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HIGH RESOLUTION CHARACTERIZATION OF MATERIALS USED IN PACKAGES THROUGH DIGITAL IMAGE CORRELATION

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ABSTRACT

In this study, we demonstrate a simple, full field displacement characterization technique based on digital image correlation (DIC). We develop a robust correlation measure implemented in a code and use it to characterize materials at high spatial and displacement resolution. We describe the methods implemented in the DIC code and compare against those available in the literature. We show how sample preparation may be entirely eliminated by using the natural speckle inherent in specular (rough) surfaces. We demonstrate further that the use of natural speckle enables very high spatial resolution (100 microns or less) since creating artificial speckle patterns in miscroscale spatial regions is a significant challenge. The software is also designed to be robust to varying contrasts between the deformed and the undeformed images. Its accuracy is enhanced by using NURBS (Non-Uniform Rational B-Spline) as the interpolating function in the code. We demonstrate the developed software and the underlying procedure on several packaging problems of interest. We measure the CTE of Alumina (Al2O3) using its natural speckle, we calculate the strain and therefore the modulus during mechanical testing of composite materials and we characterize the time dependent behavior of a micro-fiber reinforced composite (RT/Duroid) at high temperature.

INTRODUCTION

The continued integration and the consequent challenges of length scale and high power dissipation combined with the use of low-cost organic materials has imposed many new reliability challenges. The reliability constraints substantially affect the product cost and performance requirements and, in some cases, supersede them. In such a scenario, accurate reliability modeling is very critical in optimizing the performance for maximum reliability. An improved understanding of the material properties and failure mechanisms would enable development of accurate reliability models and tools for lifetime estimation. Complete thermo-mechanical characterization of the materials, components and assemblies through full field displacement and strain measurement is essential for reliability estimation.

Conventionally, strain gages or optical techniques such as moiré interferometry [1], holography [2] or electronic speckle pattern interferometry [3] have been used for microscopic characterization of electronic packages. The interferometric techniques provide high-resolution whole-field deformation, however, they are limited by time-consuming sample preparation and stringent requirements on the system's stability. The processing of the fringe patterns may be laborious as well although automated procedures are being developed for this purpose. Digital Image Correlation is a simple non-contact, non-destructive alternative to the above mentioned techniques [4-6]. It is a simple technique since it doesn't require challenging sample preparation or any expensive experimental setup in the form of a laser source or an anti-vibration table. It can easily be automated to provide full-field displacement and strain with a wide range of measurement sensitivity and resolution. The spatial resolution of the DIC technique theoretically depends on the imaging system. If a camera is used for imaging, the spatial resolution is determined by the optical magnification of the camera lens system and the pixel pitch of the CCD sensor pitch. Nanoscale resolutions can be obtained by using images obtained from an Atomic Force Microscope or a Scanning Electron Microscope [7].

There have been a few applications in the literature where digital image correlation has been used for microscopic strain measurements in electronics packaging. Pendse et al.[8] and Lu et al.[9] have experimentally evaluated the thermal strain in solder joints used in electronic packages using digital image correlation. Zhou and Goodson, 2000 [10] utilized DIC for deformation measurement in electronic packages. The purpose of their study was to demonstrate that the DIC technique is an alternative and powerful tool for electronic packaging. In another study, Zhou and Goodson, 2001 [11] developed an iterative, spatial-gradient based algorithm, using only first-order spatial derivatives of the image before and after deformation in order to reduce computational complexity. They then demonstrated their algorithm by applying it to a flip-chip package. Chevalier et al., 2001 [12] investigated the mechanical behavior of a polymeric material using a multiaxial tester. The overall displacement field was measured through digital image correlation (DIC). They also found that the DIC was well suited for large displacement measurements where it is difficult to obtain homogeneous strain fields. There are also studies in the literature utilizing the digital image correlation technique at a high temperature. For instance, Lyons et al., 1996 [13] and Turner et al., 1990 [14] performed the experiment at up to 650°C to demonstrate that the DIC is a high-temperature, whole field surface strain measurement tool. In the latter study, the Coefficient of Thermal expansion (CTE) measurements obtained from the DIC techniques were validated using the results from strain gage measurements.

