Optical surface profile tracking for high resolution strain measurement

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Abstract. Characterisation of the mechanical behaviour of materials often requires accurate determination of specimen strain. This paper presents an optical method whereby the surface displacements of a cylindrical specimen undergoing uniaxial loading are measured by tracking the profile of its surface texture. These profiles are obtained through sub-pixel edge detection from a digital image.

High resolution digital imaging with sub-pixel edge detection is used to measure the radial position of edges in images of the specimen. Edges are compared in consecutive images to track the positions of zero-crossings and local maxima of the surface roughness. A method for dealing with cases in which the mean wavelength of the surface texture is shorter than the displacement between frames is presented. False matches can still occur and are removed by modal average proximity filtering in sub-regions spanning short axial-lengths and several frames.

The new method of finding specimen displacement is found to yield high data densities (in our case 32 independent measurements per mm). The data compare favourably with measurements made using a laser extensometer: surface roughness tracking produces a drop in accuracy of $\pm 25\text{ }\mu\text{m}$ whilst increasing the spatial data density. A further advantage of the technique is that no specimen preparation is required. The data are also used to calculate strain, values of which are validated against strains inferred from the change in cross-sectional area.

PACS numbers: 07.05.Pj, 62.20.F

Keywords: Strain, displacement, extensometer, optical, digital image processing, surface roughness, edge detection Submitted to: *Meas. Sci. Technol.*

1. Introduction and prior work

There are a number of well-established optical techniques that may be used for measurement of displacement in material characterisation experiments. Digital Image Correlation tracks the motion of applied or natural random features on the specimen surface, and is capable of achieving sub-pixel displacement resolution, at the expense of spatial resolution. Laser speckle metrology uses similar analysis, but here the pattern is provided by the laser speckle effect, which occurs when coherent light impinges on a textured surface. For small displacements, laser speckle interferometry may be used, and the Moiré and Fine Grid methods also provide excellent displacement resolution, although only in one direction in the case of Moiré. Reviews of these techniques may be found in [1–7].

However, there is a class of material characterisation experiments that are (a) uniaxial, so that data are only required in one direction, and (b) difficult to photograph face-on. In particular, the authors have recently developed a methodology for reconstructing the geometry of a uniaxially deformed specimen, which, due to material anisotropy, may not remain cylindrically symmetrical even if it starts off so, see [8–10]. Successful reconstruction requires views of the specimen from multiple angles, with no artificial markings on the specimen surface. For this reason, the current paper presents a method for measuring axial displacement, and calculating axial strains, by tracking the profile of the surface texture to obtain displacements. As well as removing the requirement for specimens to be marked, this technique will be shown to provide very high spatial data densities which allow high quality strain calculations.

Visual feature tracking is a broad field of research (see e.g. [11–13]) and two-dimensional features in images are often tracked through a combination of methods that include cross correlation. For surface profile feature tracking a one dimensional method is required, but many of the problems encountered, such as occlusions and noise, and the strategies used to overcome them, are applicable here too. The features tracked in this paper primarily suffer from the picket fence problem: in that they look very similar to their neighbours. In addition to this, noise in the images and changing specimen surface texture due to elongation make matching features from one frame to the next, using anything other than their position, problematic. Strategies have been developed to overcome the challenges of this task that should prove useful to others who would like to implement this technique.

2. Method

2.1. Obtaining specimen edge features

Specimens manufactured by turning on a lathe have surface textures that are approximately periodic with axial position, overlaid with irregular variations due to random fluctuations in the process. This paper will use a single tensile test specimen as an example of the new measurement technique. The surface height of a patch from

Figure 1. (a) Surface height of a specimen showing the pseudo-random undulations of surface texture running axially due to the manufacturing process. The horizon of the surface is shown in (b), and the tangential positions of the horizon are shown as a line in (a). It is observed that the circumferential locations of the horizon vary significantly with axial position.

this specimen has been measured using an Alicona Infinite Focus Surface Profiler, and is shown in figure 1. The surface of this specimen, in the axial direction, had a mean absolute deviation from its mean height, R_a , of $0.7 \mu\text{m}$ and an RMS value, R_q , of $0.8 \mu\text{m}$. The mean peak to valley height of the roughness in the axial direction was $2.9 \mu\text{m}$, with a maximum value of $3.9 \mu\text{m}$. The smoothly varying roughness of this surface was not expected to initiate premature fracture in a relatively ductile material such as the Ti-6Al-4V here, but if it had, then smoother specimens would have been required to measure accurate values of strain and stress at fracture. It should be noted that with a suitable camera, any discernible surface roughness can be used: specimen preparation can be designed to provide accurate measurements of material properties, whilst the resulting level of roughness in the surface can be viewed using the correctly chosen imaging device.

