Moiré Fringe Method for Analysis of Time-Dependent Strain Distribution in Polymer Components

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Abstract

A means to study strain distributions at elevated temperature, in a thermoplastic polymer component in plate form, subject to a complex stress history has been developed. The approach is to employ a tensile creep machine and oven, together with the geometric moiré strain analysis method. A telecentric optical lens system was constructed for generating moiré fringe patterns, with no physical contact between the specimen and reference gratings. Computer-based image analysis was applied to fringe patterns to obtain the full-field strain distribution. Experiments were carried out on plate specimens poly (methyl methacrylate) (PMMA) with a central hole, subject to creep loading at 70°C.

The geometric moiré set-up has proved to be a powerful tool for measuring full-field time-dependent strain distributions on a thermoplastic component at elevated temperature, and for testing FE predictions of strain in such materials.

Keywords: Engineering Polymers, Strain measurement, Moire fringe method, FE analysis

1. Introduction

Glassy engineering polymers are increasingly used as metal replacements especially in the automotive industry, to reduce vehicle weight and thus save energy. In such applications, polymer parts are often required to bear complex histories of non-uniform stress at elevated temperatures. Under these conditions, polymers typically exhibit pronounced nonlinear viscoelastic behaviour, which cannot yet be captured confidently with stress analysis tools such as Finite Element codes. This poses a serious problem in predicting service performance at the design stage.

In the work described here, a means was developed to study strain distributions at elevated temperature, in a thermoplastic polymer component in plate form, subject to a complex stress history. The approach adopted was to employ a custom-built tensile creep machine and oven, together with the geometric moiré strain analysis method. Experiments were carried out on plate specimens of glassy poly(methyl methacrylate) (PMMA) with a central hole, subject to creep loading at 70°C.

The strain measurements can be used for validating predictions obtained from Finite element codes.

2. Background to the geometric moiré fringe method

When two sets of periodic patterns such as equi-spaced parallel lines or arrays of dots are geometrically superimposed, the interference patterns of white and dark bands, so-called geometric moiré fringe patterns, are generated.

The moiré fringe patterns can provide a visual picture of displacements in the specimen over the area of interest. The in-plane geometric moiré patterns can be produced by applying a set of equispaced lines to a flat surface of the specimen to be analysed. This set of lines is called specimen grating. A second set is a stationary reference grating which can be put in contact either physically or optically with the specimen grating. When the specimen is loaded, or moved, moire fringe patterns are generated.

The light-intensity distribution resulting from the geometric interference of two equal opaque and transparent grating is a harmonic series [1].

The fringe order function $N_x(x,y)$ and $N_y(x,y)$ are related to the relative displacement u between the reference and specimen gratings in x direction and relative displacement v in y direction through the following equation.

$$u(x)=pN_x\,,\quad v(y)=pN_y \qquad (1)$$

Where p is the reference grating pitch. Thus the fringe pattern represents a contour map of the displacement component perpendicular to the grating lines.

Sensitivity of the geometric moire fringe method is defined as the smallest displacemen, that can be detected which is determined by the pitch of the specimen grating. The Accuracy of the method is limited by the precision in determing position of a point on a fringe and its order.

3. Measurement of strain distribution

The material studied was cast PMMA (ICI Perspex) in the form of 1 mm thick sheet. Before machining it was normalised at 140°C, to remove any residual molecular orientation or residual stress from the casting process. Specimens were then machined with a waisted shape, with a guage section 30 mm wide and 80 mm long in the loading direction. A hole of diameter of 8 mm was drilled at the centre of the specimen. After cutting of the specimen, a cross grating of 40 lines/mm in each direction was printed on one surface, by means of photoresist lithography. Specimens were annealed at 90

°C and finally aged at 70 °C for 100 hrs, to prevent further physical ageing during the experiment.

A schematic diagram of the experimental set-up is shown in Figure 1. The equipment used for applying tensile loading was a Biaxial Tensile Creep Machine (BTCM). It is capable of applying constant load via application of dead weights to a load pan and counter-balance mechanism. For the experiments discussed here, only one loading axis of the BTCM was used. The machine had a thermostatted oven unit, providing temperature control to ±0.2°C.