However, there have been some technical issues such as inconsistency in strain results and appropriate speckle size due to which the digital image correlation technique has not been widely applied to material characterization and in particular, to the field of electronics packaging. The strain results have been found to be inconsistent under varying lighting conditions [15]. The results were found to be poor especially if the image contrast is low. If the underlying strain field that needs to be determined is inhomogeneous, then the interpolating function used in the digital correlation procedure becomes very important.

Thus, an important goal of the present study is to develop a high resolution, robust but low cost whole field strain measurement technique using DIC that will enable characterization of material properties even at a high temperature up to 1000°C. A robust correlation measure and NURBS (Non-Uniform Rational B-Spline) as the interpolating function have been implemented in a code to characterize materials at high spatial and displacement resolution. It has also been shown that specimen preparation can be completely eliminated by using the natural speckle on the specimen surface using the robust correlation measure. The performance of the DIC software is demonstrated for real packaging problems which involve measurement of the CTE, elastic modulus and characterization of time dependent material behavior of materials used in electronic packages. The DIC software that is developed is described in the following sections along with the experimental procedure.

DIGITAL IMAGE CORRELATION METHOD

The digital image correlation technique is well established at the present time and hence only a brief description of the technique is presented below. The reader is referred to [4-6] for a more detailed description of the method.

Digital image correlation is a whole field deformation measurement technique that extracts whole field displacement data by comparing a pair of digital images of a specimen surface before and after deformation. A mathematical correlation function given by Eq. (1) is used to obtain the displacements and strains from the digital image data while the sample is subjected to mechanical or thermal stresses. In order to correlate the intensity distribution of the deformed image to the un-deformed image, the images are divided into small subsets (Figure 1). By minimizing the correlation function over a subset image region, in-plane displacements, u and v, and the displacement gradients, du/dx, du/dy, dv/dx, and dv/dy are determined. By repeating the process over the entire image region, a whole-field in-plane deformation mapping is achieved. The correlation function (C_L) is defined as follows [5]:

$$C_L\left(u,v,\frac{\partial u}{\partial x},\frac{\partial u}{\partial y},\frac{\partial v}{\partial x},\frac{\partial v}{\partial y}\right)=1-\frac{\sum_{i=1}^{i=N}\sum_{j=1}^{j=M} I_u\left(x_i,y_j\right)\cdot I_d\left(x_i+u_a,\ y_j+v_a\right)}{\left(\sum_{i=1}^{i=N}\sum_{j=1}^{j=M} I_u^2\left(x_i,y_j\right)\cdot\sum_{i=1}^{i=N}\sum_{j=1}^{j=M} I_d^2\left(x_i+u_a,\ y_j+v_a\right)\right)^{1/2}} \quad (1)$$

where

$$u_a=u+\frac{\partial u}{\partial x}\cdot\left(x_a-x_c\right)+\frac{\partial u}{\partial y}\cdot\left(y_a-y_c\right) \quad (2)$$

and

$$v_a=v+\frac{\partial v}{\partial x}\cdot\left(x_a-x_c\right)+\frac{\partial v}{\partial y}\cdot\left(y_a-y_c\right) \quad (3)$$

In the above expression, u and v are the displacements of a subset's center point, located at the image plane coordinates (x_c, y_c), while u_a and v_a are the displacements of an arbitrary point (x_a, y_a) within the subset, and I_u and I_d are the subset intensity patterns from the undeformed and deformed images, respectively.

A NEW PROCEDURE FOR ROBUST DIC

Generally, a speckled specimen is necessary to generate a unique intensity pattern with sufficient contrast on the specimen surface. The correlation measure given by Eq. (1) would not be able to give accurate results for images with insufficient contrast or differing contrast between the two images (due to change in image illumination across image sequence). In this study, a more robust correlation measure (Eq. (4)) that would account for low contrast or varying contrast between the images is proposed here.

$$C_L\left(u,v,\frac{\partial u}{\partial x},\frac{\partial u}{\partial y},\frac{\partial v}{\partial x},\frac{\partial v}{\partial y}\right)=1-\frac{\sum_{i=1}^{i=N}\sum_{j=1}^{j=M}\left(I_u\left(x_i,y_j\right)-\bar{I}_u\right)\cdot\left(I_d\left(x_i+u_a,\ y_j+v_a\right)-\bar{I}_d\right)}{\left(\sum_{i=1}^{i=N}\sum_{j=1}^{j=M}\left(I_u\left(x_i,y_j\right)-\bar{I}_u\right)^2\right)^{1/2}\left(\sum_{i=1}^{i=N}\sum_{j=1}^{j=M}\left(I_d\left(x_i+u_a,\ y_j+v_a\right)-\bar{I}_d\right)^2\right)^{1/2}} \quad (4)$$