The edge seen in an image of the specimen is ideally a visible horizon of this surface, figure 1(b). The peaks, troughs and zeros of this edge, after high-pass filtering, are used to generate displacement data using the new method. In reality, the surface seen is close to the horizon shape, but will differ because the camera lens is not a true pinhole camera and rays of light from the horizon reach the sensor from multiple angles.

This paper reports data from a quasi-static, uniaxial tensile experiment performed on specimens of commercial Ti-6Al-4V with nominal gauge length 8 mm and gauge diameter 3 mm, figure 4(a). Specimens were loaded using a commercial screw driven

Hounsfield Tensometer with a cross-head speed of 0.5 mm/min. The nominal stress-strain curve for this specimen can be seen in figure 2, the strain of which was calculated using laser extensometer tracked positions within the gauge length. The nominal-stress-against-time curve can be seen in figure 3. The specimen began to yield at 130 s and fractured at 291 s.

Photographs were acquired at a rate of one every three seconds using a single TELI Digital Camera (CSB4000CL), with a 4 megapixel 10-bit greyscale CMOS sensor, and a Computar Megapixel lens. The experiment was uniaxial, which held the specimen at a constant distance from the camera, maintaining the focus on the profile and preventing any apparent change in specimen size. The specimen was illuminated by lights on both sides and the background was kept dark, although a backlit specimen could also have been used.

Figure 2. The nominal stress-strain curve for the specimen tested.

The edge detection and surface peak tracking were implemented in Matlab and performed off-line, after the experiment. For comparison, laser extensometer measurements were also performed using a FIEDLER Optoelektronik model P-50, which had a sampling frequency of 50 Hz and was found to have an accuracy of $\pm 3 \mu\text{m}$ in practice. This device works by tracking the position of a series of white lines which are usually painted onto the relatively dark specimen surface.

Using this apparatus, digital images, figure 4(a), of the cylindrical specimen were acquired with a sufficiently high resolution to discern the surface texture in the edges. The specific resolution that is required depends on both the specimen and the apparatus; $6.5 \mu\text{m}$ per pixel was used in this experiment. The acquisition equipment was focused

Figure 3. Nominal stress against time during the experiment.

on the edges of the specimen and the lens was calibrated so that radial distortions could be removed by rectification [14, 15].

The cameras were orientated so that the specimen's edges were nominally aligned vertically in the images, figures 4(b) and 5(a). The edge detection algorithm here is a sub-pixel implementation of the difference-of-boxes operator, which maximises the signal to noise ratio for simple step edges [16, 17]. To detect, for instance, the right-hand edge of the specimen in each image, the maximum greyscale gradient in each row of pixels was found by cross-correlation with a white and black rectangular patch of size 4 rows by 20 columns, where the left 10 columns were white (maximum intensity) and the right 10 columns were black. The edge position within the row was found by locating the maximum correlation value. The cross-correlation process produces a correlation image, figure 5(b). In figure 5(b) there appear to be two vertical edges, but the left one is the response to a faint highlight on the specimen surface, barely visible in figure 5(a). A patch rather than a single pair of white and black pixels was used so that the response was less affected by noise in the image, even so, a significant amount of noise can be seen in figure 5(b). On each row of this image, figure 5(c), the position of the peak value is equivalent to the position of the specimen edge. In order to find the location of the edge to sub-pixel accuracy, a parabola was fitted, by least squares, to up to 5 correlation values around each peak that were greater than a pre-defined threshold. To obtain left-hand edge positions, the negative of the correlation values were used and the new peak positions found. The process was repeated for each row, so that in an ideal situation the edge locations trace the shape of the horizon of the

Figure 4. (a) A typical tensile specimen of gauge length 8 mm and gauge diameter 3 mm, its size was specified so that it could be used in both quasi-static and high strain rate ($> 10^3 \text{ s}^{-1}$) experiments. (b) An image of this specimen in-situ where the gauge length spans ~ 1250 pixels.

surface seen in figure 1(b); an example is given in figure 6 (dashed line). Other edge detection algorithms were evaluated, including the Canny, Harris, Sobel and Prewitt detectors [17–19], but the method implemented here was found to be most accurate for automatic determination of the correct edge position with sub-pixel accuracy.

