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TRENDS OF EXPERIMENTAL MECHANICS[1]

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The present contribution aims at presentation of modern trends of experimental mechanics as well as fields of greatest activity and advanced experimental methods enabling acquisition of yet unattainable or more reliable information.
Widespread application of experimental methods observed nowadays has emerged as a result of linear approach limits being reached, together with the necessity for new states and processess to be observed. On the other hand, it should be noted that experimental methods have been developed rapidlly for the last decade due to application of the techniques used till now only in physical laboratories, revealing new capabilities emerging from advanced computer methods of data acquisition and data processing.
The survey has been made basing on over thirty papers presented in 1993-94 at most representative conferences on experimental mechanics.

1. Introduction

There have been many anniversaries celebrated these days, raising an excellent occasion for proving the experimental mechanics usefulness as well as showing modern trends prevailing in its development identification. In 1993 the 50th Anniversary of American Society for Experimental Mechanics was celebrated and a 40-year tradition of International Conferences on Experimental Mechanics was continued under the patronage of the European Committee for Experimental Mechanics. In 1994 the XIII IMEKO WORLD CONGRESS was held in Torino, having the subtitle "From Measurement to Innovation". In 1994 the XVI Experimental Mechanics Symposium was held in Poland,

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what means that these conferences have been organised for over thirty years. Also, the Second SPIE International Conference "Interferometry 94" was held in Warsaw, subconference of which "Photomechanics" was attended by researchers from several countries dealing with optical methods applied to experimental mechanics.

The problems solved in mechanical laboratories change with time, so do aims and possibilities of investigation. Application of experimental mechanics to the stress analysis and solving problems of vibrations as well as motion and structure stability has been considerably limited, since these problems can be efficiently solved using numerical methods. There arise, however, a number of new problems analytical solutions to which are impossible, while the application of numerical modelling demands observations, investigations into physical phenomena and precise statement of the constitutive equations. A strong need for efficient, precise and reliable measurement methods for determination of quantities governing a system state and a course of a process can be therefore stated.

The present contribution aims at presentation of areas of greatest activity within the scope of experimental mechanics as well as modern methods used.

Main scope of activity covers mechanics of materials, investigation into fatigue and fracture, analysis of the residual stresses affected by technological process or exploitation, examination of structures subject to critical conditions, research in the field of robotics, biomechanical systems testing, process control and quality inspection.

Thermomechanical and ultrasonic methods are being developed rapidly, especially in the field of stress analysis, as well as optical methods, moiré interference method, speckle interferometry and moiré methods applying scanning electron microscope. Researchers are working on application to experiments the physical phenomena discovered earlier, e.g., Villari's effect may occur to be useful in material structure changes observation.

Unfortunately, only several percent of the physical phenomena being discovered and explained have been applied to experimental investigations. Further development of experimental methods requires more and more physical phenomena to be employed, which should be accompanied by constructing more and more sophisticated experimental stands for new information and more precise results to be obtained quicker.

Let me present below some selected papers presented on the aforementioned conferences, which, in my opinion show trends towards experimental mechanics development.

2. Fields of greatest activity

2.1. Mechanics of materials

Modern methods of modelling require more detailed investigation into material properties under both quasi-static and dynamic loads, at low and high temperatures as well as when exposed to aggressive working environment, even in space to be undertaken.

From among a variety of works on material testing the paper by Plazek (1993) should be mentioned here, in which the viscoelastic properties of polymers were described. These materials can, like branched amorphous polymers, "flow" when subject to load and therefore can be treated as viscoelastic liquids. Crosslinked polymers, in turn, are classified as viscoelastic solids. It should be noted that the creep rate for viscoelastic solids under a constant load decreases with time, while for viscoelastic liquids it remains constant. After the load has been removed the reversible part of strain corresponds to the viscoelastic solid deformation, while the permanent strain results from the viscoelastic liquid flow.

These properties are visible also in the stress relaxation process. The stress relaxation completes with time in viscoelastic liquids, while in viscoelastic solids the stress decreases to a certain presumed value.

Another important property of these materials consist in the response to instantaneous or high frequency periodic load.

Plazek (1993) presented a survey of mathematical models being employed to material testing and compared the results with those obtained from experiments.

The papers devoted to composites create an essential part of the literature on mechanics of materials. Roush and Shankar Mall (1993), for example, described experiments on the SCS-9/β21s metal matrix composite used in advanced space structures. Silicon carbide fibbers SCS-9 of this composite, of 81μm in nominal diameter are embedded in the β21s titanium matrix. Tests were performed at room and elevated temperatures, up to 650°C, on samples both smooth and notched, with the holes of 3.175 in diameter, i.e., covering 1/6 of the sample width. These holes were open or filled with rivets made of the 7075-T6 or Mar-m-246 material with a suitable tolerance ensured. The surface damaged under a static load was observed with the aid of microscope or Scanning Electron Microscope (SEM). Material integrity, residual stress, interfacial failures, failure progression and notch sensibility were examined.

One of the results obtained was determination of the Stress Reduction

Factor (SRF) defined as

SRF = Unnotched and notched strength at a given temperature/Unnotched strength at room temperature

It has been found that the SFR decreases as the temperature rises and both curves (for unnotched and notched specimens) converge at elevated temperatures proving the notch effect weakening at these temperatures (Fig.1).

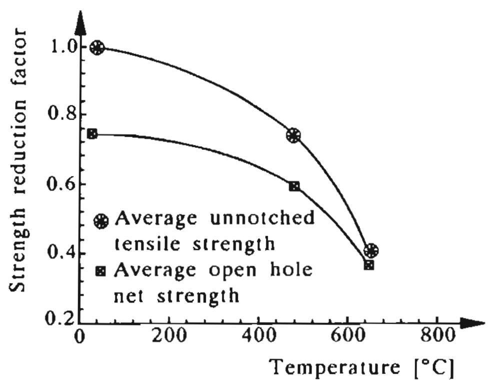

Fig. 1. Strength Reduction Factor (SRF) vs. temperature

The problems of residual stresses appearing in the matrix of Fibre Reinforced Plastic (FRP) composites due to the polymerisation shrinkage and the strain affected by temperature difference between elements in the course of hardening are also discussed in the literature on composites. Miyamo et al. (1993) analysed the process of residual stress generation, having the thermal expansion factors, as well as the polymerisation shrinkage factors assumed and applying the linear viscoelasticity theory to the matrix. Residual stresses were measured on three-layered plates using the destructive method, i.e., grinding the layers one after another with the abrasive paper at room temperature. Deformations of samples were measured with strain gauges. The magnitudes of stress obtained from experiments are almost 100% greater then the theoretically predicted ones, proving therefore the analysis drawbacks or measurement errors.

