A computer aided optical technique for creep strain determination

K. Zarrabi & Z. Lu
The School of Mechanical and Manufacturing Engineering
The University of New South Wales, Australia

Abstract

One of the unresolved engineering problems is the creep strain measurement at elevated temperatures. A non-destructive computer aided optical technique using a digital image cross-correlation scheme is developed. It is shown that the technique is capable of measuring creep strains at elevated temperatures with the maximum error of 1.9%.

1 Introduction

One of the as yet unresolved engineering problems is the measurement of creep strains at elevated temperatures. Although weldable resistance and capacitance strain gauges are commercially available, they do not produce reliable and repeatable results for many applications involving creep strain measurements [1]. Ideally, a robust full-field measurement technique is needed. Displacement/strain measurement methods that have been used include laser interferometry methods, stereo-imaging, acoustic emission and ultrasonic and computerised tomography. These methods suffer either from high sensitivity to the vibrations from testing machines, low measuring accuracy or cumbersome post-processing. In recent years, computer aided optical techniques have emerged as significant tools in the area of experimental mechanics. Among various computer aided optical techniques, the electronic speckle pattern interferometry (ESPI) and electronic shearing speckle pattern interferometry (ESSPI) have been developed for ambient displacement and displacement derivatives measurements respectively [2]. The advantages of these methods are the absence of chemical processing and darkroom operations. In 1982, Peter and Ranson [3] introduce a computer aided
optical technique (CAOT) for displacement/strain measurement that was based on digitally correlating the object images before and after deformation. Some other researchers have further refined and improved the accuracy of CAOT, but its application to gross creep strain measurements at elevated temperatures have not been studied to the authors’ knowledge. This paper describes the development of a new high resolution CAOT and its applications to high temperature gross creep strain measurements.

2 Computer aided optical technique (CAOT)

Our CAOT (Figure 1) consisted of: a Data Translation® DT3157 PCI frame grabber installed inside a Pentium II-333 personal computer, a PULNiX TM-1300 monochrome progressive CCD camera with a spatial resolution of 1300 x 1030 and 10-bit gray-level, a Navitar Zoom 7000 (F2.5/18-108MN) lens and fibre optic light guides with an ELH lamp of 120V 300 W as the light source. The CCD camera was mounted on a 3-Axis Macrobloc Flexure Stage with a differential micrometer driver having a resolution of 0.001 mm. The assembly of the camera and Macrobloc Flexure Stage was mounted on a tripod. This arrangement allowed the system to be set up and calibrated in the laboratory with relative ease (see later). Other components used in the research were: an Instron 5582 universal testing machine (for applying loads to the specimen), a three-zone furnace (for uniformly heating the specimen), a LVDT for measuring displacements.

![Diagram](image)

**Figure 1:** Main components of CAOT
The furnace had a Pyrex glass window so that the specimen surface can be optically accessed. The window was 13 mm wide and 110 mm long. Fibre optic was used to direct the light to the specimen surface. The measured displacements by the CAOT were verified by comparing them with those measured by the LVDT. The measured displacements by the CAOT system were converted to strains by surface-fitting and numerical differentiation processes. The measured displacements by the LVDT were also converted to strain using the standard natural logarithmic definition for strain. Strains computed using the two methods were compared with each other. To measure displacements by the CAOT, a speckle pattern was first created on the surface of a specimen. To this end, the surface of the specimen was uniformly covered by white paint and then sprayed by black paint. To avoid peeling and surface oxidation, the Power Plus heatproof paint with heat resistance up to 750 °C was used. The principle of strain measurement using CAOT was to track the displacements of a small sub-image of size $M \times M$ pixels within the speckle region. The centre of this sub-image coincided with the point of interest. The original and some of the subsequently developed CAOT relied on measuring both the displacement components and the displacement gradients of the sub-image. But to the authors’ experience [5], CAOT cannot measure the displacement gradients accurately in presence of creep deformation. In the present study, therefore, the measured displacements were fitted a bicubic spline surface in a piece-wise manner. Then, the spline surface was numerically differentiated to obtain strains at various time steps. The bicubic spline surface implemented a third-order polynomial that allowed both grey-level values and $C^2$ continuous gradients to be obtained at any location within the domain over which the displacement was measured. The principal of strain measurement using our CAOT is as follows. Using CAOT, one measures in-plane displacements in the $x$ and $y$-directions where the $x$ and $y$-axes represent a local coordinate system attached to the specimen surface. As mentioned before, the measured displacements are then converted to strains by numerical differentiation. The displacement measurement is based on grabbing two speckle images of the object surface at two different time points. The images are then digitised and numerically correlated to obtain the displacements at various points within the area of interest on the specimen surface during the time interval. This was achieved by maximizing cross-correlation function. This function was optimised using a direct search method. This method first searched for the peak point of the function along the $x$ - direction. Then through this peak point it completed a second line search along the $y$ - direction to discover the second peak point that was closer to the absolute maximum value of the function. If the value of the function was not large enough, then this search algorithm was repeated. To increase the accuracy of measurements to the sub-pixel level, the cubic spline interpolation function was used to compute gray-levels of points fell between pixels. The initial search step was set to 2 pixels and then it reduced continually to a sub-pixel level until the desired accuracy was achieved. An object-oriented software using a C++ compiler was developed to perform required computations.
A standard uniaxial tensile specimen was machined from 2.25%Cr1%Mo steel. The specimen had a solid circular cross-section with a diameter of 10.01 mm and gauge length of 59 mm. It contained two circular knife-edges for holding a gauge clamp on the specimen. Displacements of the knife-edges were transmitted to the LVDT positioned outside of the furnace by the gauge clamp and extension rods. The gauge length of the specimen was covered by ‘white-light speckle’ pattern as mentioned before.

