

A DEVELOPED FULL-FIELD FEM ANALYSIS COMBINED WITH ESPI FOR THE INVESTIGATION OF DEFECT EVOLUTION IN POLYMER FILMS*

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Abstract A full-field finite element method (FEM) analysis combined with electronic speckle pattern interferometry (ESPI) measurement was developed to investigate defect evolution in polymer films. Different from the previous reports, which only compare the ESPI experimental and FEM simulated results at several points or lines, herein the full-field FEM results were exported, subtracted with a continuous distribution. By choosing proper parameters and number of substeps, the simulated and experimental results showed excellent correspondence. Furthermore, the displacement fields vertical to the tensional direction were also presented, and the strain field was preliminarily evaluated. The current method of combination of ESPI and FEM allows for capturing the experimental fringe maps to validate and optimize FEM results simulated, and would give a higher security to structural and mechanical analysis of polymeric materials.

Keywords: Electronic speckle pattern interferometry; Finite element method; Defect; In-plane displacement; Polymer film.

INTRODUCTION

Many service failures of structural or mechanical components start from small defects^[1, 2], which are formed inevitably during fabrication such as injecting, stamping or casting. These weak positions readily arouse strain concentration, microcracks and even bring out great disaster. Therefore, to detect and understand the strain field around defects in materials under various conditions is of great importance.

Finite element method (FEM), as a convenient and comprehensive full-field analysis technique, has shown great potential in defect analysis^[3–5]. The accuracy of numerical results by FEM software tightly depends on the model, boundary condition, loading process and proper parameters^[6], and improper analysis always leads to deviated results. On the other hand, some optical interferometric techniques, such as double-exposure holographic interferometry^[7, 8], grating interferometry^[9], moiré interferometry^[10, 11] and electronic speckle pattern interferometry (ESPI)^[12–18] are also used for experimental analysis of defects in materials. In particular, with the advent of inexpensive lasers, digital recording and computing facilities, real-time image preprocess system, ESPI attracts more attention. Nevertheless ESPI is complex and much information cannot be adequately addressed, such as displacement in three dimensions at one time^[19]. Accordingly, some researches proposed to combine ESPI and FEM to let ESPI offer theoretically good opportunity to validate FEM. Lamberiti and co-leaguers^[20] demonstrated the proportional comparability between ESPI and FEM results by artificially enlarging the load. Zhang *et al.*^[21] presented a three dimensional digital speckle pattern interferometry (3D-DSPI) system

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for strain analysis and compared the measured and the simulated FEM analysis data at different points. Lee *et al.*^[22] applied ESPI to evaluate the thermal deformation in a flip-chip package and further verified the measurements along several joint points. Furthermore, some other works compared experimental and FEM results through extracting several data along some lines^[23–27]. However, these studies failed to reflect the full-field and one-by-one comparison continuously.

In this paper, we demonstrated a developed FEM analysis matched with ESPI observation mode to monitor defect evolution in polymer films. ESPI collected displacement fringe maps of polyethylene (PE) film during uniaxial tensile test. Meanwhile, an FEM was developed and the list results were exported, subtracted with a continuous full-field distribution. By choosing proper parameters and the number of substeps, the simulated and experimental results showed excellent consistencies. It also suggests that, the combined ESPI observation and FEM will give a higher security to structural and mechanical analysis. Furthermore, the displacement fields vertical to the tensional direction were also presented, and the strain field was preliminarily evaluated.

EXPERIMENTAL

Experimental Setup and Basic Principle

As referred in many works^[28–30], the experimental setup constructed is shown in Fig. 1. The laser beam is divided into two beams by a beam splitter and towards the specimen symmetrically. The sample is mounted on the uniaxial tensile machine and Charge Coupled Device (CCD) as image recording system is located facing the positive direction of the sample. When the object is subjected to a tensile test, the speckle fields were influenced.