Gibson and Cartian (1993) investigated vibration damping in composites establishing the influence of viscoelastic properties of both matrix and fibres and thermoelastic properties of matrix upon composite damping properties, which were affected also by the heat transfer from compressed areas to those under tension. Damping properties are also influenced by both the friction effect appearing in the areas of imperfect fibre-to-matrix bonding and energy dissipation in the delamination regions.

Desired damping properties can be attained either on macro level, i.e., by the structure elements shaping or on the micro level, i.e., by controlling the composite setting.

Applying the first approach one obtains hybrid structures, in which damping polyethylene layers co-operate with carbon fibre layers of great strength. The micro level approach consists in covering each carrying fibre with a special coating of great damping. Three-layered models, with the cover constituting the third phase, enable such composites to be analysed. For higher degrees of damping to be attained, discontinuous fibres can be applied, in which a considerable increase of damping can be achieved for the values of length to diameter ratio less then a hundred $(1/d < 100)$. Composite materials with whiskers seem to reveal very useful properties.

The ability to dissipate and accumulate energy is also very important feature of composite materials. This issue has become crucial since the regulations related to the vehicles crash damage resistance were put in force. Thorton (1993) analysed composite beams and tubes of a rectangular or circular cross-section subject to failure load. A variety of factors were discussed; i.e., those of mass, costs, material volume, element dimensions, as well as reinforcement arrangement, fibre percentage and orientation of the fibres effects, respectively. It has been stated that not only geometry of the system but also the load direction and matrix material (especially the interphase bonds) can be regarded as significant elements of the process.

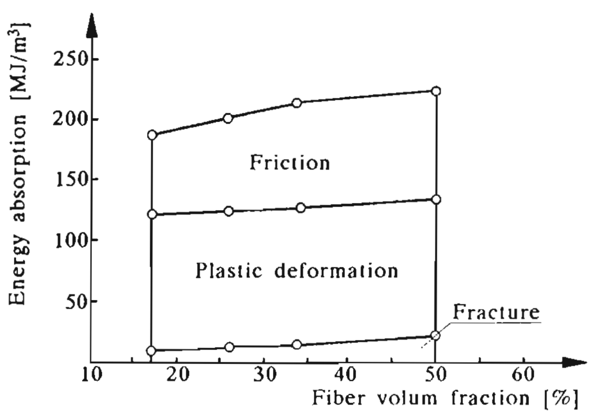

Fig. 2. Apportionment of energy between various energy sinks

It should be noted, that a strong influence of internal friction upon energy absorption was also pointed out. Fig.2 shows the effect of fibre percentage in composite on the way in which the total energy absorbed divides into fracture energy, plastic strain energy and internal friction, respectively.

Investigations of the "men made materials" designed and produced each time for the specified requirements to be satisfied and the "smart materials", some properties of which are the same as those of living organisms constitute a new research domain. In these materials, filaments capable of carrying loads are distinguished, supplied with load detectors as well as elements generating motions or deformations.

The filament made either of conventional materials or, more often, of composites is supplied with the sensor system, e.g., fibre optics sensors, having the form of network corresponding to the neural network in living organisms. The actuator systems, e.g., Fast Twich Muscles or Slow Twitch Muscles are also provided.

Till now, smart materials which have been applied to the space structures only, but they are becoming present in our every day life.

Koichi Egawa et al. (1994) presented the research activity in this field undertaken in Japan. During early 1990s many research teams have been established and government laboratories have also raised this subject. Japanese researchers have aimed at smart material application to automotive, opto-electronic, precise and building industries, highways and the other.

2.2. Measurements in the field of robotics

Robot is a smart machine and therefore, it should be capable of realising not only its normal functions but also taking measurements and making decisions adequate to the results obtained. Rebaglia (1994) presented three basic regions of measurement activity within the scope of robotics.

• *Measurements for robots* are those taken for the necessary information to be obtained ensuring their operation, corresponding to that obtainable from the living creature senses. A widespread development of contact and image detectors has proceeded recently.

The contact detectors determine the pressure in the area of contact, which enables a sufficient force to be applied in the grip, preventing the object from slipping and not involving a damage at the same time. Detectors can determine the object shape, its surface roughness, hardness, temperature and heat conductivity. Touch sensors simulate the human finger perception, in which each $1\,\mathrm{mm}^2$ contains about 50 sensors.

Lisko et al. (1994) presented typical pressure-capacitive sensors proving that such sensor density could be obtained. Construction of the Pressure Sensitive Field Effective Transistor (PS-FET) will probably result in a considerable increase of sensitivity as well as the possibility of supply voltage affected sensitivity control.

Contact detectors made of piezoelectric bands of several μm in width embedded in the rubber matrix respond to loading of the frequency range from 10 to 1000 Hz. Setting a miniature thermocouple into a grip enables the object temperature to be sensed.

The sensors mounted in grips need not to reveal high precision, since they should only supply a computer with qualitative information, enabling the adequate decision to be made.

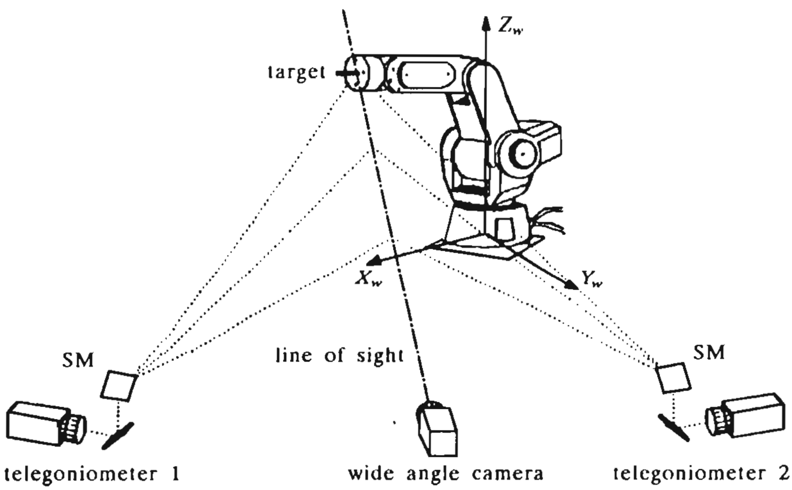

Fig. 3. Schematic representation of the three-eyes vision system that matches an accurate position measurement capability, designed within the framework of Italian National Project on Robotics

• *Measurements on robots* are of crucial importance in industrial robots for the repeatability of motion to be ensured, being therefore greatly advanced. High precision is reached by means of measuring adequate robot arms revolution angles and storing these results in computer memory. Position checking or calibration can be performed taking two approaches. When taking the first one, the proper sensor should be mounted on the robot working tool head and deviations from the required position are measured, basing on which a computer generates a corrective impulse. The second approach consists in placing the robot within the operation zone of a special measuring system (Telegoniometer), which monitors the robot head position correcting it on-line (see Gratoni et al. (1993) for details).

