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Strain analysis in deformation experiments with pattern matching or a stereoscope

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Abstract—The subject of this paper is the analysis of planar deformation in deformation experiments where the specimen can be observed throughout deformation, or at regular intervals. The critical step in the analysis of deformation is the determination of displacements of material points over a deformation increment. Pattern matching is a useful and accurate method to perform this task. This method is most suited for the measurement of strain over small deformation increments, where it can produce better results than strain measurements with strain markers or inscribed grids. It is well suited for geological deformation experiments with for instance sand or clay boxes or transparent deformation cells.

The distribution of strain can be made visible with a stereoscope and two images of the deforming specimen taken at different stages of deformation. The differences in relative displacement of features on the images are translated by the brain to apparent elevation. The gradient of the slope depends on the magnitude of finite strain. A stereoscope is thus a cheap and simple tool to quickly and qualitatively assess strain distribution in a deforming specimen.

INTRODUCTION

Several types of deformation experiments have been developed that allow observation of the deforming specimen throughout the experiment, or at regular intervals. These are for instance sand box experiments, shear box experiments with clays, putties or wax and transparent deformation cell experiments (Fig. 1). In general these experiments produce a planar displacement field. An important part of the analysis of these experiments is the determination of the strain distribution within the specimen. This is usually done with strain markers, for instance circles or a grid inscribed on the specimen (Mancktelow 1991) or marker particles mixed with the sample material (Jessell 1986, Means 1989, Bons *et al.* 1993). Images of the specimens (e.g. photographs) are recorded at regular intervals during deformation. The change in shape or (relative) position of the strain markers over a certain applied deformation increment then provides information on the magnitude and distribution of strain within the specimen.

In this paper we would like to draw attention to a relatively simple method to analyse planar deformation in experiments as described above. The method is based on pattern matching to determine the displacements of material points in the deforming sample. This pattern matching can be done by a computer using digitized images, or by eye with the aid of a conventional stereoscope. The principles of this method are not new. Pattern matching is widely used for flow visualization in fluid dynamics (e.g. Chang & Tatterson 1983). Butterfield *et al.* (1970) already suggested the use of a stereoscope to determine displacement distributions in soil deformation experiments. The present day availability of computerized image analysis methods has made it possible to perform the same task automatically, as has been done by Blanchard & Page (1991). However, the possibilities of the method have not yet been fully exploited in the field of structural geological experiments.

PRINCIPLES OF STRAIN ANALYSIS IN EXPERIMENTS

The first step of the strain analysis in a deforming sample is to determine the change in position of material points as a function of their original position. This defines the *displacement vector* field (Figs. 1c & d). Once this displacement vector field is known, one can differentiate it with respect to the X- and Y-axis to obtain the *displacement gradient tensor* field. This tells us for instance the incremental strain at any point between the undeformed and the deformed state (Fig. 1e). The duration of the deformation increment is usually known in an experiment. Division of the displacement vector field by the duration then gives the *mean velocity vector* field and, by differentiation, the *mean velocity gradient* tensor field. If we only know the position of a material point at the beginning and the end of a deformation increment, we do not know the path the material point has taken between these two positions. The adjective

