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STRAIN MEASUREMENT OF MICROSAMPLES USING LASER INTERFEROMETRY

Helena Jin, Wei-Yang Lu
Materials and Mechanics Department, MS 9409
Sandia National Laboratories, Livermore, California, 94550

ABSTRACT

As the specimen gets smaller and thinner, traditional strain measurement method using the strain gage is impossible. In this paper, the strain is measured using non-contact laser interferometry method. Two markers are placed on the LIGA specimens along the loading direction to reflect the laser beams to generate the interferometric fringe patterns. The markers are generated using micro-hardness indentation for the LIGA specimens. A pair of CCD cameras is used to capture the interferometric fringes during each step of the loading along the longitudinal direction. Fast Fourier Transform (FFT) is then applied to calculate the frequency and phase shift of the fringes. The displacement and strain can be obtained from the phase shift of the fringe pattern.

This ISDG strain measurement technique is further developed by using multi markers to obtain fringes during the whole loading when the specimen undergoes larger motion. Biaxial strain measurement using ISDG is also developed to obtain both Young's modulus and Poisson's ratio simultaneously. A third marker is located orthogonal to the first pair of markers along the loading direction. Two pairs of CCD cameras are used to acquire the digital images of the interferometric fringes patterns along both longitudinal and transverse directions. The stress-strain curves as well as the material properties are very consistent from the different tests using ISDG.

KEYWORDS

LIGA, ISDG, FFT, Biaxial strain measurement

INTRODUCTION

LIGA (an acronym from German words for lithography, electroplating, and molding) MEMS structures have been developed for many applications, such as coplanar waveguide, millimotor, precision stepping motor, tribology test vehicle and heat exchanger [1]. LIGA could use a variety of materials including metal. They have the small and accurate in-plane dimensions as silicon-based microstructures. But the thickness can vary from several hundred micrometers to millimeters. These are 3-D microstructures defined by 2-D lithography. The properties of LIGA materials are strongly dependent on processing conditions. Understanding the material properties and their relations to processing parameters will provide guidelines to achieve optimum conditions for the micro-fabrication process.

Sharpe has demonstrated the direct strain measurement on the gage length using the laser interferometric strain/displacement gage (ISDG) [2-6]. Two markers were placed on the specimen for the laser reflection. The motion of these two markers can then be calculated from the fringe motion generated by the reflected laser. Zupan *et al* improved the ISDG technique by applying Fourier analysis to the fringe pattern [7].

Testing LIGA specimen has some unique experimental requirements. The testing system should have the capabilities of both handling microstructures and applying relatively larger force than that for 2-D silicon based MEMS structures. In our testing system, a loading stage which is capable of tension, compression and bending is used to load the LIGA specimen. A standard dog-bone tensile testing design is used for the characterization purpose. Load is acquired by the load-cell during the test. Due to the size limitation, the general strain gauge method is unsuitable for the strain measurement. Instead, the displacement and strain were measured directly by using laser interferometric strain/displacement gage (IDSG). The two indent markers on the specimen define the gage section.

THE OPTICAL BASICS OF ISDG

The principle of ISDG is similar to Young's double slit experiment as shown in *Figure 1*, but laser reflection is used instead of laser transmission. The relation between the fringe pattern and the space of reflection markers can be expressed as following equation:

$$m\lambda = d\sin(\theta) \tag{1}$$

Where *m* is the order of fringe, λ is the wavelength, *d* is the space between the two markers, θ is the incident laser light angle. According to this equation, the change of the space of the markers Δd can be measured by the change of the fringe location and the strain can be calculated from the displacement of markers:

$$\Delta m\lambda = \Delta d\sin(\theta) \tag{2}$$

$$\Delta \mathrm{d} = \frac{\Delta m\lambda}{\sin\theta} \tag{3}$$

$$\varepsilon = \frac{\Delta d}{d_0} = \frac{\Delta m\lambda}{d_0\sin\theta} \tag{4}$$

The location of the fringe can be decided by the phase of the fringe pattern. Therefore the motion of the fringe, as well the displacement and strain can be measured from the phase shift of the fringe patterns:

$$\Delta m = \frac{\Delta\Phi}{2\pi} \tag{5}$$

$$\varepsilon = \frac{\left(\frac{\Delta\Phi}{2\pi}\right)\lambda}{d\sin(\theta)} \tag{6}$$

SPECIMEN AND UNIAXIAL STRAIN MEASUREMENT

The standard dog-bone tensile specimen is used for the characterization of LIGA microstructures. The gage length is 7.62mm (0.3 inch), width is 0.76mm (0.03 inch) and thickness is 0.254 mm (0.01 inch).