• *Robot aided measurements* are performed with the use of them in the cases when human operators' direct action is impossible due to aggressive working environment or structure inaccessibility. These are; e.g., underwater measurements and those taken in regions exposed to hard radiation, inside tanks or pipelines, as well as measurements of surgical equipment and microtools injected into a cardiovascular or alimentary system for operation or observation.

It is noteworthy to mention that the robotics development creates a strong need to invent new detecting methods, as well as more efficient systems of data acquisition and processing.

2.3. Biomechanics, biomechanical system and material testing

Some issues of experimental mechanics, scope of which covers biological process investigations, medical diagnostics and prosthetics are being developed rapidly. Experiments on living tissues are carried out under natural or laboratory conditions, in the course of which bones, joints and vertebral columns are tested with the mechanical aspects of motion introduced. Results of these experiments are presented on all the conferences on this subject mentioned above.

The results worth mentioning were presented by Dado et al. (1994) who tested dragonfly wings in a wind tunnel. Those very precise and sophisticated measurements were applied to explanation of superb flying abilities of a dragonfly, raising on the other hand a new approach to the aircraft design, in which a lifting force due to vibrating wings could be employed.

2.4. Fatigue and fracture mechanics

In this field many works considering the effects of material state, type of loading, temperature, and environmental aggressivity, respectively, on crack development and stress threshold values were presented. Investigations into crack development in composites and model testing of interphase boundaries, e.g., between glass and epoxy resin or metal and ceramics, are also of crucial importance.

Papers devoted to the possibilities of crack repair or crack propagation slowing down realised by introducing residual stresses into the crack development path by means of the laser beam application, have been also published.

The only result of progress achieved in this field is more accurate and detailed information to be obtainable, an advance has been made in methods for crack detection and its development observation, the generalised theory is still at the stage of expectation.

2.5. Investigation of residual stresses

The residual stresses due to technological processes or exploitation exert substantial influence on service lifetime, reliability and safety of the structure and therefore attract more and more attention. A number of methods for residual stresses evaluation are used. There are three groups of these methods; i.e., non-destructive ones: X-ray and neutron diffraction, ultrasonic method and magnetostriction; semi-destructive ones: material outflow measurement when pressing a penetrator into material, examination of strain state variation when drilling a small hole or groove; and destructive ones (most reliable): evaluation of released stresses after trepanation or cutting element into pieces. For deformations affected by the penetrator pressing to be determined the optical interference method is applied, while strain gauges, moiré interferometry and holographic interferometry are used in other methods.

Each of the aforementioned methods (except the trepanation) involves a hardly detectable error and therefore can be treated as reliable only to some extent. Some experiment called "Round robin test on residual stress measurement in Germany" was carried out in 1994. Ficker et al. (1995) presented the final results of tests carried out on the same segment of the UIC 60 rail by 34 different laboratories. The following conclusion was drawn: "... the scattering of the results of different laboratories using the same method is mostly higher than the difference between the results of the mean values obtained by different methods". Which means that these methods are to be improved and new, better ones are to be soughtafter.

Rajic et al. (1993) basing on the effect that an element subject to tension is heated when exceeding the yield point, on the contrary to the Kelvin effect, according to which the cooling should appear. (Fig.4), put forward a thermomechanical technique. On this assumption, the loci of the observation area points of lowest temperature correspond to the border of plastic zone affected by an unknown state of residual stresses and the known state of stress due to an external load applied to the tested object.

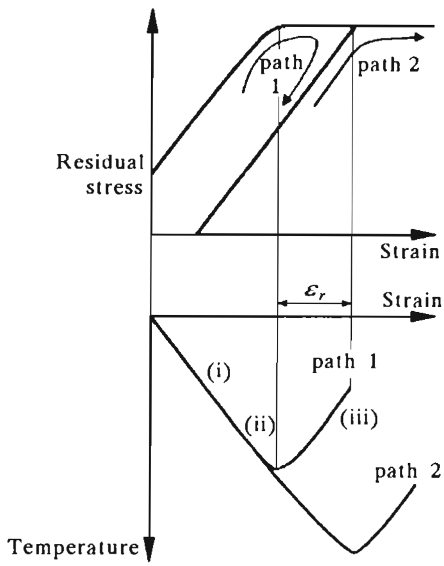

Fig. 4. Stress-strain response (a), temperature response (b). Under tensile loading the temperature drops linearly due to the thermoelastic effect. As the stress approaches the yield strength of material, yielding occurs in the specimen and energy dissipation causes the increase of temperature

By means of the step-wise load increase, in the course of testing it is possible to observe the propagation of plastic zones, from which the residual stresses distribution can be determined. This concept seems to be very interesting, but the authors did not explain the influence of plastic zones due to the first loading step upon the values of residual stress being measured at successive load steps.

Residual stresses appearing in the layers protecting microelectronic packages from aggressive environmental agents may affect their damages. Voloshin et al. (1993) examined stresses generated in 0.5 mm thick silicon wafer of dimensions 4.72 mm×4.72 mm due to the protective layer application. Protective covers of 0.02 to 0.44 mm in thickness were tested.

The "out of plane" displacements were examined using the moiré interference method applying the grid of density 1200 lines per mm, which corresponded to the sensitivity of 0.417μm per fringe order. Light signal to be registered by a camera revealed almost cosine brightness distribution for each fringe, enabling a twenty times multiplication of the fringe order, using a computer program.

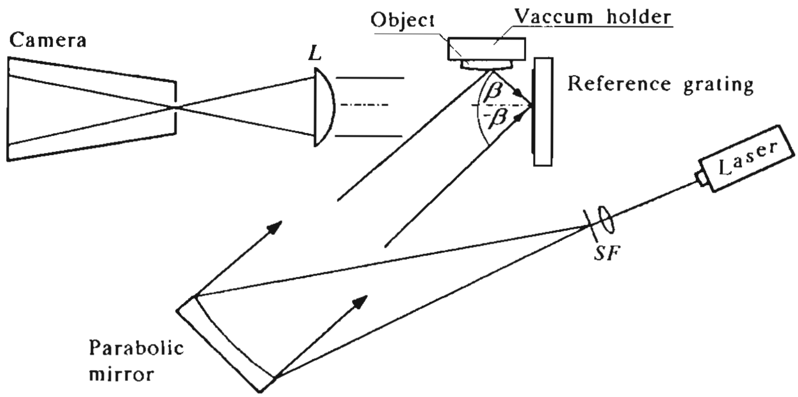

Fig. 5. Optical arrangement for the two-beam moiré interferometer

The reference grid was reproduced from a photographic mould. The optical experimental set-up is shown in Fig.5. The silicon wafer was tested at two successive steps. First, before protective cover application the wafer was mounted in the interferometer using a vacuum holder and the whole system was justified for the minimal number of fringes to appear in the observation area. Those fringes, which could not be eliminated established the null field corresponding to the initial wafer shape. At the next step the wafer was removed from the holder and covered with a protective layer. After hardening the wafer was remounted on the set-up and a final fringe pattern was registered. The wafer deflection function $W(xy)$ was determined by means of subtracting the final pattern fringe order from that of the null one, taking the arrows into consideration.