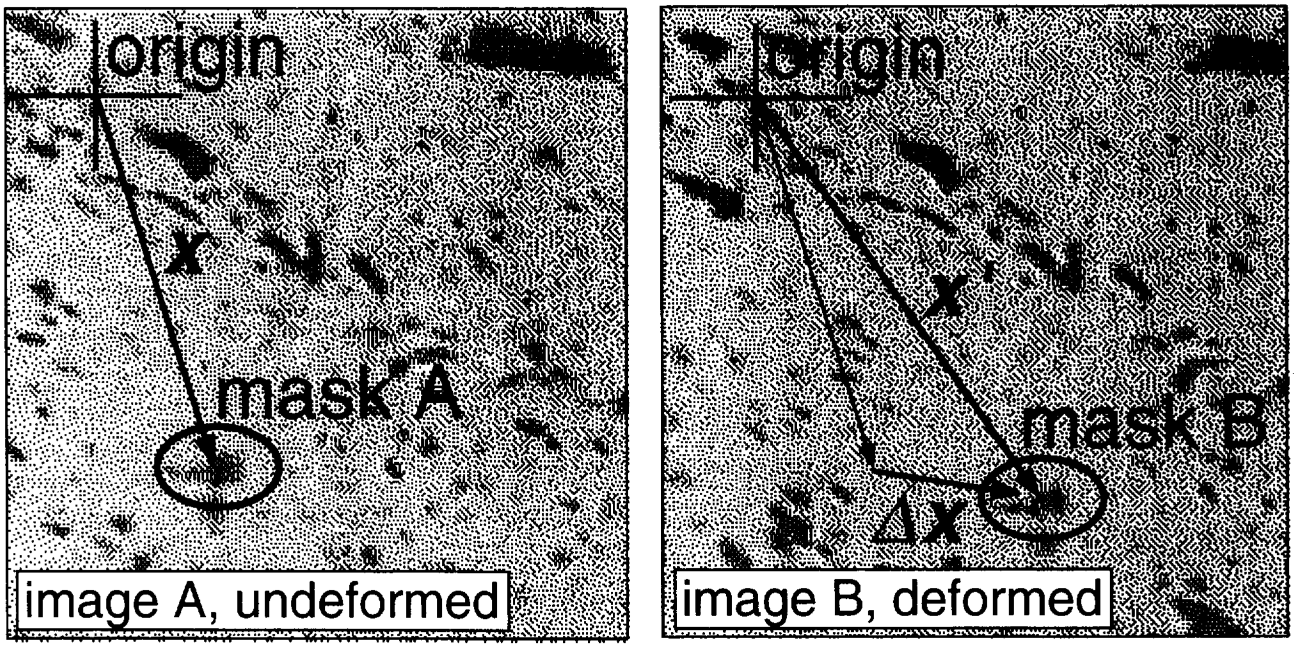


Fig. 2. Explanation of the principle of pattern matching to determine the displacement ($\Delta\mathbf{x}$) from the original position of a material point, given by the position vector $\mathbf{x}$ in image A, to its position after a deformation increment ($\mathbf{x}'$, in image B). A mask is centred around $\mathbf{x}$ in image A. A similar mask is shifted over image B, until the best resemblance between the regions under the masks in A and B is found. The centre of the mask in image B is then taken as the new position, $\mathbf{x}'$, of the given material point.

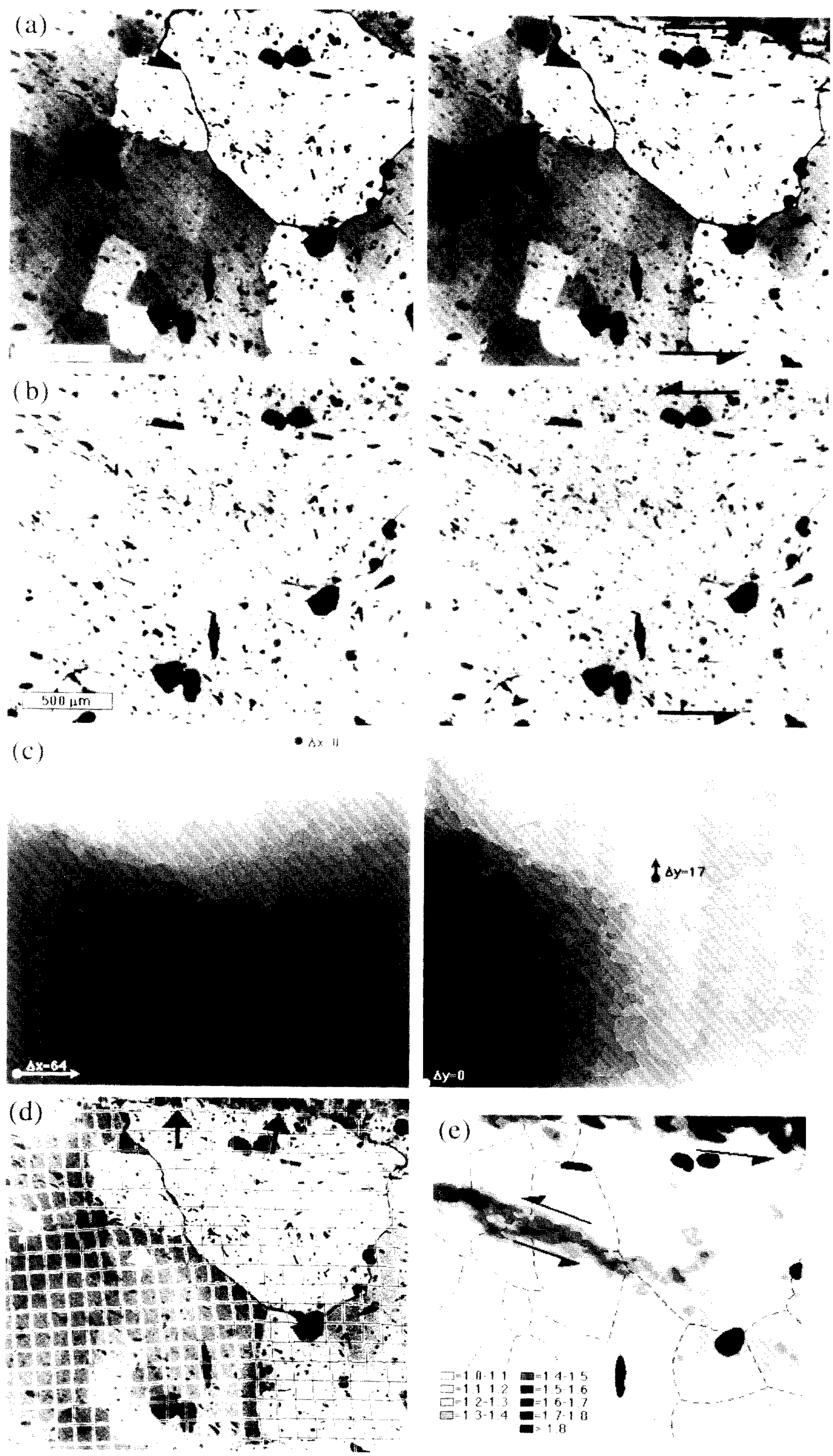
'mean' therefore refers to the mean over time of the velocity of a particular material point. The difference between the mean velocity and the true velocity vector becomes negligible when the deformation increment is very small.