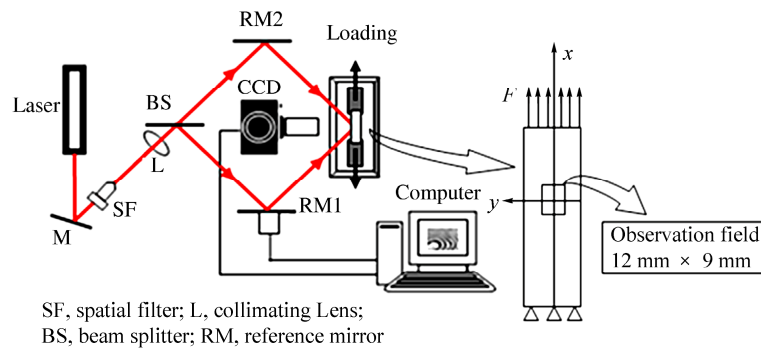


Fig. 1 Schematic diagram of the optical setup: beam splitter (BS), spatial filter (SF), mirror (M), loading cell (LC)
Sketch of the specimen, with a load size of 50 mm × 20 mm and thickness of 50 μm; The observation field has a size of 12 mm × 9 mm in the center of sample.

The subtraction between the deformed and predetermined reference images will generate fringe pattern as record intensity of speckle pattern:

$$I(x, y) = |I_{\text{def}} - I_{\text{ref}}| = 4\sqrt{I_A I_B} \left| \sin \frac{1}{2} (2\psi + \phi) \sin \left(\frac{\phi}{2} \right) \right| \quad (1)$$

where I_{ref} and I_{def} are the scattered intensities associated with the predetermined reference and deformed state, the amplitudes of which are I_A and I_B , respectively, ψ is a composite phase angle incorporated a random speckle phase term, ϕ as an important parameter denotes the relative phase change between the two speckle patterns, the term of $\sin(\phi/2)$ modulates the signals between the maximum and minimum values and gives the light and dark fringes. Thus, the phase change ϕ , which is induced by the micro-deformation u , can be expressed by:

$$\frac{\phi}{2\pi} = \frac{2\Delta u \sin \theta}{\lambda} = n \quad (2)$$

where λ is the wavelength of the laser, θ is the incident angle symmetrically^[31, 32], and n is the fringe number for the intensity of speckle fringe images indicating the magnitude of displacement^[33]. In our optical system, λ of 632.8 nm and θ of 45° are used, so the sensitivity is up to 0.448 μm per fringe.

Test Specimen and Performance

The samples were cut from commercially available PE films (Shanghai Huanmao Man. & Trading Co., LTD). PE film with a thickness of about 50 μm was clamped to loading cell and the loading size was 50 mm $\times$ 20 mm. The PE films were punctured by a needle to factitiously form a hole with a diameter of about 0.6 mm. Samples with four different defect patterns were tested. If we situated the origin of coordinates in the centre of the sample and the x axis was along the pulling direction, the defects were located at the coordinate points of (0, 0) for the single defect pattern, (−2.0, 0), (2.0, 0) for the two defects pattern, (−2.0, −1.15), (2.0, −1.15), (0, 2.3) for the three defects pattern and (−2.0, −2.0), (−2.0, 2.0), (2.0, −2.0), (2.0, 2.0) for the four defects pattern, respectively. All the coordinate values given above were in millimeters. When the tensile testing machine ran at a velocity of 0.01 mm/min, the random speckle images recorded by CCD were processed and displayed on computer lively. Software was developed with MATLAB for the acquisition, subtraction, and display of the interference phase. Median filter and contrast enhancement were applied to give clear images.

ESPI of Single Defect

Our analysis started from the pattern with a single defect to compare with the common hole drilling technique^[34]. When the polymer film with hole was subjected to a uniaxial pulling gradually and continuously, the fringes around the hole were not semi-circular arc type symmetrically as previously reported^[14–17], but the vertical fringes were distorted towards the through hole. Figure 3 displays the evolution of displacement contour map with sensitivity vector along pulling direction at sequential subtraction mode. It can be seen that as the tensile stress increases from 0.275 MPa to 0.295 MPa, the fringe number increases and most fringes converge towards the defect.