The wafer curvature was determined within the framework of thin plate theory enabling stresses both in the wafer and protective cover to be determined. The authors stated, that the results obtained from many numerical simulations of the stress state in a cover were far from the reality, which resulted from the obstacles appearing when modelling a viscoelastic material of the cover subject to the polymerisation process.

The influence of vacuum holder mounting upon the wafer deformation was not discussed in the paper.

2.6. Micromechanics

Trends towards miniaturisation appearing in machine design generate a great interest in testing very small objects. Those object can be sometimes tested on a larger scale, but often the real size should remain. As an example may serve the research by Mylnikov (1994), who investigated the residual stress in multilayered optical fibres.

A shortage of material for the sample to be taken creates sometimes needs for miniaturisation of specimen, which are crucial, e.g., when testing a bone segment taken from the living organism. Sharpe and Keown (1993) tested samples, lengths of which were smaller than 3 mm using a miniature test machine designed and constructed for this purpose. Main obstacles appearing in the course of this testing consisted in adequate sample preparation, proper mounting it in the machine, proper loading and precise examination of strains, respectively. Dog's bone shaped samples were chosen, which made the mounting much easier. Strains appearing in samples under the load due to the loading frame deformation were measured with the aid of interferometric displacement gauge. Two tiny indentations were made on the sample surface at a distance of 200μm. Two beams of coherent light diffracted on each of these indentations, generating two spherical waves, which travel out of indentations and interfere in space. Two interfering wave fronts were registered using a linear diode array of 512 elements, which had density of 40 pixels per mm and $5 \div 6$ fringes were registered on each diode array. A distance between indentations varied due to loading, affecting the interference fringe displacements, which caused the variation of electronic signal from the array stored then in computer memory. The strains were then calculated straightforward. The experimental stand was estimated to reveal accuracy of 1%, for the $0.3 \div 1 \cdot 10^{-6}$ microstrain measurable.

Tested on this machine, the samples made of bronze were loaded till the yield stress exceeding, $\sigma > 300$ MPa which corresponded to 1.2% strain. In the case of bones, however, some obstacles appeared in precise cutting the samples out of the bones also the attempts to mark indentations collapsed and therefore signs had to be made on the holders. In result, the distance between indentations was affected not only by the sample deformations but also by unavoidable slips in the grips. This affected the accuracy fall, which was estimated as 10% in this case.

Samples made of metal of 250μm in width were cut out by the wires Electro-Drilling Machine (EDM), while those made of materials to which this method is not applicable were prepared using the Computer Numerical Control Milling Machine (CNCMM) with the milling cutter of 1 mm in diameter.

Chen and Lim (1993) made a survey of experimental methods successfully applied to microelectronic packages testing under thermal loading, vibrations and upon environmental influence. The following methods were mentioned as being most frequently applied: photo-elasticity, moiré interferometry, Twyman/Green interferometry, optical interferometry and moiré shadow interferometry. Current capabilities of these methods are given in Table 1. From Table 1 it follows that modern methods for examination of the "in plane" displacements reveal the sensitivity, of three orders higher than that attainable in conventional methods and can be applied to small objects, dimensions of which are smaller than $2 \times 2\,\mathrm{mm}$. The accuracy level of modern methods for the "out of plane" displacements testing has been risen by two orders of magnitude.

Table 1. List of current photomechanics capabilities

"In plane" (x, y) measurement techniques			
	Geometric moiré	Moiré interferometry	Microscopic moiré interferometry
Measurement sensitivity (no. of fringes per 1 mm displacemen)	< 40	2400	48 000
Contour interval (displacement/fringe order)	$> 25\mu m$	417 nm	20.8 nm
Spatial resolution	0.1 mm	$10\mu m$	optic.microscope resolution ($\approx 2\mu m$)
Field of view	$\sim 100 \times 100$mm	$\sim 50 \times 50$ mm	$0.4 \times 0.4 \div$ $\div 2 \times 2$mm
"Out of plane" (z) measurement techniques			
	Shadow moiré	Holography	Twyman/Green interferometer
Measurement sensitivity (no. of fringes per 1 mm displacemen)	< 20	2 900	3 100
Contour interval (displacement/fringe order)	$> 50\mu m$	345 nm	322 nm
Spatial resolution	0.1 mm	$10\mu m$	$10\mu m$
Field of view	$\sim 100 \times 100$mm	$\sim 100 \times 100$mm	$\sim 50 \times 50$mm

Microelectronic packages comprising the printed-circuit boards can be treated as composites made of epoxy impregnated glass fabric having holes filled with solder, copper layers and copper wires. Thermal expansion coefficients revealed by each layer differ significantly and therefore even slight temperature changes affect deformations resulting in fatigue failure of material. Therefore, the necessity for fatigue testing arose and special fatigue testers have been constructed. Chang and Lim (1993) described the test stand capable of multiaxaial loading generation, both static and fatigue ones, at room, elevated as well as cryogenic temperatures. Further improvement of this machine enabled the examined object to be observed by the SEM in the process of loading.

3. New experimental methods

3.1. Thermomechanical method for stress measurement

Great effort has been recently made to improve the methods for stress analysis, among them the development of thermomechanical methods ended with a real success. Thermomechanical methods employ the Kelvin effect i.e., cooling and heating of the object subjected to tension and compression, respectively. Technical applicability of this well known phenomenon arose when the temperature measurement methods development enabled the surface temperature within the range of 0.01 to 0.1°C to be measured.

In 1980s the Stress Pattern Analysis by Thermal Emission (SPATE) system was designed and constructed enabling the infrared radiation pattern emitted by a surface under periodical load to be observed. It was stated that the radiation intensity (within the elastic range) depends upon the principal stresses sum.

Stanley (1994) presented the current achievement and trends of the method development. The author suggested new fields of application of the thermomechanics; e.g., experiments at elevated temperatures, epoxy-glass composites testing, examination of constructions under stochastic load, and tests carried out on the models made using the "rapid prototyping" technique.

The author presented also the FAST (Focal-plane Array for Synchronous Thermography) system, designed and constructed in Australia by Ryall et al. which, being an improved version of the SPATE system, revealed the operational speed three orders of magnitude higher than the latter enabling the acquisition of data from the object surface in a few seconds only.

As stated above, each line of constant radiation level corresponds to a constant sum of principal stresses. In many cases, the areas of most intensive radiation correspond to the regions of stress concentration. It is not a rule, however, and determination of each stress tensor component is a subject of interest. Rauch and Rowlands (1993), put forward a numerical procedure for separation of principal stress components, basing on the least-square collocation finite element formulation.