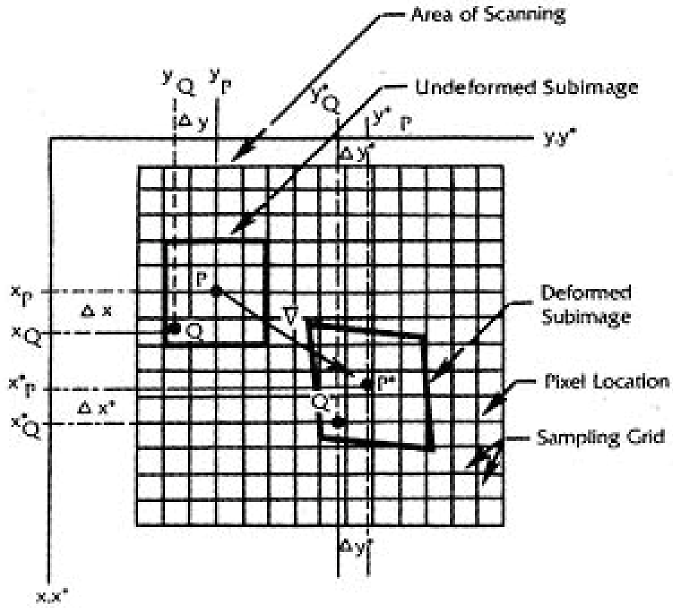

Fig 1: DIC Strain mapping by identifying grids with similar intensity patterns [5]

In Eq. (4), $\overline{I}_u$ is the mean pixel value in the reference image and $\overline{I}_d$ is the mean pixel value in the image of the deformed sample.

In this way, the correlation coefficient C_L is normalized with respect to both the reference image and the deformed image and lies in the range [-1, 1]. The robustness of this correlation measure is demonstrated for Alumina where the characterization is done without applying any speckle, that is, using the natural speckle on the specimen surface. Figure 2 shows a sample image before and after contrast enhancement using "Histogram Enhancement" feature in MATLAB. The above correlation is later demonstrated to yield the effect of enhancing the contrast.

In order to achieve subpixel measurement accuracy, a NURBS interpolation method was employed in this study to obtain the intensity information between pixels.

$$I(u,v) = \sum_{i=0}^{n}\sum_{j=0}^{m} \frac{N_{i,p}(u)N_{j,p}(v)}{\sum_{i=0}^{n}\sum_{j=0}^{m} N_{i,p}(u)N_{j,p}(v)w_{ij}} w_{ij}\mathbf{P}_{ij} \qquad (5)$$

where, P is the control point, w is the weight associated with it and $N_{i,p}(u)$ is the basis function of degree p. A NURBS interpolation, compared to a quadratic or bicubic interpolation enhances the accuracy of the correlation performed. If the underlying strain field is inhomogeneous, NURBS interpolation would be able to capture the field more accurately.

