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Optical identification of the plastic zone shape and size on the cracked body surface.

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An advanced system has been developed to measure surface strains that occur during in situ deformation of mechanical deposited test specimens. The system uses photolithographically deposited displacement markers and computer image recognition routines to determine in-plane strains from digital images. Plastic strains are calculated from these strains.

1. Introduction

In spite of the classical fracture mechanics (*FM*) there is the only integral theory of crack instability in solid bodies, lately generally considered to be unsatisfactory, namely from the point of view of non-linear *FM.* This attitude has resulted in the endeavour to formulate a new corrective (two-parameter *FM*) or more general (thermodynamical *FM*) approaches.

A team in the *ITAM AS CR* is developing the concept of the thermodynamical *FM,* which one should give the more accurate predictions of the behaviour (evolution) of the ductile structures with defects. The basic diversity classical *FM* and thermodynamical *FM* is firmly rooted in fact that thermodynamical *FM* does not find energy dissipation in structures to be material constant (called fracture toughness) but as a cumulative non-local process. Its' history is significanthy influenced by the size of the body and by the type of loading. By the way, this fact is proved by the number of experimental fracture toughness measurements. The basic mechanism of the energy dissipation in the metal materials, is plastic work. From this reason, the identification (numerical and/or experimental) of the plastic yielding is fundamental task for every thermodynamical analysis of the fracture processes.

In the next part of article, the new method of the plastic zone shape and size identification in front of the crack will be described.

2. Determination of the plastic zone shape and size in front of the crack

We will plastic zone shape and size determine from total strain data measured on the surface of spcecimen. A new experimental method of the plastic zone identification has been developed. This method is based on the optical observations of deformations of hexagonal points grid deposited on the test specimen surface.

Orthogonal points grid is used in a classical grid method for determination of the surface strains. Strains ε_x, ε_y and consequented stresses σ_x, σ_y are calcutated from differences of neighbour points distances and shear strain γ_{xy} and consequented shear stress τ_{xy} is calculated from change of grid rectangularity:

$$\varepsilon_x = \frac{x_{i,j+1} - x_{i,j}}{k} \quad ; \quad \varepsilon_y = \frac{y_{i+1,j} - y_{i,j}}{k} ; \quad \gamma_{xy} = \alpha + \beta \qquad (1)$$

the indexes i,j determine location of observed point in matrix of grid points. Grid constant k is distance of points before grid deformation. The other is clear from fig. 1.

It is obvious that in the case of general in-plane strain we obtain all three components of strains and consequented stresses. Those components do not describe in-plane strains in the point but in the area defined by four points. The components are averaged on this area. It is necessary to use higher points density respectively reduce grid constant k proportionally to higher strains gradients. It is possible to calculate principal strains with assistence of Moire circles:

$$\varepsilon_1 = \frac{\varepsilon_x + \varepsilon_y}{2} + \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \gamma_{xy}^{\ 2}} \ ; \ \varepsilon_2 = \frac{\varepsilon_x + \varepsilon_y}{2} - \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \gamma_{xy}^{\ 2}} \ ; \ \gamma_{\max} = \frac{\varepsilon_1 - \varepsilon_2}{2} \qquad (2)$$

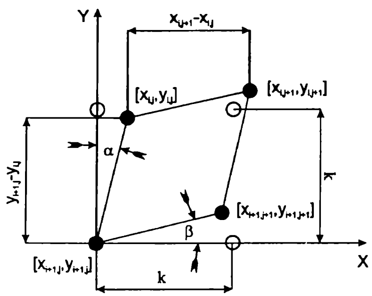

Fig.1: Orthogonal points grid

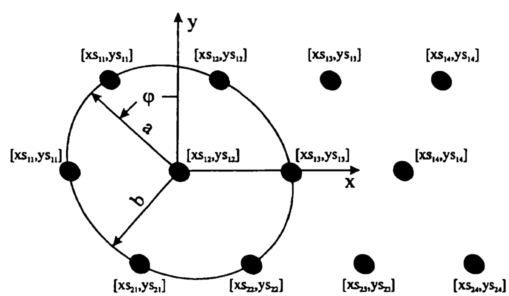

Fig.2: Deformed hexagonal points grid

Opposite to above, there is not orthogonal but hexagonal points grid (fig.2) used in the new method described in this article. It is more complicated to analyse experimental data if we use hexagonal grid but it is much more advantageous, as we will describe later.