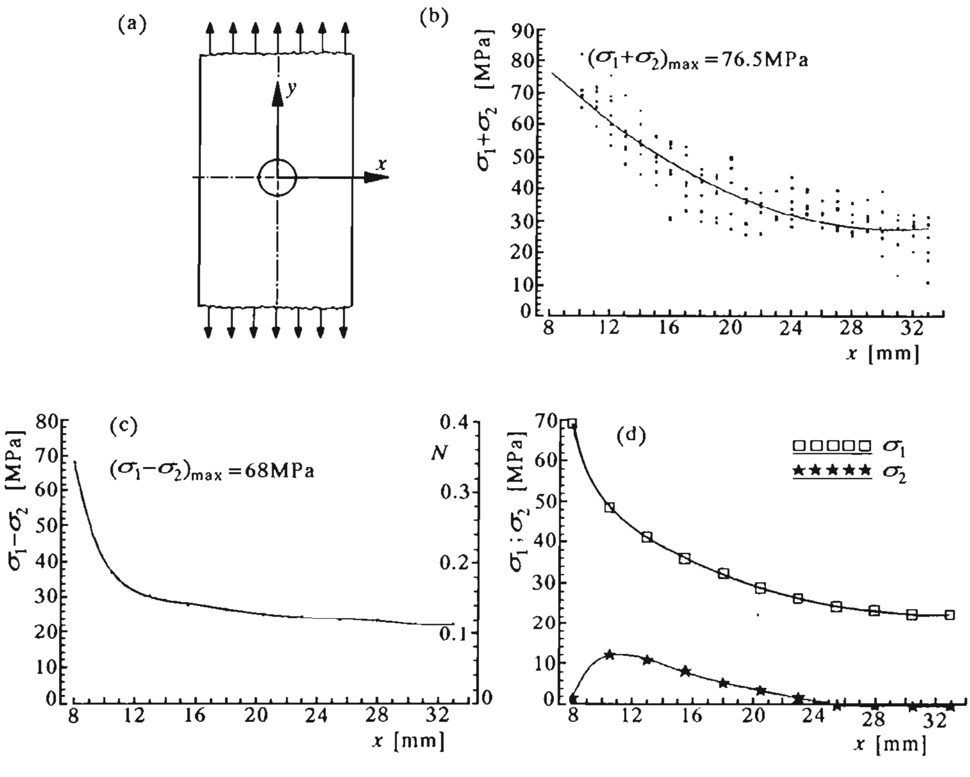

Fig. 6. Separation of principal stress by means of the thermovision and photoelastic coating. A strip with circular hole loaded along the y-axis (a), sum of principal stresses distribution along the x-axis obtained in terms of thermovision measurement (b), fringe order N distribution along the x-axis obtained by the use of photoelastic coating and principal stress difference (c), principal stresses σ_1 and σ_2 distribution along the x-axis (d)

Stanley and Dulieu-Smith (1995) proposed a different approach to the stress separation problem, in which additional stain gauges were bonded to the examined surface. These strain gauges, having a form of strips or rectangles were bonded to the object surface by the ends (for strips) or along the entire length (for rectangles), yielded information about the radiation intensity. In authors' opinion this information was enough for the stress separation and there was no need for additional equipment.

Pasierski et al. (1994) proposed the method for stress tensor component separation combining the thermomechanics with photoelastic coating. Fig.6 show the thermomechanical signal distribution along the x-axis transversal to the axis of the strip with a circular hole loaded along y-axis, isochromatic fringe pattern distribution and σ_x and σ_y stress distributions, respectively.

3.2. Tomographic examination of stress

The acousto-elastic effect combines the ultrasonic wave propagation speed in an elastic body with the strain state. The time of ultrasonic wave passage along the straight line across the investigated object is a function of mean speed of sound in the material, which depends on the strain.

If it can be assumed that only one component of the stress tensor predominates in the tested object and the stress variation along the wave propagation path can be neglected, therefore the mean value of this stress component in the tested object can be calculated straightforward (cf Pao et al. (1984)).

Having a spatial distribution of the velocity of propagation wave and its 3D image one can determine distribution of the corresponding stress tensor component employing the tomography analysis (cf Hildebrandt and Harrington (1981)).

Trachler (1994) attempted to evaluate the components of 3D stress tensor basing on the tomography analysis results of propagation velocities of transverse and longitudinal ultrasonic waves, respectively. To this end, the correspondence between the propagation velocity and a kind of stress tensor to be analysed was examined, and the wave modes, which should be used were determined. It was stated that it was possible, in theory, to predict a longitudinal wave propagation time, as well as a sum of two transverse waves propagation times. Two quantities were obtained, the scalar one independent of the direction of wave propagation at a given point and the second, vector quantity depending on it.

Having the scalar quantity one can determine a sum of principal stresses in the plane perpendicular to the direction of wave propagation. The latter one, in turn, can be used in determination of the solenoid component of the stress field. If the stress tensor has irrotational components affected, e.g., by body forces, total determination of the stress tensor is possible only when having some additional information a priori.

The reconstruction problem was stated in the Fourier domain using the projection slice theorem, which is very important for theoretical tomography.

This theoretical research was not supplied with experimental results and no results sensitivity to measurement errors analysis was undertaken, as well.

3.3. Optical methods, holographic and speckle interferometry, moiré interferometry methods

Optical methods are those, which have been developed most rapidly, while TV cameras used for fringe pattern registration and automatic image analysis and data processing have supplied them with new capabilities.

Pyrzanowski et al. (1994) presented a method of holographic interferometry for determination of displacement vector components of the objects in the cases when all points of the object surface underwent displacements, hence no zero fringe order existed in the observation area. A computer aided procedure used for determination of the displacement components had the options which enabled taking into account the physical data known a priori or from separate measurements. In the discussed case the fringe order of selected points of the object surface was determined basing on the displacement vector components measured by means of the speckle photography.

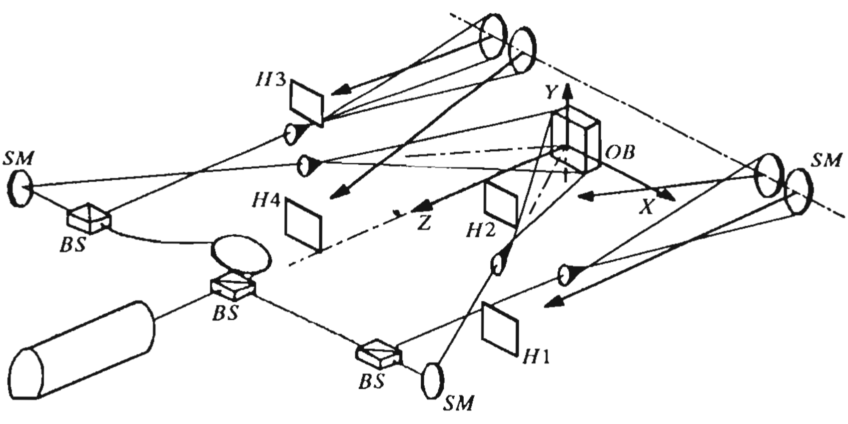

Fig. 7. Optical arrangement for registration of four interferograms; OB – object, BS – beam splitters, SM – steering mirrors, $H1 \div H4$ – hologram

Experiments were carried out by means of the optical set-up with two not interacting object beams shown in Fig.7. The experimental set-up for registration of the photographic plate for speckle photography is shown in Fig.8a and for reconstruction of the displacement in Fig.8b. A CCD camera has been used to register interferometric fringe patterns, stored then in computer memory.

