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Test Method

Measurement of coefficient of thermal expansion of films using digital image correlation method

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ABSTRACT

Applications of the digital image correlation method (DIC) for the determination the coefficient of thermal expansion (CTE) of films is investigated in this paper. A heating chamber was designed for applying thermal load and DIC provides the full-field thermal deformation fields of the test film sample due to temperature changes. The average normal strains in the x and y direction from the region of interest are then extracted for the determination of CTE. The influence of unavoidable small rigid body rotation is discussed and a method to eliminate it to show the pure thermal expansion of the test film is demonstrated. For validation, the CTE of a pure copper sample is determined and compared with the textbook value, confirming the effectiveness and accuracy of the proposed technique. Finally, the CTE of Polyimide (PI) composite film in the temperature range of 20–140 °C is measured. The results reveal that the DIC is a practical and effective tool for full-field thermal deformation and CTE measurement of films.

1. Introduction

Thin films have widespread applications in microelectronics and micro-electro mechanical systems (MEMS). For instance, due to their low thermal conductivity and high breakdown voltage, polymer films are often used as thermal and electrical insulating materials in MEMS. However, the higher coefficient of thermal expansion (CTE) of organic polymer films compared with that of the insulated substrates (e.g., ceramics or metals) will cause thermal stress build-up and result in device failure through peeling and cracking at the interface between the film and substrate. Therefore, to ensure the reliability of the device, accurate measurement of CTE of films is of great importance.

Conventional techniques, such as thermal-mechanical analysis, strain gauges and quartz tube dilatometer techniques are suitable only for bulk materials. The CCD imaging technique proposed by Wang et al. [1] can extract the average thermal expansion strain between the two edges of the film sample. Correspondingly, it can only be utilized to determine the CTE of isotropic film materials [2]. Full-field optical techniques, such as phase-shifting interferometry [3] and Electronic Speckle Pattern Interferometry (ESPI) [4] have been proposed to determine the whole field thermal expansion of thin film under thermal loading. Since full-field thermo-mechanical behavior of the test sample can be obtained with these techniques, therefore, they can be used to characterize the thermal expansion of both isotropic and anisotropic film materials. For example, tests conducted by Dudescu et al. [4] successfully determined the CTEs of unidirectional and bidirectional carbon fiber laminates using phase-shifting ESPI. Although these interferometric optical techniques greatly improve the accuracy of thermal deformation measurement, they also have some limitations. For instance, these techniques generally have strict requirements on the experimental environment, such as vibration isolation, and the

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experimental set-up and procedure are also complicated and cumbersome. Moreover, subsequent fringe pattern analysis technique (e.g., phase unwrapping) is required to extract the thermal expansion from the obtained fringe patterns, which further increases the complexity of measurement.

In this paper, an alternative simpler yet effective technique for non-contact full-field deformation measurement, namely, the digital image correlation (DIC) technique [5–8] is proposed to determine the thermal expansion as well as the CTE of films. Compared with the above-mentioned interferometric optical techniques for thermal deformation measurement, DIC offers the following advantages: 1) simple experimental set-up and specimen preparation, 2) low environmental vulnerability, 3) flexible measurement sensitivity and adjustable spatial resolution, 4) easy and automatic data processing. DIC has been established as a practical and effective deformation measurement technique and acquired widespread applications. For example, DIC has been used to determine the mechanical properties of low dimensional materials (e.g., fibers and films) [9] as well as the deformation of polymer materials [10]. However, to the author's knowledge, measurement of the CTE of films using DIC method has not been reported.