Let us suppose homogenous deformation of homogenous material - it is possible to suppose in sufficiently small observed area (practically all similar methods are based on this presumption). Circle with diameter $2r$ is changing to ellipse with major axis $2a$ and conjugate axis *2b*. If we know ellipse parametres *a* and *b,* we can directly calculate principal strains in plane of specimen surface.

$$\varepsilon_1 = \frac{a-r}{r}; \qquad \varepsilon_2 = \frac{b-r}{r} \qquad (3)$$

The angle φ in fig.2 represents rotation of observed element relatively to global Carthesian system *x,y*.

We are limited by finite resolution ability of record equipment (a CCD camera in our case) when we are optically observering loaded specimen with deposited points grid. It is necessary to go to maximal record equipment resolution when we want to analyse interesting strains gradients (it means accuracy of determination of grid points position). As above, when we are determining deformations defined by differences of neighbour points distances, strains are averaged on the measure lenght of the grid. Measure constant is grid points pitch *k* for orthogonal grid and circle diameter *2r* for hexagonal grid measure constant. It is necessary to tell that when we are determining ellipse parameters central point of ellipse is not included in calculating. And so, orthogonal grid constant *k* really corresponds to measure lenght *2r* with the same resolution ability.

Basic advantage of hexagonal grid appears when we are working with maximal resolution ability of record equipment (especially in not proportional loading case). For instance, when accuracy required for strain determination is one percent and limit equipment resolution is the same, then both grids will be equivalent on their resolution ability, only if $\varphi = 0$ (it means directions of principal stresses are coincident with axis directions *x,y*). But, if strains field is not homogenous, φ can be significantly different from zero (it appeared with experiments where φ exceeded *20* degrees at the same places of observed field). Strains determination accuracy is invariant to changing of angle φ because in the case of hexagonal grid, we are working in local axis system of the ellipse.

This pressumption is not valid for orthogonal grid. For single axial loading, we can write:

$$\varepsilon_1 = \frac{\sigma_1}{E}; \qquad \varepsilon_2 \cong \varepsilon_3 \cong -\frac{\mu \cdot \sigma_1}{E} \qquad (4)$$

If we assume, for instance: we will observe strain ε_x, orthogonal grid axis will be coincident with loading axis, measured deformation will be *1%*, grid constant *k=1* and record equipment resolution *1%* will be its′ finite resolution ability. When grid axis is rotated for *22.5* degrees, we are under resolution ability, but haxagonal grid is still capble to capture this deformation. For observed strains with Mohr circle assistance, we can write:

$$\varepsilon_x = 0{,}85 \cdot \frac{\sigma_1}{E} = 0{,}85 \cdot \varepsilon_1; \quad \varepsilon_y = 0{,}146 \cdot \frac{\sigma_1}{E} = 0{,}146 \cdot \varepsilon_1 \qquad (5)$$

It is obvious that accuracy of strain determination is around *15%* less with orthogonal grid in comparison with hexagonal grid under non-homogenous field conditions.

A principle using pressumption of changing a circle to the ellipse is described on Zigel method [1], but parameters of ellipses were determined from the orthogonal grid and so advantage of invariance ellipses to global axis system was not used.

Above described method had been used with experiments connected with work mentioned in the article [2].

Three types of tensile loading specimens had been used: a specimen with boundary crack, a specimen with central crack and a specimen with central crack weakened by boundary notches. Hexagonal grid was deposited on polished specimen surface by photoresist method. Grid constant was alternatively *0.6* and *1.2mm*. The surface was observed by *CCD* camera and experiment course was recorded on *SVHS* videorecorder. Selected pictures were digitalised and consequentely processed by software developed in *Matlab 4.2c.1* with *Image Processing Toolbox 1.0b.*

3. Image data analysing

Computer processing is possible to describe schematically in allowing steps:

I. digitalisation of selected pictures through standard SVHS interface of workstation Indy *SGI*
II. increasing picture contrast and removing undesirable picture components
III. determination of grid points centres
IV. aproximations ellipses by grid points
V. calculating of total strains field with ellipses parameters assistance
VI. determination of plastical strains components of total strains

ad. II. Essential increasing of picture contrast and removing undesirable picture components were achieved by cosine Fourrier transformation. Components of Fourrier transformation matrixes corresponded to low frequences were substituted by zeros and back transformation was applied. In this way picture components with areal size considerable higher than point area were removed (arised from non-uniform lightening, reflections etc.).

