XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

FULL FIELD TENSILE STRAIN MEASUREMENT BY SHEAROGRAPHY

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Abstract: Digital shearography is a coherent optical method in conjunction with the digital image processing. It allows the shearogram, which depicts directly displacement derivatives, in real time to be observed and to be evaluated numerically. Strains are functions of the displacement derivatives. Thus, the shearogram contains the strain information, but usually it includes both the in-plane strain, e.g. ¶u/¶x, and the out-of-plane component, e.g. ¶w/¶x. In order to get the pure in-plane strain as well as the pure out-of-plane component, two linearly independent directions of illumination (usually the same but mutual and sequential illuminations) are introduced in the measuring device. The shearograms for each illuminating direction are evaluated by applying the phase shifting technique. The result by subtracting the phase maps of the two shearograms yields a new fringe pattern depicting the pure in-plane strain component and the result by adding the phase maps corresponds to the pure out-of-plane component. The theory and nondestructive tensile testing are demonstrated in this paper. Its applications for determining the strain distribution of the homogeneous and inhomogeneous material are presented.

Keywords: In-plane strain measurement, tensile test, phase shifting technique, digital shearography

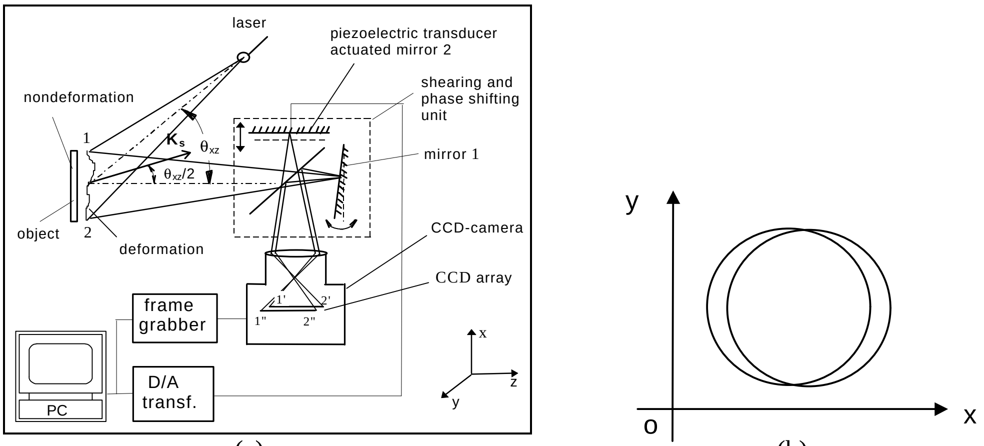
1 INTRODUCTION

Full field tensile strains are measured across the whole surface of the specimen by shearography identifying the local strains as well. Digital shearography, also called digital speckle pattern shearing interferometry (DSPSI) or TV - shearography, is a coherent optical method in combination with digital image processing. The optical theory is the same for the digital and the photographic shearography, but digital shearography is a computer aided evaluating process which eliminates wet processing and optical reconstruction. This results in a rapidly increased testing speed so that the shearogram can be observed in ***real time*** (i.e. at video rate). By using the phase shift technique digital shearography realizes the shearogram to be evaluated automatically and numerically. This offers new possibilities for applications of shearography in industry.

Contrary to holographic and speckle pattern interferometry which measure surface displacements, shearography measures the derivatives of surface displacements directly. Strains are functions of displacement derivatives, thus shearography yields directly the strain information and it is suited well for nondestructive testing [1]. But its applications for strain measurement has not been widely adopted in industry, because the shearogram contains usually both the out-of-plane component and the in-plane strain component.

