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Micromechanical Applications of Digital Image Correlation Techniques

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Abstract. Digital image correlation (DIC) is applied to images obtained with a scanning electron microscope (SEM) in order to determine the local strain field in a heterogeneous material on a representative domain of the microstructure, millimetric in size, the local contrast being provided by a microgrid deposited on the surface of the sample, with a typical $5\mu\text{m}$ step. The specific difficulties encountered when applying this classical technique for CCD images to SEM images are discussed. They are related to geometric images defects, high noise levels or imperfect scanning or to the non optimal local contrast, which are all potential sources of loss of accuracy. Several procedures to correct such imperfections are presented. The investigation of the residual strain field in a ferritic-martensitic steel after 1% total strain under uniaxial traction is then shortly presented.

1 Micromechanical Investigations

Micromechanical investigations of heterogeneous materials aim at characterising the local mechanism of plasticity or damage which control the overall mechanical behaviour, in order to identify, through scale transition models, physically based constitutive equations to be used in structural analysis, or to optimise the microstructure for improved effective properties. For classical materials such as metallic polycrystals, particle or fibre reinforced composites, the typical length of the local heterogeneities, given by the grain or particle size, ranges from about one micrometer to a few hundred ones. The scanning electron microscope is the appropriate tool for observations at such scales and is widely used. In order to observe the mechanism while they are acting and not only their final consequences, testing devices have been developed since the early 80's in order to apply mechanical loads, such as tension, compression, torsion or shear, on samples inside the chamber of the SEM. Moreover, since the relative local displacements induced by the mechanisms under investigation might be small and the phases not be very contrasted, the use of a local marking such as that provided by microgrids is very helpful [1]. They are obtained by an adapted microelectrolithographic procedure [2] that uses the beam of the SEM for the writing of the mask. When the control of the beam is combined with that of the stage, a wide combination of step sizes (ranging typically from $1\mu\text{m}$ to several $10\mu\text{m}$) and covered areas (typically several square millimeters) can be obtained. Such fiducial microgrids provide an incomparable help for the identification of

fine local mechanisms that generate displacement discontinuities, such as crystallographic glide, twinning, slip at interfaces or debonding. A substantial advantage of microgrids over other markings such as random spray paintings is that they do not mask the microstructure and allow the correlation between mechanisms and microstructure, since the width of the lines can be below $0.2\mu\text{m}$.

The identification of local mechanisms is only one part of the investigations to be done within a full micromechanical study: their relative effect on the overall behaviour has also to be investigated from a statistical point of view. That's why investigations have also to be performed at the scale of a representative volume element (RVE), which is typically 100 times larger than the local scale. The analysis at this scale can advantageously be performed with the use of strain maps that give the local strain distribution within an RVE: they provide not only the local conditions that activate the local mechanisms discussed above, which is the right quantity to consider for their characterisation, since global and local mechanical states might be very different because of the local heterogeneity within the RVE, but also give a global view of the interactions between mechanisms, for a quantification of the average contribution to the overall deformation of each mechanism, such as the plastic deformation in a given phase, in grains of a given orientation, or the slip at interfaces, or for a detection of long range interactions such as a localisation into deformation bands.

Such an analysis cannot be performed efficiently with a simple qualitative observation of the microgrids, even on large areas, and even when Moiré pattern are generated through the interferences between the deformed microgrid and the regular scanning of the SEM. A better accuracy is necessary and can be obtained by image analysis techniques that aim at locating precisely the position of the grid intersections in several mechanical configurations. Primary attempts dating back to the late 80's required to many manual operations for an unprecise result. The limitation were due, on one hand, to the image acquisition devices that could only generate images with conventional resolutions, and imposed the recording of a lot of images to ensure the statistical representativity of the investigated domain, and, on the other hand, to the imperfect image analysis techniques, based on operations such as thresholding and particle detection, with a low accuracy in terms of spatial positioning, and a high sensitivity to image or grid defects, which requires a time consuming manual assistance of the image processing operations. However, these attempts [2] clearly showed the advantage of such investigations, which are able to detect physical phenomena that could not be seen otherwise, such as long range deformation bands.

More recently, the availability of reasonably priced high resolution acquisition devices for classical SEMs (typical $4\text{K}\times 4\text{K}\times 8\text{bits}$ pixel images) made it possible to get images of large areas without long manipulations and within a short time (typically 10 to 20 minutes per image). In the meanwhile, DIC techniques developed in the late 80's [3,4] had proved to be efficient, easy to use and robust tools for the investigation of strain fields on macroscopic structures. They are usually based on optical images recorded with conventional or high resolution

CCD cameras, and marking of sample with spray paintings. The local displacement accuracy in optimal conditions is close to 0.01 pixel, thanks to bilinear or bicubic grey level interpolation.