FEM SIMULATION

Procedure of Developed FEM

The flowchart of combined FEM analysis and ESPI observation is shown in Fig. 2. The left hand of Fig. 2 shows the ESPI measurement process, and the right hand is its corresponding FEM simulation. The commercial FEM software Ansys 10.0 was employed to simulate the tension process. The procedure is as follows:

- (a) Each pair of loading forces at ESPI subtracted instance was recorded carefully.
- (b) The tension process is simulated at the same loading condition.

Here, the 2-D 6-node triangular plane stress elements (PLANE2) were used and the very fine mesh was performed especially around the hole. Moreover, every step is divided into 100 substeps. It was crucial to set proper load step and its substeps in order to relevant with the tensional test at a very low velocity.

- (c) The displacement and coordinate values were exported for subtraction. As noted, the exported lists at different loading substeps are random. We must rank the lists, and subtract the z values at the same x , y coordinate values.

- (d) The nodes in a measured field of 12 mm $\times$ 9 mm are extracted, and converted the displacement to matrix with Kriging calculation^[35]. Kriging is an optimal prediction method designed for geophysical variables with a continuous distribution. Here, the gridding method is based on the correlation. The displacement is interpolated to 200 columns by 200 rows. The search radius is 2.0 and smoothness is 0.5. To simplify this step, we also can convert the subtracted displacement volume to matrix with Origin software 6.1.

- (e) The calculated gridding matrixes are illustrated as contour map with Matlab software. For comparison with the ESPI pattern distinctly, we set the contour interval of neighbored dark fringes and light fringes to be 0.224 μm , and the gray value of background, dark line and light line to be 110, 0 and 225, respectively.