The present experiments consisted of tensile creep tests at constant nominal stress σ_n, followed by recovery. A small pre-load of 2.1 MPa was employed. The temperature was 70°C throughout.

Measurement of strain distribution was achieved by employing the geometric moiré fringe method. Moiré fringe patterns were generated optically via an optical bench system built above the BTCM, as shown in Figure 1. The lens system was designed to be telecentric, so that systematic errors due to out-of-plane displacement of the specimen were minimised. The system imaged the specimen grating onto a reference grating with a ruling pattern of 40 lines/mm along one axis. With this lens system, it was also possible to generate an adjustable initial mismatch fringe pattern, as very small magnification of the imaged specimen grating was achieved by slight adjustment of the lenses. The moiré fringe patterns were recorded using a CCD camera and recorded on video tape. The images of fringe patterns were grabbed using a PC frame grabber and digitised in 8 bit grey scale format.

Typical moiré fringe patterns are shown in Figure 2, obtained at different times during creep under constant tensile load at 70°C, and during recovery after load removal. The intensity profiles from the moiré patterns were obtained using the image analysis software package Optimas. For each image, the data of intensity and co-ordinate of sampling points along straight lines in the area of interest were extracted and imported into an ASCII text file. The position of a peak or a trough was defined as the point where the gradient of its intensity profile was zero. Peak and trough positions gave displacement data points at positions separated by half a fringe order.

For the case of small displacement gradients encountered in the present work ($\varepsilon < 0.03$ with negligible rigid body rotation), strain ε_{xx} could be determined by differentiation of x-wise displacement u with respect to x. For a given y co-ordinate therefore, the displacement profile was fitted piecewise to a cubic function u(x), and the derivative ε_{xx} determined analytically.

A series of FORTRAN programs were written to perform the task from finding the position of peaks and trough, converting intensity into displacement profile and then calculate the strain profile.

4. Results and discussions

The results of displacement and strain contour plot represented here are at the selected rectangular region on the specimen as drawn with dash line in Figure 2c).

Figure 3a) and Figure 3b) show the deduced strain contour during creep at time 1 min and 60 min. The strain re-distribution with creep time can be clearly seen from these figures. As creep time increased, the region of high strain concentration was seen enlarging and the magnitude of the maximum strain was increasing. The maximum creep strain at 60 min was found to be in the region of 2.2 x 10^{-2}. The deduced strain field after removal of nominal creep stress σ_n for 1 min and 60 min are shown in Figure 3c) and Figure 3d) respectively. It can be seen that, shortly after the stress σ_n was removed, the residual strain was seen concentrated around the region near the pole of the hole. At 1 min after stress removal, the highest residual strain was found to be in region of 4 x 10^{-3}. After 60 min after the removal of applied load, small trace of residual strain was still present near the pole of the hole.

For the purpose of illustrating the effectiveness of moiré method as a tool for FE analysis validation, a finite element analysis with a linear viscoelastic model [2] was used to simulate the experiments of tensile creep on a plate specimen with a central hole. The results of strain obtained from the FE simulations were compared with strain data measured experimentally by moiré method at different times during creep. The strain distribution of ε_{xx} along the y axis, at x = 0.0 during creep obtained from the moiré and FE analysis are plotted together in Figure 4.

From the figures above it can be seen that the linear-viscoelastic FE analysis much under predicts the stain ε_{xx} along, the y-axis at x = 0.0 in the region near to the hole edge, for the whole creep period, and that the differences increase as the creep progresses.

5. Conclusion

In conclusion, the geometric moire set-up has proved to be a powerful tool for measuring full-field time-dependent strain distributions on a thermoplastic component at elevated temperature, and for testing FE predictions of strain in such materials.

To within experimental scatter, this validation exercise showed that the FE analysis with a linear viscoelastic model failed to give good predictions of the strain-field during creep. Thus, for more accurate predictions, a FE analysis with an appropriate non-linear viscoelastic model is necessary [2].