2 PRINCIPLE OF THE DIGITAL SHEAROGRAPHY

The experimental setup for digital shearography is shown in Fig. 1a. The tested object is illuminated by an expanded laser beam. The light reflected from the object surface is focused on the image plane of an image-shearing CCD camera where a Michelson interferometer is implemented in front of its lens; so a pair of laterally sheared images of the tested object is generated on the image plane of the CCD camera by turning the mirror 1 for a very small angle from the normal position (Fig. 1b). The two shearing images interfere with each other producing a speckle pattern. The intensity distribution I (x,y) of the speckle pattern is given as for other types of interferometer by



(a) (b)

Figure 1. The principle of digital shearography, (a) experimental and (b) two sheared images in the x-direction resulting δx

$$I(x,y) = I_0 [1 + \gamma \cos \phi (x,y)], \quad (1)$$

where I_0 represents the average intensity of these two sheared light waves, γ is the modulation of the interference term and ϕ (x,y) represents the random relative phase angle between the two sheared images before the object is deformed. This intensity distribution is registered by the CCD - camera and it is processed by the data aquisition and evaluation program ***Shearwin***.. When the object is deformed, the intensity distribution of the speckle pattern is slightly altered:

$$I^{'}(x,y) = I_0 [1 + \gamma \cos \phi^{'}(x,y)], \quad (2)$$

It is recorded by the CCD - camera as well. The result of the subtraction operation between the two digitized informations yields a fringe pattern, i.e. the so called “digital shearogram'', which describes the relative phase change Δ due to the object deformation, and it is displayed on the monitor in real - time (at video rate).

It has been shown that the relative phase change Δ is related to the displacement derivatives instead of displacement itself due to the shearing function of shearography. If the shearing direction is in the x - direction, Δ is given by:

The fundamental equations show that shearographic fringes are whole-field representations of the loci of the first derivative of the deformation. Moreover, rigid body motions do not produce strain, thus shearography is insensitive against such motions and does not require any particular device for vibration isolation.

In order to determine the relative phase change Δ automatically and quantitatively, the well-known phase shifting technique is applied in the experimental setup. Generally speaking, there are three unknowns in the intensity distribution of the Eq. (1); they are I_0, γ and ϕ. Therefore, a minimum of three measurements is necessary to determine the relative phase angle. For each recorded intensity an additional 120° (for three measurements) or 90° (for four measurements) phase for one beam in the Michelson interferometer is shifted. The piezoelectric transducer actuated mirror 2 is used in Fig. 1a just for this purpose.

When the object is deformed, three (or four) more frames of the intensity data are taken while shifting the phase for the same amount as for the first set of data. The phase distribution ϕ' of the interference pattern after the deformation can be also calculated like ϕ. The detailed reports for the phase calculation of interference pattern, the noise processing and the phase unwrapping can be found in the reference [3]. Once these data are taken, the relative phase change Δ can be calculated simply by subtracting ϕ from ϕ' ($\Delta = \phi^{'}(x,y) - \phi(x,y)$). Thus, the out-of-plane component in each point can be evaluated quantitatively and automatically.

3 EXPERIMENTAL PROCEDURE FOR MEASURING THE IN-PLANE STRAIN

Fig. 2 shows the experimental setup of digital shearography for pure in-plane strain measurement with two independent directions of illumination. In this setup the same but mutual two independent illuminating beams are adopted. It is obvious that the sensitivity vector $\boldsymbol{k_s}$ for the $+\theta$ illuminating beam lies in the direction of +θ/2 and for the -θ illuminating beam in the direction of -θ/2. If the illumination angles are oriented in the xz-plane, the new sensitivity vector $\boldsymbol{k_{si}}$ lies exactly in the x-direction and it is created by subtracting $\boldsymbol{k_s}$ belonging to the -θ/2 direction from $\boldsymbol{k_s}$ belonging to the +θ/2 direction. In other words, a new fringe pattern which has a sensitivity vector $\boldsymbol{k_{si}}$ in the x-direction will be obtained by subtracting the shearogram corresponding to the -θ illuminating beam from that corresponding to the +θ illuminating beam. When measuring, shutter 5 is first opened and the shutter 6 is closed (Fig. 2); they are controlled by the ***Shearwin*** program, shutter 5 is then closed and shutter 6 is opened:

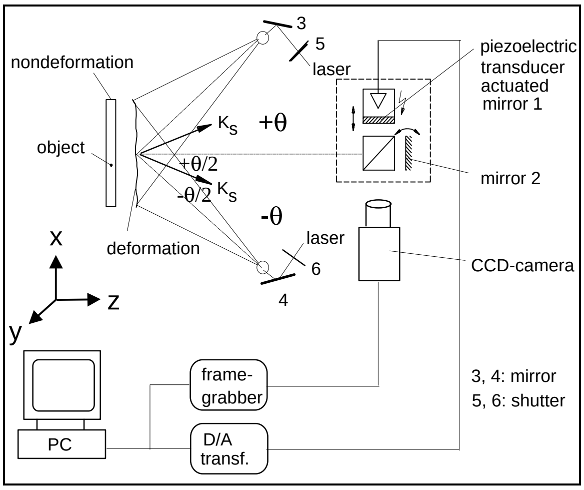


Figure 2. Principle of shearography for pure in-plane strain measurement

$$\Delta_{+\theta}= \frac{2\pi}{\lambda}\left\{\frac{\partial u}{\partial x}\sin(+\theta_{xz})+\frac{\partial w}{\partial x}\left[1+\cos(+\theta_{xz})\right]\right\}\delta x \qquad (3a)$$

$$\Delta_{-\theta}= \frac{2\pi}{\lambda}\left\{\frac{\partial u}{\partial x}\sin(-\theta_{xz})+\frac{\partial w}{\partial x}\left[1+\cos(-\theta_{xz})\right]\right\}\delta x \qquad (3b)$$

Because $\boldsymbol{k_{si}}\ \boldsymbol{e_y} = \boldsymbol{k_{si}}\ \boldsymbol{e_z} = 0$ and $\boldsymbol{k_{si}}\ \boldsymbol{e_x} = |\boldsymbol{k_{si}}|$, therefore the in-plane strain ∂u/∂x can be measured for the x-shearing direction directly

$$\Delta_{Ixx} = \Delta_{+\theta} - \Delta_{-\theta} = \frac{4\pi\delta x \sin\theta_{xz}}{\lambda}\frac{\partial u}{\partial x} = \frac{\partial u}{\partial x}\,|\boldsymbol{k_{si}}|\,\delta x \text{ (shearing direction in the x-direction),} \qquad (4)$$

where Δ_{Ixx} is the phase distribution of the new fringe pattern. Due to the application of the phase shifting technique, the phase distributions of the shearograms corresponding to the ±θ illuminating beams, i.e. $\Delta_{x\,(-\theta)}$ and $\Delta_{x\,(+\theta)}$, have been determined. Thus the phase distribution Δ_{Ixx} is obtained by subtracting $\Delta_{x\,(-\theta)}$ from $\Delta_{x\,(+\theta)}$. $|\boldsymbol{k_{si}}|$ and δ x are system parameters and they are known. Therefore the in-plane strain ∂u/∂x can be determined.

Besides measuring the in-plane strain, the out-of-plane component ∂w/∂x can also be measured at the same time by adding $\Delta_{x\,(-\theta)}$ to $\Delta_{x\,(+\theta)}$ considering the sensitivity vector $\boldsymbol{k_{so}}$ [cf. Eq. (5.5)].

The program ***Shearwin*** was implemented which controls the shutters 5 and 6, the piezoelectric transducer, the data transfer from the CCD array and the calculation of the relative phase distribution (Fig. 2). The testing procedure can be finished within one or two seconds, if the loading can be performed very fast. The compact measuring device illuminates an observation area of 300 x 300 mm² by using two 50 mW laser diodes.