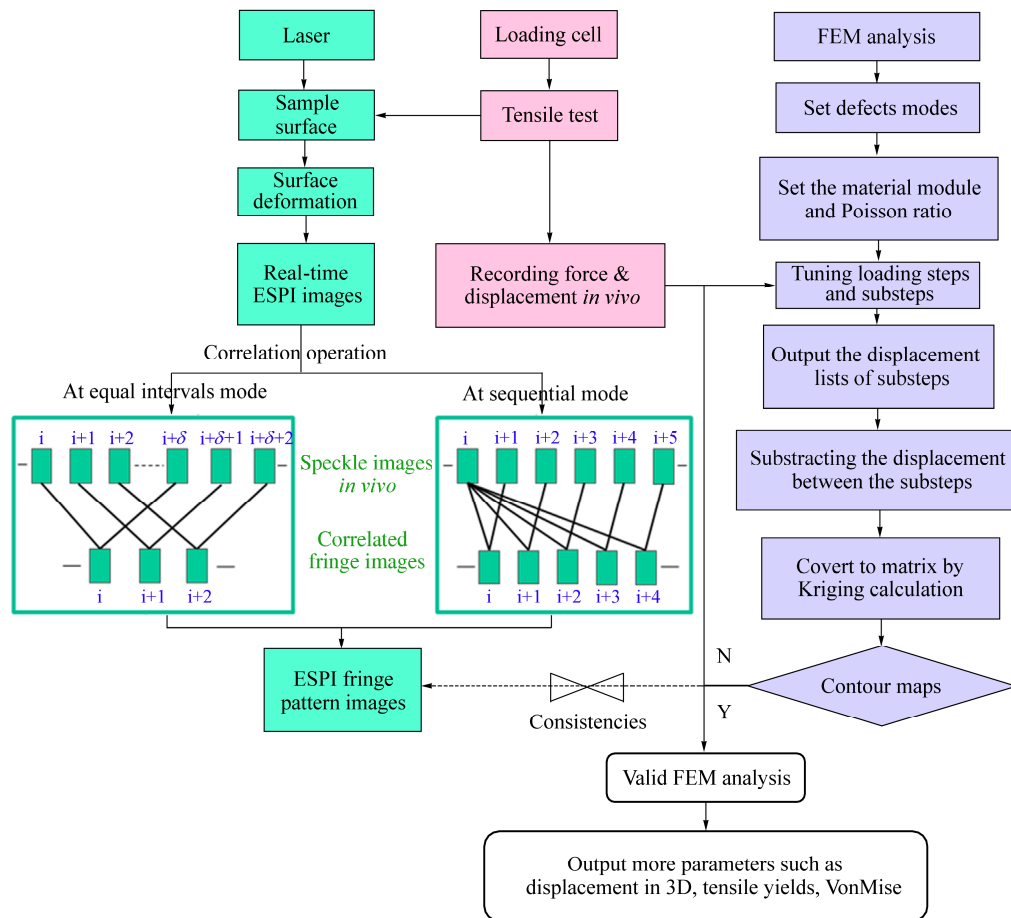


Fig. 2 Flowchart of the developed full-field FEM analysis matched with ESPI for investigation of defect evolution on polymer films

FEM Displacement Field of Defects

Figure 3 shows the contrastive displacement evolution of contour map experimentally (Fig. 3a) and numerically (Fig. 3b). It is seen the experimental and simulated results show excellent agreement. Every fringe accords well in the one-to-one corresponding location. To further illustrate quantitatively, Fig. 4 plots the profile along a parallel line at y position of +2 mm. Here, we set the zero point calibration at the left edge of observation field to show better contrast. Clearly, the experimental fringe values and the analytical solution are nearly superposed each other. As the loading pressure gradually evolved from 0.275 MPa to 0.295 MPa, the relative displacement in the observation length of 12 mm went up to about 3.8 μm .

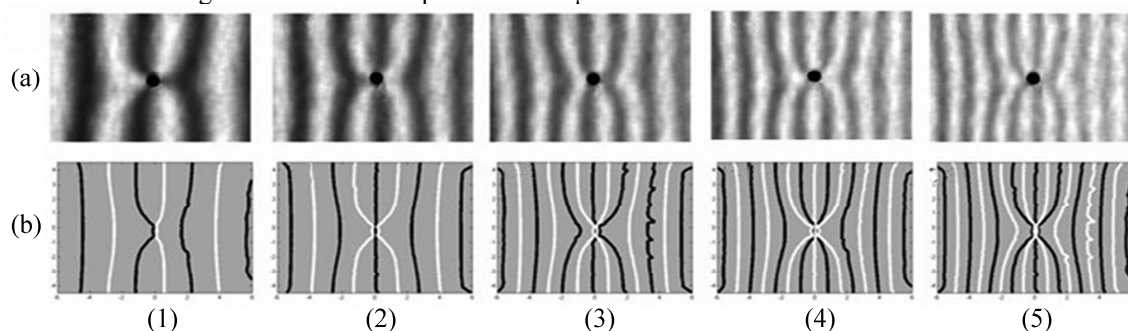


Fig. 3 (a) ESPI observation and (b) FEM simulation of the evolution of single defect displacement contour maps at sequential mode in the uniaxial loading process

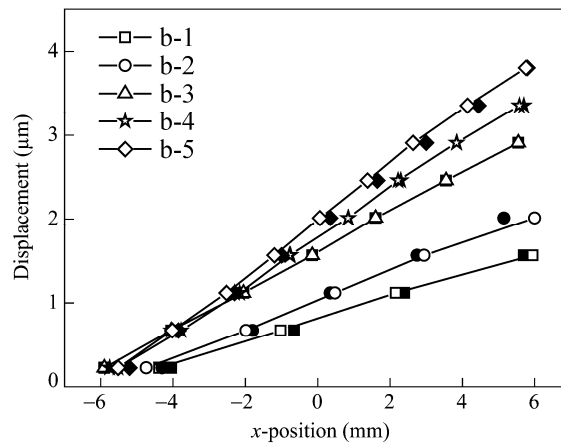


Fig. 4 Plot of the displacement comparison along line at $y = +2$ mm in Fig. 3
b-1–b-5 are corresponding to b-1–b-5 in Fig. 3; Solid and open symbols denote the ESPI results and FEM simulation, respectively.