References

[1] Sciammarella, C. A., Experimental Mechanics, 418-431,1982

[2] Chaikittiratana, A., Nonlinear viscoelastic strain analysis for engineering polymers, D.Phil. thesis, University of Oxford, 2000.

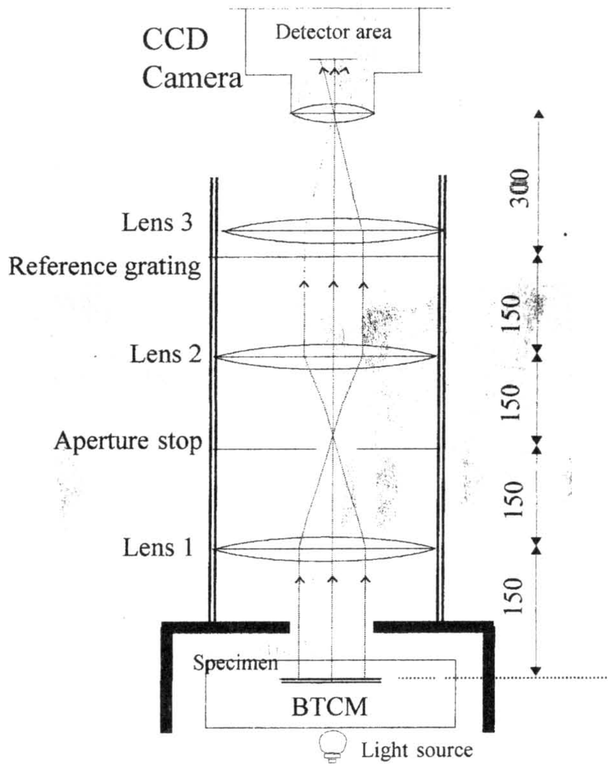


Figure 1 The experimental set up (dimensions are given in mm)

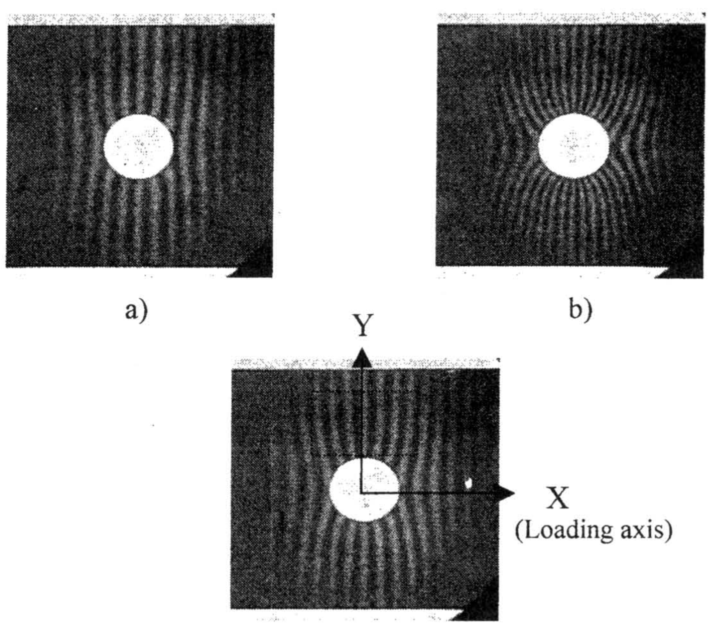
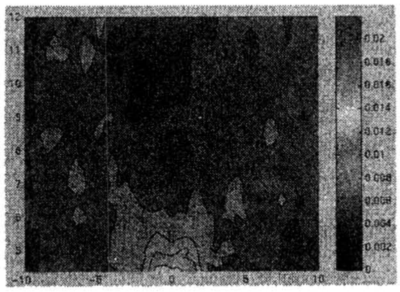
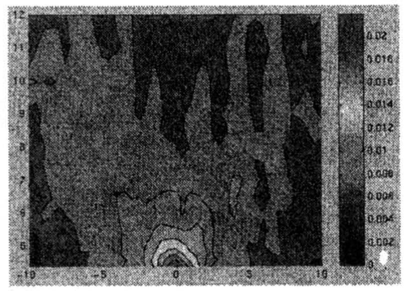