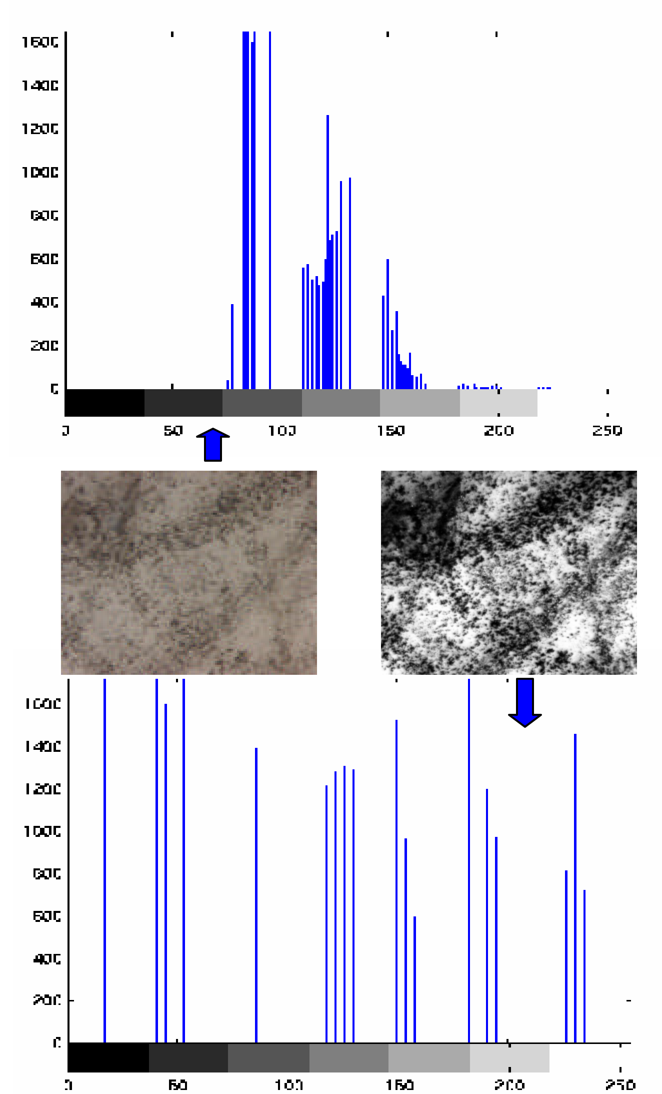

Fig 2: Alumina sample image before (Left image) and after (Right image) contrast enhancement using "Histogram Equalization" feature in MATLAB

THE "STRAIN MAPPER" PROGRAM

A DIC analysis software called Strain Mapper implementing the above mentioned correlation measure and NURBS interpolation function was developed. The DIC software is written in Java in an object-oriented framework. It implements a graphical user interface where the DIC parameter values are input (Figure 3). After the program is run, in the "Post-DIC" tools provided by the software, correlated data is processed to filter the noise in the displacement data (Figure 4). There are four options for surface fitting (a) "smoothing with a number of passes" to repeat the fitting, (b) "bilinear fitting", (c) constant strain, or (d) "do nothing", in which case, the strain will be based on the original noisy displacement gradients. Finally, the displacement and the displacement gradients are computed.