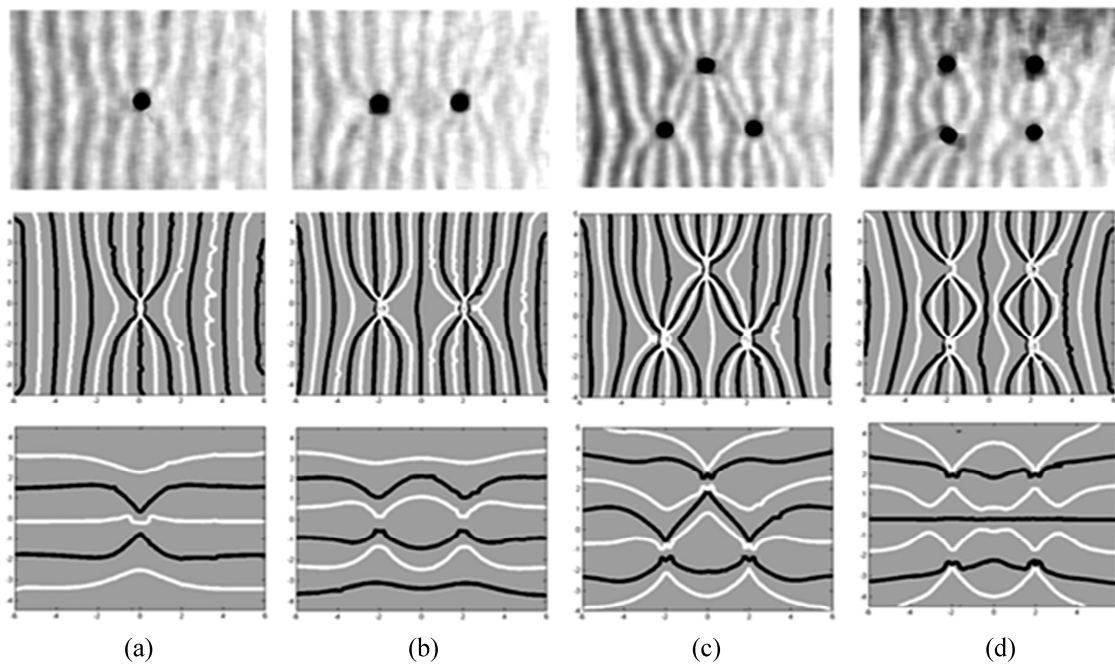


Fig. 5 Experimental (first row) and simulated (second row) speckle pattern displacement contour of PE films with single (a), double (b), three (c) and four (d) defects
The third row is the y displacement contour calculated from FEM analysis.

To verify this method further, we also demonstrated the experimental and FEM analysis of samples with two, three and four defects under loading. Figure 5 displays the speckle images of PE films with single (Fig. 5a), two (Fig. 5b), three (Fig. 5c) and four (Fig. 5d) holes undergoing uniaxial tensile tests. The corresponding simulated FEM contour maps are also given in the second row of Fig. 5. All the FEM analysis employed the same multilinear isotropic parameters and substeps due to the same material property. Obviously, the simulated results are consistent with the experimental results. It indicates that the combination of ESPI observation and FEM is a feasible approach to investigate the defect evolution in structural and mechanical field.

Methodological Exploitation and Discussion

Thanks to the valid and comprehensive FEM results, some other information can be obtained easily, such as y displacement field, strain contour and vector field. The third row of Fig. 5 shows the y displacement field. Since the deformation at the y direction is mainly from the shrinkage of sample, it is only about one third of that at the x displacement.

