Alternative speckle photography techniques for plastic deformation investigation

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Abstract
An alternative method for visualization of plastic flow localization is proposed which is based on first order statistics of laser speckle patterns. The specific features, applicability and limitations of the proposed method are considered. The setup designed for sample testing is described. The experimental evidence obtained for plastic flow localization in commercial aluminum alloy is considered.

Keywords: Digital speckle photography, speckle pattern, plastic deformation

1. Introduction
It is found experimentally [1, 2] that by constant-rate loading, the plastic deformation tends to localize over the entire flow process, which results in space-time structures emerging spontaneously in the deforming solid. The deformation fields obtained for the test samples in plastic flow investigations have to be reconstructed. A method intended for this purpose must meet the following requirements: field of vision ~100×100 mm; accuracy of displacement vector measurement 0.1 μm; recorded local strains 0.01; sufficient vibration protection and last but not least, ease of realization, in particular, in physical metallurgy laboratory conditions. In view of its numerous merits, double exposure speckle photography technique was chosen for investigating localized plastic flow patterns. However, productive application of this method is open to question, especially, for long-term investigations.

The application of digital speckle photography [3] provides for high-speed and real-time performance of the measurement system, eliminating the need for photographic materials. However, the method’s sensitivity and the reproducibility of results would prove insufficient, in particular, by investigating highly inhomogeneous deformation fields and significant changes in the deforming sample surface. This stimulated a search for other, more workable, methods and approaches. Thus speckle decorrelation technique [4] is found to be sufficiently straightforward; moreover, it enables in situ determination of deformation gradient zones without calculating displacement vector fields; however, direct estimation of local stains is not feasible in this case.

Another method for local rate estimation is first order statistics of laser speckle patterns. The physical basis of this method is presented in [5-7]; its implementation is described for the case of diffuse object in the work by J. Ohtsubo and T. Asakura [8]. According to these workers, the rate of any point on a diffuse object surface is given by

$$\nu = \frac{2w}{T} \frac{<I^2>}{<I^2>-<I>^2},$$

where $w$ is the laser beam radius; $T$ is the measurement interval; $I$ is the brightness at the measured point and $\sigma^2 = <I^2>-<I>^2$. It follows from the above that the rate of the point is inversely proportional to the mean-square dispersion of brightness and is directly proportional to mean brightness squared for the measured point in the time period $T$. An analysis of the speckle patterns observed experimentally for a diffuse scattering object suggests that the rate measured for a point on the sample surface is directly proportional to brightness dispersion in the time interval $T$.  

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2. Experimental setup

The tests were carried on for commercial aluminum alloy. The standard test samples had gauge 10×50 mm. These were tested in tension on a test machine Instron-1185 having cross-head motion rates in the range of 0.01 to 100 mm/min. A block-diagram of the experimental setup is shown in Fig. 1. The test sample was illuminated by coherent He-Ne laser light (1); speckle structure recording was performed for the deforming sample with the aid of a CCD camera having resolution of 1280×1024×10 bit, which was connected with a computer by a bus IEE1394.

![Block-diagram of the experimental setup](image)

Fig. 1. A block-diagram of the experimental setup.

The setup features motorized zoom (3), CCD camera (4) and laser power supply block (2). The control program of a microcontroller provides for the effectiveness of setup operation, i.e. changes in the illumination intensity, exposure, focus and magnification as well as stepping up/down the lens.

In a series of preliminary runs no loading was applied; the sample was moved at different rates to see in what way the quantity $F_v = \sigma^2/\langle I \rangle^2$ would be affected by the motion rate of the sample surface. The motion rates were calculated for each point of the speckle pattern, using sampling for a time of 1.7 s; then the average rate value was calculated for sample surface area. The function $F_v = \sigma^2/\langle I \rangle^2$ against motion rates is presented in Fig. 2.