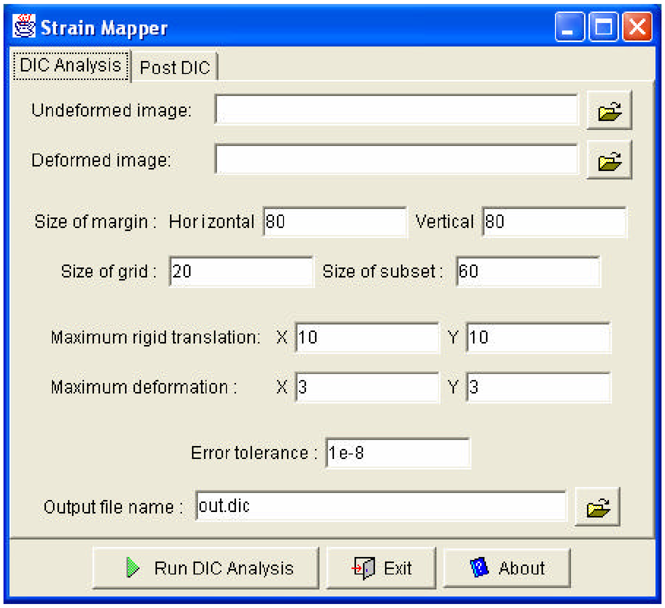

Fig 3: DIC analysis GUI for the strain mapper code developed in this paper

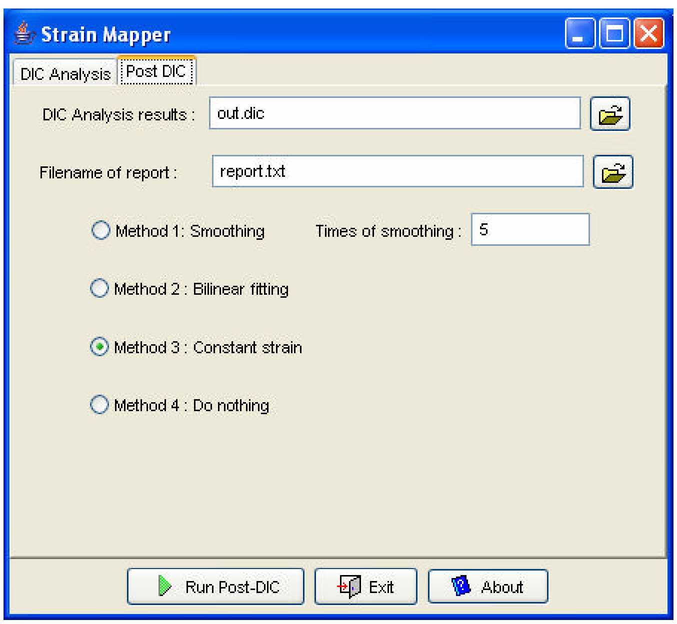

Fig 4: DIC post-processing GUI

The experimental procedure is described in the next section.

EXPERIMENTAL PROCEDURE

The experimental setup consists of a camera, a camera stand, a light source, a loading frame for applying tensile loads or a thermal chamber in case of thermal loads, image grabber board, a PC and an image acquisition software.

The mechanical testing was performed using an Instron 5848 Micro Tester (Figure 5)and a two-axis micromechanical tester (Figure 6) which was designed and developed in the authors' earlier work [16]. Imaging was done using a JAI CV-S3200 CCD camera fitted with a high power camera lens, VZM 450i. The system is capable of resolving 720X480 pixels and real time measurement by recording images to a video file. The video file can be later analyzed frame by frame. A Schott Fiber Optic Illuminator Model 20 was used to provide illumination to the specimen surface.


Fig 5: Experimental setup combined with the DIC characterization with tensile testing using Instron 5848 Micro Tester

Samples of size smaller than 10x10 mm were heated in the THMS 600 Linkam High Temperature stage (Figure 7) for measuring their coefficient of thermal expansion (CTE). They were imaged using the Nikon DXM1200 camera attached to the Nikon SMZ 1500 Stereomicroscope. The ACT-1 software package was used to capture images up to an upper resolution of 3,840 x 3,072 pixels using the Nikon DXM 1200 camera.

This high resolution whole-field experimental setup was developed by coupling the micro tester (for tensile loads) or the thermal chamber (for thermal loads) with the digital image correlation technique. Whereas the micro tester provides an accurate load, digital image correlation based on the use of the above camera setup provides a high-resolution measurement of displacement. This experimental setup combined with the developed robust DIC software has been used to characterize materials used in electronic packages, which is described in the next section.

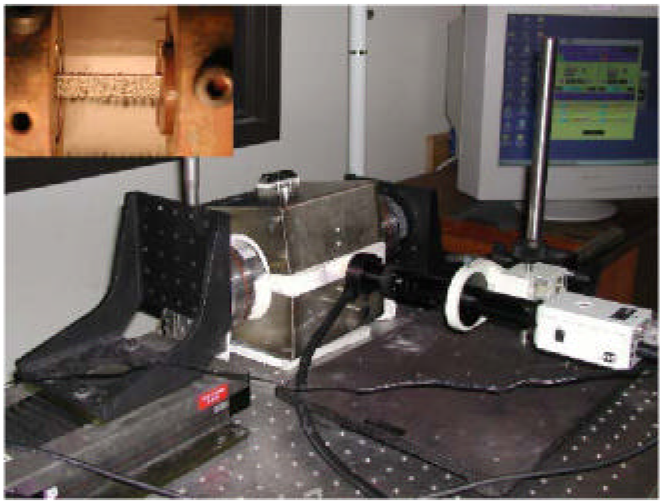

Fig 6: Experimental setup combined with the DIC technique for tensile testing of epoxies using a two-axis micromechanical tester [16]

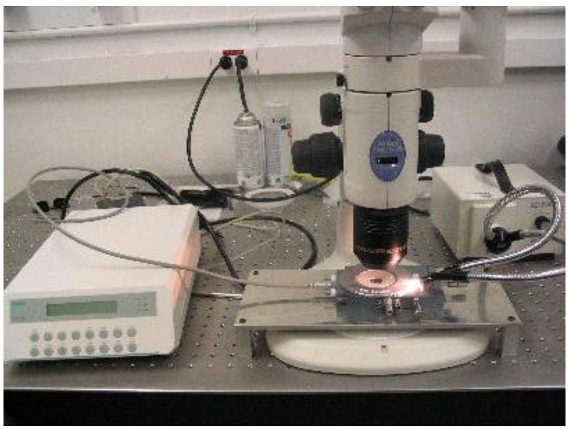

Fig 7: THMS 600 Linkam high temperature stage for CTE measurement

SOURCES OF ERROR AND THEIR RECTIFICATION

In general, the DIC characterization is susceptible to several experimental errors. The sources of this error are identified below and corrections to the test procedure are implemented.

