Measurement of the Hygroscopic Swelling Coefficient of Thin Film Polymers Used in Semiconductor Packaging

Changsoo Jang, Samson Yoon, and Bongtae Han

***Abstract*—An advanced method based on the digital image correlation technique is implemented for characterization of hygroscopic swelling of thin film polymers. The accuracy of the proposed method is experimentally validated through a comparison with the well-established Moiré interferometry technique. It is applied to various thin film polymers, including polyimide, solder resist, anisotropic conductive film, and thin woven glass/resin composite. The magnitude of hygroscopic swelling coefficients ranges from 0.067 to 0.25 %strain/%wt for those films. A practical guideline for specimen preparation and experimental setup is provided for proper implementation of the proposed method.**

***Index Terms*—Digital image correlation, hygroscopic swelling coefficient, thin film polymer.**

I. Introduction

THIS PAPER presents a continuation of the previous work [1] in an effort to measure accurately the hygroscopic swelling of polymers used in semiconductor packaging. In the preceding work, the Moiré interferometry (MI) technique was introduced as an effective tool for achieving a high level of accuracy in hygroscopic swelling measurement [2] because of its ability to cope with the limitations of existing point-measurement methods [3]–[7]. It has been successfully implemented to determine the coefficient of hygroscopic swelling (CHS) of epoxy molding compounds and to measure moisture-induced strains in a semiconductor package [1].

In spite of its excellent accuracy and repeatability, however, the MI technique has an inherent limitation when applied to a thin film specimen. A grating layer with a finite thickness (approximately $10\,\mu$m in general) can reinforce a thin specimen. Although it does not affect the behavior of a thick specimen significantly, the epoxy grating layer may change the characteristic of a thin film specimen, thus resulting in a measurement error.

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There are several polymeric thin films used in semiconductor packaging. They include solder resist, woven glass/resin cores (in a thin printed circuit board for mobile applications), dielectric resins, and polyimide tape. They are characterized in a film form using techniques and devices dedicated to thin film applications for a few reasons: a thick specimen is neither available (polyimide) nor possible to fabricate (ultraviolet-cured solder resist), and the material properties can be changed substantially when fabricated in a thick shape (woven glass/resin cores).

An indirect method that measures swelling-induced bending of the polymer film/silicon substrate by utilizing Michelson interferometry [4] is the only available technique to determine the CHS of thin film polymer. Besides its complex specimen preparation and measurement procedure, however, this method has inherent limitations due to the indirect and point-measurement nature of the method [2].

Although they are required for accurate evaluation of hygroscopic stresses developed in semiconductor packages, the CHS data of polymer films are extremely rare due to the absence of feasible techniques. To the best of the authors' knowledge, the CHS of polyimide films as determined through the indirect method [4] is the only published data. The ever-increasing use of thin film polymers in packages warrants an advanced technique for accurate measurement of hygroscopic swelling. This need of the measurement method and the lack of measurement data are the motivation of the paper.

The digital image correlation (DIC) technique [8] is a well-established technique that provides full-field displacements of a specimen as does the MI technique. When applied to a thin film, the DIC technique has a substantial advantage over the MI: it does not need a grating layer. Instead, a random pattern is used for the correlation of two images before and after deformation. Isolated speckles in the random pattern have a far lesser reinforcing effect than the grating layer used in MI.

The objectives of this paper are: 1) to present an experimental procedure to measure the swelling coefficient of thin films using the DIC technique, and 2) to report the hygroscopic swelling coefficients of thin films. Challenges are addressed and a suitable measurement procedure is proposed. The accuracy of the proposed method is validated with MI through a hygroscopic swelling measurement of thick specimens. The proposed method is further applied to various

thin film polymers used in semiconductor packaging, and their CHS values are provided.