A data set consisting of the radial positions of the left and right hand edges of the specimen as functions of axial position along the specimen length was thus created. In order to calculate specimen displacement it was necessary to track material positions by following the movement, between images, of features on these edges. The discernible features that were most likely to be present throughout the experiment, and not to move with respect to the material, were the zero-crossings of the high-pass filtered curve that had a positive gradient (although negative gradient features were equally valid). In order to locate these features, the edge curve was filtered using a high-pass Butterworth filter with a cut-off frequency chosen so that the detected shape of the nominal specimen geometry could be removed, but the underlying surface roughness would remain with a zero mean, figure 6. In this experiment the cut-off frequency was determined to be 6 periods per mm.

To improve the repeatability of locating the zero-crossing at the same material position in each frame, a least-squares spline fit to the detected edge of the specimen was calculated using the Matlab ‘csaps’ function [20]. This also allowed the determination of the position of zero-crossings in the surface roughness to an accuracy better than the

Figure 5. (a) A cropped region of the specimen image shown in figure 4(b), the specimen comprises the dark region on the left and its highlighted right edge. (b) The result of the correlation with a patch of 4 rows by 10 columns of white pixels attached horizontally to 4 rows by 10 columns of black pixels. (c) A row of correlation values, highlighted by a dashed line in (b). (d) The least-squares parabolic fit to correlation values above a threshold of 0.85 in (c) that lie around the highest value (highlighted by the square) in (c). The position of the peak of this parabolic fit is the sub-pixel edge position of the right hand edge in this row.

nearest pixel, which is the best resolution obtainable from the original, pixelated, data. Figure 7 shows the result of spline fitting and the calculation of the zero-crossings in a small region of the edge curve.

2.2. Robust tracking of features between frames

Once zero-crossings had been located, they were tracked between frames. If the zero-crossings had been farther apart, making the inter-frame displacement of the material less than wavelength of the roughness, and noise had had less of an influence on the edge data, then tracking them would have been a relatively simple matter of matching one feature to its closest neighbour in a subsequent frame. In the current example, the surface roughness wavelength, $\sim 60 \mu\text{m}$, was short enough in some sections of the gauge length so as to make matching to closest neighbours produce too many false matches

Figure 6. The original detected left-hand edge of the specimen with the low-pass filtered edge and the high-pass filtered edge shown at offset positions for clarity. The large ‘bucket’ shaped bump is the outline of the paint marker required for the laser extensometer. The width of a pixel in the image, $6.5 \mu\text{m}$, is also shown.

to be useful. In order to overcome this limitation, the cross-head displacement of the loading device was used to produce a model of expected displacement. Matches between zero crossings were only made when the feature in the second frame was within a given distance of the predicted position. Figure 8(a) shows the matches found using this guided matching. By assuming that one end of the specimen moved with the cross-head, whilst the other was stationary and the displacement was otherwise linear in position, a predicted displacement was obtained for each axial position.

Using this method, many features were matched correctly, but false matches remained. False matches were found and removed using a similar prediction method, this time using the modal-average displacement of regions that spanned a fraction of the whole length and time of the experiment. Figure 8 demonstrates the process, whereby the displacements of all features within a certain region of axial length and

Figure 7. The original, discrete, edge positions determined by cross-correlation and the continuous spline interpolating fit. The surface features used to track the material are the zero-crossings.