1. Camera Rotation: The axis of the camera may not be aligned along the axis of loading and can be at a small angle to the loading axis which will introduce an error in the strains.
2. Misalignment at Grips: The tensile or compression specimen may not be exactly parallel to the loading axis.
3. The camera may not be exactly perpendicular to the plane of the specimen. This is particularly likely if the specimen is "sloppy" in grips; i.e., it is not preloaded when the initial image is recorded.

The following corrections overcome the errors identified above. The strain tensor on the plane that is being characterized is given by Eq. (6), where u and v are the horizontal and vertical displacements respectively. The eigenvalues of this matrix are the principal strain values. These will be the strain values for an element under pure tension, i.e., without any shear strain. So this correction will account for the errors (shear strains) due to axis misalignment and camera rotation. This feature of outputting the principal strains has been incorporated into the software. Note: This does not correct for misalignment of the grips either in-plane or out-of-plane relative to the camera.

$$[e] = \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{1}{2}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right) \\ \frac{1}{2}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right) & \frac{\partial v}{\partial y} \end{bmatrix} \qquad (6)$$

If the plane of the specimen is not perpendicular to the camera one needs to ensure that the specimen is not "sloppy" in the grips. If the specimen is loose in the grips, then potentially upon loading, the camera may record positive lateral strains when the specimen straightens under the applied load. This effect can be corrected by pre-loading the sample. Pre-loading the sample, say to 30N, will make the specimen plane perpendicular to the camera. So, the reference image for the DIC software will be the image taken when the sample is loaded to 30N. Preloading has been verified to produce accurate and consistent strains as described below.

DESCRIPTION OF THE CONDUCTED TESTS

With the DIC software and experimental setup explained in the previous section, high resolution microscopic strain measurement and materials property characterization is possible. The performance of the DIC software is demonstrated for real packaging problems by characterizing the following materials used in packages.

The coefficient of thermal expansion for Alumina is measured using the Linkam thermal chamber in conjunction with the Nikon SMZ1500 stereomicroscope (with camera) for imaging the sample. The Alumina samples, of the size 8.9 mm x 8.9 mm were placed on 7mm quartz cover slip and encased within a pure silver lid so that it is heated from all sides to ensure a perfectly uniform temperature. The samples were subjected to a temperature increase of 10^{o}C by heating the thermal chamber from 30^{o}C to 40^{o}C. Since, the sample size was very small, artificial speckle could not be applied by spray painting the sample surface. The natural speckle of the specimen surface was used as the intensity pattern for the DIC software. The improved results due to the more robust correlation measure are described in the next section.

The mechanical testing of composite materials for measuring elastic modulus was performed using the Instron Micro Tester and JAI CV-S3200 camera. These samples were rectangular in cross-section and were measured to be 38.1 mm x 5.15 mm x 1.55 mm. The specimen was subjected to a maximum load of 110 N (0.06% strain). The images of the sample were captured at different load points and strains were found using the DIC software. The linear plot of Stress vs. Strain was used to find the Elastic modulus of the composite material.

High Temperature testing of epoxies was carried out for two epoxies namely EMI Emcast 501 epoxy, EPO-TEK H20E and one underfill material LOCTITE Hysol FP4549 determine their modulus. Both the epoxy materials contain silver particles to conduct static electricity having response to thermal cure conditions. EMI Emcast 501 epoxy was cured at 125^{o}C for 30 minutes, while EPO-TEK H20 E epoxy was cured at 150^{o}C for 15 minutes. The underfill material HYSOL FP4549 was also thermally cured at 165^{o}C for 30 minutes. The cured epoxy and the underfill material were then cut into small samples of size 35 x 10 x 2 mm.