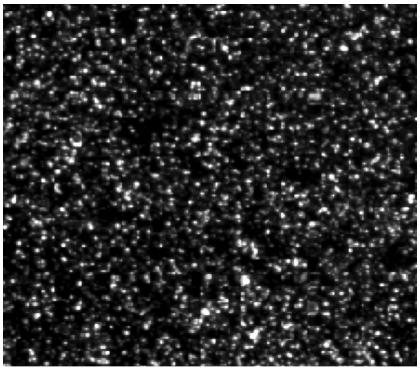
II. Experimentation

A. Specimen Preparation

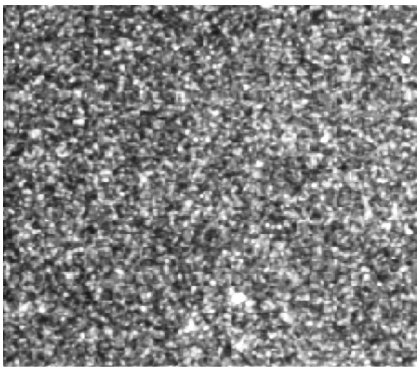
Various packaging thin film polymers were characterized in this paper. They include polyimide (PI) tape (t = 125 μm), photo-sensitive solder resist (PSR) (t = 40 μm), anisotropic conductive film (ACF) (t = 50 μm), and woven glass/resin core for printed circuit boards (t = 150 μm). Epoxy molding compound (EMC) materials (t = 1.7 mm) were also characterized for the purpose of a comparison between the DIC-based method and the MI-based method.

The speckles required for DIC analysis were generated by spraying white or black paint on one side of a specimen that has been cleaned with ethanol. After the paint has dried, the painted surface is wiped off with soft tissue to get rid of paint dots with weak adhesion to the surface, thus preventing errors caused by falling-off and/or migration of those loose dots during the measurement process.

Although isolated speckles have a much lesser reinforcing effect than a layer of epoxy grating does when used in MI, they may affect the accuracy substantially if their volume fraction is excessive. The paint should be cautiously applied to the specimen in such a way that the thickness and density of the spray speckles are minimized while providing good correlation in the DIC analysis. One way to attain a good speckle pattern would be to spray paint on a specimen from a sufficient distance, which would depend on the paint being used. Fig. 1 shows two speckle images obtained from a PI film specimen with different paint weight fractions, 0.15 and 0.85%. The weight fraction of the dense speckles was smaller than 1% when the paint was properly applied. The effect of the paint content on the accuracy of the measurement will be discussed later.



(a)



(b)

Fig. 1. Speckle images (230 × 260 pixels) when weight fractions of paint were: (a) 0.15% and (b) 0.85% for polyimide film with a thickness of 125 μm.

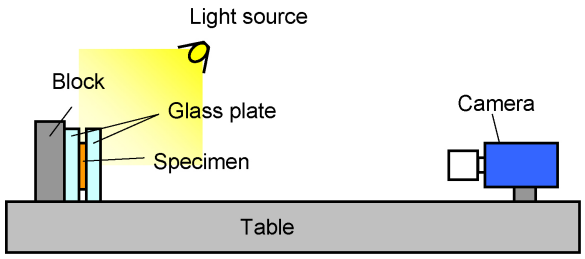


Fig. 2. Schematic diagram of experimental setup for swelling measurement.

B. Experimental Setup and Procedure

The procedure for measuring hygroscopic swelling using the DIC technique is straightforward. Two images of a specimen with paint speckles are captured before and after moisture absorption, and then DIC analysis proceeds with those images to determine hygroscopic swelling strains. An experimental setup for image capturing is illustrated schematically in Fig. 2. It consists of a camera, a supporting block for specimen setup, and a light source. A specimen sandwiched between two glass plates is set against the block. All the elements except for the specimen assembly are firmly fixed on the table. It is important for accurate measurement that the configuration of the camera, lens, and illumination, as well as the locations of all the elements, must not be changed throughout the measurement.

A digital camera (Pentax *istDS, 6 megapixels) assembled with a prime lens (Pentax-M 50 mm/f1.4) was used as an image device. The aperture was adjusted to obtain well-focused images with good sharpness. The captured images were converted to 8-bit monochrome images for correlation processing by a commercial software package (Vic-2-D by Correlated Solutions). A preliminary test showed that the use of areas close to corners could cause excessive errors caused by image distortion. Hence, an area at the center (300–400 pixels in each direction), where image distortion was the smallest, was used for the correlation process. If the field of view provides sufficient resolution for speckles, a longer distance between the camera and the specimen in general reduces errors by image distortion and minute perturbations in the sample placement (in-plane and out-of-plane rigid body translations). In the experiment, the distance between the camera lens tip and the specimen plane was 500 mm.