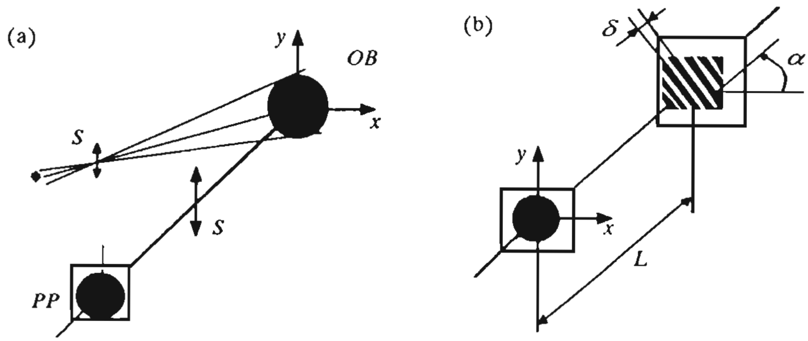

Fig. 8. (a) – Optical arrangement for measurements of the displacement vector components using speckle photography; OB – object, S – lens, PP – photographic plate. (b) – Optical arrangement for reconstruction of Young's fringes and measurement of the distances d between fringes, and angle of inclination a. Displacement vector of a chosen point is given by the formula: $d = \lambda L/\delta M$, where λ – light wave length, L – distance, M – magnification

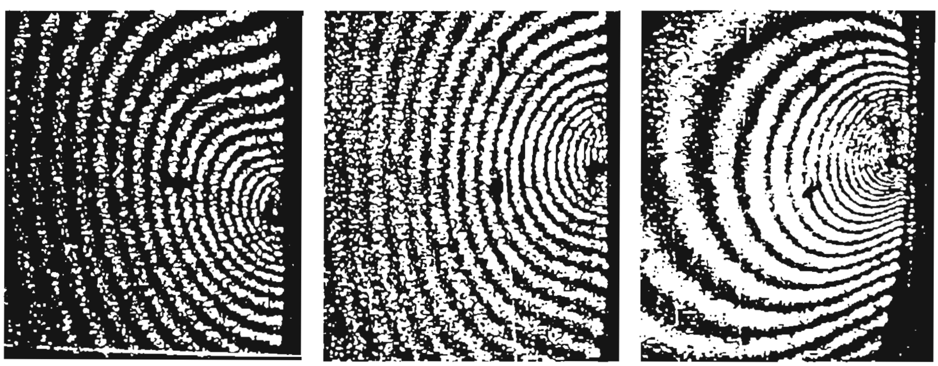

Fig. 9. Three interferograms registered on the holographic plates in position $H1$, $H2$, and $H3$ respectively, reconstructed using the CCD camera and stored in the computer memory

Fig.9abc presents three interferometric fringe patterns registered on the holographic plates placed in the positions $H1$, $H2$, $H3$ (see Fig.7) for the part of circular disc close to the loading point. Using the displacement results obtained from the speckle photography for the point P $(x = 28, y = 0, z = 0)$ the fringe order at this point was determined. Taking into account the loading system, the increase in the fringe order from right to left is obvious.

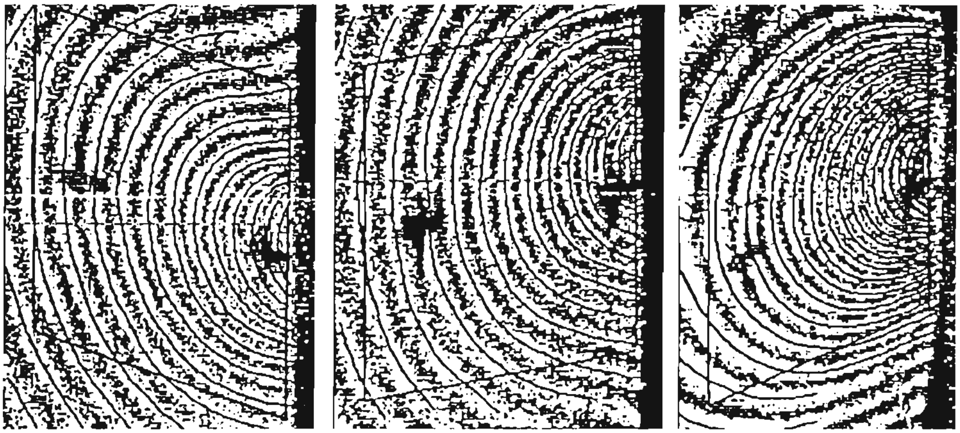

Fig. 10. Skeletonized fringe pattern, and domain of analysis

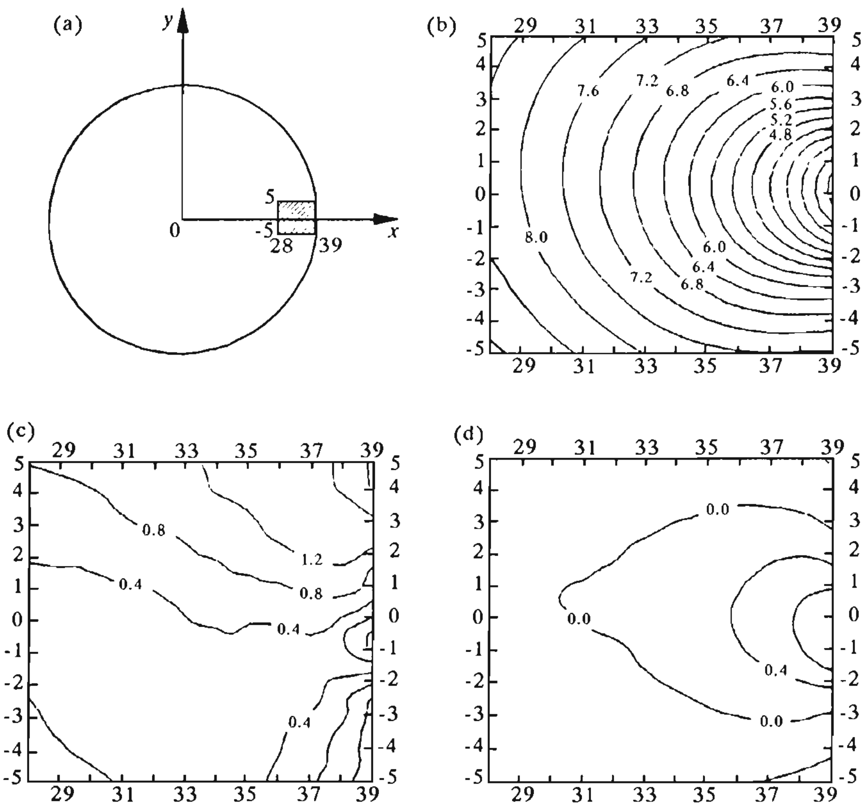

Fig. 11. (a) – The object of investigation, circular disc loaded along horizontal diameter, domain of analysis close to the loading point; (b), (c) and (d) – contour lines of the displacement components u, v and w, respectively

The analysis of interferograms was made using the computer program. The skeleton lines of fringe pattern are given in the Fig.10abc. Contour lines of the displacement vector components u, v, w for the part of the object close to the loading point are shown in Fig.11.