Calibrations tests were carried out to determine: (a) the size of the sub-image $M \times M$ whose centre was the point of interest and (b) to relate displacements in units of pixel to that in unit of millimetre. Two factors decided the size of the sub-image $M \times M$. Firstly, each $M \times M$ sub-image in two speckle patterns represented areas over which strains were assumed to be constant. Therefore, to make measurement pertinent to a point on the specimen surface, $M$ should be selected as small as possible. Secondly and on the other hand, the correlation algorithm was based on the assumption that the sum of gray-levels over each sub-image of the size of $M \times M$ in two speckle patterns was statistically unique. To satisfy this requirement, $M$ should be sufficiently large. Following calibration tests were carried out to decide the size of $M$. In the first calibration test, two consecutive images of the speckle specimen surface were taken while keeping the specimen unloaded and the camera stationary. Ideally and for a correct value of $M$ the two digitised speckle patterns were identical and hence when used in conjunction with the numerical correlation algorithm described before should result in zero displacements and thus zero strains. However, because of various noises in the system measured displacements were not zero. In measuring displacements, this test however indicated that the standard deviation of the error could be minimized to 0.03 pixels by setting $M$ to 24 pixels or larger. Therefore, in the correlation algorithm that was later used to determine displacements and strains on the specimen surface, $M$ was set to 24 pixels. Second sets of calibration tests were performed to relate displacements of the points within the sub-image $M \times M$ in units of pixel to that in unit of millimetre. For this purpose, first an image of the speckle specimen surface was taken and digitised while keeping the specimen unloaded and the camera stationary. Then while the specimen was kept unloaded and stationary, the camera was moved relative to the specimen surface in the $x$ and $y$-directions in steps of 0.001 mm and at each step an image of the speckle specimen surface was taken, digitised and correlated to the first image to determine the camera displacements in units of pixels. From these tests it was concluded that a displacement of 0.00153317 mm in the $x$-direction and 0.00153393 mm in the $y$-direction were equivalent to 1 pixel movement in each direction respectively.
3 Tests & results

First a reference image of the speckle surface of the specimen was taken when it was unloaded and at ambient temperature. Then the specimen temperature was raised at a ramp rate of 10 °C per minute until it reached 550 °C. Next, while the specimen temperature was kept constant at 550 °C, the specimen was subjected to a constant load of 32.58 KN by operating the test machine in load control mode. At various time steps, an image of the specimen surface was captured and compared with the image at the previous time step to measure displacement and strain increments between the two time steps. Measured strains in the longitudinal direction of the specimen by the LVDT and the CAOT are compared in Figure 2. Figure 2 shows that the maximum difference between strains measured by the LVDT and the CAOT was 1.9%. It is apparent, therefore that the algorithm that was used in the present study to obtain strains from measured displacements introduced insignificant errors. The above results also show that the non-flatness of the specimen surface was not a hindrance to obtain accurate results.

Figure 2: Strains at 550 °C measured by LVDT and CAOT
4 Conclusions

A full-field and high resolution measuring system based on computer aided optical techniques was developed and successfully applied to measure gross creep strains at high temperatures. The system was based on digital correlation of two images of the speckled specimen surface at two consecutive time points. The paper has demonstrated that this method is a robust technique and can produce sufficiently accurate results.

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References