2 Digital Correlation of SEM Images

The combination of both techniques was a potential open way to the measurement of elastic strains (below 0.1%) at a local scale (typical 10 μ m gage length) on representative surfaces (typically 1mm²) and could open a broad new field of micromechanical investigations (detection of early plasticity, fatigue crack evolutions or plastic accommodation, microcrack generation in brittle materials...). This has been attempted but did not lead to the expected results, the local accuracy of the displacement determination being hardly better than 0.3 pixels [5]. The reasons for that are mostly related to intrinsic or extrinsic geometric defects of the SEM images, non optimal conditions for their acquisition, non optimal contrast provided by the microgrid, and small deformations of the testing stage during the load. These problems are -non exhaustively- listed hereafter and indications for their correction are given when available. Some aspects won't be detailed since they have been discussed in a previous paper [6]. Full details can be found in [7].

2.1 Digital Image Correlation

This technique [3,4] aims at matching homologous domains in a reference and deformed image of the same material submitted to a mechanical load, by means of a correlation coefficient which measures the similarity of both domain in terms of pixel grey levels. The classical assumption of grey level conservation is not appropriate for SEM images since they may evolve with time, even under fixed acquisition conditions, because of the evolution of the material properties under irradiation (contamination effects) and possible electronic instabilities of the SEM detectors and their amplifiers, especially when a long time separates the recording of both images. A good correlation coefficient should thus be insensitive to brightness and contrast fluctuations and a scalar product formulation computed on the grey level fluctuation around the average level is an appropriate choice [4,6]. However one should set acquisition conditions so as to get a wide grey level histogram, without saturation, in order to record the maximum information on the available grey level scale (with typically 256 levels).

Several tests on simulated images generated with the procedure described in [6] suggest that the image resolution should ensure that a grid line has a thickness of at least three pixels and that the correlation domain centred on a grid intersection should contain at least 7x7pixels for perfect images but should be larger for noisy

ones: 20x20pixels seems to be reasonable compromise for a low computational time and a good accuracy.

2.2 Geometric Distortions

Theoretical SEM images should provide an exact correspondence between the pixel co-ordinates in the image and the physical position in the plane of observation, only characterised by the magnification. This is of course never the case in practice. The homogeneous linear approximation of this function is characterised by the magnification g , an angle of rotation θ , a pixel aspect ratio k , and a distortion angle ϕ , and can be given the matrix representation:

$$F = g.R(\theta)H \quad \text{with} \quad H = \begin{bmatrix} 1 & -\tan(\phi) \\ 0 & \frac{1}{k \cos(\phi)} \end{bmatrix}, \quad (1)$$

$R(\theta)$ being the rotation of angle θ . The fact that k differs from 1 is due to a slight difference in the digitisation step along a scanline and the distance between two scanlines; it can reach 5% or more. The distortion ϕ results from a slight relative shift of successive scanlines and its consequence is that a square object will appear as a parallelogram. It is usually small, below 1degree, but may induce a non physical apparent deformation. The magnification g may fluctuate slightly from the value indicated by the SEM, because on some devices it might not be controlled continuously with the focus. A small variation of the working distance, which may be induced by the deformation of the testing stage under load, induces a magnification variation which is not compensated by the scanning; it may reach up to 2%. The rotation θ is also induced by the working distance variation, but it does not have any effect on deformation measurements and can be ignored.

The aspect ratio and distortion angle are mostly related to the scan generator, and their value should not be much dependant on the working distance. Under such an assumption they can be determined quite precisely by recording two images of a same object that is rotated from an angle close 90 degrees. The apparent overall deformation of this object, computed by means of DIC, can be interpreted to determine the values of k and ϕ [7]. This operation should be done for any scan combination used to record images, since these parameters might not be constants. Magnification fluctuations can be controlled with the use of a reference object close to the investigated area that does not deform during the mechanical test. Its apparent deformation, again determined with DIC, gives access to the magnification fluctuation of the images of the sample. When the sample and this reference object are not in the same observation plane, additional corrections, using the focus variation between both planes, might be necessary [7].