In case that the shearing direction lies in the y-direction, the terms ∂u/∂y and ∂w/∂y are measured. Similarly, the in-plane strain terms ∂v/∂x and ∂v/∂y are measured, if the illumination angles ±θ lie in the yz-plane. It should be emphasized that the components ∂u/∂z, ∂v/∂z and ∂w/∂z can not be measured by digital shearography, because it can not produce a shearing amount in the z-direction. Only the following six terms can be measured by digital shearography:

$$\Delta_{Ixx} = \frac{\partial u}{\partial x} \, | \boldsymbol{k_{si}} | \, \delta x \qquad \text{(xz-illuminating plane, x-shearing direction),}$$

$$\Delta_{Ixy} = \frac{\partial u}{\partial y} \, | \boldsymbol{k_{si}} | \, \delta y \qquad \text{(xz-illuminating plane, y-shearing direction),}$$

$$\Delta_{Iyx} = \frac{\partial v}{\partial x} \, | \boldsymbol{k_{si}} | \, \delta x \qquad \text{(yz-illuminating plane, x-shearing direction),} \qquad (5)$$

$$\Delta_{Iyy} = \frac{\partial v}{\partial y} \, | \boldsymbol{k_{si}} | \, \delta y \qquad \text{(yz-illuminating plane, y-shearing direction),}$$

$$\Delta_{Ox} = \frac{\partial w}{\partial x} \, | \boldsymbol{k_{so}} | \, \delta x \qquad \text{(xz or yz - illuminating plane, x-shearing direction),}$$

$$\Delta_{Ox} = \frac{\partial w}{\partial y} \, | \boldsymbol{k_{so}} | \, \delta y \qquad \text{(xz or yz - illuminating plane, y-shearing direction).}$$

4 APPLICATION FOR DETERMINING THE TENSILE STRAIN

The following specimen has the dimensions of 250 mm x 20 mm x 2 mm. It was investigated on a tensile testing machine in the Lab SHS. The experimental setup consists of four 50 mW laser diodes emitting 690 nm wavelength each and which are assembled in the orthogonal crossends of the measuring device. Considering that the first principal strain is in the y-direction, two illuminating beams $\pm\theta_{yz}$ were used.

The specimen made from aluminium 2024-T3 was friction stir welded which is a joining method especially for Al-material without any additional material and without preparing and curing the welding seam. Only the friction of the rotating thorn-tool generates the energy for the strong connection under compression moving along the butt welding of the basic material.

As described in Eq.(3) the fringe patterns to be measured directly are two resp. four shearograms longitudinally and laterally respectively. The results are evaluated as the in-plane strain $\partial v/\partial y$ and the out-of-plane component $\partial w/\partial y$ by subtracting and adding operations. The system parameters are given as following: $\theta_{yz} = \pm 40°$ and $\delta y = 1.5$ mm where $\pm\theta_{yz}$ is the angle of illumination in the y, z – plane and δy the shearing amount in the y-direction.

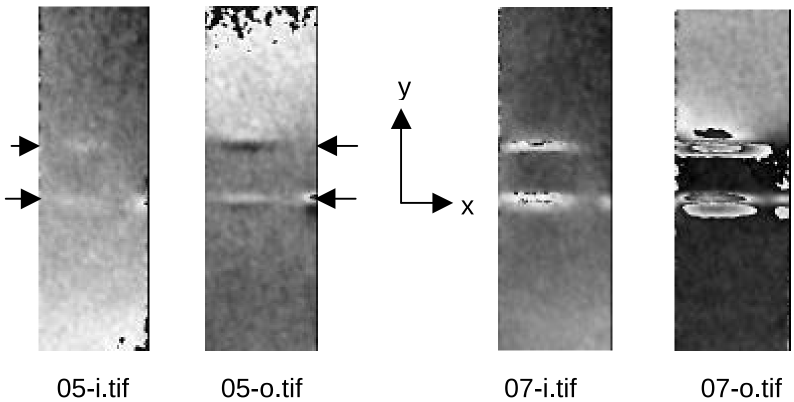


Figure 3. The phase maps of the in-plane (i) strain $\partial v/\partial y$ and the out-of-plane (o) component $\partial w/\partial y$ for the loading from 6.8 to 7.4 kN (left) resp. from 7.8 to 8.25 kN (right)

The investigation starts with a loading level of 5 kN, i.e. the specimen was preloaded until 5 kN. No strain anomaly is observed when the loading is smaller than 6.8 kN. The strain distribution on the object surface is constant. Therefore, the grey value distribution of the phase maps representing the in-plane strain $\partial v/\partial y$ is almost constant.

