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MICROMECHANICS – A NEW CHALLENGE TO EXPERIMENTAL MECHANICS

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Quite new technologies and new constructions appearing nowadays bring about a new task to be dealt with in experimental mechanics: examination of microregions. The paper presents new experimental methods and sample applications of these methods.
Unique advantages of the described methods are: contactless and non-destructive character of the measurement and the possibility of obtaining of the full field results.

Key words: micromechanics, interferometry methods, electron beam moiré

1. Introduction

The impetuous development of new technologies, to which we witness at the end of the 20th century, brings about new problems to be dealt with by experimental mechanics. One of such important tasks is the examination of processes, states of material deformation, and material properties in micro-regions. The need for that kind of research is stimulated by the tendency for miniaturization of machines and devices, particularly in microelectronics, where energy could be highly concentrated within small areas, and that high density of energy produces thermal gradients, which in turn, due to differences of expansion coefficients, generate high internal strains. It also pertains to the construction of new biomedical devices for monitoring internal organs in animals and humans; the micro-devices make it possible to limit the amount of material taken from a living organism for examination of its mechanical properties. Besides, it is commonly believed that what is most interesting in the processes of material destruction, such as, for example, crack progression, takes place in a micro-region in the neighborhood of crack tip, and the properties of complex materials, including composites, are determined by the relations of adhesion between the surfaces of fibers and the matrix.

The subject of interest is usually a field with overall dimensions from tenths to several hundreds of micrometers, in which high deformation gradients could occur, and for which both anisotropy and inhomogeneity of the medium should be expected. The conventional methods of deformation state examination prove ineffective. In some cases, such micro-objects can be examined in an increased scale, but usually the scale of the object must remain unchanged. A good example of such a situation is the residual stress examination. Hereinafter, selected attempts of micro-region investigations will be presented. In the opinion of the authors, these works were the most successful ones, and yieled meaningful results for micromechanics.

2. Micro-specimen examination

The tendency for decreasing the sample size follows from the necessity of minimization of the volume of material extracted from a structure in order to examine material properties. It becomes especially important in the case of examining tissue samples drawn from living organisms. In this case, minimization is additionally rationalized by inhomogeneity of the tissue, whose properties can change even at a small distance. An example of successful attempt in this field is the work of Sharpe and McKeown (1993), who constructed a micro-machine for examination of specimens of total length less than 3 mm, in which the measuring length and width were $750\,\mu$m and $250\,\mu$m, respectively. There, the main difficulties consisted in preparing the specimens, holding them in the gripping jaws of the apparatus, and performing load and deformation measurement. Fig.1 presents the load frame used in the system, and the shape of specimen. The deformations were measured by means of an interferometric strain/displacement gauge. For this purpose, two tiny indentation were cut at a distance of $200\,\mu$m. Two beams of coherent light illuminated the sample, and their radii, scattered on the indentations, formed two spherical beams which interfered in the surrounding space. The interfering beams illuminated two linear photodiode arrays (resolution of which was equal to 40 pixels/mm), creating five to six interferometric lines. As deformation of the sample took place, the lines moved along the arrays. The information, carried by electrical signal from the photodiodes, was transmitted to computer memory, and then used to determine the deformations.

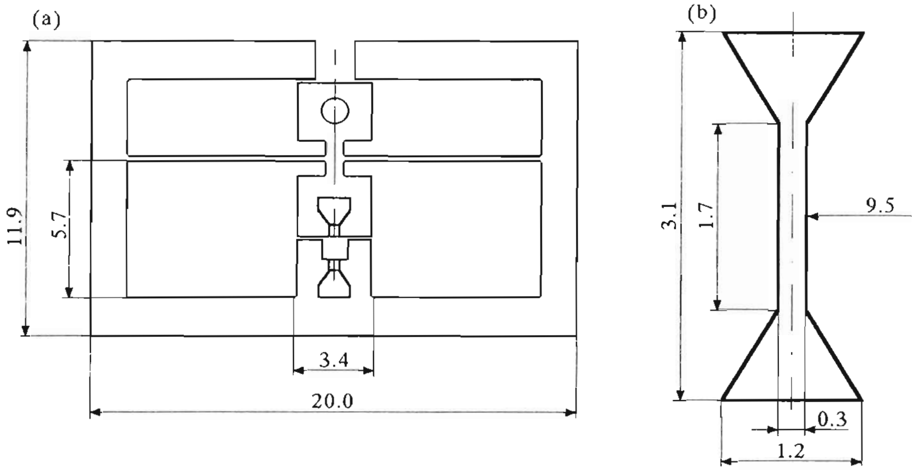

Fig. 1. Drawings of: (a) the teste machine load frame (dimensions are in milimiters), (b) the flat "dog bone" specimen

The error of deformation measurement by the device was estimated as 1%, for deformations in the range up to 1.2%, i.e. far beyond the limit of elasticity. Some problems aroused in the examination of organic materials such as bone samples. It was difficult to cut the sample out of a bone with an adequate precision, and make the indentations on the sample. The problems were solved by making indentations across the grips of the machine, and monitoring the grip displacement. However, this deteriorated the accuracy of stress measurement – because the actual displacement of grips contains elongation of the sample as well as the microslip of the sample in the grips.

The examination of deformation of the samples makes it possible to determine elasticity properties of sample material in one direction. However, it requires an *a priori* assumption about isotropy of the material, otherwise several samples cut in various directions must be examined. Such assumptions are not necessary in the case of field methods of deformation measurement, presented below.

3. Methods of interferometry

In this work, the following optical interferometric methods used for examining the states of surface displacement will be presented:

- holographic interferometry,
- moiré interferometry,
- Electronic Speckle Pattern Interferometry (ESPI).

In these methods, the examination yields a fringe pattern, resulting from relative phase differences between light waves of beams reflected by, or transmitted through an object, in different states of deformation.

The above mentioned methods give a field result, and are contactless, so that they do not have any effect on the object. They are very sensitive, allowing one do detect displacement as low as a fraction of wavelength of the the applied light. These qualities make interferometric methods especially suitable for examination of micro-regions.

3.1. Holographic interferometry

Holographic interferometry is a widely used method of non-destructive measurements of surface displacements. The investigated object does not need to undergo any preliminary preparation, and may have virtually any shape; it suffices that the specimen surfaces scatter light.

Schematic drawings of holographic interferometer assembly are shown in Fig.2.

Examination of deformation by means of the method of holographic interferometry consists of two stages: hologram recording, and its reconstruction. In the first stage (Fig.2a), the light is split into two beams: the object beam, and the reference beam. The object beam illuminates the examined object, then, after being scattered on the object surface, the light falls on a photosensitive element inserted into the system (usually a holographic plate covered with light-sensitive emulsion), where it interferes with the reference beam.

In this way, the relative difference phase of the beam scattered on the object surface are recorded – in two different states of the load.

In the second stage, the fringe pattern reconstruction takes place, by illuminating the holographic plate using the reference beam. Observations, and/or registration of fringe patterns are then performed.