The glass plates sandwiching the specimen had a two-fold purpose. First, they enabled a film specimen, which was likely to wrinkle, to be placed repeatedly in the same longitudinal plane from the camera and simultaneously at the same transverse location. The proposed procedure in this paper is a non-standard use of the DIC technique. A significant error may result from even a very slight relative rigid body motion

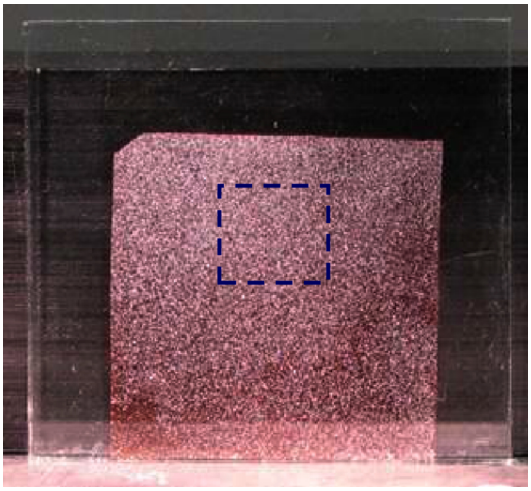


Fig. 3. Photograph of sandwiched PI film specimen placed on fixture block. The rectangle with blue dashed lines indicates an area analyzed in the image correlation process.

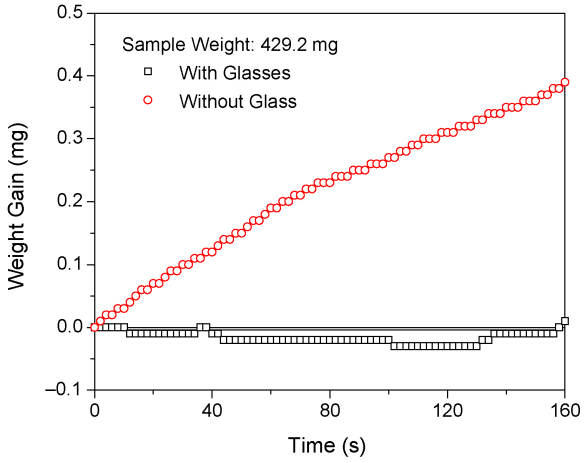


Fig. 4. Moisture weight gain of polyimide film under room environment (25 °C/40%RH) after baking at 130 °C.

between two images, since erroneous strains can be generated by inconsistent image distortion at all the matching speckles.

A proposed procedure to set a specimen in the same position repeatedly is as follows: in order to minimize random rigid body in-plane rotation, the specimen is put in between two glass plates in such a way that the bottom edge becomes flush with the bottom edge of the plates. After it is placed on the supporting block (the focal plane of the camera), the transverse position of the specimen is adjusted by referring to the live view of the film/speckle image displayed on a monitor. Fiducial marks can be set up at reference edge positions on the glass panel of a monitor for the purpose of alignment. Fig. 3 shows an example of a sandwiched PI film specimen that has been put on the supporting block for image capturing.

The second purpose of the glass plates is to retain the moisture content of the specimen during the image capturing process. Thin film polymers can lose or gain a significant amount of moisture in a short time even at room temperature. Such a quick moisture loss or gain during measurement makes it difficult to correlate the moisture weight with the corresponding hygroscopic swelling strains. The glass plates act as impervious barriers to moisture so that the specimen does not gain or lose moisture during the measurement process.

The sealing performance of the glass plates was experimentally examined. A 50 mm × 50 mm polyimide film sandwiched between two glass plates was subjected to moisture soaking at a room condition [25 °C/40%RH (relative humidity)] after it was fully baked at 130 °C. For comparison, the bare film without glass plates was also subjected to the same condition after baking. A high precision electronic balance (Denver Instrument PI-225D) was used for the real-time documentation of the polyimide film weight. The weight gain history for the first 2 min is plotted in Fig. 4 for the specimen with and without glass sandwiching. The results of the sandwiched film show only fluctuations caused by the inherent unstable behavior of the balance within its repeatability range (±0.02 mg), whereas the bare film showed a continuous moisture weight gain during the test. This confirms the effectiveness of glass plates in retaining moisture content in film specimens.