The crucial stage in the analysis is the determination of the displacement vectors. The classical approach is to determine the displacements of a selected number of points (grid lines and nodes, marker particles) and interpolate between these points to obtain the whole displacement vector field (Mancktelow 1991, Bons *et al.* 1993). Even the most sophisticated interpolation method relies on some assumptions about the displacement field, and the interpolation inevitably introduces a certain amount of uncertainty and error. The most important assumption is that the displacement is continuous: discontinuous displacement fields, such as grain boundary sliding, are not well treated by a continuous interpolation method. Ideally one would rather determine the displacement vectors of all material points. Although the determination of the displacement for each point requires some assumptions and interpolation as part of the pattern matching, no second step of interpolation *between* these points is necessary.

STRAIN ANALYSIS WITH PATTERN MATCHING

The analysis is based on two images of a sample, taken at stages A and B during deformation (Fig. 2). To determine the displacement of a material point between the two stages, one selects a small region or 'mask' around the point in image A. One then searches in image B for the region (with the same size as the mask) that most resembles the mask. The midpoint of this region in image B is the new position of the material point under consideration. This routine can be applied to a set of points in the specimen, for instance the intersection points of a square grid (Blanchard & Page 1991), or the strain markers that were used. The advantage of this approach is that one can determine the displacement at any point. Although the pattern matching involves some interpolation within the mask, there is no second stage of interpolation between strain markers.

Fig. 1. Example of the application of strain analysis with pattern matching to a deformation experiment with the organic rock analogue octachloropropane (OCP), deformed in a transparent deformation cell. See Jessell (1986) for details on OCP and Jessell & Lister (1991) for description of deformation cell used. (a) Digital image (446 × 381 pixels) of a thin sheet of OCP grains, before (left) and after (right) an applied shear strain of 0.15 (bottom to right) in 4 min. The edge of the shear zone is at the top of the image (dashed line). Cross polarized light. (b) Digital image of same area as (a) in plane polarized light, before (left) and after (right) deformation. Black dots are particles of aluminium powder mixed with the OCP to provide recognizable material points for strain analysis. (c) Grey scale contour maps of the X- (left) and Y-component (right) of the displacement field, calculated with the plane polarized light images of (b). Arrows indicate the magnitude of the displacement in pixels. A weighted cross-correlation routine with an oval shaped mask of 30 × 20 pixels was used. (d) Deformation visualized by an imaginary (originally rectangular) grid passively deformed according to the displacement field shown in (c), superimposed on the image of the deformed grains. Note localization of shear at the edge of the shear zone (black arrows) and in a narrow zone on the left (white arrows). (e) Grey scale map of axial ratios of the finite strain ellipse. The two areas of localized shear stand out clearly. One coincides with grain boundaries, which signifies grain boundary sliding as one of the operating deformation mechanisms. This sliding would not have been visible without the detailed strain analysis.