![Graph of F_v](image)

Fig. 2. The quantity $F_v = \sigma^2/\langle I \rangle^2$ as a function of sample motion rate.
It can be seen that the linear dependence has a knee in the region of motion rates of 1.3 mm/min, which can be explained as follows. For the given experimental scheme, a light-sensitive element of the CCD camera has size of 39 μm. A point on the sample surface moving at a rate less than 1.3 mm/min would pass such a distance in a time of 1.7 s, i.e. time of one measurement. Thus the maximal surface motion rate can be determined for a different time interval or else the required time interval can be defined by assigning the maximal surface motion rate in the range of measured values. The use of $I_v = \sigma^2 / \langle I \rangle^2$ values normalized to imaging device range would enable deformation field visualization or else the same values could be converted to local rates, using a calibration graph illustrated in Fig. 2, with subsequent integration in time and differentiation in co-ordinates performed for the recalculated values.

In plastic deformation investigations an analysis of first order statistics may be supplemented by the application of conventional speckle photography technique; then both sets of data on local strain fields could be matched. To this end, the opposite side of the sample placed in the clamps of the testing machine is illuminated by the coherent light and its speckle photographs are obtained as well. The decoding procedure of speckle photographs is as follows. First the tilt and step of the Yung bands is determined for pre-assigned points of specklograms and displacement vector fields $\mathbf{r}(x, y)$ are calculated for the following plastic distortion tensor components:

$$\beta_{ij} = \nabla \mathbf{r}(x, y) = \begin{vmatrix} e_{xx} & e_{xy} \\ e_{yx} & e_{yy} \end{vmatrix} + \omega_z,$$

where $\begin{vmatrix} e_{xx} & e_{xy} \\ e_{yx} & e_{yy} \end{vmatrix}$ is the plastic distortion tensor and $\omega_z$ is the rotation about the axis $z; e_{xx} = \frac{\partial u}{\partial x}, e_{yy} = \frac{\partial v}{\partial y}, e_{xy} = e_{yx} = \frac{1}{2} \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)$ and $\omega_z = \frac{1}{2} \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)$ are the local strains from (1), i.e. elongation, reduction, shear and rotation, respectively; here $u = r \cos \varphi$ and $v = r \sin \varphi$ are, respectively, the longitudinal and transverse components of the plastic distortion tensor $\mathbf{r}$, and $\varphi$ is the angle the vector $\mathbf{r}$ makes with the sample extension axis.

3. Investigation of plastic deformation localization

Figure 3 shows a half-tone picture of local elongation distributions. The $e_{xx}$ data was obtained by the method of speckle photography for the sample tested in tension along the axis $x$ for the total deformation $\varepsilon_{tot} = 0.032$. The sample areas designated by the symbols A and B are localization zones. Such zones are observed for a wide range of materials by deformation. It is found that these are space-time structures having auto-wave characteristics [1]. A localization zone may comprise either a single mobile or stationary front or a set of equidistant fronts; depending on the flow stage, they would propagate along the sample extension axis or form a stationary structure. Of particular significance is the geometry and dynamics of localization zones observed for a deforming material.

Using digital speckle photography, one can obtain localization maps having high space-time resolution, i.e. 0.03 mm and 1 s$^{-1}$ (cf. 1 mm and 30 s$^{-1}$ for conventional speckle photography), which, consequently, affords a better accuracy of measurement. A fragment of a deformation map is demonstrated in Fig. 4; the positions of localization fronts in the deformed sample are designated by the symbols A, B and C.
Fig. 3. A map of plastic deformation localization obtained by the method of speckle photography for the test sample of duralumin for $\varepsilon_{\text{tot}} = 3.2\%$.

Fig. 4. Maps of plastic deformation localization obtained for the test sample of duralumin, using calculated values of $F_v = \sigma^2 / \langle I \rangle^2$.

Fig. 5. A plot of deformation front’s co-ordinates against deformation time obtained for the test sample of duralumin (sample elongation rate 0.5 mm/min).
First the position of a front is determined for each instant of time and then its co-ordinates are plotted as a function of deformation time (see Fig. 5). It should be noted that the localization front moves over the sample in a regular manner. After the front traverses the entire sample length, it would start moving in the opposite direction, its motion rate decreasing monotonically with growing total deformation (see the tilted trajectories \( v = \Delta X / \Delta t \) in Fig. 5). At the onset of necking, the fronts would become stationary, which is an indication of imminent fracture of the sample.

4. Conclusion
The above technique is an effective tool for plastic deformation investigations, which is easy to use and is more informative relative to conventional speckle photography. Moreover, the performance of the experimental setup could be improved significantly by the use of a high-capacity computer and a CCD camera of the last generation.

References