The time-temperature dependent deformation behavior of a micro-fiber reinforced composite (RT/Duroid) provided by Rogers Corporation was characterized using the micro-mechanical tester and DIC [18]. The specimens, 0.762 mm in thickness, were cut into a rectangular shape, 30 mm in length and 5.0 mm in width. The tests were conducted at various temperatures, ranging from room temperature to 300^{o}C in steps of 100^{o}C. A crosshead speed of 50 µm/sec was used until a strain of 5% was reached at each temperature [17]. A slower rate implies a greater deformation at a given stress and accordingly implies a lower stress at a given strain. To test at an elevated temperature, the specimen was heated and held until it reached thermal equilibrium. Once the crosshead was stopped, the stress required to maintain the fixed strain was measured as a function of time at a constant temperature. The strains themselves were obtained using DIC.

The viscoelastic behavior of the material was represented by a "Standard Solid" model [19] which is illustrated in Figure 8. Using this model, the following equation for the relationship between the stress, the strain and strain rate can be derived.

$$s\,(t) = e_0\left(E_\infty + \left(E_0 - E_\infty\right)\exp\left(-\frac{\left(E_0+E_1\right)\left(t-x_0\right)}{h}\right)\right) \qquad (7)$$

where $E_\infty = \dfrac{E_0 E_1}{E_0 + E_1}$, E_0 and E_1 are the moduli of the springs in Figure 8, ξ_0 is a time reference and η is the coefficient of viscosity, ε_0 is the initial applied strain and s(t) is the stress at time t. Based on Eq. (7) and the experimental data of the stress relaxation test obtained using DIC, we can determine moduli E_0, E_1, and the coefficient of viscosity, η.

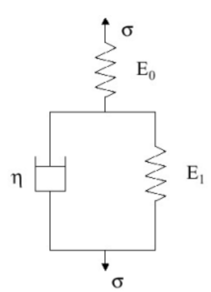

Fig 8: Standard Solid Model

RESULTS AND DISCUSSION

All the samples (except the alumina samples used in the first test) that were characterized using DIC were spray painted with white and black paint to get a random speckle pattern on the specimen surface.

The coefficient of thermal expansion (CTE) of the alumina sample measured using the correlation given by Eq. (4) was 5.06 x 10^{-6}/^{o}C. This result was obtained using the natural speckle from the specimen surface using the more robust correlation measure incorporated into the software. When the correlation measure is not normalized with respect to both the reference image and the deformed image as in Eq. (1), then the CTE value obtained from the software is -4.45 x 10^{-6}/^{o}C. Since the CTE value for Alumina cannot be negative, it is clear that the normal correlation measure fails when the natural speckle on the alumina surface is used. It was further confirmed that the low contrast of these images was the reason for its failure by enhancing the contrast of the two images using the "Histogram Equalization" feature in MATLAB (Figure 2). When these high contrast images were given as input to the software implementing the correlation measure given by Eq. (1), then it gave the correct CTE value of 5.67 x 10^{-6}/^{o}C. This example clearly shows that, the correlation measure given by Eq. (4) implemented in the DIC software was capable of taking into account low contrast in the images.

The elastic modulus of two composite samples were obtained using the DIC technique as a strain gage for the Instron Micro Tester. The Stress-Strain curve obtained from one of the samples is shown in Figure 9. A linear relationship was obtained between stress and strain as expected. The elastic modulus obtained for the two samples were 16.27 GPa and 16.29 GPa, respectively. These values were also verified by characterizing the composite samples with strain gages.

The epoxies and the underfill material were tested in a temperature range of room temp to 250^{o}C. The glass transition temperature of the epoxies and underfill as prescribed by the manufacturers were 125^{o}C for EMI Emcast 501 epoxy, >80^{o}C for EPO-TEK H20E and 140^{o}C for Hysol FP4549 underfill. The glass transition temperatures were bracketed by conducting experiments at 10^{o}C on either side of the critical temperature. A video was taken using the setup as shown in Figure 6 at each temperature. The video frames at various instants were then used to determine the strain with respect to time using the DIC software. The corresponding force values recorded in the LABVIEW software were then used along with the strain values from DIC to determine the modulus value. This procedure was repeated at each temperature for both the epoxies and the underfill material. The modulus variation with respect to temperature is plotted in Figure 10.