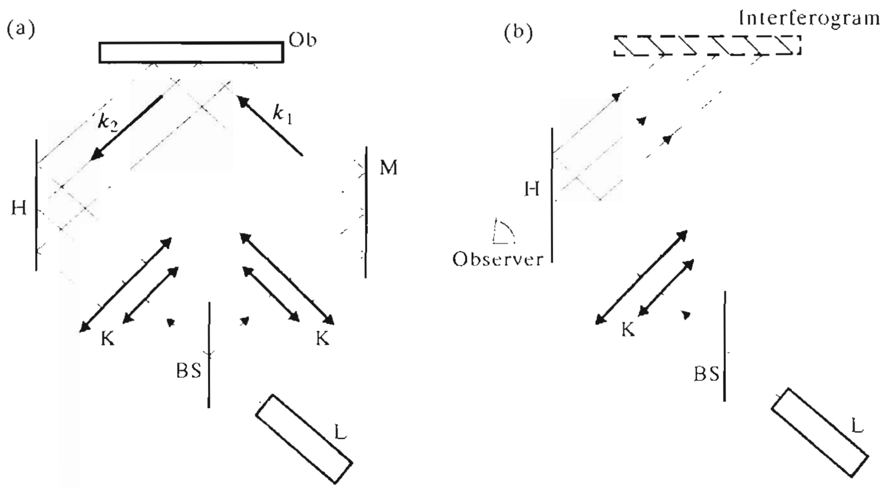

Fig. 2. Holographic interferometer; (a) recording setup, (b) observation setup; L – laser, BS – beam spliter, K – kolimator, H – holographic plate, M – mirror for object illumination, Ob – object

The analysis of fringe pattern images is based on the assumption that what one observes on a hologram is the result of superposition of two waves originating from the same point of the examined object, before and after its displacement, respectively.

At a given point, the basic relationship between phase difference and displacement is described by the equation

$$\phi = \boldsymbol{K}\boldsymbol{u} \tag{3.1}$$

where

ϕ – phase shift

$\boldsymbol{K}$ – sensitivity vector

$\boldsymbol{u}$ – displacement vector.

The sensitivity vector is determined on the basis of geometric characteristics of the system, and is given by the formula

$$\boldsymbol{K} = \boldsymbol{k}_2 - \boldsymbol{k}_1 \tag{3.2}$$

where $\boldsymbol{k}_2, \boldsymbol{k}_1$ – vectors defining the directions of illumination and observation, respectively.

The phase shift, evaluated on the basis of fringe patterns, uniquely defines the component of displacement vector in the direction of the system sensitivity vector.

The system composed of three sensitivity vectors allows one to determine all the components of displacement vector.

Holographic interferometry, combined with microscopy, gives the possibility of examining very small specimens. However, due to high optical magnification, the contrast and the fringe pattern resolution may significantly deteriorate.

The above effects are caused by aberration of the magnifying system, and the speckle effect resulting from application of coherent light. In some of the experimental systems, a partial solution to these problems has been found.

Hormung and Wernicke (1992), and then Kruschke and Wernicke (1995), presented examples of investigations on complex structures of small dimensions, subjected to the influence of thermal fields. The object of investigations were alumina resistors (Al_2O_3) mounted in an array. A DC current of 7 mA, flowing through the resistors, generated heat which increased their temperature by approx. $\Delta t = 40\,\mathrm{K}$, producing mounting stresses around the solder joints. The two elements, the resistors and the wiring board had different thermal expansion coefficient of $7 \cdot 10^{-6}/\mathrm{K}$ and $25 \cdot 10^{-6}/\mathrm{K}$, respectively. The aim of the research was to assess the cumulative displacements in the areas where the solder, made of an Sn-Pb alloy, was laid. The investigations were performed by means of a measuring set, whose schematic is presented in Fig.3. The object was illuminated from three directions, which made it possible to obtain three independent fringe patterns, and, basing on the previously mentioned relationship (3.1), determine three components of displacement vectors.

In order to improve the quality of fringe pattern images, first image holograms of the object were taken, and then the hologram was reconstructed using a beam conjugate to the reference beam (Fig.3b).

On the basis of experimental results it was found that

- Maximum magnitude of displacement vector components was approximately $3\,\mu\mathrm{m}$

- Most significant influence on the increase of deformation concentration had the u component of displacement, in the direction of resistor axis, while the contribution of the w component (normal to the surface of element), increased in the neighborhood of the solder posts.

It was estimated that the relative measurement error was less than 20%.

Dudderar et al. (1985) presented a measuring set for examination of displacements normal to the surface of multilayer printed boards made of an epoxy-fiberglass composite, on which the leadless ceramic-chip carriers with

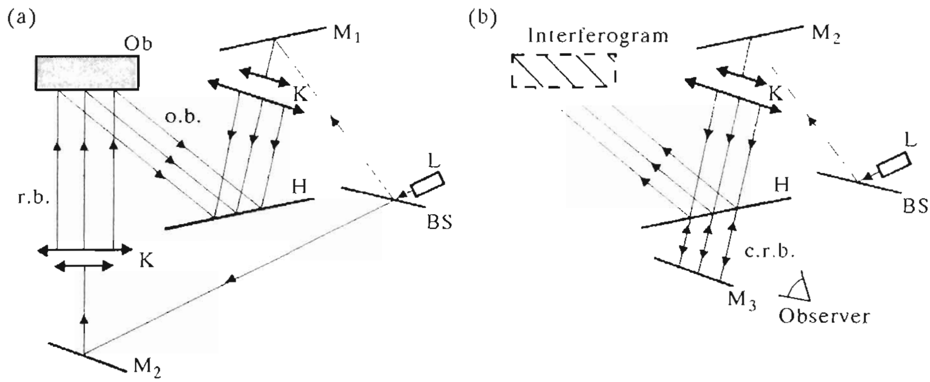

Fig. 3. Holographic interferometric microscope optimized by conjugate reconstruction; (a) recording setup; (b) observation setup; L – laser, BS – beam spliter, K – kolimator, H – holographic plate, M_1, M_2 – mirrors for object illumination and for reference beam, M_3 – mirror to form conjugate reference beam, Ob – object, o.b. – object beam, r.b. – reference beam, c.r.b. – conjugate reference beam

to overall dimensions of 16.5mm × 16.5mm × 0.216mm were mounted. Similarly as in the previous case, the board was subjected to thermal deformations. The aim of investigations was to determine in detail the influence of microstructure of the board on the thermal response of the microcircuit module samples subjected to thermal cycling.

Illumination in the measuring set was transmitted through single-mode optical fibers in order to facilitate adjustment of the system, reduce the number of optical elements, and diminish the influence of disturbances resulting from thermal fluctuations of air. The fundamental equation used by the authors, upon which the analysis of fringe patterns was based, was derived from Eq (3.1). For a system sensitive to only one displacement component, normal to the object surface, the equation takes the following form

$$n\lambda = 2w\cos\beta \tag{3.3}$$

where

n – fringe order

w – component of displacement vector normal to the surface

β – angle between illumination and observation vectors, $2\beta \cong 0°$.

On the basis of the interferograms, the distribution of displacement was determined, and then deformations were found. The reported investigations brought about exhaustive information about the influence, which the composite microstructure had on deformations of critical solder-joint connections between the surface-mounted ceramic chip carriers and the wiring printed board, under the conditions when temperature of the elements changed in power cycles.

Another example of application of microscopic holographic interferometry to investigation of phenomena in micro-regions is the examination of material properties in the neighborhood of crack tip, by Sciammarella and Narayanan (1984).