The two markers for laser reflection are Vickers micro-hardness indents, with half-angle of 68^o, as shown in *Figure 2*. Therefore, the fringes are located at 45^o angle relative to the specimen surface.

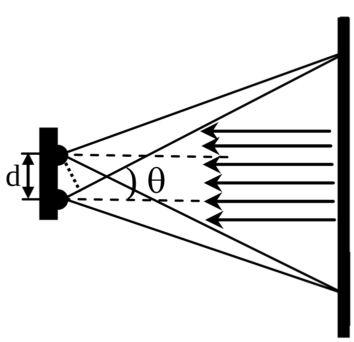


Figure 1: The principle of ISDG

The experimental configuration for uniaxial strain measurement is shown in *Figure 3*. He-Ne red laser with wavelength $\lambda = 633nm$ is shined onto the two indents reflection marker on the specimen surface. The fringes are captured by a pair of CCD cameras aligned along the two reflection markers. The CCD cameras have resolution of 1024x1280 pixels. The fringes for the strain measurement are shown in *Figure 4*. The specimen is loaded by a stage capable of both tension and compression.

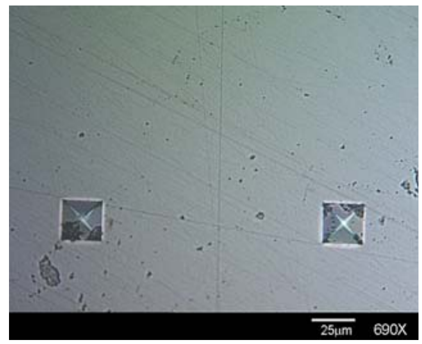


Figure 2: Micro-hardness indents for laser reflection

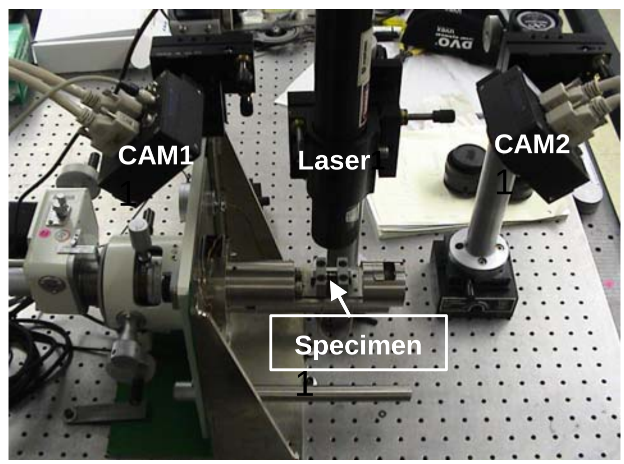


Figure 3: Experimental configuration for uniaxial strain measurement

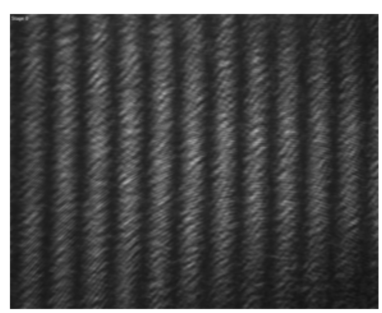


Figure 4: Fringes captured by CCD cameras

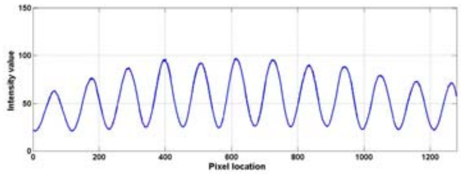
DATA ACQUISITION AND REDUCTION

In this testing system, the load was induced by the loading stage and recorded by the load cell attached to the fixture of the specimen. The fringes were recorded by the CCD cameras during each step of the loading.

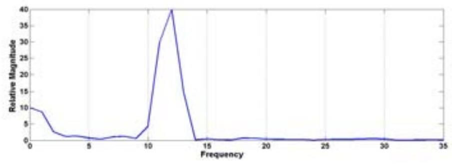
As discussed in the optical basics of ISDG, the displacement and strain of the specimen can be calculated from the motion of the fringe pattern, i.e. the phase shift of the fringe. The motion in each fringe pattern is the sum of both rigid body motion and strain of the specimen. The rigid body motion of the specimen will cause the fringe patterns in both cameras to move in the same direction, while the strain will cause the fringe patterns to move in the opposite direction. Therefore, in order to obtain the strain, a pair of cameras is needed to capture the fringe patterns on both sides of the incident laser beams. The strain is calculated by subtracting the motion of these two fringe patterns:

$$\begin{aligned}\Delta\Phi &= \Delta\Phi_{1\mathrm{total}} - \Delta\Phi_{2\mathrm{total}} \\ &= \Delta\Phi_{1\mathrm{RBM}} + \Delta\Phi_{1\mathrm{strain}} - (\Delta\Phi_{2RBM} + \Delta\Phi_{2\mathrm{strain}})\end{aligned} \quad (7)$$