The time-temperature dependent behavior of RT/Duroid was characterized using DIC by running the test at various temperatures, from room temperature to 300^{0}C, with a cross-head speed of 50 µm/sec. The strain measurements using DIC are tabulated in Table 1. The “Standard Solid” model (Equation 7) was fitted to the result of the stress relaxation tests as shown in Figure 11, resulting in the identification of the three parameters, E_0, E_1, and η, at each temperature as tabulated in Table 5.8. It can be noticed that the viscosity of RT/duroid 6002 decreases rapidly at 300°C. This result indicates that the glass transition temperature of RT/duroid 6002 is in the vicinity of 300°C. This result is supported well by measurements using a Thermo Mechanical Analyzer which showed that the glass transition temperature of RT/duroid 6002 was in the range 330-340°C.

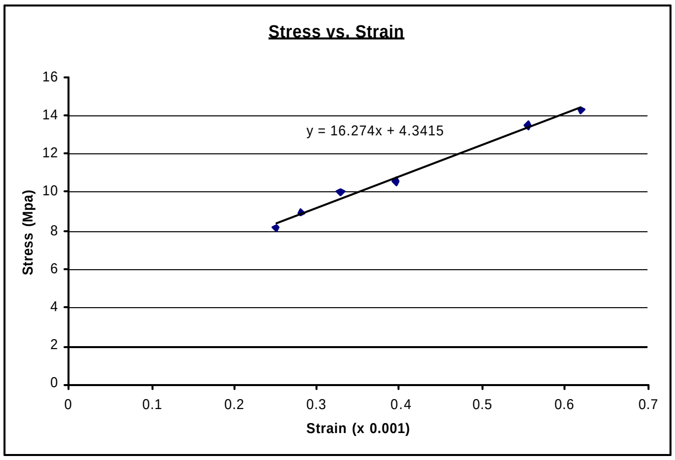

Fig 9: Stress-strain curve for a composite sample

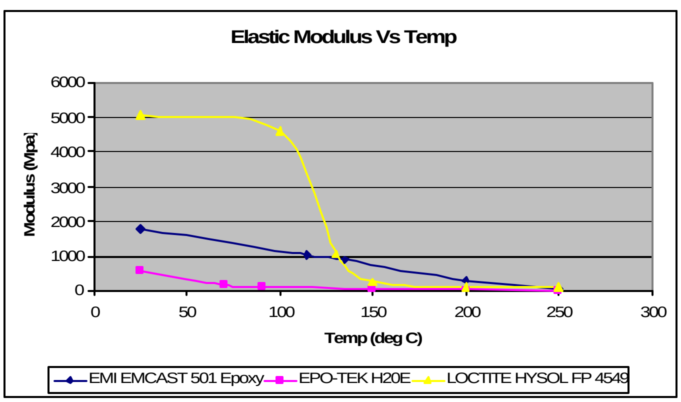

Fig 10: Modulus values of the epoxies and underfill material with respect to temperature characterized using DIC

Table 1: Strain values measured using DIC along with the standard solid model parameters

Temp(°C)	Strain DIC	Data fit using Standard Solid model		
		E_0 (MPa)	E_1 (MPa)	η(MPa.s)
25	0.034	288.20	2806.20	3.43E+06
100	0.038	193.05	581.92	9.38E+05
200	0.039	119.28	88.25	2.79E+05
300	0.039	0.00	0.002	1.38E-04

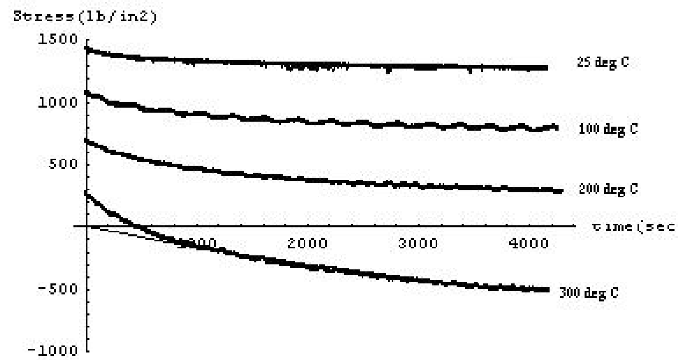

Fig 11: Data Fit curve to determine model parameters of Eq. (6)

CONCLUDING REMARKS

In this study, a robust digital image correlation measure and implementation was described. The software was demonstrated for several complex material characterization problems. DIC has been shown to be a simple technique which can provide whole-field high resolution characterization of materials used in electronic packages at the micro-scale, which are not amenable to facile characterization. The corrections to procedure that have been suggested also lead to more accuracy in the measured strains.

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