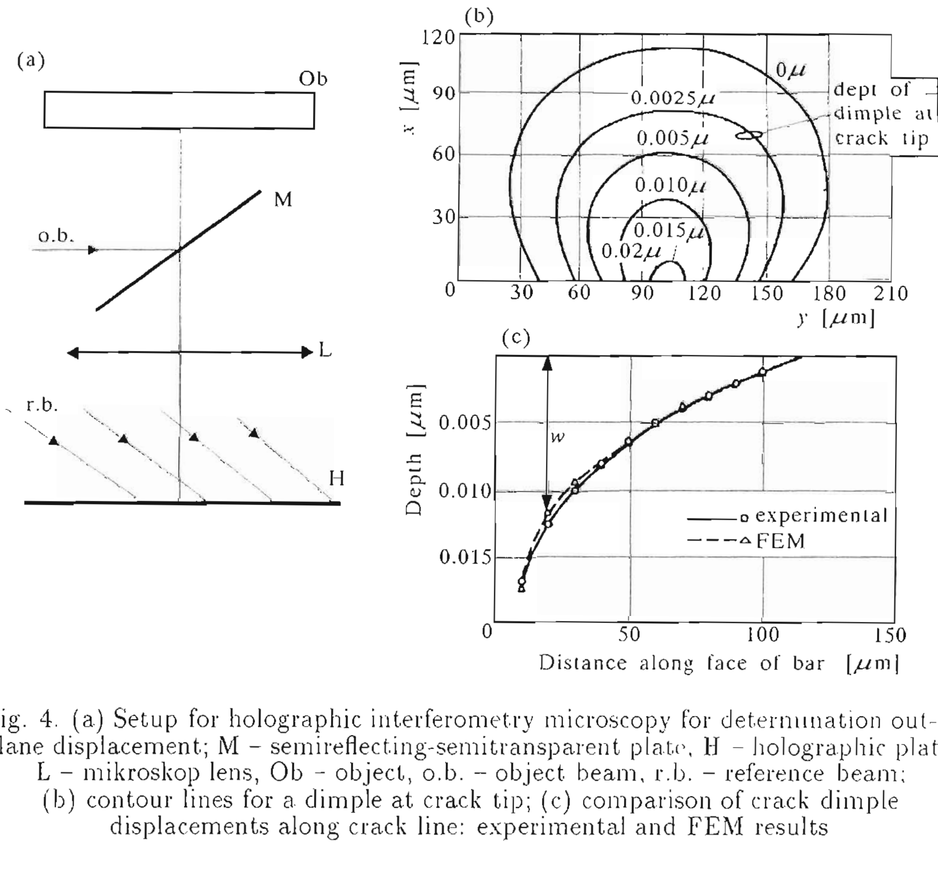

Fig. 4. (a) Setup for holographic interferometry microscopy for determination out-of plane displacement; M – semireflecting-semitransparent plate, H – holographic plate, L – mikroskop lens, Ob – object, o.b. – object beam, r.b. – reference beam; (b) contour lines for a dimple at crack tip; (c) comparison of crack dimple displacements along crack line: experimental and FEM results

A microscopic holo-interferometer assembly was applied to detect the presence and determine the shape of a crack 200 μm long and 100 μm deep, in a silicon-carbide bar subjected to three points bending. The scheme of the experimental set-up is shown in Fig.4a.

The interferometric system was sensitive to the normal component of displacement only. The field of view was located around the crack tip. The experimental results, and their comparison with the results of numerical calculations, are shown in Fig.4b and Fig.4c.

In order to avoid complications of three-dimensional analysis, one assumed for numerical calculations that, in such a small area, the effect of bending can be neglected. Consequently, only two-dimensional state of stress was taken into account.

The experimental results conform well to the results of calculations done by means of the finite element method. This confirmed the correctness of the applied experimental method, and the validity of assumptions accepted for the numerical analysis.

Summarizing the results of the above mentioned works, one can assert that the basic advantages of holographic interferometry in application to the deformation examinations in micro-regions are: high sensitivity, combined with the ability of non-destructive examination of small objects, and the possibility of determining the components of displacement vector, over the whole observed region, on the basis of one fringe pattern recording.

The drawback of the method is its high sensitivity to external, environmental effects, such as vibrations. The process of fringe pattern recording is laborious, involving wet chemical treatment of holographic pictures. Besides, it is necessary to reconstruct the hologram in the place, and in the assembly where it was recorded - which calls for a participation of highly qualified experimenter.

Some of these problems were solved in the ESPI method, i.e. the Electronic Speckle Pattern Interferometry with electronic recording of the interferograms. In this method, recording of light intensity is done directly through a CCD camera, omitting the holographic plate and the associated chemical processes. Application of this method significantly speeds-up and facilitates the experiment. Electronic recording of fringe patterns extends the measuring range, because the recordings can be done many times, for consecutive increments of displacement. At the same time, it requires less attention from the persons supervising the experiment, which makes it possible to continue observations of the processes for a longer period of time. However, the application of this method requires sophisticated software to be used for image processing, because of high content of noise in the recordings.

Some examples of micro-region deformation examination, done using the ESPI method, will be described hereinafter.

3.2. Electronic Speckle Pattern Interferometer (ESPI)

The ESPI method, also known as the electronic holography, is in general terms a method very similar to holographic interferometry. The images of fringe patterns, obtained resulting from digital signal processing, conform to the basic equation (3.1) of holographic interferometry.

This method, similarly as the holographic interferometry, is a contactless measuring method, giving a field result for the displacement field, with a precision of a fraction of the wavelength. However, as far as the way of recording and reconstructing the fringe pattern image is concerned, the two methods differ significantly.

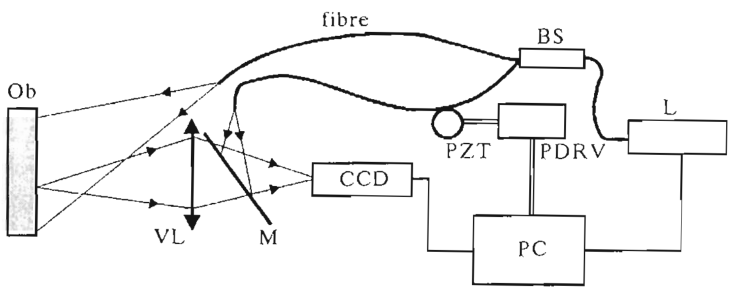

Fig. 5. Setup of the ESPI system; Ob – object, CCD – camera CCD, M – semireflecting-semitransparent plate, L – laser, BS – beam spliter, VL – video lens, PZT – the piezoceramic tranducer phase shifter, PDRV – the phase shifter driver

A typical scheme of electronic speckle pattern interferometer assembly is shown in Fig.5. Light from a laser diode is split into two beams. One of them is directed, through an optical system, onto the object, and the other one runs directly to a CCD camera, on whose array the two beams interfere with one another (a typical resolution of the array is 512×480 pixels). Through a frame grabber card, the signal from the CCD array is transmitted to a computer for further digital processing. The first recording is done for an unloaded object, in the next step the load is applied, and the second recording performed. The images, obtained in this way, are analyzed by an appropriate software being an inherent part of the electronic speckle pattern interferometer system. In the result of calculations, one obtains the phase maps, based on which the maps of displacements on the surface of the examined object can be drawn.

In the literature, one can find numerous examples of application of electronic speckle pattern interferometer to the analysis of properties of new materials, and the influence of material microstructure on the behaviour of the element as a whole.