In this paper, the following work to measure the full-field thermal deformation of test film sample associated with temperature change is reported. A heating chamber (i.e., elevated temperature oven) was fabricated and employed to exert thermal loading for the test film sample. Digital images of the film sample at different temperature were recorded and processed by the DIC method to obtain the in-plane displacement fields associated with temperature increase. The CTEs in x and y directions were then computed based on the average thermal strains extracted from the thermal deformation fields using a simple linear plane fitting algorithm. Some key issues, such as the effect of small rigid body rotation accompanying thermal expansion of the test sample on the displacement fields, is addressed. In order to verify the feasibility and effectiveness of the proposed technique, the CTE of pure copper specimen was measured and compared with the recommended data given by a Thermal Properties Research Center (TPRC) handbook [11]. The good agreement clearly demonstrates the validity and accuracy of the proposed technique, confirming the DIC method can be used for thermal deformation measurement for films. As an application example, the CTEs of PI/SiO_2 composite films were determined in the temperature range of 20–140 °C.

2. Measurement of CTE by DIC

2.1. Digital image correlation method

DIC directly provides full-field in-plane deformation fields of the test planar specimen surface by comparing the digital images of the specimen surface acquired before and after deformation. The basic principle of DIC is schematically illustrated in Fig. 1. A square reference subset of $(2M+1)\times(2M+1)$ pixels centered at the current point $P(x_0, y_0)$ from the reference image is chosen and used to find its corresponding location in the deformed image. Once the location of the target subset in the deformed image is found, the displacement components of the reference and target subset centers can be determined. In practical implementation of DIC, a region of interest (ROI) in the reference image is specified first and divided into evenly spaced virtual grids. The displacements are computed at each point of the virtual grids to obtain the full-field deformation.

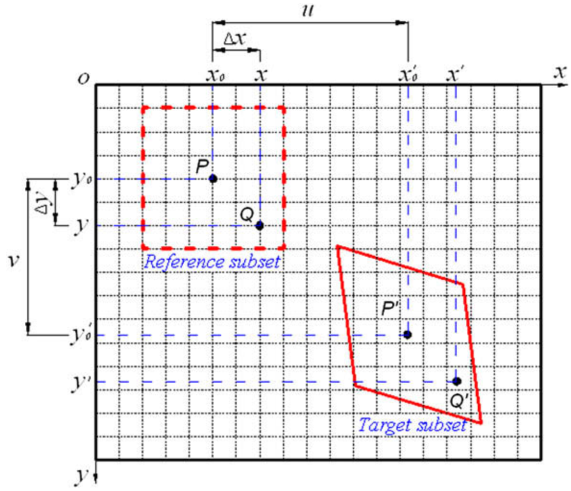

Fig. 1. Schematic figure of reference square subset of reference image and target (or deformed) subset of the deformed image, the differences of positions of the reference subset center and target subset center yield in-plane displacement components u and v.

To obtain accurate estimation for the displacement components of the same point in the reference and deformed images, the following Zero-Normalized Sum of Squared Differences (ZNSSD) correlation criteria [7], which is insensitive to the scale and offset of illumination lighting fluctuations, is utilized to evaluate the similarity in reference and target subsets:

$$C_{f,g}(p) = \sum_{x=-M}^{M}\sum_{y=-M}^{M}\left[\frac{f(x,y)-f_m}{\sqrt{\sum_{x=-M}^{M}\sum_{y=-M}^{M}[f(x,y)-f_m]^2}} - \frac{g(x',y')-g_m}{\sqrt{\sum_{x=-M}^{M}\sum_{y=-M}^{M}[g(x',y')-g_m]^2}}\right]^2 \tag{1}$$

where $f(x, y)$ is the gray level intensity at coordinates (x, y) in the reference subset of the reference image and $g(x', y')$ is the gray level intensity at coordinates (x', y') in the target subsets of the deformed image, $f_m = (1/(2M+1)^2)\sum_{x=-M}^{M}\sum_{y=-M}^{M}[f(x,y)]$ and $g_m = (1/(2M+1)^2)\sum_{x=-M}^{M}\sum_{y=-M}^{M}[g(x',y')]$ are the mean intensity values of reference and target subsets, respectively. $p = (u, u_x, u_y, v, v_x, v_y)^T$ denotes the desired vector with respect to six mapping parameters.