(a)
(b)
500 μm
(c)
Δx=64
Δy=0
Δy=17
(d)
(e)
=1.0-1.1
=1.1-1.2
=1.2-1.3
=1.3-1.4
=1.4-1.5
=1.5-1.6
=1.6-1.7
=1.7-1.8
>1.8

The resolution and accuracy of this method are firstly limited by the type of the image features or patterns that are visible on the images: a high spatial frequency, high contrast pattern with little repeating structure is ideal. Thus for a clay-box experiment one would spray the specimen with different colours or shades of paint and for the transparent deformation cell experiments one would mix the sample material with as many very small particles as possible without significantly influencing the deformational behaviour (Fig. 1). The second limitation is that strain increments must be small enough to ensure that the region under the mask can still be recognized after the strain increment. Pattern matching is therefore best suited to small strain increments, which is where strain analysis with strain markers is the least accurate. Subsequent small strain increments can be integrated to determine the finite strain distribution over a large increment. This way one can achieve a high resolution in both space and time.

Manual pattern matching is possible, but is extremely cumbersome and not always accurate. Pattern matching is extensively used in the fields of fluid dynamics, geodesy (photogrammetry), image analysis, robotics, etc. (e.g. Russ 1992). These fields of science have produced algorithms for computerized pattern matching which can easily be incorporated into programs designed for strain analysis. Such a program, being developed by the authors, has been used for Fig. 1, which gives an example of the application of pattern matching. The program uses the normalized cross-correlation function, $R_{(m,n)}$, to determine the displacements (Russ 1992). $R_{(m,n)}$ is a measure for the correlation between the brightness distribution under the two masks for a displacement of (m,n). $R_{(m,n)}$ is maximized for each pixel by varying m and n to find the displacement of each pixel. A weighting is used to let pixels near the centre of the mask count more in the correlation than pixels further away.

The use of computerized pattern matching or digital images can introduce one problem. Displacements (with pixels as length unit) are rounded off to whole numbers if a simple and fast pattern matching routine is used. This becomes a problem when calculating the gradient of the displacement field. The problem can be overcome by increasing the resolution of the digitized image, or using a more sophisticated pattern matching routine, but at the expense of increased computing time and memory use.

VISUALIZATION WITH A STEREOSCOPE

The best and fastest pattern matching is still done by the eyes and brain together. For our three-dimensional vision, the brain uses pattern matching to determine the relative difference in position of an object in the two images it receives from the eyes. This difference in position, the parallax, is translated to a measure of distance to the object. If one looks at two images of a deforming specimen (e.g. Fig. 1a) with a stereoscope (as if they were aerial photographs), the brain 'mistakenly' interprets the differences in position of objects due to deformation for parallax. One therefore sees a 'landscape of hills and valleys'. High strain areas appear as steep slopes, whereas areas with no strain appear as flat. Discontinuous deformation (for instance grain boundary sliding) shows up as sharp ledges. This use of stereophotogrammetry to visualize planar displacement fields has been described by Butterfield *et al.* (1970). Note that the eye preferentially picks up a horizontal parallax. A stereoscope is therefore most suited to visualize simple shear deformation. The cumbersome work of contouring 'elevations' with a parallax bar or projection plotters can fortunately be avoided with the present availability of computerized image processing tools. The stereoscope can however still be a very simple but effective tool to get an impression of the strain distribution in a deformed specimen. It is useful to locate areas of interest and visually to check computerized pattern matching. One can do this assessment during an experiment when instant prints (e.g. Polaroid prints) can be made.

CONCLUSIONS

Mapping of planar strain in deformation experiments using strain markers often does not provide the desired resolution in space and time. Pattern matching may produce a better result, especially for small strain increments. Pattern matching can be done by computer, where a large volume of work from other fields of science is available. Deformation can also be visualized with the help of a stereoscope.

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