3-D cracked bodies

One of the up-to-date task in the field of optical methods of experimental stress analysis is to develop reliable and effective methods for the measurement of three-dimensional stress state. We used holographic interferometry as a non-destructive method for the SIF determination in three-dimensional cracked specimens. The basic principle is to record a double-exposure image hologram with perpendicular illumination of the crack surface and filtration of space frequencies for the separation of the out-of-plane displacement component. Arrangement of the optical system with the model is shown schematically in Fig. 6. Surface of the crack is illuminated by a beam passing through the polished side surface of the transparent model. The image of the crack is observed from the same direction and is projected by an objective on a holographic plate where the hologram with

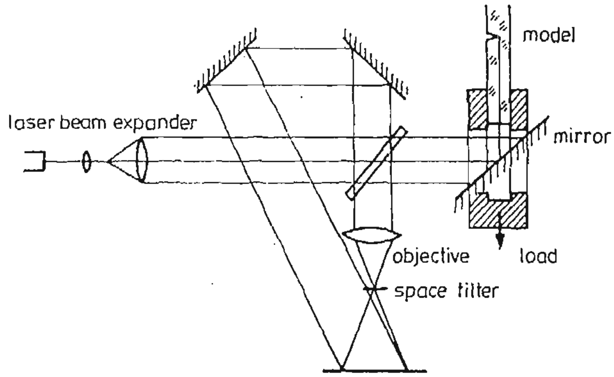

Fig. 6. Scheme of optical arrangement of the holographic interferometer for crack opening displacements measurement

the reference beam is formed. In the focal plane of the lens the space filter — diaphragm with circle aperture — is positioned for the separation of the near-to-zero space frequencies. Moreover, in this manner, not only the separation of the out-of-plane displacements is performed but an improvement of the correlation between the first and second exposure records may be reached, too. The radius of the correlation which is characterized by the speckle size may be varied by a suitable choice of the aperture diameter in the space filter, consequently contrast of the fringes may be increased. Light rays immediatelly behind the reflection from the crack surface spread through the thickness of the transparent model material. This is the reason, why the value of material index of refraction n will be included in the expression for the quantitative evaluation of the out-of-plane component w. Using the diffraction theory this expression may be derived for the interpretation of interference fringes [2]

$$w = N\frac{\lambda}{2n}, \tag{1}$$

where N is the order number and λ is the wave length.

Illumination and observation of the inside crack was experimentally achieved with the aid of small mirror which turns the light beam to the polished side of the model. The mirror was placed in the sight-hole of jaw on one margin of the model. By these groove steel chuck jaws the tension loaded beam including a surface flaw was fixed on both ends where the loading force was applied.

Application of the „classic" speckle method to the measurement of the displacements inside a transparent body was another optical method for the non-destructive SIF evaluation on the same specimen as in the previous case of holographic interferometry. Laser beam with a diameter of 0.5 mm from the 60 mW power He-Ne laser was penetrating across the PMMA model near the crack front (see Fig. 7). Intensity of the light radiation in the beam was sufficient to the observable light scattering along the beam trace which arose from the Tyndal effect. Scattered coherent light was concentrated on a holographic plate where the image of the light line was focused by the photographic objective. Microstructure of that image represents a speckle record and when the double-exposure procedure is used we can evaluate the displacements of the points on the light line. Evaluating

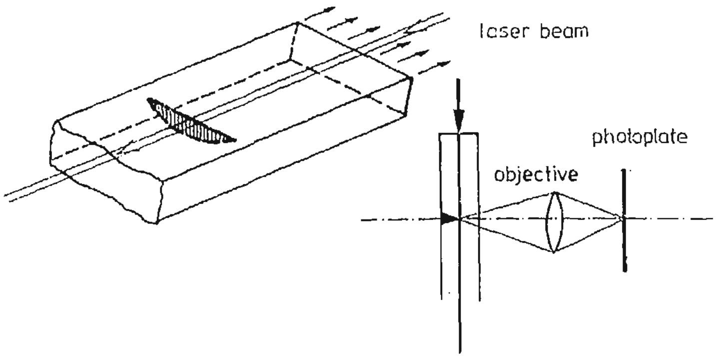

Fig. 7. Schematic drawing of the speckle interferometry arrangement in the measurement of inside body displacements

of the specklegrams has been carried out by the usual Young's fringes point by point method. The objective used for the measurement was wide open Helios lens with aperture number 1.5 and focal distance 85 mm. Magnification of the image was 4 times and corresponding exposure times were several tens of seconds on Agfa-Gevaert holographic plates.

Both, the holographic method of crack opening displacements measurement and the speckle method using inside scattered light were experimentally tested on the same three tensile loading beam specimens including a semi elliptical surface cracks. The surface flaws as an imitation of natural cracks were machined with the aid of a circular milling cutter.