Gross et al. (1992) observed the process of defect development around holes made in a multilayer plate. The object was subjected to thermal stresses resulting from differences in thermal expansion coefficients of individual layers of the plate, in the temperature range from 30°C to 155°C. The field of view on the object had the dimensions of 1.6 mm × 3.5 mm around the holes of diameter 0.457 mm. The applied system was sensitive to normal displacements only.

The field of displacements normal to the object plane was determined for the bottom, the top surfaces of the plate. The results obtained in the experiments are shown in Fig.6.

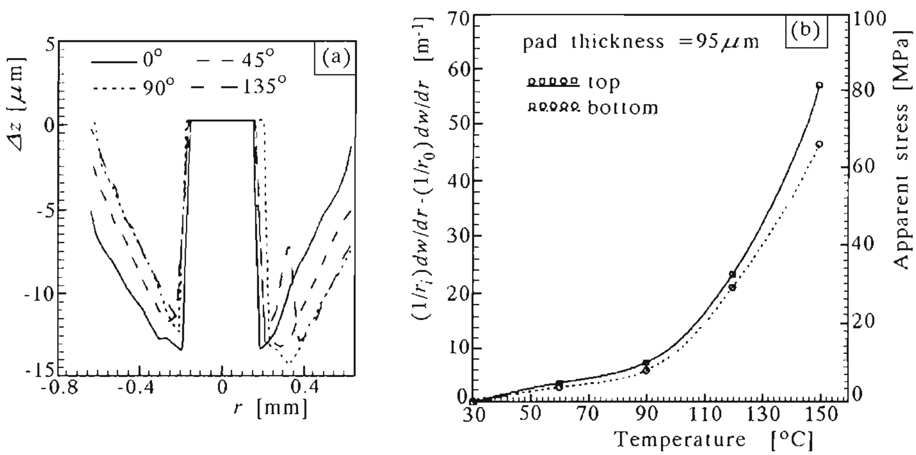

Fig. 6. (a) The distribution of out-of-plane displacement along four slices 0°, 45°, 90°, 135° on the bottom of the board. The displacements in the hole are encoded as zero; (b) the influence of temperature on the apparent stress

A substantial advantage of using the ESPI method in this case was an almost unlimited range of measurable displacements. In the case of holographic interferometry, displacements in such a wide range of temperature would effect de-correlation of interferometric fringe patterns, making observation of the whole process practically impossible.

In the literature, there are numerous examples of application of hybrid methods, in which an electronic speckle pattern interferometer was used for determining the field of displacements, later used as the boundary conditions in a precise numerical analysis of deformation field.

In the work by Olszak and Pryputniewicz (1995), the subject of research was the process of stress relaxation in small elements made of material utilized in micro-connections of electronic circuits designed for reliable long-term operation.

The object under investigation was a cantilever beam, made of brass, of dimensions 20 mm × 1.25 mm × 0.25 mm, rigidly fixed at the lower end. The beam was loaded at the upper end by applying a known displacement in the direction normal to the plane of observation.

In the experimental set-up presented in this work, in order to make the assembly very compact, elements of fiber optics were applied to the light transmission. A laser diode was used as the source of light, with a maximum of 30 mW of optical power in a single longitudinal mode at 830 nm. The vector of system sensitivity was normal to the object plane. The detector used was a CCD camera with the maximum resolution of 512 × 480 pixels. A piezoceramic tranducer drum with a wrapped fiber used as the phase shifter made it possible to employ the method of discrete phase shifting in the analysis of interferograms.

A 486DX2 type PC computer, equipped with a specially designed software, was used for image acquisition and the analysis of interferograms.

In the result of the experiment, a field of displacements normal to the object plane was found. This field made up the boundary conditions for calculating stresses in the object. Stress variations in time, occurring during the relaxation process, were observed in the interval of 120 hrs. In effect, a stress relaxation curve was obtained. A change in displacement by nearly 5% was recorded, which corresponded to a decrease of stress by 10% in the region of maximum stress level as compared with the initial stress at the instant of loading.

The quoted work shows the possibility of applying an electronic speckle pattern interferometer assembly to long-term examination of small objects, particularly for the relaxation processes analysis.

Owing to automatization of interferogram recording, the experimenter does not need to be present in person during the tests, which is advantageous, especially in long-term experiments.

Obviously, the experiment carried out during such a long time requires the system to be very stable, which involves the necessity of maintaining a constant ambient temperature.

Brown and Pryputniewicz (1995) also applied a hybrid method, combining numerical method (FEM) and an experimental one, to determine dynamical characteristics of microelements manufactured for the use in sensors. Optimization of element shape, and maximization of its first resonant frequency while preserving the overall element dimensions, was also performed. The objects under investigation were two vibrating elements, made of pure silicon and silicon nitride, of dimensions ranging from 450 μm down to 10 μm. The resonant frequencies and the shapes of bending and torsional vibration modes were determined both experimentally and numerically.

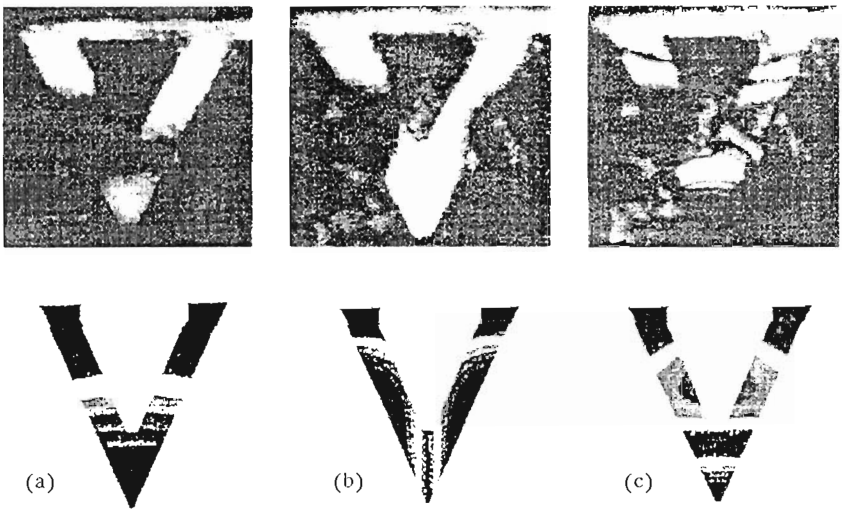

Fig. 7. Sample images of the first three modes for the 150 microns long triangular shaped microbeam; (a) experimental measured freaquency is 33.6 kHz, FEM predicted frequency is 36 kHz, (b) experimental measured freaquency is 137 kHz. FEM predicted frequency is 140 kHz, (c) experimental measured freaquency is 145 kHz, FEM predicted frequency is 150 kHz

An effect of hysteresis in the third vibration mode was discovered experimentally; this effect had not been predicted theoretically. The results obtained in these experiments are shown in Fig.7a, the numerical results are shown in Fig.7b. The discrepancies between numerical and experimental results depended on mode order and sample shape, and varied from 1.2% to 5.8%.

The electronic speckle pattern interferometer system also offers a possibility of selecting individual components of displacement in the plane. Scheme of such an assembly was shown in Fig.8a.