III. Experimental Result

A. Polyimide Film

A hygroscopic swelling measurement was conducted with the PI film shown in Fig. 3. Displacement contour plots obtained from DIC analyses at 85 °C/60%RH, 75%RH, and 90%RH conditions (baked at 130 °C) are shown in Fig. 5. Inclined contour lines in the plots imply that a certain amount of in-plane rigid body rotation was involved during the placement of the film specimen. The displacements by in-plane rigid body rotation do not affect the hygroscopic strain calculation if the rotation angle is relatively small (e.g., the rotation angle of the result in Fig. 5 is less than 0.1°).

Strains in horizontal (U) and vertical (V) directions are determined as

$$\varepsilon_x = \frac{\partial U}{\partial x} \quad \text{and} \quad \varepsilon_y = \frac{\partial V}{\partial y} \tag{1}$$

where ε is the normal strain component in the x or y direction. Considering local strain variations caused by correlation uncertainties or spatial property variations, the strains are averaged over the image to attain representative values by

$$\varepsilon_x = \frac{\sum_{i=1}^{N_y} [d_x(N_x, i) - d_x(1, i)]}{(N_x - 1)N_y} \quad \text{and} \quad \varepsilon_y = \frac{\sum_{i=1}^{N_x} [d_y(1, i) - d_y(N_y, i)]}{N_x(N_y - 1)} \tag{2}$$

where d is the displacement in pixels at (x, y) and N is the total pixel count in each direction. Note that the origin pixel $(1, 1)$ of the coordinate system in the DIC analysis is located at the upper-left corner. The CHS in each direction is then given by

$$\beta_x = \frac{100\varepsilon_x}{C} \quad \text{and} \quad \beta_y = \frac{100\varepsilon_y}{C} \tag{3}$$

where β is the CHS (%strain/%wt) and C is the moisture content in %wt.

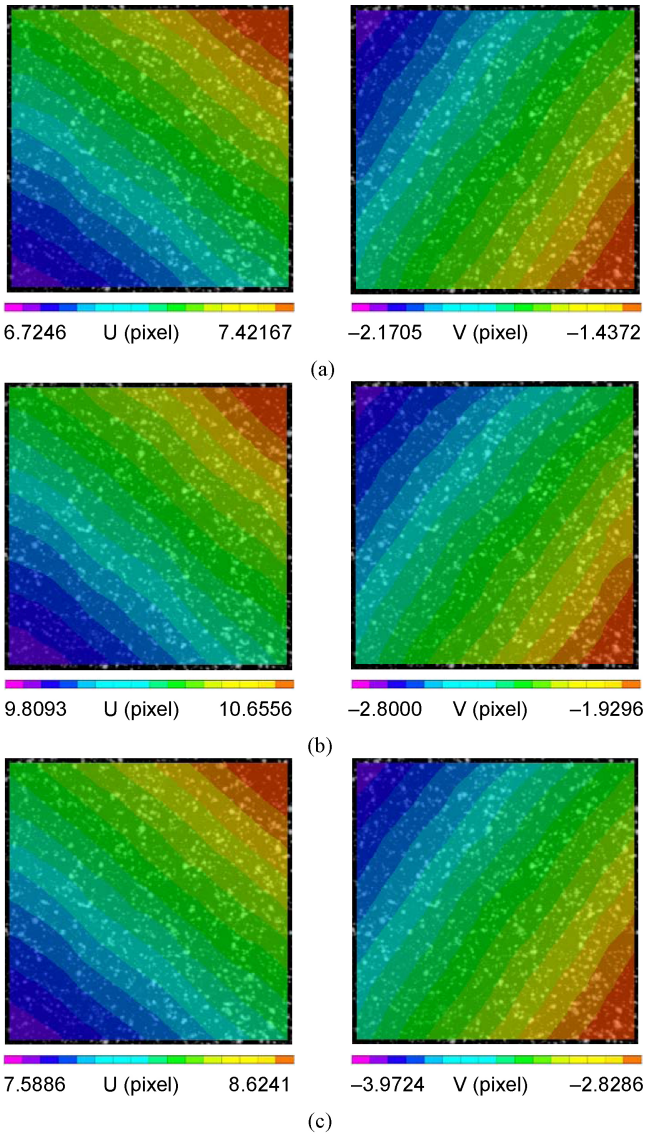


Fig. 5. Displacement contour images obtained from DIC analysis after saturation at (a) 85 °C/60%RH, (b) 85 °C/75%RH, and (c) 85 °C/90%RH. The size of the contour image is 13.6 × 13.6 mm (310 × 310 pixels) and the subset size is 81.