In respect of the in-plane strains, they are generally determined by differentiating operation at each point of the measured area:

$$\varepsilon_x = \frac{\partial u}{\partial x} \quad (3)$$

where ε_x is the strain along the x -direction. Figure 6 displays the strain induced by the deformation over some parallel lines of $y = 0.5$ mm (solid line), 1.0 mm (dash line), 2.0 mm (dot line) and 3.0 mm (dash dot line) for samples of single (Fig. 6a) and two defects (Fig. 6b). It can be seen the strain ε_x of single defect sample has only one peak value, and that of the two defects one has two peak values. As the Eq. (3) implies, the denser the fringes, the larger the strain values. The larger the strains occur as the locations are closer to the defect center.

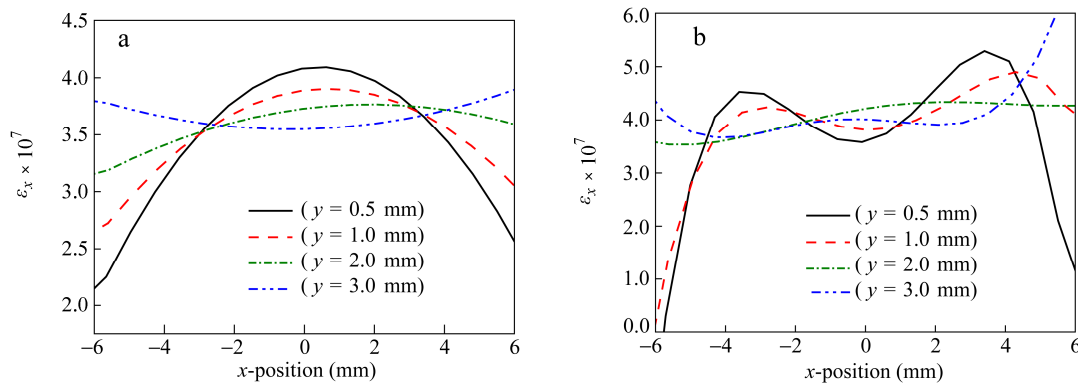


Fig. 6 Strain ε_x of (a) single and (b) double defects samples induced by the deformation over lines of $y = 0.5$ mm (solid line), 1.0 mm (dash line), 2.0 mm (dash dot line) and 3.0 mm (dash dot dot line) parallel to the x -coordinate

Till now, the method has been demonstrated well, but there are some points should be noted. When the sample was elongated too much and many properties had changed gradually, such as the Young's modulus and the Poisson's ratio, the developed FEM analysis may not suit to follow the experimental results. Besides, the use of this method is still at an immature stage. In future work, the unwrapping technique should be refined. It would include more appropriate constitutive relation to make the results more unsuspected. Anyway, the combination of ESPI and FEM analysis is an available method. It provides a good guidance to improve the present FEM analysis software and verify the analysis results.

CONCLUSIONS

A method of combined ESPI observation and FEM analyze is proposed to analyze the surface deformation. An application of this method is demonstrated on monitoring the evolution of defect displacements in polymer films. The ESPI has the advantages of full-field and non-contacting, while the developed FEM gives a one-to-one corresponding displacement distribution directly. For the different defect patterns, the fringe speckle images and simulated results show excellent consistency. Indeed, other information can also be obtained from the powerful software. The current method not only provides a continuous full-field displacement measurement, but also can be used to calibrate and improve FEM analysis models and further guide the design of structural and mechanical components.