In a similar system to that shown Fig.8a, the microscopic crack tip field in a compact tension specimen was observed (Sciammarella, 1994). The observed crack tip had the shape of a notch. The object was illuminated by two beams, running symmetrically about the normal to the object plane. The interferometric image, created in this way, was recorded by a CCD camera. A field of view around the crack tip had the dimensions 1470 μm × 1470 μm. Owing to a precise optomechanical system, there was a possibility of compensation of the movement of the object treated as a rigid body, as well as neutralize the

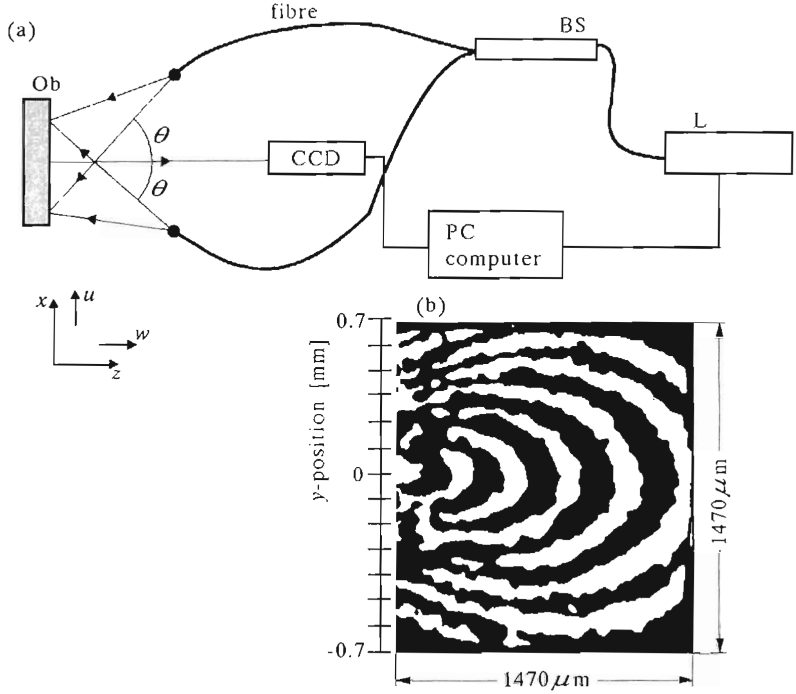

Fig. 8. (a) Setup of holographic microscope interferometer for determination of in-plane displacement of the object: BS – beam spliter, CCD – camera CCD, Ob – object; (b) the example of obtained u-displacement pattern, the sensitivity is 0.365 micrometer per fringe

influence of external disturbances.

The field of relative displacement in the neighborhood of the crack, and in the direction perpendicular to it, was obtained there. The measuring sensitivity of 2.06 nm was achieved. An example interferogram is shown in Fig.8b.

Summarizing the above presented works one can say that the electronic speckle pattern interferometer is, in principle, a hybrid of electronics and optics. The following advantages result from that fact:

- The process of data acquisition and analysis can be performed much faster and easier than in the case of holo-interferometer system
- The measuring range is virtually unlimited, owing to the step-wise recording method; however, there is a theoretical limit on a one step recording range, resulting from the dimension of speckles, as de-correlation of interferometric patterns arises with the increase of displacement

- Sensitivity of the system to external disturbances is reduced, compared with that of a holo-interferometer
- Owing to the use of CCD camera, the operating costs (costs of materials) are lowered. However, the costs of construction of the measuring set-up are higher, because implementation of the ESPI method needs an adequate electronic hardware, including a CCD camera of resolution 512×512 pixels with 256 degrees of gray scale, a PC computer with 486DX type (or more powerful) microprocessor, a phase control element, i.e. piezoelectric transducer, and an appropriate software for the analysis of interferograms.

Thanks to the characteristics described in the previous paragraphs, the ESPI method can be easily employed in industrial applications. It facilitates the measurements, which can be performed even by persons with lower qualifications. Besides, because permanent attention of the personnel is not required, examining of long-term processes becomes more convenient.

Similarly as in the holographic interferometry method, representation of total displacement can be obtained by the ESPI method, if the measurement of three components of displacement vector is implemented in the experimental system. Measurement accuracy, achievable in electronic speckle pattern interferometer, depends to a high extent on resolution of the CCD camera. Measurement precision is inversely proportional to pixel dimension, which, in cameras presently available, varies from $0.1\,\mu$m to $0.25\,\mu$m.

The drawbacks of electronic speckle pattern interferometer are high noise level, and low resolution of the CCD camera, compared with that of a holographic plate. This could be a significant impediment, specially in examining small objects.

3.3. Interferometric moiré method

The interferometric moiré method finds its application in examining relatively flat objects. A general scheme of the optical system used in this method is shown in Fig.9.

The object under investigation must be appropriately prepared for the test, namely a reflective phase grating must be cast on its surface. For this reason, the object surface must be flat, and relatively smooth. The object, prepared in this way, is then illuminated in the optical system by two laser beams, symmetrical about the normal to object plane, which thereby form a virtual reference grating.

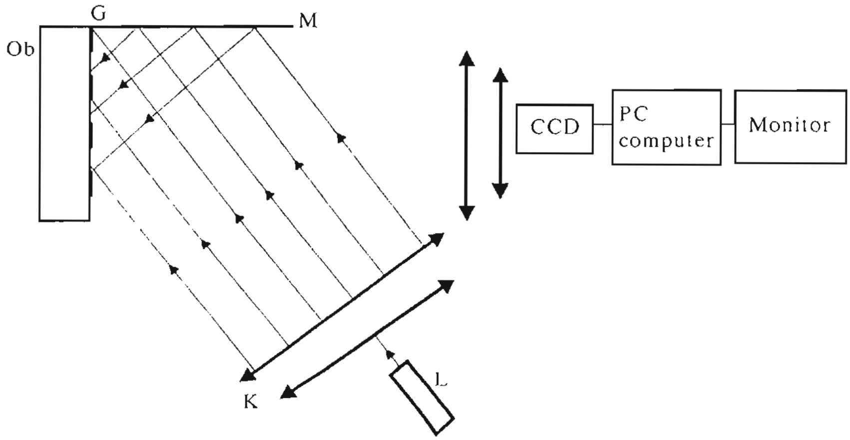

Fig. 9. Scheme of the setup of grating interferometer; CCD – camera CCD, Ob – object, M – mirror, K – Kolimator, L – laser, G – grating attached to the object

In the system, the moiré fringes are registered in two states of object load. After comparing the two images, one obtains an interferogram in which fringe patterns depend on the object deformation which took place between the two states, and the spatial frequency of virtual grating. These relationships are described by equations

$$u = \frac{N_x}{f} \qquad v = \frac{N_y}{f} \tag{3.4}$$

where

u, v – orthogonal displacement components

f – spatial frequency of virtual grating.

In order to obtain at once two components of displacement vector in object plane, a four-beam illumination system can be used, providing the possibility of simultaneous registration of displacement field in the directions u and v. This means that, in fact, one can determine the components of displacement vector in an arbitrary direction.

The method is practically insensitive to displacements normal to the object plane. Nevertheless, this effect can be easily detected and compensated.

Microscopic moiré interferometry is the extension of moiré interferometric methods to micromechanical applications. In these systems, an optical microscope is used to enhance resolution of interference patterns of the examined objects, and an immersion interferometer is applied to increase sensitivity of the method. Additionally, the sensitivity can be further improved by the optical/digital fringe multiplication (O/DFM) method.