These corrections allow to reduce the error on overall strains (i.e. the average strain on a full image, covering about 0.25mm^2) below 0.3%. Additional corrections would be necessary to improve the accuracy. One of them is related to

the image shifting during acquisition: it is well known that the electron beam undergoes a small continuous deflection during scanning, due to some non linear and non reversible behaviour of the scan coils. Its amplitude has been measured for a particular combination and turned out to be around a few pixels for the 15 minutes that lasts an acquisition of one 4Kx4K image, inducing an apparent deformation around 0.1%. It could be corrected under the assumption that the deflection speed is constant during the image acquisition: this speed could be estimated with a second acquisition of the, say, 30 first lines of an image immediately after its full record: the DIC technique applied to some points in this upper part of the image would give access to the apparent translation during the acquisition and, after dividing by the acquisition time, to this speed, to be used to correct the pixel positions in the full image. This procedure is under investigation.

All above mentioned image defects are homogeneous ones that affect uniformly the local deformation measurements. In addition to these, there are non linear imperfections, of two types. The first one is related to the nonlinearity of the scanlines due to the imperfections of the SEM column design. It seems difficult to characterise and to correct them since they might be dependant on many scan parameters. Fortunately they seem to be most sensitive at low magnification (below x100) and can be neglected at the magnifications classically used for micromechanical investigations (x200 and more). The second source of inhomogeneous geometric defects may be induced by the external scan generator that is usually part of a high resolution image acquisition device. It is based on D/A converters that generate an X and Y input tension to control the beam deflection. These converters may be more or less precise, inducing local fluctuations of the beam position with respect to its theoretical position. For instance, a 12bit converter with a systematic noise of 0.3bit, could lead to apparent deformations of up to 0.5% on a gage length of 80 pixels (i.e. 10 μ m on a 500x500 μ m area recorded on a 4Kx4K image). It turns out that this is the main limitation on one of our device, this defect generating regularly spaced vertical or horizontal lines on deformation maps. The use of higher quality 16bit scan generators is recommended, even if only 4K steps on the available 64K are used.

2.3 Noise and Spot Size

SEM images might be very noisy, especially when they are acquired at high scan speeds. Now DIC techniques are very sensitive to noise levels: it can be shown that the presence of noise may transform the absolute minimum of the correlation function into several local minima that might be located quite far away from the exact solution. A systematic study on simulated images shows that the error on displacement measurements due to a gaussian noise may vary from 0.16pixels to 0.05pixel when the standard deviation goes from 40 (classical value for standard SEM images acquired under usual conditions) to 10 grey levels on 256. For a given materials and a given detector (secondary or back scattered electrons), the

noise is mostly controlled by the beam current and the time per pixel. Its exact level can be measured by subtraction of two consecutively acquired images.

Another important parameter is the spot size, which controls the area of the material that interacts with the electron beam: the signal recorded by the detector can be seen as an integral over this area. When the spot is too small with respect to the distance between two subsequent scanlines (which is 122nm for a 4Kx4K image that covers a 500x500 μ m area), the information relative to the intrinsic grey level of the material is undersampled. This has a very bad effect on DIC techniques: simulations on generated images show that the accuracy is worth than 0.25 pixel with a spot size equal to half the scanline step, while it is better than 0.05 pixel for a spot size equal to or larger than the line step.

More details on these two aspects can be found in references [6] and [7]. One should however keep in mind that these are among the most important parameters: before acquiring any SEM image for DIC, one should make sure the spot size corresponds to the magnification in use and modify the beam current if necessary (or unfocus slightly). Then the noise level should be measured and the time per pixel chosen so as to reduce it to a level below 10 grey levels.

2.4 Optimal Marking

When all the above described procedures are applied, the local accuracy should be around 0.05 pixels, which is the theoretical accuracy estimated from simulated images with a microgrid-type contrast. This value is still much larger than the accuracy classically admitted for DIC techniques applied on images obtained with CCD cameras and with a random spray painting type contrast, close to 0.01 pixels. This can be explained by the non optimal contrast provided by the microgrid: the grey level transition between the grid and the underlying material is probably too fast and the shape of the grid intersection is too anisotropic. This again can be confirmed on simulated images. Figure 1 shows tested contrast patterns on which DIC techniques have been applied, the reference and the deformed images being translated from a known value ranging from 0 to 1 pixel by steps of 0.05 (see [6,7] for details on the generation of such images). The discrepancy between the estimated translation and the imposed one has been analysed statistically and the results in terms of standard deviation and maximal error are given in table 1: it can be seen that the random pattern indeed provides an accuracy close to 0.01pixel, with a maximum error around 0.025pixel, while the grid intersection is limited to an average 0.05pixel accuracy and a maximum close to 0.12 pixels. A better result is obtained when the grid is rotated, since more grey levels are generated, but this is only a particular configuration which cannot be ensured in practice since grids may rotate, locally or globally. A circle provides an accuracy almost as good as the random pattern with the advantage that it does not mask the underlying microstructure. Work is under progress to modify the lithographic procedure for an efficient generation of such a pattern.