time, 1.5 mm and 9 s, were binned to produce a histogram of displacement, shown in figure 8(b). Features were accepted as correctly matched if their displacements were within a threshold of the most frequent displacement, otherwise they were rejected. This threshold was determined by the maximum expected strain rate in the specimen and the region's time span and axial length; a threshold of $\delta = \pm \dot{\epsilon}(\Delta t)(\Delta L)/2 = \pm 0.015$ mm was used in this experiment. The displacements of the acceptably matched features were averaged and taken to be the displacement of that region. The centre of the region was recalculated as the average location of the acceptable features. The modal-average displacement was calculated at a grid of time and axial positions using overlapping sub-regions across the whole set of features, which produced the displacement data shown in figure 9. This method of filtering relied on the strain within the region being approximately constant, which was the case for the regions selected, which were

Figure 8. (a) ‘Raw’ feature tracks showing the motion of corresponding features plotted as a function of time in the camera frame of reference. The parallel gauge length of the specimen is between 2 mm and 9 mm. A 9 s by 1.5 mm sub-region is shown as a box surrounding a group of features. The lines either side of the box indicate the modal average displacement direction. (b) The histogram of displacement within the box in (a). The threshold displacement values are shown by dashed lines; the mean of the displacements between these values is taken as the sub-region’s modal average displacement.

sufficiently small, and the homogeneous material.

Figure 9 plots material displacement over time in the vertical image position. It can be seen that at around 11 mm and 250 s, the displacement has been incorrectly determined, showing that this technique could not be relied upon to obtain correct displacements for all locations within the experiment. To ensure the validity of the results, a manual check for erroneous data, such as this, had to be performed.

After filtering, features that were previously unmatched or incorrectly matched could then be guided using the displacement data in figure 9(a), with more precision than the linearly interpolated cross-head data, and consequently the allowed threshold in matching could be reduced, preventing the majority of false matches. The resulting

Figure 9. (a) The displacement of overlapping sub-regions, 9 s by 1.5 mm, across the range of time and axial position in the camera frame of reference. The shading represents average displacement at that location between two subsequent frames. (b) A finer determination of displacement with non-overlapping sub-regions of 3 s by 1 mm (3 s was the inter-frame time). The time and vertical positions of the displacement are irregularly spaced because they are plotted at the mean location of the features found to be in that sub-region, and not the nominal location of the sub-region.

set of matches was filtered using a smaller region size, 3 s by 1 mm, to give a finer representation of displacement of the material in the camera frame of reference, as shown in figure 9(b). Using this even finer description to guide the matching process yet again, with an even further reduced threshold for guidance, a detailed set of matching features could be found.

The average number of pixel rows between consecutive positive-gradient zero-crossings was 10 pixels and within one period of roughness there are more phases that can be tracked than just the positive-gradient zero-crossings: these are the zero-crossings with negative gradient and the local maxima and minima. The fine displacement data in figure 9(b) could also be used to guide matches for these three feature types as they all had similar displacements. Given the matches for features of all four types, a

detailed measurement of specimen displacement along the gauge length can be obtained by following features that are successfully tracked throughout the experiment. These data are shown in figure 10 where 252 features were tracked at a mean initial spacing of $31\text{ }\mu\text{m}$ and a median initial spacing of $16\text{ }\mu\text{m}$. This figure does not show features that could not be tracked for the entire experiment, but if those that could be tracked continuously for at least two thirds of the time were considered, the mean initial spacing would decrease to $26\text{ }\mu\text{m}$ while the median would be unchanged.

Figure 10. The position of specimen edge curve features that could be tracked throughout the experiment are plotted. At the left and right sides side of the tracks are photos of the specimen at the start and the end of the experiment; the negative of their images has been shown for clarity. Along the edges of the specimens, crosses indicate the initial and final locations of the tracked positions. The dashed lines show the laser extensometer tracked positions throughout the experiment.

2.3. Laser extensometer validation

To validate the new method against an established position measurement technique, the position of two locations within the gauge section, highlighted in figure 10, were measured with a laser extensometer. The comparison data are shown in figure 11, which shows the difference between the two laser displacement measurements and the displacement measurements derived from the closest tracks. The laser positions, y_L , were initially at 8.66 mm and 2.23 mm and the roughness tracks, y_C , were initially at 8.74 mm and 2.18 mm . The laser extensometer recorded its measurements at a rate

of 50 Hz, whilst the inter-frame time of the cameras was 3 s, and therefore the laser extensometer data was smoothed with an averaging filter of 150 samples to obtain more accurate values for comparison. A maximum error of 23 μm was seen in these results. However, some of this error is due to the strain of the samples which tends to move the lines apart.