The hygroscopic strains as a function of moisture weight gain are plotted in Fig. 6 (the effect of subset size, n, on the result will be discussed in the next section). A good linearity was obtained as expected. The CHS of the PI film was determined to be 0.073 and 0.089% strain/%wt in the x and y directions, respectively. These values fall within the CHS range of various PI materials measured by Bushhold *et al.* (0.03–0.17% strain/%wt) [4].

B. Measurement Accuracy

In order to experimentally validate its accuracy for hygroscopic swelling measurement, the DIC technique was applied to EMC materials whose CHS had previously been measured using the MI technique [1]. Typical fringe contours of EMC obtained from MI and displacement contours from DIC are shown in Fig. 7. The effect of out-of-plane swelling on accuracy was negligible due to a small strain range (i.e.,

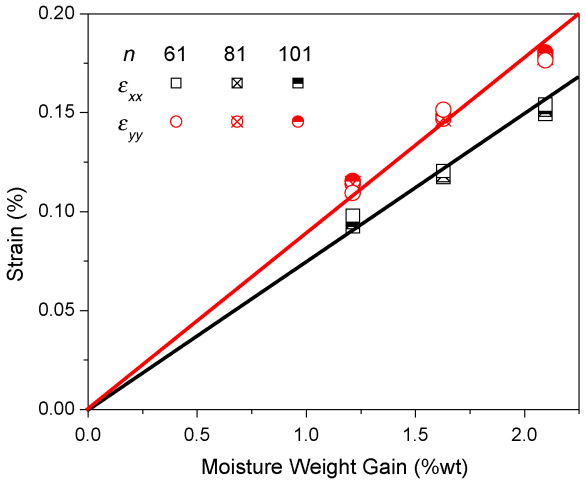


Fig. 6. Hygroscopic strains of polyimide film measured through DIC analyses (n: subset size).

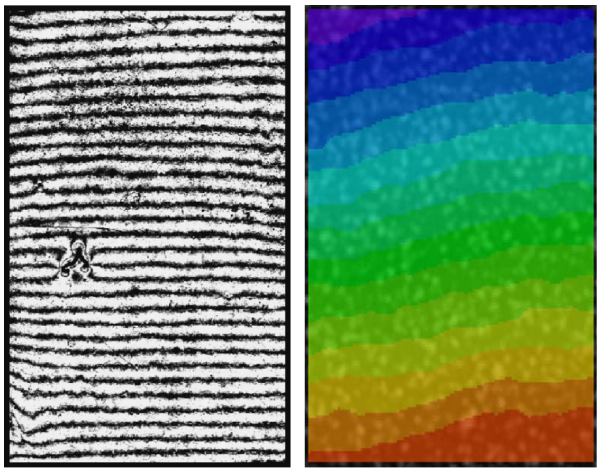


Fig. 7. Typical contour images of EMC C obtained from: (a) MI and (b) DIC.

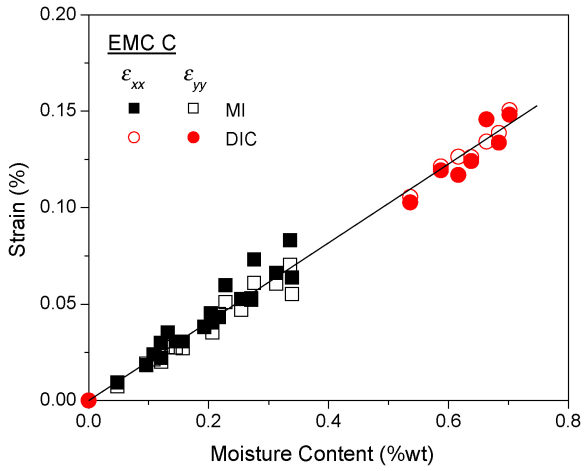
$error(\%) = 1.7\varepsilon(\%)/500$). Two EMC materials (C and D) characterized in the preceding work [1] were selected as specimens for the DIC test. Since the specimens were thick, the glass plates were not used in the measurement.