Table 1. Theoretical standard deviation of error and maximal error (pixels)

Pattern	Grid	Rotated	Circle	Disc	Random
Standard deviation	0,0545	0,0221	0,014	0,0196	0,0140
Maximal error	0,118	0,0346	0,0285	0,0379	0,0253

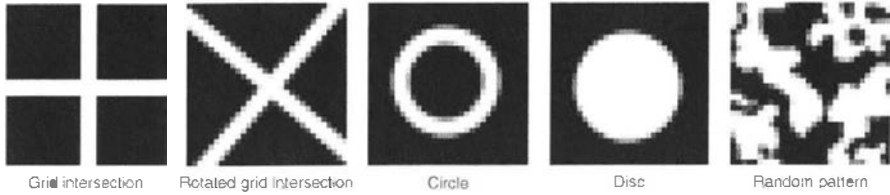


Fig. 1. Tested marking patterns

3 Residual Strain Field in a Dual-phase Steel

Dual phase steel combine a very hard martensitic phase with a ductile ferritic one to get very high strength without limiting the ductility. The very high phase contrast leads to large strain heterogeneities at the scale of the microstructure which can advantageously be analysed by the above described microextensometric technique for an optimisation of the phase morphology. Here we focus on the residual strain field in a sample that was submitted to a uniaxial tension of 1% and then unloaded, the overall residual strain being equal to 0.7%. The surface was previously marked with a gold microgrid with a $2.5\mu\text{m}$ step over a $2\times 2\text{mm}^2$ area. Four slightly overlapping 4000×3162 pixels images of a particular zone were recorded before and after deformation, with a resolution of $0.1\mu\text{m}/\text{pixel}$, and an area of $650\times 490\mu\text{m}^2$ was analysed, including about 50000 grid intersections. Optimal spot size and pixel time were used and the images were obtained with a 16bit external scan generator.

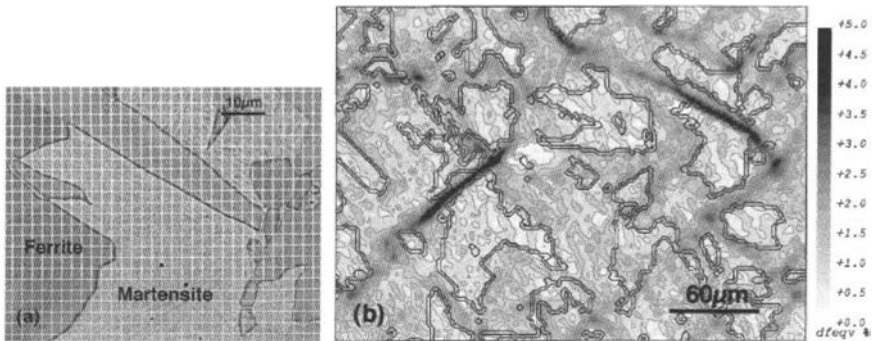


Fig. 2. Deformed microgrid on a dual phase steel (a); 0.7% overall residual strain. Local residual strain map (b); the double black line is the interface

Figure 2a shows a detail of the deformed grid and Figure 2b the obtained equivalent strain map on one fourth of the investigated area (upper right image). A strong localisation initiated at the interfaces can be seen.

4 Conclusion

Digital image correlation is a powerful tool for the automatic determination of local displacements and strains between two mechanical configurations of a same system. While classically used on optical images obtained with CCD cameras with a random spray painting type of contrast, it applies to SEM images as well and allows to measure strain fields at a scale of a few micrometers. When high resolution 4Kx4Kpixel images are used, areas millimetric in size and statistically representative of the local deformation mechanisms occurring in heterogeneous materials can be investigated. The local contrast is provided by a microgrid when the natural contrast of the observed structure is not sufficient. However, several procedures to correct the geometric image imperfections or the fluctuations of the scanning, or to optimise the acquisition of the images in order to reduce the noise level or to avoid the undersampling of the signal, are required to reach an accuracy for the displacement measurements of 0.1pixel or less. Early stages of the plastic deformation in heterogeneous materials can then be investigated.

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