Figure 11. The displacement of roughness tracks measured close to initial axial positions of 8.7 mm and 2.2 mm in the gauge section, shown in figure 10, are subtracted from the displacement of laser extensometer measured tracks at these locations. Due to the initial separation of laser-tracked and roughness-tracked positions the increasing strain in the specimen tends to increase the error.

2.4. Calculation of specimen strain

The high resolution displacement data contain a certain amount of noise; when differentiating these data to obtain strain, the noise will have a significant effect on the results. Smoothing of one sort or another is often employed in these situations to extract the underlying derivative. Here, a method of smoothing is presented that allows computation of strain.

To calculate strain from the continuously tracked material positions shown in figure 10 would have ignored the displacement data from tracks that could not be followed during the whole experiment; however, such partial tracks still contribute useful data some of the time. The Eulerian displacement plotted in figure 9(b) includes *all* data, with averaging of displacements over an axial length of 1 mm. Using the

averaged representation of the material displacement allowed the calculation of strain that included all of the available displacement data combined with an averaging filter that prevented the differentiation of measurements becoming too noisy.

Knowledge of the Lagrangian displacement, as opposed to the Eulerian displacement seen in figure 9, allows the calculation of strain as a function of initial axial position. The Lagrangian form is commonly required for the comparison of material strain at different times during an experiment. The paths of material movement can be derived from the Eulerian displacement. The location of a material point, $x(t)$, initially at $x(0)$, can be found by adding the inter-frame displacement, $u(x(t), t)$, interpolated at $x(0)$ and $t = 0$. This means that $x(\Delta t) = x(0) + u(x(0), 0)$, where Δt is the inter-frame time. The material's subsequent position can be found by further additions of the interpolated Eulerian displacement at those positions, giving $x(t + \Delta t) = x(t) + u(x(t), t)$. The tracked material paths derived in this way are shown in figure 12, where it can be seen that the regions in the data set with poorly determined displacement result in poorly tracked material positions, as expected. The displacement from the initial position for a point within the material can be found as $U(x(t), t) = x(t) - x(0)$.

It should be noted that this method also allows estimation of material displacement in regions of the specimen where features cannot be robustly tracked and axial gaps are left in the tracking record, as seen in figure 10. The data in figure 12 are not simply an interpolation of those in figure 10, because more information has been included. This is the preferable method of calculating material displacement when individual features cannot be tracked continuously.

The reconstructed displacement data were then smoothed using a least-squares spline-fit (see the `csaps` function of Matlab [20]) in the time and axial dimensions and then differentiated to obtain the engineering strain, $\epsilon_s(x, t) = \frac{\partial U}{\partial x}|_t$, shown in figure 13(a). In order to validate these data, strain was also calculated as a function of initial axial position using the areas of the cross-section, which were calculated using the technique presented in [8]. Before calculating the areas, the edge curves were also smoothed axially by low-pass filtering with a roll-off frequency of 17 periods per mm. Since the elastic strain is small, the volume of the specimen was assumed constant, allowing the engineering strain to be calculated at time t as $\epsilon_a(x, t) = (A(x(0), 0) - A(x(t), t))/A(x(t), t)$, where $A(x(0), 0)$ and $A(x(t), t)$ are the original and current cross-sectional areas respectively, for the material at axial position $x(t)$. The initial area could not have been found without the derived material paths shown in figure 12, since the initial axial position corresponding to each current axial position could not have been known. Knowing the paths also allowed the strain, $\epsilon(x, t)$, to be calculated as a function of the initial location of the material, and not only its current location. The result of the areal strain calculation is shown in figure 13(b).

Comparison of the two methods for calculating engineering strain: areal and modal averaged displacement, provides validation of the new technique. Figure 14 shows the comparison of the shaded contours of areal strain with four different representations of strain from the tracks. Shown in figure 14(a) and figure 14(c) is the strain from the

Figure 12. The tracks of material positions from the finely determined displacement data of figure 9(b).

finely determined displacement in figure 9(b). Figure 14(b) and figure 14(d) show the strain from the coarser displacement data of figure 9(a). Figure 14(c) and figure 14(d) show how smoothing with a least squares spline function can improve the appearance of the data by removing noise.