Sciammarella et al. (1993) described a portable interferometer for the "in plane" deformation measurement, which, being insensible to environmental factors, could be also used in outdoor tests. The device was called "holostrain system". The state of the art electro-optical devices and software were applied to vibrations as well as load-affected rigid body motions compensation, respectively. The electronic speckle pattern interferometry with illumination of the object by optical fibres was employed. In this method, in contrast to a conventional holographic interferometry, the hologram is registered by a CCD camera, instead of the high resolution holographic plates, which however, make the tests easier to conduct. Due to low camera resolution a small angle between the object and reference beams should be maintained. The electronic reconstruction process is realised. The optical set-up is shown in Fig.12.

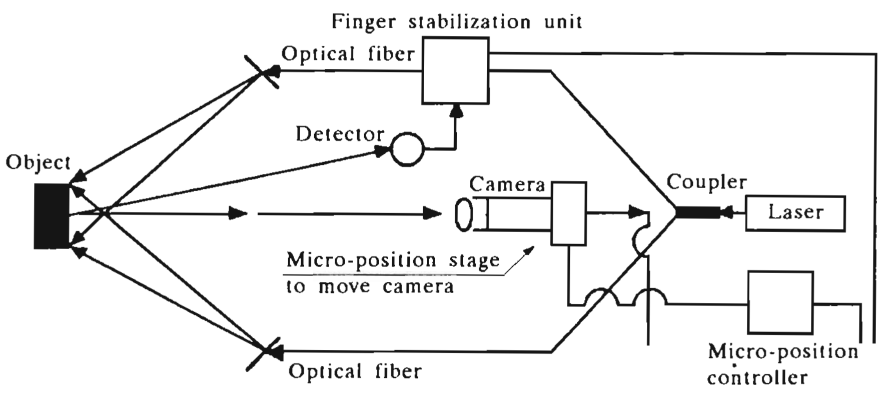

Fig. 12. Optical arrangement for the two beam Holostrain system

Two object beams are arranged in the zx plane, symmetrically with respect to the z-axis (when the displacements in the direction of x-axis are to be measured). Each beam, after scattering on the object surface, plays the role of reference beam to the other one. Interfering front waves are registered by a camera, analysed and processed by a computer for the deformations to be calculated. Active stabilisation of fringes and rigid body motions has been applied, for which two points have been marked on the object surface and a line between them has been determined. After loading, the displacement of one point and the rotation of the line are compensated by means of the camera displacement and revolution, respectively.

The authors established mathematical formulae for the light beam path lengths differences before and after loading and presented basic image processing procedures for the stress and strain state to be determined. Sample results obtained for a circular disc compressed along its diameter were presented. A good correlation between the results obtained and theoretical predictions was attained.

3.4. Electron beam moiré method

Until quite lately, only the field optical methods have been applied to stress state in microregions examination. Capabilities of this methods are given in Table 1. It has been found that limits of application of the moiré effect based methods have been reached now, due the light wave length restriction making further increase of the grid density impossible. The electron beam has appeared to be a solution to this problem.

Dally and Read (1993); Read and Dally (1993a) presented the moiré method application to strain examination using the scanning electron microscope. Line or point rasters were made on polished specimen surfaces by a computer controlled electron beam of a adequate intensity on the PMMA resist, which enabled grids of density of 10 000 up to 13 300 lines per mm to be obtained. It turned out that these grids could be applied on surfaces of both homogeneous materials; like aluminium or bronze and non-homogeneous ones, e.g., glass fibres composites.

The specimens subject to load were observed under scanning electron microscope at a scanning pitch adequate to the grid density and magnification suitable for observation.

Skeleton line patterns of moiré fringes determined for epoxy-glass fibres composite specimens are shown in Fig.13. The fringes appearing in the matrix, in the vicinity of cracked fibre are clearly visible. The following parameters were taken in experiments: magnification of 1900 times, grid density of 10 000 lines per mm (at this density almost 40 raster lines fell on the glass fibre cross-section) and scanning pitch of 100 nm.

Read and Dally (1993b) formulated also the theory of beam electron moiré.

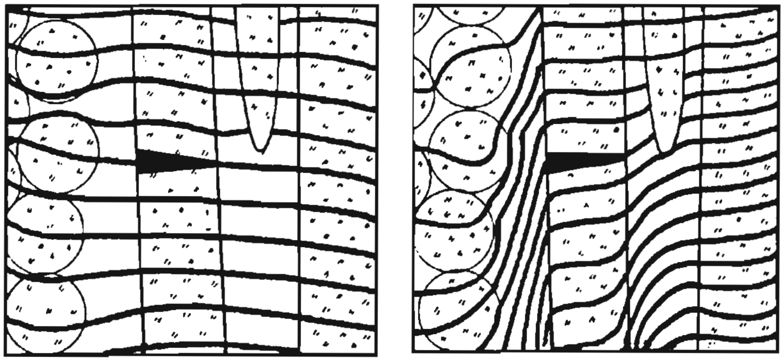

Fig. 13. Skeletonized moiré fringe pattern at an interface between a 0° and 90° ply, at a stress of 347 MPa (a); skeletonized moiré fringe pattern prior to delamination cracking at a stress of 933 MPa (b)

3.5. Fatigue investigation and crack observation methods

Kaleta and Żebracki (1994) proposed the magneto-mechanic Villari effect application to fatigue observation in sintered steels with nickel and molybdenum additions. The following quantities were measured: magnetic induction B, magnetic field strength H, magnetic energy loop ΔM and plastic strain ε_{pl}. Both the cycle yield point σ_{cyc} and the endurance limit σ_f were determined.