In Sharpe's work, the fringe is captured using a linear diode array, which can only capture one dimensional information of the fringe. In this work, two dimensional information of the fringe pattern was recorded using CCD cameras, as shown in Figure 4. The values along each column are added and averaged to remove noise. The averaged intensity value versus the row pixel location shows nice sinusoidal curve. By applying FFT, the frequency, as well as the amplitude and phase shift can be calculated for the fringe pattern of each step. The intensity curve and the converted frequency curve are shown in *Figure 5(a) and (b)* for the fringe pattern in Figure 4. Using the load recorded by load cell and the strain obtained from the fringe pattern for each step during the loading, the stress and strain curve for LIGA specimen can be obtained. *Figure 6* shows a stress-strain curve obtained using ISDG method. The edge length of the marker is about 25µm. The original space between the two markers is 150 µm.



(a)



(b)

Figure 5: (a) Intensity curve and (b) the FFT result of the intensity curve for the fringe pattern in figure (4)

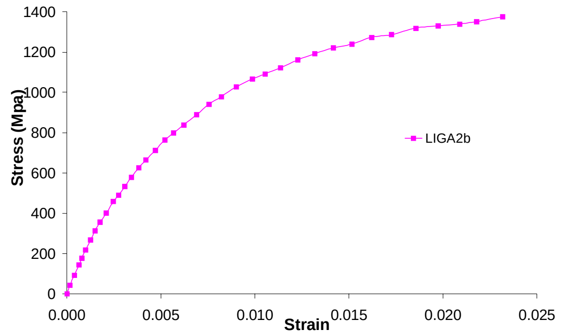


Figure 6: Stress-strain curve obtained using ISDG

MULTI MARKERS ISDG MEASUREMENT

From equation (1), we know that the fringe location and fringe number are decided by the space of the two markers and the incident laser angle. In order for CCD cameras to capture enough fringes to obtain the phase shift information, the space between the two markers is usually a couple of hundred micrometers. With some inevitable rigid body motion of the specimen, it is possible that the markers will move out of the laser spot during loading. One benefit of using multi markers in the longitudinal direction is that there will always be markers in the laser spot to generate fringes even the displacement is large during loading. When one marker moves out of the laser spot, a different marker will move in to form new marker pair(s) and generate fringes. Another benefit of using multi markers ISDG is to measure non-uniform strain over the specimen for inhomogeneous materials. The markers at different location can measure the local strain at that location.

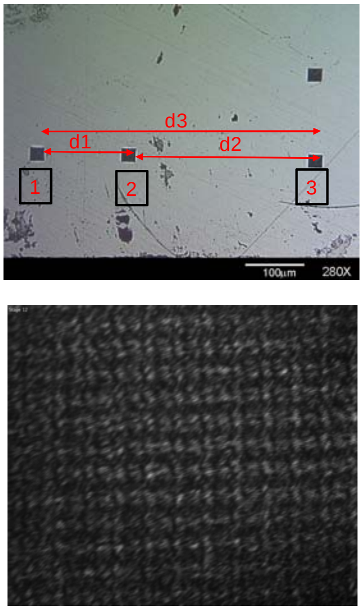


Figure 7: (a) Multi markers on the specimen and (b) The fringes from the multi markers

In this work, the strain measurement using multi markers ISDG is demonstrated on the LIGA specimen from the same fabrication batch as the previous uniaxial strain measurement specimen. The markers generated by micro-hardness indents and the corresponding fringes are shown in *Figure 7*(a) and (b). There are three markers pairs and Figure 7(b) includes three sets of fringes. The stress-strain curves obtained from these three markers are shown in *Figure 8*. It is clearly shown that the results from three sets of fringes are very consistent with each other. The curve also agrees well with the result of other LIGA specimen shown in Figure 6.