3. Discussion

The new technique constitutes a method for the determination of material displacement and strain with high spatial data resolution. It is applicable in situations where the roughness on the surface of a specimen is discernible in the edge profile, moves with the deforming material, and photographs can be obtained at a sufficiently high rate. A strategy for tracking features in this profile has been presented that can reduce false matches and allow the continuous tracking of material positions. For regions in the

Figure 13. (a) Engineering strain, $\epsilon_s(x, t)$, calculated using the displacement of the tracked surface roughness. (b) Engineering strain, $\epsilon_a(x, t)$, calculated using the cross-sectional areas as a function of initial position and time.

profile that cannot be confidently tracked throughout the experiment, a method for determining average displacement and expected material paths has also been presented. These data have also been shown to provide a reliable method for calculating strain with a high spatial resolution.

This technique presents advantages over speckle digital image correlation because it does not require the specimen to be marked, which obscures the surface and prevents accurate simultaneous measurement of specimen geometry. This is demonstrated by figure 6, where the paint used for the laser extensometer is visible in the edge position. Marking also obscures potentially important failure mechanisms. In addition paint, or its equivalent, used for marking specimens, also has the potential to move with respect to the surface, which would reduce the accuracy of the results - this has been found to be the case in some ductile metal specimens. The application of paint on fine scales can be

Figure 14. Contours of strain as functions of axial position and time. The shaded contours represent the areal strain and the lines represent roughness tracking strain with different levels of smoothing. (a) Modal averaging taken over 1 mm of length and consecutive frames only. (b) Coarser modal averaging taken over 1.5 mm of length and 3 periods spanning 4 frames. (c) The data in (a) with spline smoothing applied. (d) The data in (b) with spline smoothing applied. Note that the data in (b) and (d) do not cover the entire duration of the experiment because of the broad filtering.

difficult to achieve, whereas roughness from manufacturing is a by-product. This method provides an alternative technique to DIC which we find to be more straightforward to apply in many circumstances, and may give better data densities.

As the technique here is non-contacting, it has the associated advantages of other non-contacting techniques in that it can be used in high speed and/or high temperature experiments. The surface roughness in this experiment was the result of the manufacturing process (turning on a lathe) which left a smoothly varying surface roughness with peaks separated by an average of $\sim 60 \mu\text{m}$, allowing the technique to track material positions with a high spatial resolution that may be difficult to achieve

by digital image correlation of speckles. The equipment required to implement this technique is also readily available.

Data from a cylindrical specimen have been displayed. However the technique need not be limited to this geometry. This method provides an accurate technique for measuring localised strain at an abundance of locations throughout the gauge length of any specimen.

The new technique compares well when validated against displacement measurements from a laser extensometer and calculation of strain from specimen area. Figure 14 shows good agreement between areal strain and roughness tracked strain.

The low frequency component of the difference in displacements shown in figure 11 could have been caused by the initial disparity in the position being tracked by the two methods. Because the surface roughness was not uniform, and hence did not guarantee a distinct feature at a certain location, the two locations under comparison were not the same; in fact they were separated in these two cases by 0.08 mm and -0.05 mm. Given that the strain at these locations rose to $\sim 10\%$ during the experiment, part of the difference can be attributed to this disparity, rather than a fault with the roughness tracking.

One proposed reason for small differences between the measurements is that the separation of neighbouring features, $\sim 30\text{ }\mu\text{m}$, is similar to the structural length scale in the material, viz. the grain size. Thus the material is inhomogeneous on this scale and some noise may be due to the different axial strain of neighbouring grains. However further experiments would be required to determine the extent of this effect.

There are a number of further sources of error which may need to be investigated in future studies. These include: errors in detecting the position of features with sub-pixel accuracy; noise in the digital images; lens distortion; changing lighting conditions. One issue not discussed thus far is that of using a perspective camera lens and thus the limited ability to look down the parallel ridges in the specimen surface, apparent in figure 1(a). Ideally a telecentric lens would be used for this purpose, however using a lens with a long focal length should ensure that the light rays are close to parallel, and hence allow the camera to see along the ridges, because the light would fall on the image plane perpendicularly to it. However, as we move further from the centre of the image, the assumption of perpendicular light rays becomes less valid, and the features on the edge horizon may become less distinct as peaks appear to overlap more.