It should be noted that MI provides superior measurement accuracy when applied to thick specimens. Sensitivity up to 1/10 of the contour interval (=412 nm) can be attained through a digital image processing technique [9]. The uncertainty of MI is then calculated as

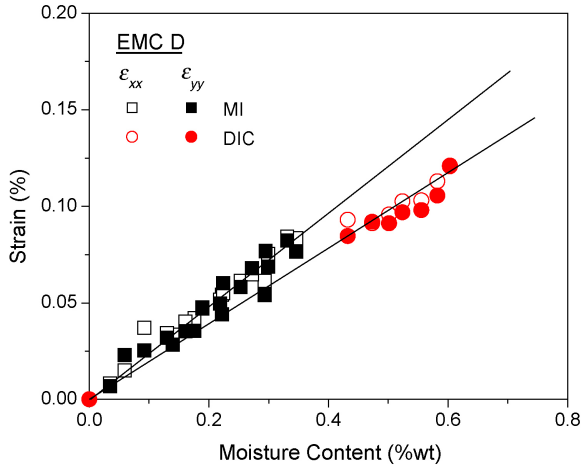
$$e\,(\mu\text{strain}) = \frac{41}{L} \Rightarrow e\,(\text{pixel}) = \frac{e\,(\mu\text{strain}) \cdot N}{10^6} = 4.1 \times 10^{-5}\frac{N}{L} \tag{4}$$

where e is the error bound (in μstrain or pixels) and L is the specimen length (mm). For the EMC specimens (13 mm × 20 mm), the uncertainty of the MI technique was one to two orders lower than that of the DIC technique (e (pixel) = 0.02 pixel [8]). Therefore, measuring using the MI technique is suitable for validation of the DIC-based method.

The hygroscopic strains in terms of moisture weight gain obtained from the DIC technique are plotted in Fig. 8 together



(a)



(b)

Fig. 8. Hygroscopic strain versus moisture content for (a) EMC C and (b) EMC D. The solid lines are for reference only.

TABLE I
COMPARISON OF CHS BETWEEN MI AND DIC

	EMC C		EMC D	
	MI	DIC	MI	DIC
ε_x	0.217	0.206	0.246	0.194
ε_y	0.194	0.205	0.227	0.187

with the results from the MI technique [1]. The corresponding CHS values are listed in Table I. In order to attain better accuracy, the DIC-based measurement was conducted at high relative humidity conditions. In the case of EMC C, the results from both techniques agreed well with each other, while in the case of EMC D, a discrepancy of close to 20% was shown. The discrepancy was within the range of variations in the CHS of EMC specimens [1]. This comparison confirms the accuracy of the DIC technique when applied to the hygroscopic swelling of polymers.

IV. OTHER FILM MATERIALS

The DIC-based method was further applied to various thin film polymers, including PSR, ACF, and thin woven glass/resin core (printed circuit board (PCB) core). The CHS values of those film materials are listed in Table II together with the CHS values of bulk packaging polymers available in the literature. The CHS is dependent upon the polymer itself and any specific trend or difference in the CHS is not found between film materials and bulk materials.

TABLE II
SUMMARY OF CHS OF SELECTED THIN FILM MATERIALS AND BULK MATERIALS

Materials	CHS (%str/%wt)	Thickness
PI	x: 0.073 y: 0.089	125 μm
PSR	0.235	40 μm
ACF	x: 0.224 y: 0.188	50 μm
PCB core	x: 0.125 y: 0.067	150 μm
EMC	0.05 ~ 0.11 [1]	Bulk
Underfill	0.22 [17]	
Die attach	0.2 [18]	

The majority of thin film polymers showed anisotropic behavior. In the case of woven glass/resin composites, the reason is the characteristics of anisotropic woven fabric. In the case of other homogeneous materials, this behavior results from the anisotropic nature of cross-linked polymer chains when produced in film form [10], [11].

V. DISCUSSION

A. Effect of Speckles on Measurement Accuracy

The volume fraction of painted speckles can affect the accuracy of measurement. The apparent CHS of a film specimen with paint speckles can be approximately calculated from the rule-of-mixture equation, which is expressed as

$$\beta = \frac{\beta_{\text{film}} E_{\text{film}} \left(1 - v_{\text{paint}}\right) + \beta_{\text{paint}} E_{\text{paint}} v_{\text{paint}}}{E_{\text{film}} \left(1 - v_{\text{paint}}\right) + E_{\text{paint}} v_{\text{paint}}} \tag{5}$$

where E is the modulus and v_{paint} is the volume fraction of the paint. The corresponding error is determined as

$$error = \frac{\beta_{\text{film}} - \beta}{\beta_{\text{film}}} = \frac{E_{\text{paint}} v_{\text{paint}} \left[1 - \left(\beta_{\text{paint}} / \beta_{\text{film}}\right)\right]}{E_{\text{film}} \left(1 - v_{\text{paint}}\right) + E_{\text{paint}} v_{\text{paint}}}. \tag{6}$$