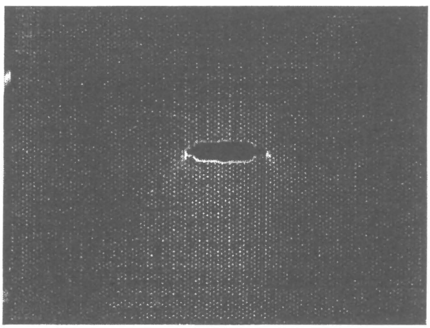

Fig.3.: Digitallized experimental picture. Rectangle shows analyzed area.

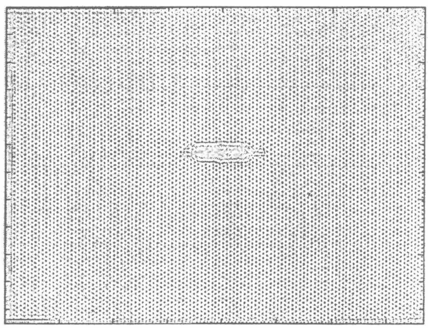

Fig.4.: Picture from fig.3 after filtering

ad. III. As in [3], it is possible to reach esentially higher accuracy of determination of grid points centres than one followed directly from record equipment resolution ability. We could reach resolution *0.02 pixels* of digitalised image (each pixel corresponding to one CCD camera chip point). We reached resolution „only" around *0.1 pixel* in our experiments in consequents of noises.

ad. IV. We used method of smallest squares in aproximation of ellipses by grid points. Every grid point was used for six different ellipses (it is possible because grid was hexagonal).

ad. V. Parameter *r* was reached from picture of non-loaded specimen. Other ellipses parameters: major axis *2a* conjugate axis *2b* and angle of rotation of observed element relatively to global Carthesian system x,y φ in every grid point were calculated for every selected picture. Conseqentually we were calculate principal strains field from ellipses parameters a and b.

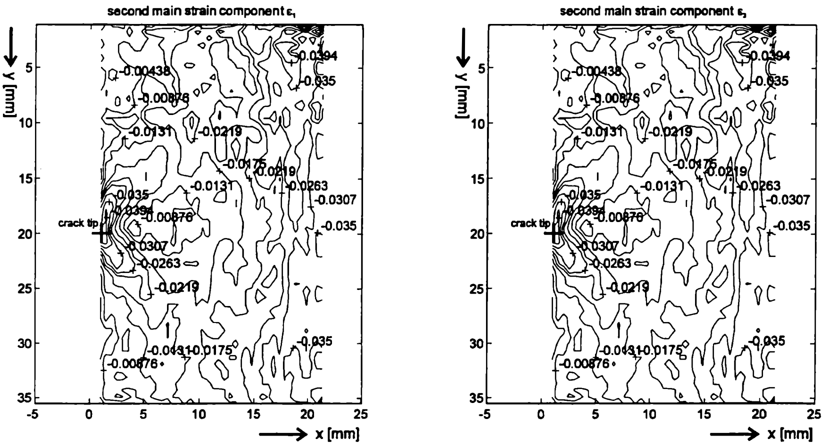

Fig.5: Main strains components

ad. VI. Plastic strains components of total strains were determined on base of deformation theory of plasticity in first approaching.

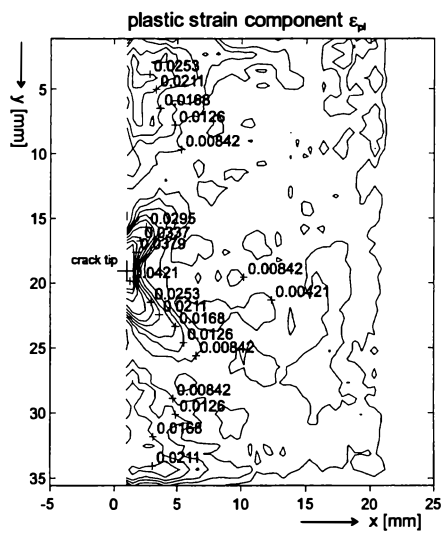

Fig.6.: Plastic strain component of equivalent strain.

References:

[1]: Smirnov-Aljajev, G.A.: *Soprotivlenie materialov plasticeskomu teceniu.*Masinostrojenie, Leningrad, 1978

[2]. Zemánková J., Jaroš P., Vavřík D.: *Experimental Part of Thermodynamical Fracture Mechanics Programme*, in this proceedings.

[3]. P. J. Sewenhuijsen: *Current trends in obtaining deformation data from grids*, Experimental Techniques, May/June 1993, p. 22.

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