By holography a field of interference fringes on a crack plane was reached several times on each sample for different loading levels. One example of the measured fringe patterns of crack opening displacements is shown in Fig. 8. In addition to the direct focused

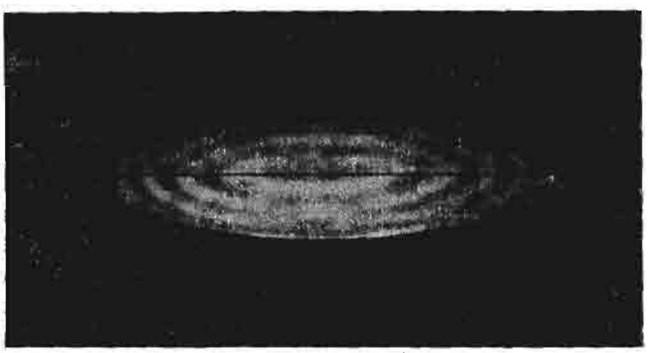

Fig. 8. Interference pattern of crack opening displacements on the semi elliptical crack

image of the crack surface a total reflex on an inside mirror smooth surface of the model is imaged, too (see bottom part of Fig. 8).

Being based on values of crack opening displacements the stress intensity factor can be calculated by means of asymptotic relations for the displacements around two-dimensional crack in the state of plane strain [3]. For the points on a perpendicular line to the crack front the factor K_I may be given by the well-known relationship described here for the polar angle $\theta = 180°$

$$K_I = \frac{E(2\pi)^{1/2}w}{4(1-\nu^2)r^{1/2}} \tag{2}$$

where E, ν are material constants and r is the polar distance from the crack tip. To calculate the factor K_I by Eq. (2), points in the close vicinity of the crack tip are taken into account. The stress intensity factors are obtained along the whole crack front.

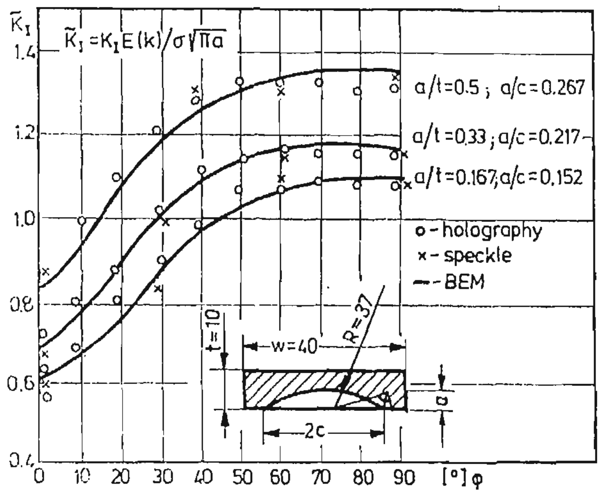

Fig. 9. Variations of the stress intensity factor along the crack front as were measured by holographic and speckle interferometry and calculated by boundary element method [4]

To calculate the factor K_I from the data obtained by the speckle interferometry the same asymptotic expression but for the polar angle $\theta = 90°$ may be used

$$K_I = \frac{E(2\pi)^{1/2}w}{2(1+\nu)\sin\frac{\theta}{2}\left(2-2\nu-\cos^2\frac{\theta}{2}\right)r^{1/2}}. \tag{3}$$

Results for the test specimens are summarized in the form of K_I relationships on the radial angle of the given crack front point. Values of the factor $\tilde{K}_I$ plotted in Fig. 9 are normalized by the maximum value of the factor K_I for an elliptical crack in an infinite space. The evaluated data obtained by holography and speckle methods are compared with those calculated by the numerical boundary element method [4].

3. Conclusions

Results and experience acquired during the last years show that the exploitation of optical methods in the field of stress state investigation in the bodies including cracks are adequately exact and effective in the solution of both engineering tasks and problems of fundamental research. Problems connected with a material evaluation and testing with regard to the influence of cracks measurement of fracture toughness parameters as well as a research of non-linear effects in the cracked bodies, all these questions call for experimental measurements. Moreover, methods of experimental mechanics, an important part of what are optical methods, allow successfully work out also very complicated problems in static and dynamic conditions. In comparison with the numerical computational method an experiment has the advantage where the specified boundary conditions are inaccurate or complicated (thermal, dynamical problems).

This is why we can say that application of optical methods in fracture mechanics has a bright perspective.

References

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Резюме

ОПРЕДЕЛЕНИЕ КОЭФИЦИЕНТОВ ИНТЕНСИВНОСТИ НАПРЯЖЕНИЙ ОПТИЧЕСКИМИ МЕТОДАМИ

Для определения коэфициентов интенсивности напряжений в случае плоского трехмерного состояний напряжения, в условиях статики и динамики, применено ряд оптических методов, а именно голографической интерферометрии ,,спекль'' интерферометрии и оптической фильтрации в соединенио с фотоэлектрической записю.

Результаты и опыт последних лет показывают, что применение оптических методов в обланстн исследования напряжения тел с трещинами являются соответственно точными и эффективными так в задачах инжинерных, как и в основных исследованиях.

Streszczenie

WYZNACZANIE WSPÓŁCZYNNIKÓW INTENSYWNOŚCI NAPRĘŻEŃ METODAMI OPTYCZNYMI

Do wyznaczenia współczynników intensywności naprężeń w przypadku płaskiego i trójwymiarowego stanu naprężenia, w warunkach statycznych jak i dynamicznych, zastosowano szereg metod optycznych, a mianowicie interferometrii holograficznej, interferometrii plamkowej i optycznej filtracji połączonej z zapisem fotoelektrycznym. Wyniki i doświadczenia ostatnich lat pokazują, że zastosowanie metod optycznych w dziedzinie badania stanu naprężeń spękanych ciał są odpowiednio dokładne i efektywne zarówno w rozwiązaniach zagadnień inżynierskich jak i badaniach podstawowych.

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