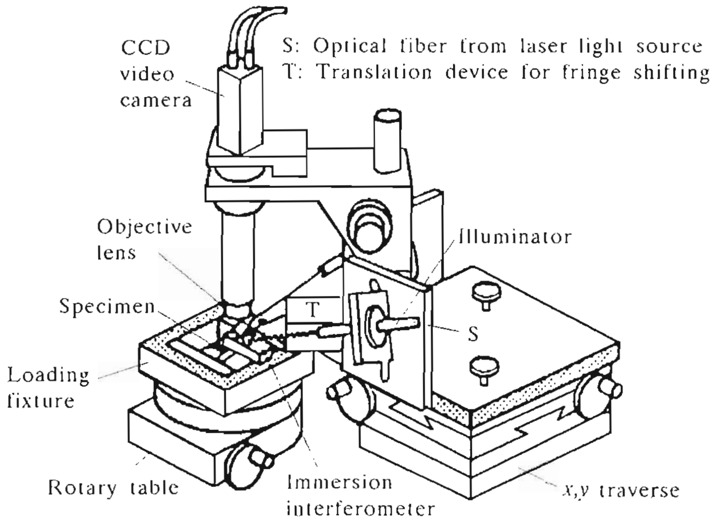

Fig. 10. Optical and mechanical assembly of the microscopic moiré interferometry, used by Han (1994)

A scheme of microscopic moiré interferometer assembly, in one of possible configurations, is shown in Fig.10. As reported by Han (1994), the reference (virtual) and the object gratings had spatial frequency of 4800 lines/mm and 2400 lines/mm, respectively, and the fundamental sensitivity, achieved in this method, was 208nm displacement per fringe order (4.8 fringes per one micrometer of displacement). Owing to its configuration, the system was relatively insensitive to environmental disturbances.

In the described system, a multilayered copper/alumina (Cu/Al_2O_3) composite was examined by Dadkhoh et al. (1994). The aim of the research was to analyze the crack propagation process in a specimen subjected to external forces were examined, taking into account the microstructure of ceramic/metal components of the composite materials.

The specimens of $(3 \times 4 \times 30)$ mm or $(1 \times 8 \times 25)$ mm dimensions, and the field of view size was $600\,\mu$m $\times$ $600\,\mu$m.

Examples of interferograms obtained from these tests are shown in Fig.11. Based on the interferogram, a map of displacement in the plane u, v was determined, and consequently used to evaluate deformations. It allowed determination of the changes of stress gradients in various layers, and made it possible to find relationships between the stresses and layer thicknesses and

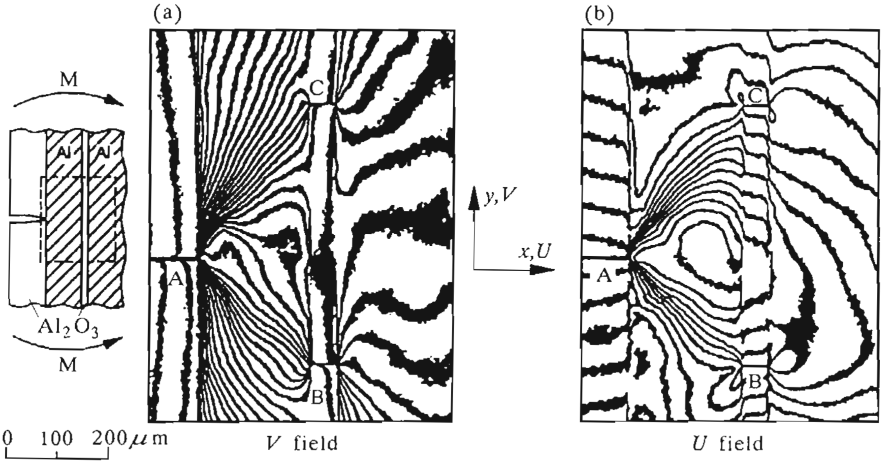

Fig. 11. The examples of obtained interferograms in the microscopic moiré interferometer: u, v microscopic moiré patterns of the crack tip region in a Al/Al_2O_3 multilayer when subjected to the stress intensity factor of $K_I = 7.7\,\mathrm{MPam}^{1/2}$, a contour interval of 104 nm/fringe was used

types of material applied. Owing to these results, an analysis of parameters influencing crack progression could be performed. For the first time, an experimental evidence was found showing why the crack in the brittle phase propagates offset to its original plane after passing through the ductile layer.

Han (1994) reported application of the above described system to registration of micro-mechanical behaviour of a large grain β alloy titanium in elastic/plastic and elastic tension, in a specimen made of policristaline metal. The field of view had dimensions of approxing $500\,\mu\mathrm{m} \times 500\,\mu\mathrm{m}$. It was found that local stress concentration arises in the neighborhood of grains already in the early stage of loading. The results showed anomalous structural deformations within grains, and near the boundaries between grains. Some of the images are shown in Fig.12.

Very often, the subject of interest is simply a qualitative assessment of the behaviour of objects subjected to loading, for instance detection of local stress concentrations. An example of application of the moiré interferometry to qualitative investigations is the work of Sirkis and Singh (1994).

The work presented the research into a composite in which an embedded optical fiber played the role of sensor of mechanical strains. Optical fibers are often used in what is called the *smart* sensors, because of their high-strain sensitivity, chemical inertness and electromagnetic immunity – which makes them favourable candidates for sensing devices. The aim of the experiment