The modulus of paint is highly dependent on a binder material used with a pigment. It ranges from several hundred MPa to a few GPa at room temperature [12]–[14], which is below or comparable to the modulus of packaging polymer films (for example, the modulus of a polyimide film is generally higher than 3 GPa).

It was illustrated previously that a weight fraction of speckles that is less than 1% is sufficient for accurate DIC analysis if the spraying process is conducted properly. Considering the fact that the density of most polymeric materials falls within 0.9–2.2 g/cc [15], it can be predicted by using (6) that an error caused by paint would be negligible.

VI. TECHNICAL CONSIDERATIONS IN USING THE DIC TECHNIQUE

In the DIC analysis, the displacement is determined at each subset comprised of $n \times n$ pixels. A proper selection of the

subset size (n) is important: a large size can result in a loss of detailed displacement information, while a small size can increase a measurement error ($\approx 0.02/n$) [8]. The hygroscopic swelling of thin film presents nearly uniform deformations. Since a displacement gradient in the subset remains constant, a larger subset size can be employed to attain a higher level of accuracy in analysis. In the result shown in Fig. 6, the subset size was varied from 61 to 101 (the maximum subset size allowed by the software), which corresponds to a sensitivity of approximately 328–198 μstrain. Although the sensitivity is considerably large compared with the actual hygroscopic strains (>750 μstrain), each set of the result showed a good agreement and expected linearity due to the uniform nature of hygroscopic swelling.

The overall uncertainty of measurement can be determined from the maximum deformation. It is expressed mathematically as

$$e_x(\%) = \frac{0.02 \times 100}{N_x \varepsilon_x} \text{ and } e_y(\%) = \frac{0.02 \times 100}{N_y \varepsilon_y}. \quad (7)$$

The denominator of the above equation ranges from 0.3 to 0.5 in the measurement of the PI film (Fig. 6). The uncertainty of those particular analyses is calculated as 4–7%. When the hygroscopic strain is as small as the sensitivity of a subset, e.g., $\epsilon_X = 328\,\mu$strain for $n = 101$, the uncertainty can be increased up to 20% for the same image size.

Unlike MI, the sensitivity of the DIC technique is dependent on the strain range and the image size of a specimen, not the specimen size, as illustrated above. There are two ways to increase the accuracy of the DIC analysis: 1) to conduct the measurement at a condition where the strain of the specimen is high, and/or 2) to increase the total pixel count of an imaging device (and the resolution of an imaging lens correspondingly). The former can be done by measuring the hygroscopic strain of a specimen fully saturated at a high relative humidity condition. It can also eliminate a potential uncertainty associated with non-uniform moisture distribution through the thickness direction [16].

It has been shown above that the specimen size does not affect the measurement accuracy. Therefore, the specimen size is not constrained by the measurement accuracy but by the measurement setup. While the maximum specimen size should be smaller than the size of the sandwiching glass plates, the minimum allowable size should be greater than the requirement of an optical system used in a measurement (image sensor size, magnification factor of a lens, etc.). One rough but practical guideline would be that a specimen should take more than a half area in an image captured by the optical system that can sufficiently resolve speckles on the specimen.

VII. Conclusion

An advanced method based on the DIC technique was implemented to characterize the hygroscopic swelling of thin film polymers used in semiconductor packaging. The accuracy of the proposed method was confirmed by using the MI technique. It was then applied to various thin film polymers and their hygroscopic swelling coefficients were determined. The majority of polymer films showed anisotropic behaviors due to the anisotropic nature of cross-linked polymer chains. The CHSs of various films in the x and y directions were determined and the values were provided. The formulation to determine the uncertainty of the measurement was also established to provide a guideline for specimen preparation and experimental setup.

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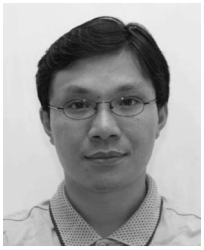

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