Fig. 3 shows the phase maps of the in-plane (i) strain $\partial v/\partial y$ and the out-of-plane (o) component $\partial w/\partial y$. The strain anomaly begins to be viewed feebly when the loading reaches 6.8 kN (Fig. 3 left). The load is increased until 8.25 kN and the strain anomaly is observed clearly in Fig. 3 right from both the in-plane (i) and the out-of-plane (o) images.

The incipient plastic flow begins at the loading of about 9 kN. During this step, the strain distribution, i.e. the fringe pattern, in the region of the welded position is still similar to that without the plastic flow. The evaluation of Fig. 4 shows this type of the strain distribution $\partial v/\partial y$. The displayed surface in Fig. 4 is about 62 mm in length and 20 mm in width, the loading for the image is from 9.35 to 9.7 kN.

The strain in the position of the basic part of the aluminium bar is called ε_1 and the left strain maximum is called ε_2 (cf. 2D-display on the right hand side from the top, Fig. 4). The section I is the reference for the further evaluation. The strains ε_1 and ε_2 were thus taken in the section I (cf. the phase map on left hand side of the top).

In general, the fringes in the shearograms or in the images of ∂v/∂y and ∂w/∂y in the welded position are parallel to x-axis like in Fig. 3. However, the fringe form is changed when the loading increases until 11.8 kN (corresponding to Fig. 5 left). From Fig. 5 the fringes are not longer parallel fringes. This means that the strain distribution in the region of the welding position is changing strongly. The specimen breaks into two pieces when the loading exceeds more than 16 kN, 23 steps are required until fracture.

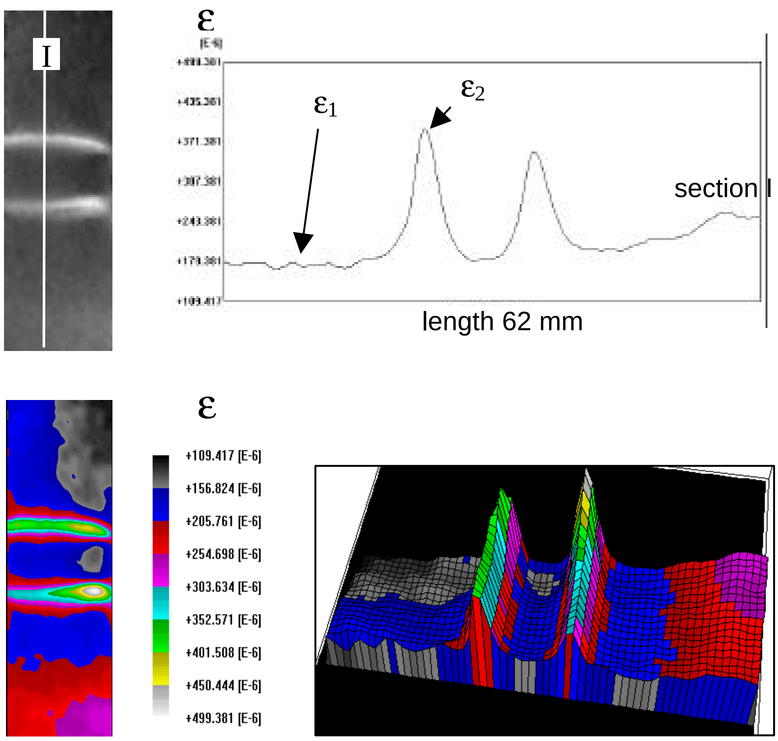
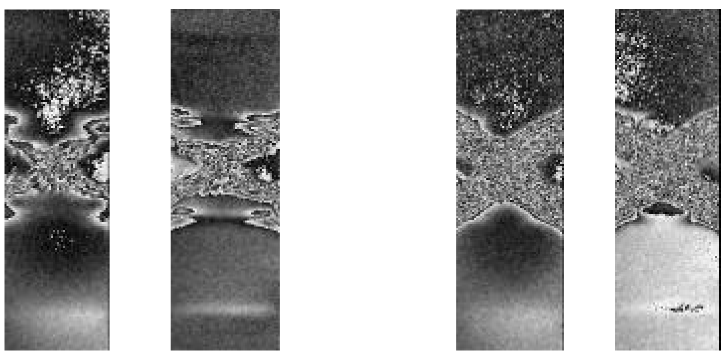