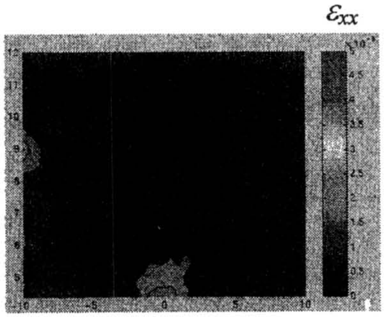
Figure 2 Moiré fringes during creep and recovery at 70°C: **a)** with pre-load; initial fringe pattern resulted from the effects of optical mismatch, thermal expansion and pre-load. **b)** After applying nominal stress $\sigma = 11.9$ MPa for 60 min. **c)** After removal of stress for 1 min.



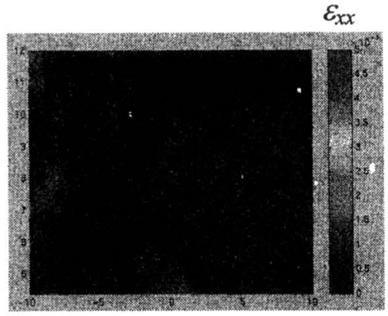
a) after applying load for 1 min



b) after applying load for 60 min



c) after load removal for 1 min



d) after load removal for 60 min

Figure 3 Deduced strain contour at different times during the creep and recovery

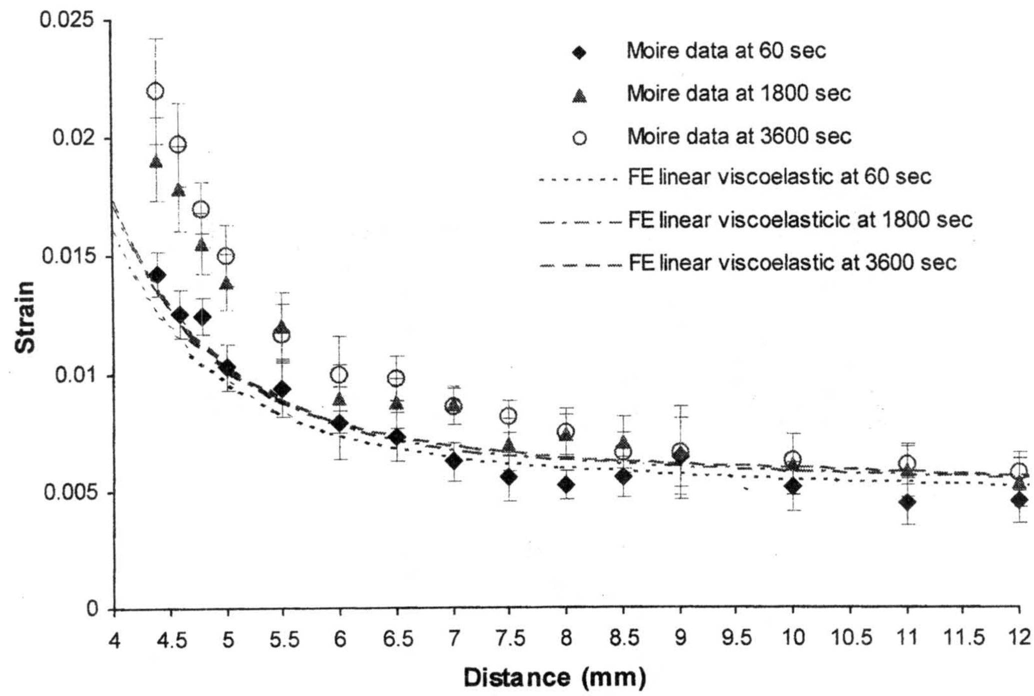


Figure 4 Comparison of distribution of strain ε_{xx} as measured from moiré method and as computed by FE analysis at different times (with linear viscoelastic model) during creep along distance y at x = 0.0 for the case of σ_n=11.93 Mpa