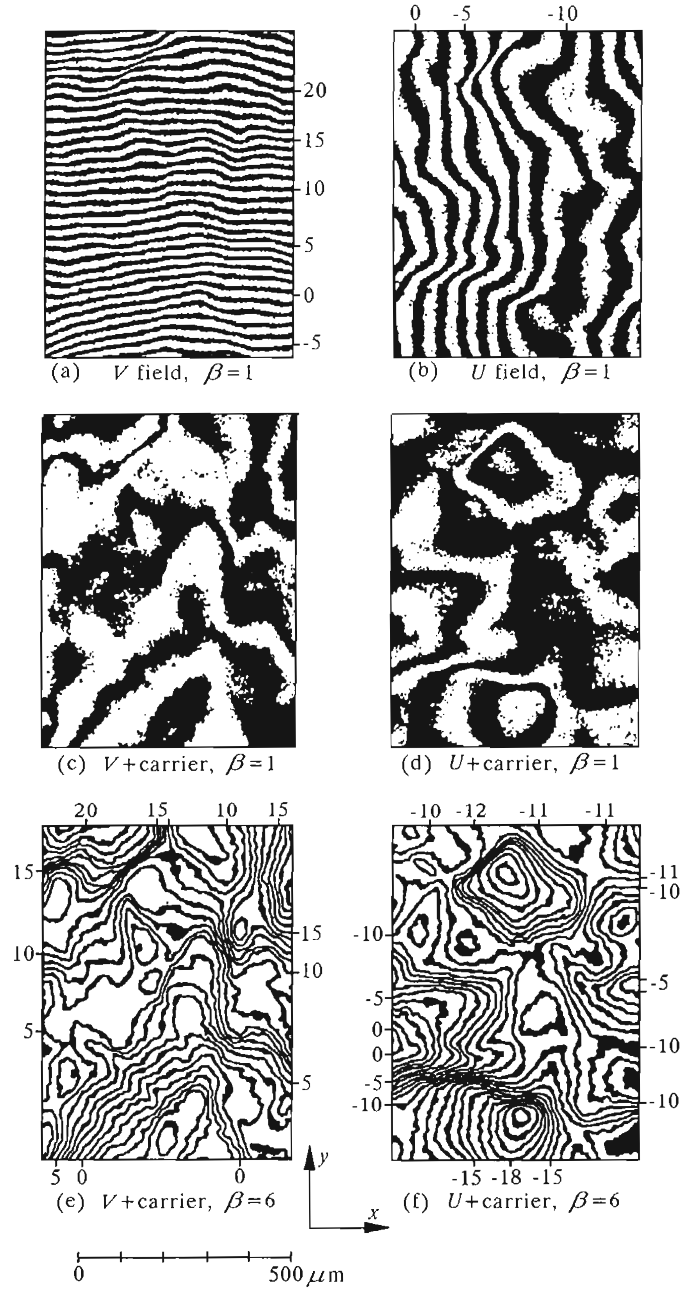

Fig. 12. The examples of interferograms obtained in the microscopic moiré interferometer: for the specimen material which was a large grain β alloy titanium at the average strains equal to 0.85% which is 57% of the yield point strain. The contour intervals are 208 nm/contour and 35 nm/contour for $\beta = 1$ and 6, respectively

was to determine whether the presence of embedded fiber had any effect on the growth of local strains in the specimen. The examined region had dimensions of $3175\,\mu$m × $2120\,\mu$m, and the fiber diameter was $125\,\mu$m. The research showed that the fiber embedded parallel to reinforcing fibers had, owing to its filamentary geometry, a minute effect on the strain concentration, thus it could be used as an unobtrusive internal sensor. It also followed from the investigations that, in this case, the ratio of diameters of optical and reinforcing fibers, as well as material of the fibers, had an important meaning.

Guo and Lim (1944) presented the application of a hybrid method, combining the experimental results produced by moiré interferometry with the results given by the FEM to precise stress/strain analysis of an object subjected to thermal loading.

The areas of connection of ceramic microchip modules to a glass-epoxy printed board by means of the solder column connect (SCC) technology were investigated. Thermal loading was applied to the specimen, and temperature was increased by $\Delta t = 50°$C. The strains arose in the process as a consequence of differences in thermal expansion coefficients of the ceramic module, and the circuit card. The objects under investigation (solder columns) had dimensions of 0.5 mm × 2.8 mm; the spatial frequency of the object grating was 1200 lines/mm, and the measurement sensitivity achieved in the method was 417 nm of displacement per fringe order. Sample interferograms of displacement fringe patterns from this experiment are shown in Fig.13.

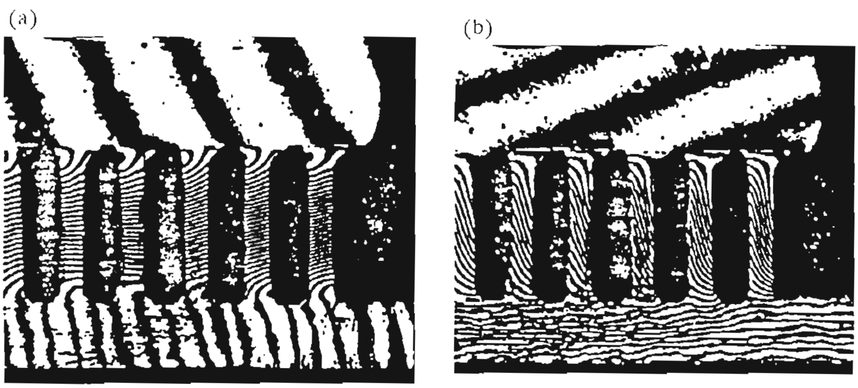

Fig. 13. The moiré fringe pattern of displacement u and v fields of solder column connect assembly, the dimentions of every solder column is 0.5 mm × 2.8 mm

The investigation showed that the highest concentration of strains occurred in the areas of connection of elements with different thermal expansion coefficients.

In the application of the investigated solder column connecting technology, thermal fatigue of the solder is a major concern of the package in terms of reliability. The fatigue of the solder is related to the plastic and elastic strain, especially the local strain concentrations, which cause crack initiation in the solder.

The obtained results were used for constructing a simple FEM model aimed at optimizing the shape of solder column, and thus reducing strain concentration and increasing fatigue life of the element.

On the basis of the presented works, one can conclude that the moiré interferometry method can be successfully applied to examining deformation in relatively small areas, especially when the subject of interest is the real-time field result, or in the case of long-term observations of deformation processes.

The presented works prove the possibility of applying moiré interferometry to investigating phenomena in small objects, where other methods would not give satisfactory results. The method can be used to detecting crack propagation, determining crack profile, and examining the growth of strain concentration resulting from the changes introduced to object microstructure. The highest sensitivity of the method was achieved in the systems where spacial frequencies of object grating equal to 2400 lines/mm, and that of virtual reference grating equal to 4800 lines/mm were applied. Maximum resolution in this method is as high as $0.1\,\mu$m.

3.4. Electron beam moiré method

Until quite lately, only optical field methods were used for examining the state of stresses in micro-regions. The examples of application of such methods have been described in previous sections, and the characteristics of optical methods are summarized in Table 1. Analyzing this data, one can say that optical methods have reached the ceiling of their capabilities, because the wavelength of visible light restricts any further increase of grating density. Going beyond this limit become possible by application of electron microscope with collimated electron beam.

Dally and Read (1993), Read and Dally (1993a,b), presented a moiré method employing scanning electron microscope. By means of collimated electron beam, and computer-controlled microscope, line or dot gratings were cast on polished surface of a specimen covered with a layer of PMMA resist. Grating density varied from 10000 lines/mm to 13000 lines/mm. In the opinion of the authors, such gratings can be applied at homogeneous materials, like aluminum or bronze, as well as at inhomogeneous ones, like composites reinforced with glass fibers.

Table 1

	Sensitivity to environ-mental disturbances	Visibility (contrast) of fringe patterns	Possibility of measure-ment automa-tization	Interference of measurement method in object structure	Applicability to industrial measurement	Applicability to measurement of long-term processes
Moiré interferometry	low	good	yes	high	yes	easy
Electronic speckle pattern nterferometry	medium	bad	yes	low	yes	easy
Holographic interferometry	very high	medium	no	low	no	difficult

In the quoted works, the specimens were loaded by means of a special load frame, and then placed in the chamber of scanning microscope. The scanning electron beam moved in steps whose length was chosen according to spatial frequency of the grating applied to the specimen surface.

The examined surface was observed with the magnification factor of 1900. The grating spacial frequency was 10000 lines/mm, which meant 40 lines per one glass fiber diameter.

Sample fringe patterns obtained by this method for the examined glass-epoxy composites are shown in Fig.14. The patterns refer to consecutive stages of specimen loading. The concentration of fringes on the matrix material in the neighborhood of fiber fracture indicates a high gradient of deformation.

Theoretical relationships used for determining deformation by means of the moiré interferometry utilizing collimated electron beam were given by Read and Dally (1993b).