Figure 4. The evaluation of the in-plane strain ∂v/∂y; left on the top: the phase map of the in-plane strain ∂v/∂y; right on the top: the 2D-display of the section I; left on the bottom: the pseudo-colour display; right on the bottom, 3D – plot. The displayed surface is about 62 mm in length and 20 mm in width, the loading for the image is from 9.35 to 9.7 kN.



17-i.tif 17-o.tif 18-i.tif 18-o.tif

Figure 5. Fringes began to incline to the x-axis under the angles of about ±55° for the loading from 11.5 to 11.8 kN (left) resp. from 11.8 to 11.95 kN (right), δy = 1.0 mm

A quantitative evaluation of the strain ε_1 and ε_2 in the section I from the beginning until 9.7 kN has been performed (Fig. 4). The values between the strain and the stress are shown in the graph of Fig. 6. Principally, the strain $\partial v/\partial y$, stands only for the loading step ΔF, e.g.. from 7.8 to 8.25 kN (Fig. 3 right). The strain under a certain loading, e.g. 8.25 kN, is determined by adding all the strain values from the start step by step. The strain below 5 kN is determined according to the linear relationship.

After the plastic flow occurred, the fringes of some shearograms become very dense, the image quality of the in-plane strain $\partial v/\partial y$ and the out-of-plane component $\partial w/\partial y$ obtained by subtracting and adding the shearograms is poor. It is very difficult to evaluate quantitatively these images. Therefore, the quantitative evaluation has been performed only in the elastic range.

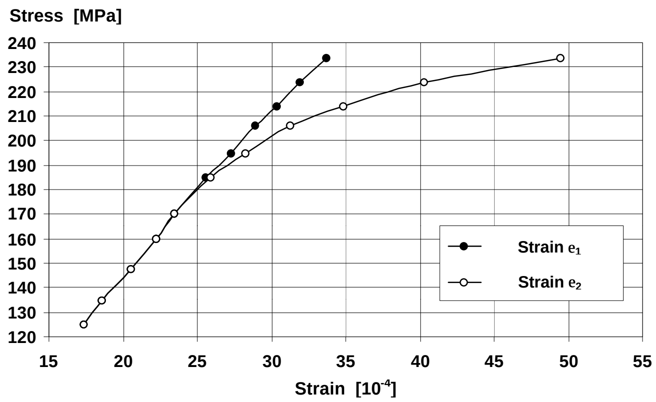


Figure 6. The stress – strain curves of the welded aluminium specimen in the regions of the basicaluminium alloy and in the joint position between basic aluminium and welded part

6 CONCLUSIONS

As a tool of nondestructive testing, digital shearography measures the strain information directly, and thus it is easier to correlate flaws with strain anomalies rather than with displacement anomalies like TV-holography. As a tool of strain analysis, TV-holography can also measure the strain via numerical differentiation from the displacement phase map. But the strain sensitivity of the method will be dependent on the displacement sensitivity of the respective interferometer. The interferometer for measuring displacement has a small controllable sensitivity range so that the larger deformation can't be measured. However, digital shearography offers several advantages over TV-holography. It permits strain measurement of being full-field, noncontacting and independent of the material and it provides a wider and more controllable sensitivity range, thus allowing the displacement gradients corresponding to the large deformation to be measured. Furthermore, rigid body motions do not produce strain, therefore digital shearography is insensitive against such motions and does not need adopting any particular device for vibration isolation.

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