REFERENCES

- 1 Tan, H.G., Wang, Z.Y., Zhu, W.F., Song, Q.G., Li, H. and Bai, C.Q., Chinese J. Polym. Sci., 2008, 26(6): 759
- 2 Huo, D.X., Yuan, X.H., Liu, D.Z., Zhang, L. and Wang, F., Chinese J. Polym. Sci., 2008, 26(1): 39
- 3 Huang, P., Zhang, G.X., Wu, Z.T., Cai, J.H. and Zhou, Z.K., NDT&E Int., 2006, 39: 578
- 4 Arman, Y., Zor, M. and Aksoy, S., Compos. Sci. Technol., 2006, 66: 2945
- 5 Li, H.Z., Jia, Y.X., Mantimin, G., Jiang, W. and An, L.J., J. Appl. Polym. Sci., 2007, 103: 64
- 6 Ghiglia, D.C. and Pritt, M.D., "Two-dimensional phase unwrapping: theory, algorithms, and software", Wiley, New York, 1998
- 7 Nelson, D.V. and McCrickerd, J.T., Exp. Mech., 1986, 26: 371
- 8 Lin, S.T., Hsieh, C.T. and Lee, C.K., Proc. SPIE, 1995, 2577: 226
- 9 Joh, D., Byun, K.J. and Ha, J., Exp. Mech., 1994, 35: 70
- 10 Nicoletto, G., Exp. Mech., 1991, 31: 252
- 11 Wu, Z., Lu, J.A. and Han, B.T., J. Appl. Mech-T. Asme., 1998, 65: 837
- 12 Shareef, S. and Schmitt, D.R., Opt. Laser. Eng., 2004, 42: 511
- 13 Albertazzi, A., Kanda, C., Borges, M.R. and Hrebabetsky, F., Proc. SPIE, 2000, 4101: 77
- 14 Pisarev, V.S., Bondarenko, M.M., Chernov, A.V. and Vinogradova, A.N., Int. J. Mech. Sci., 2005, 47: 1350
- 15 Focht, G. and Schiffner, K., Exp. Mech., 2003, 43: 97
- 16 Diaz, F., Kaufmann, G.H. and Galizzi, G.E., Opt. Laser. Eng., 2000, 33: 39
- 17 Zhang, J.B., Opt. Eng., 1998, 37: 2402
- 18 Rivera, J.L.V., Monteiro, J.M., Lopes, H.M., Vaz, M.A. P., Palacios, F., Goncalves, E., del Pino, G.G. and Perez, J.R., Opt. Laser. Eng., 2009, 47: 1139
- 19 Huang, M.J., Liu, Z.C. and Jhang, J.H., Opt. Laser. Eng., 2002, 38: 245
- 20 Genovese, K., Lamberti, L. and Pappalettere, C., Opt. Laser. Eng., 2004, 42: 543
- 21 Zhang, J. and Chong, T.C., Appl. Opt., 1998, 37: 6707
- 22 Lee, B.W., Jang, W., Kim, D.W., Jeong, J., Nah, J.W., Paik, K.W. and Kwon, D., Mat. Sci. Eng. A-Struct., 2004, 380: 231
- 23 Min, Y., Hong, M., Xi, Z. and Jian, L., Opt. Laser. Eng., 2006, 44: 68
- 24 Gonzalez-Pena, R., de Anda, R., Pino-Velazquez, A.J., Soler-de la Cruz, J. and Gonzalez-Jorge, Y., Opt. Laser. Eng., 2000, 34: 75
- 25 Hack, E. and Schumacher, A., Strain, 2007, 43: 235
- 26 Sretenovic, A., Muller, U. and Gindl, W., Compos. Part A-Appl. S, 2006, 37: 1406
- 27 Toubal, L., Karama, M. and Lorrain, B., Compos. Struct., 2005, 68: 31
- 28 Kim, D.W., Lee, N.K., Na, K.H. and Kwon, D., Opt. Laser. Eng., 2005, 43: 221
- 29 Guelorget, B., Francois, M., Vial-Edwards, C., Montay, G., Daniel, L. and Lu, J., Mat. Sci. Eng. A-Struct., 2006, 415: 234
- 30 Cordero, R.R. and Labbe, F., J. Phys. D. Appl. Phys., 2006, 39: 2419
- 31 Fletcher, M.J., Insight, 1996, 38: 270
- 32 Moore, A.J. and Tyrer, J.R., Opt. Laser. Eng., 1996, 24: 381
- 33 Li, X.D., Wei, C. and Yang, Y., Opt. Laser. Eng., 2005, 43: 869
- 34 Schajer, G.S. and Tootoonian, M., Exp. Mech., 1997, 37: 299
- 35 Davis, J.C., "Statistics and data analysis in geology", John Wiley & Sons, New York, 1988