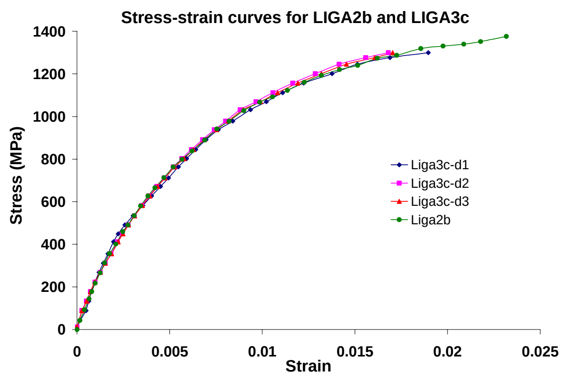


Figure 8: Stress-strain curves from multi markers ISDG

BIAXIAL ISDG MEASUREMENT

Biaxial strain measurement can be accomplished using laser interference in both longitudinal and transverse directions. Another indent marker is added orthogonal to the pair along the longitudinal direction to generate the fringe to measure the transverse strain. The three indents markers and the according fringe patterns are shown in *Figure 9*. The indents 1, 2 are generating fringes for longitudinal strain measurement and indents 2, 3 are generating fringes for transverse strain measurement. The spaces d_1 and d_2 are both equal to 150µm. In order to capture the fringe patterns in both directions, four CCD cameras are needed to record the fringe images. The experimental configuration for the biaxial strain measurement is shown in *Figure 10*, where the Camera 1 and 2 pair records fringe patterns for longitudinal strain measurement and the camera 3 and 4 pair records fringe patterns for transverse strain measurement.

Two biaxial strain measurement tests were conducted on another patch of LIGA specimens. One specimen was linearly loaded and unloaded before yield and the specimen was then loaded again. The Young's modulus and Poisson's ratio is obtained from the linear loading region of the stress-strain curve, $E = 145.9 GPa, v = 0.403$. The second specimen was loaded beyond yield and then unloaded. The Young's modulus and Poisson's ratio is obtained from the unloading portion of the stress-strain curve, $E = 149.9 GPa, v = 0.392$. The stress-strain curves for these two specimens are shown in *Figure 11*. The stress-strain curves match very well.

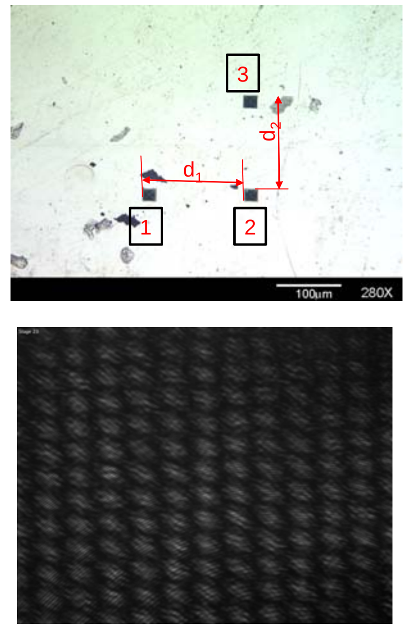


Figure 9: (a) Orthogonal markers for biaxial strain measurement and (b) Fringe patterns generated by the markers

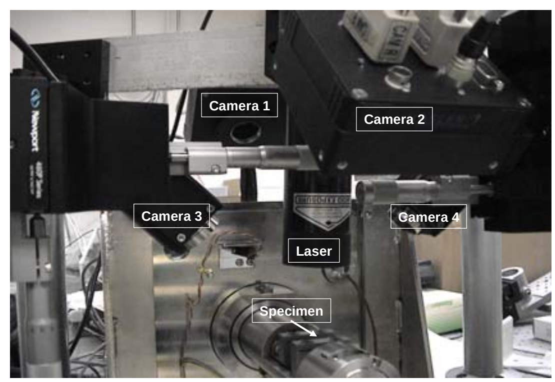


Figure 10: Experimental configuration for biaxial strain measurement

CONCLUSIONS

The non-contact laser interferometry strain/displacement gage technique can be successfully applied to measure LIGA material properties. The micro-hardness indents generate reflection markers on the LIGA specimen surface for strain measurement. CCD cameras enable to capture two dimensional information of the fringe pattern. By applying the FFT to the fringe pattern, the frequency and phase shift can be calculated for each step of the loading. The multi markers ISDG measurement shows consistent stress-strain relation over the gage section for the LIGA specimen. The biaxial strain measurement using ISDG can provide both longitudinal and transverse strains of the LIGA specimens and obtain Young's modulus and Poisson's ratio simultaneously.

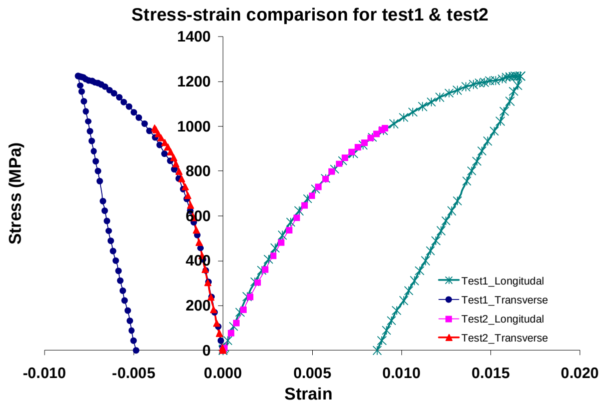


Figure 11: Stress-strain curves from biaxial ISDG measurement

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