It was found that the magnetic induction $U_B(\sigma)$ was monotonicaly increasing function, diagram of which markedly was deflected from a straight line for $\sigma_f = 120\,\text{MPa}$, i.e., the value corresponding to the endurance limit of the tested steel (Fig.14). Strong dependence of the magnetic energy loop ΔM upon the stress magnitude was also established. The $\Delta M(\sigma)$ diagram (Fig.15) reveals three regions being sharply outlined; the first of them covers $0 < \sigma_a < 40\,\text{MPa}$, the second one represents a linear dependence of ΔM upon σ, i.e., $40\text{MPa} < \sigma_a < \sigma_f$ and the last one, in which the diagram deflection from a straight line for $\sigma_a > \sigma_f$ is visible. The value of mechanical hysteresis loop $\Delta W(\sigma)$, shown also in Fig.15, equals zero for the elastic range and then increases rapidly after the yield point has been exceeded.

Michel and Kuhnert (1994) established the procedure of material properties determination when considering strains accompanying the crack, which was based on the strain examination ahead of the crack front of the CT specimen. A hybrid technique was used, combining the FEM with the micro moiré method. The square area $650\mu\text{m} \times 650\mu\text{m}$ was analysed, on which using the

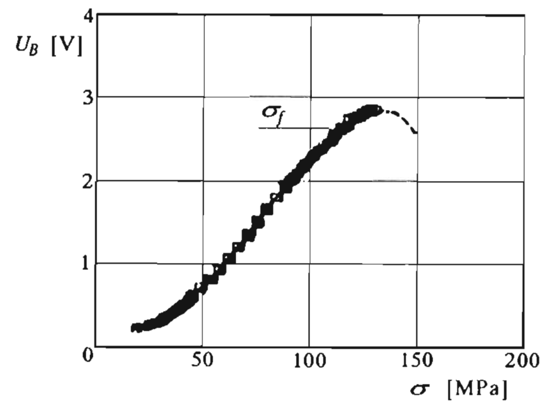

Fig. 14. $U_B(\sigma)$ for the sintered steel KA. Endurance limit σ_f indicated by arrow

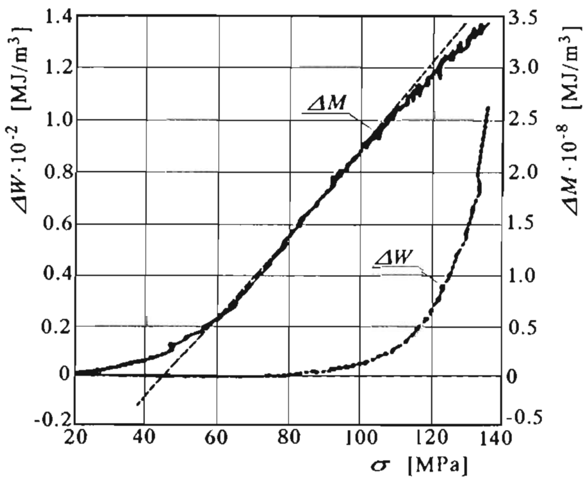

Fig. 15. $\Delta W(\sigma)$ and $\Delta M(\sigma)$ for the sintered steel KA. $\Delta W \approx 0$ in the elastic range then is rapidly increased, ΔM is deflected from the straight line for $\sigma_a > \sigma_f$

electron beam lithographic technique a rectangular grid was applied on a thin sputtered tungsten layer of 80 nm in thickness. Deformations represented by the moiré fringe patterns generated by the grid applied on the deformed specimen and the SEM beam scanning the surface at $5.42 \mu m$ scanning pitch were registered. Numerical calculations were made for 2D and 3D models of the same area assuming both elastic and elastoplastic material properties, from which displacements together with the moiré fringe pattern were determined. If a discrepancy between experimental and numerical results, respectively, appeared the material properties were changed until good correlation was reached, enabling the calculated strain distribution and material properties to be used in J and T integrals calculation. The authors considered this method to be most useful in the fracture toughness determination.

3.6. Hybrid methods

Hybrid methods combine experimental and numerical techniques in the way ensuring their mutual complementation and, on the other hand, enabling the solution to be obtained in terms of unique properties revealed by each of these methods. Hybrid methods have become more popular these days. At the International Conference on Experimental Mechanics in Lisbon several papers covering this subject were presented. They were devoted to plastic area detection, composite testing (in particular determination of the interface properties between matrix and fibre), microdeformation assessment as well as material fracture examination.

Kapkowski and Kujawińska (1994) presented the hybrid, full-field stress analysis technique applying the method of characteristics and then automatic analysis of isochromatic values at the characteristics intersection points determined on line. A sample solution to the problem of strip with a hole under tensile load was presented, showing a good correlation between the results obtained and theoretical predictions.

Laerman (1994) presented a hybrid method in its most classical form applied to the stress analysis in discs with elastic or viscoelastic inclusions. The isochromatic patterns resulting from photoelasticity, varying with time due to the viscoelastic inclusion properties underwent then digital image processing, yielding the values of isochromatic fringe order at chosen points of the observation area. These values were introduced into Volterra's integral equation valid for the viscoelastic subdomains, solving of which resulted in the principal stresses difference values at the points of analysis. These values, supplied with the sums of principal stresses determined on the boundary and the interface contact conditions were used in the BEM analysis of the whole disc.

The authors presented the relationships and the algorithm of solution, unfortunately no example was given, which would enable the method applicability as well as the results accuracy to be assessed.

4. Conclusions

Several current stimulators of the experimental methods development should be mentioned; i.e., technological advance (especially in space engineering), machine miniaturisation, microelectronics and biomechanics. The term – "experimental mechanics" has changed its meaning for the several last years and the methods employed are becoming closer to those used in physical laboratories. New physical phenomena, being found and described before, are now applied to measured quantities detection. Old-fashioned engineering approach to experimental mechanics is being changed and new methods are also introduced.

Rapid computer techniques development brought about a "revolution" in experiment, changing the way of data acquisition and data processing, rising the reliability of measurements, reducing measurements errors and enabling the hybrid methods to appear.

The present survey as it was mentioned in Section 1 is restricted to the papers published in 1993 and 1994 in the proceedings to the conferences given above, the papers available in 1995 prove, however, the choice.

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Trendy w mechanice eksperymentalnej

Streszczenie

Praca przedstawia aktualne trendy w mechanice eksperymentalnej, prezentuje dziedziny największej aktywności oraz nowe lub udoskonalone metody badań pozwalające na uzyskanie nowych lub bardziej wiarygodnych informacji.

Obserowany powrót zainteresowania metodami eksperymentalnymi wynika z jednej strony z wyczerpania się możliwości korzystania w mechanice z modeli liniowych i rodzącego się zapotrzebowania na nowe obserwacje stanów i procesów, z drugiej strony jest wynikiem szybkiego rozwoju metod eksperymentalnych, które w ciągu ubiegłej dekady coraz częściej posługują się metodami stosowanymi dawniej jedynie w laboratoriach fizyków oraz zyskały nową jakość dzięki komputerowym metodom zbierania i przetwarzania danych.

Podstawą tego opracowania bylo ponad trzydzieści prac publikowanych w latach 1993-94 na reprezentatywnych konferencjach mechaniki eksperymentalnej.

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