4. Conclusions

On the basis of the presented review of literature, and the results of the authors' own research, one can draw the conclusion that the methods of optical interferometry have certain advantageous characteristics, which predistinate them for investigation of small objects; i.e.,

- give field results,
- are highly sensitive,

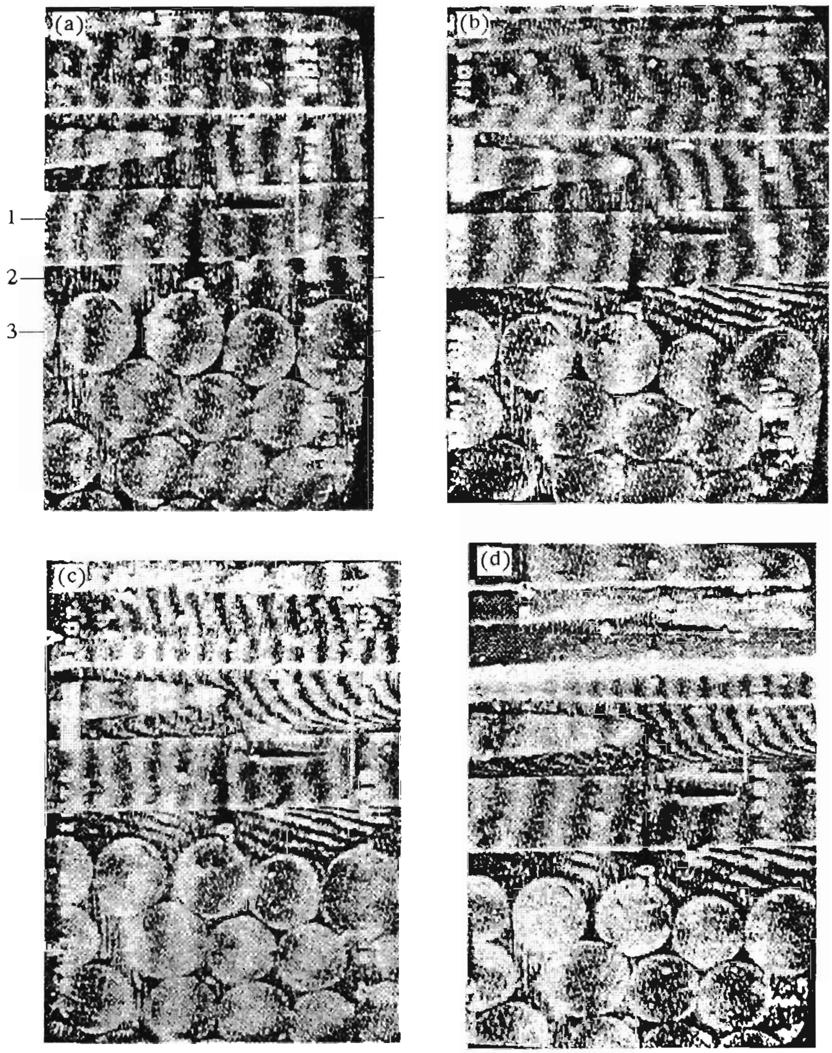

Fig. 14. Moiré fringe pattern (a) prior to cross ply cracking, at a stress of 347 MPa, (b) after cross ply cracking at a stress of 524 MPa, (c) prior to delamination cracking at a stress of 933 MPa, (d) after 0° ply delamination at a stress of 1075 MPa

- allow determination of all components of displacement vector in one measurement,
- are contactless and non-destructive.

Optical interferometry methods initially had application in qualitative investigations, since examining the interferometric fringe pattern continuity one can easily detect cracks as well as strain concentrations, and carry out observation of the damage process propagation. Quantitative measurement of displacement occured to be much more difficult. In spite of high sensitivity of these methods, deformations determined from dislocations by numerical differentiation were burdened with significant relative errors, up to 20%.

The research results show that the combination of experimental methods of interferometry and the FEM is specially advantageous. Interferometric methods allow determination of the whole dislocation field, providing high precision and resolution. The results, obtained in this way, can be applied as the boundary conditions to numerical computation of local states of deformation and strain, which can be done with high accuracy.

Juxtaposition of some characteristics of the presented methods is given in Table 1.

Nowadays, an integral and indispensable part of the measuring systems is an adequate software, whose function is to control illumination and image data recording, and to facilitate automatic analysis of the fringe pattern images.

Recording of interferometric fringe patterns is done by means of an electronic light-sensitive device (a camera with charge coupled device, the CCD array), from which optical information is transmitted to computer memory. Depending on the method applied, interferogram is recorded directly from the CCD array, through a frame grabber card, or the system records reconstructed interferograms, which have been previously registered on another photosensitive device.

Four different methods of automated analysis of interferometric fringe patterns can be distinguished. Table 2, taken from the work by Pramond and Rastogi (1994), summarizes characteristics of these methods. The methods of fringe skeletonizing, and the method based on the Fourier transform, can be applied to analysis of interferograms registered on a holographic plate or on a film. Both methods allow automated analysis, and do not require any sophisticated instrumentation to be introduced to the experimental assembly.

The phase shifting and stepping method, especially that utilizing discrete phase steps, facilitates automated measurement, and speeds up computation. However, it requires that the inserted phase shift should be controlled very precisely, which calls for the use of a precise phase shifter. Besides, examination of dynamical processes by this method is more difficult.

Table 2

	Fringe skeletonizing	Phase stepping and shifting	Fourier transform	Temporal heterodyning
Number of interferograms to be reconstructed	1	3 or 4, sometimes 5	1 (2)	1 per detection point
Resolution (λ)	$1 \div 1/10$	$1/10 \div 1/100$	$1/10 \div 1/30$	$1/100 \div 1/2000$
Automatic sign detection	no	yes	no (yes)	yes
Necessary *intervention in* experiment	none	phase *shifting*	none *(phase* shifting)	frequency *shifting*
Difficulty of method	low	high	low	very high
Sensitivity to environmental effects	low	variable	low	very high
Human intervention	possible	impossible	possible	impossible
Speed of analysis	low	high	low	very low

The temporal heterodyning method needs a lot of effort to be made in preparing the experiment, requires the system to be highly stable, and needs a long time to perform the analysis. In return, it ensures high accuracy of measurement.

In the method of fringe skeletonizing, the minimum resolution is determined by the number of fringes in the examined region; the maximum achievable resolution is equal to 0.1λ, where λ – wavelength of the light.

In the Fourier transform method, and phase shifting and stepping method, resolution is limited only by the dimensions of photosensitive element in the light detector, and does not depend on the number of fringes. In these methods, resolution can be varied by changing the system magnification. The Fourier transform method provides the accuracy enabling dislocation lower than $\lambda/20$ to be measured; similarly, in phase shift methods, resolution can be as high as $\lambda/100$.

The most accurate is the temporal heterodyning method, whose resolution can be less than $\lambda/500$.

The quoted literature sources indicate that the phase shifting and stepping methods are the most widely used ones, as they provide relatively high sensitivity and precision of measurement and are easy to implement. In some specific cases, the Fourier transform method can also be recommended, for example when pulse laser is used as the source of illumination, and/or when dynamic processes are examined.

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Mikromechanika – nowe wyzwanie dla mechaniki eksperymentalnej

Streszczenie

Pojawienie się nowych technologii i konstrukcji postawiło przed mechaniką eksperymentalną nowe zadanie prowadzenia badań w mikroobszarach.

Artykuł przedstawia nowe techniki badawcze i wybrane przykłady zastosowania metod interferencyjnych. Szczególne zalety omówionych metod to bezkontaktowy, nieniszczący pomiar oraz uzyskiwanie wyników polowych.