Removing false matches is also an important part of this technique. Whilst the matching strategy is designed to prevent these, it cannot be verified that any particular match is true. Part of the problem with making correct matches is that the edge curve changes shape from one frame to the next: noise in the images; the changing shape of the surface due to its elongation; and a changing horizon due to radial motion of the surface, all affect the apparent shape. Much effort was exerted in investigating solutions to obtain even fewer false matches. For example, cross-correlating patches of the edge curve with the edge curve in the next frame partially helps to make correct matches, but the length of the edge curve required to make a sufficiently unique patch reduces the

resolution of the tracking through an averaging effect and provides diminishing returns on the information gathered. Therefore cross-correlation was found to be of insubstantial assistance and was not used. The use of optimally strained sections of edge profile for matching using cross-correlation did not prove useful either. Again, this was because of the noise in the edge profile and the similarity of neighbouring regions, which is not a problem for speckle correlation, where the commonly used random patterns are unique over sufficiently large regions. The current technique provides a method for matching non-unique features in the presence of noise and an irregular strain field, such as that in the necking specimen presented, albeit without so much variation in the strain that the matching becomes impossible.

Better tracking was also sought by adapting stochastic methods such as RanSAC [21] and MLESAC [22] where the gradients of the zero-crossings and the heights of maxima and minima were used as *a priori* descriptors for these features so that groups could be found that agree on general displacement and false matches removed. However this was only of benefit when the descriptors had persistent values, which was found not to be the case for most of the features detected in the edge curves here, as the descriptors are second order and are affected more by noise.

In future applications of this technique, the occurrence of false matches can be reduced by using better estimates of expected displacement for matching guidance. This estimate could come from extra measurement by, for instance, sparse extensometer measurement, from predictive modelling of displacement or manual estimation. However these may not be readily available and simple linearly interpolated cross-head displacement should be adequate in most experiments where the wavelength of surface roughness is shorter than the inter-frame displacement and a prediction is therefore required. The ideal surface roughness has a period that is greater than the expected inter-frame displacement and an amplitude that makes it discernible using the photographic equipment available.

4. Conclusion

A method for measuring displacement in uniaxially loaded specimens with high position resolution, $\sim 30\ \mu\text{m}$, has been developed. The profile of surface roughness is seen in images of a specimen captured by high resolution digital cameras. This profile is measured in the images using sub-pixel accuracy edge detection. Features within this edge are detected using data from its high frequencies, ignoring the nominal specimen dimensions and using only surface roughness information. A method for tracking these features that copes with problems inherent in feature tracking where the features are not designed to be tracked is given. This method uses an estimate of the specimen displacement from the cross-head of the loading device to guide the matching of features between image frames and then using modal-average filtering in sub-regions that span a range of time and axial length to identify incorrect matches.

For specimens with a mean surface roughness wavelength shorter than the maximum

material displacement between frames, it has been found that to obtain an accurate matching of features, an estimate of displacement is required. This could be obtained through external displacement measurement, approximate finite element modelling or manual estimation of some of the matching. Here, the cross-head displacement was used and found to be suitable.

Once the features had been matched correctly, material displacement for positions at high resolution was obtained. In practice the average separation of features that could be tracked throughout the experiment was $\sim 30 \mu\text{m}$. The displacement information was also differentiated to calculate the strain in the specimens.

The technique does have drawbacks, one of which is that some of the resolution that could theoretically be achieved by measuring the displacement of all of the features in the edge curve must be sacrificed in order to gain higher accuracy through smoothing.

Difficulties also arise due to noise in images, which is a factor in most photogrammetric applications, and can be reduced by appropriate lighting conditions and equipment. Suggestions for future investigation have been made, including bespoke preparation of specimen surfaces. However, the data presented in this paper show that the technique offers significant advantages over other methods even at this stage.

5. Acknowledgements

The authors would like to thank our colleagues at the University of Oxford including Pete Hardy and Daniel Mulvihill. This work was funded by EPSRC and Rolls Royce plc.

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