OUT-OF-PLANE ESPI TECHNIQUE FOR MEASURING BULGE DEORMATION

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Abstract: Out-of-plane ESPI ESPI (Electronic Speckle Pattern Interferometric) technique was developed for measuring the bulge deformation of the film material obtained from the bulge test. In this study, the bulge test was carried out using the copper film 18 μm thick and with the bulge testing system including the ESPI system. It can be verified that the 3-dimensional profiles of the deformation measured for the rectangular and square windows were simulated with the cylindrical and spherical vessel models, respectively. From the test, pressure-deformation curve were obtained by consequently acquiring the speckle patterns of the bulged membrane. Furthermore, the stress-strain curve could be determined from the pressure-deformation curve and the elastic modulus for the copper film were determined.

Keywords: **out-of-plane ESPI, thin film material, bulge test, membrane window, mechanical properties**

1. INTRODUCTION

Bulge test has been known as a test for measuring micro-mechanical properties of nano-crystalline film materials. This method can be compared to other testing methods, like micro-tensile testing, nano-indentation, and membrane deflection test, which were used in measuring the properties.[1]. In general, the bulge test method, as an indirect method for measurement of mechanical properties, has an advantage of relatively easy preparation of the specimen. To determine the mechanical properties from the bulge test, the bulge deformation of the film specimen isolated in a film window should be measured. For most bulge tests, the bulge height, as the bulge deformation, is measured at the center of the film with height measurement system like PSD(position sensitive detector). However, actually, it may not be easy to measure the maximum height of the film due to the uncertainty for finding the position over the film for real maximum height. Therefore, the more reliable determination of the properties may be provided with the overall deformation measurement over the bulge window. So, in this study, the out-of-plane ESPI (Electronic Speckle Pattern Interferometric) technique was examined to measure the bulged shape over the film window.

2. OUT-OF-PLANE ESPI SYSTEM AND BULGE TESTING SYSTEM

2.1 Bulge deformation measurement system

The out-of-plane ESPI system can measure the 3-dimensionally deformed shape for the specimen showing out-of-plane deformation.[2] The ESPI system used in this measurement was prepared with optical arrangement sensitive to out-of-plane displacement as shown in Fig. 1, where a laser source was divided into object beam and reference beam with the ratio of 95:5. The object beam reflected from the specimen was interfered with the reference beam and then the two interfered beams generated a speckle pattern. Fig.2 presents a typical speckle pattern obtained from bulge test. Here, the speckle pattern corresponds to an out-of-plane deformation of the film subjected to a bulge pressure. The out-of-plane deformation could be obtained from the subsequent comparison of the corresponding speckle patterns and the relative out-of-plane deformation could be determined with a resolution of $\lambda/2$. High frequency noises included in the speckle interference patterns were minimized with 4 buckle phase shitting technique[3]. The relative out-of-plane deformation, d_z, could be determined from the phase difference, $\Delta\Phi$, between these patterns using the following relationship.

$$d_z = \frac{\lambda}{2\pi} \frac{\Delta\phi}{(1+cos\theta_i)} \qquad (1)$$

Here, λ and θ_i indicate the wavelength of the He-Ne laser source used in the out-of-plane ESPI system and the incidence angle to the film, respectively. Fig. 2 presents a typical interference speckle pattern obtained from the measurement of bulged deformation with the ESPI system

2.2 Bulge test system

In bulge test, a membrane window surrounding to the fixed frame or substrate frame prepared in a two-dimensional shape like circular or rectangular shape is exposed to the pressure and the film within the window is bulged with the applied pressure. Figure 3 illustrates the schematic diagram of the bulge testing system, used in this study, for applying pressure and measuring the deformation
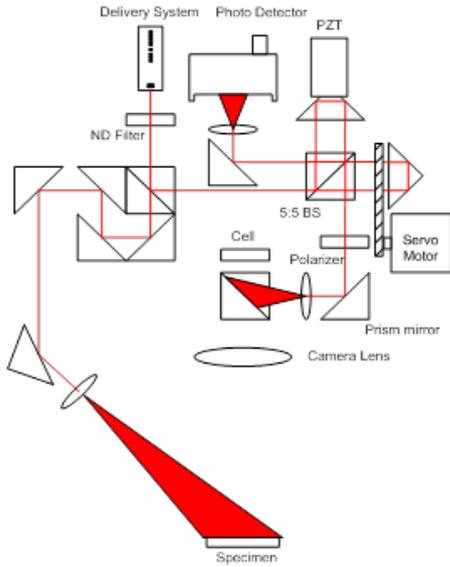
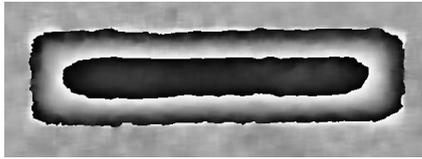Fig. 1 Arrangement of speckle interferometer sensitive to out-of-plane displacement

Fig. 2 Typical speckle pattern of the bulged film .

of the film with out-of-plane ESPI system. In this system, the bulge pressure was introduced to the internal chamber linked to the membrane window with a syringe (1700 Series Gastight syringe), where the oil pressure was generated with the syringe plunger controlled with a resolution of 1 μm/pulse. For reliably measuring the elastic modulus of the fillm, the pressure was needed to be controlled in consequent pressuring and unpressurizing processes. These processes was programmed with Visual C++6.0.
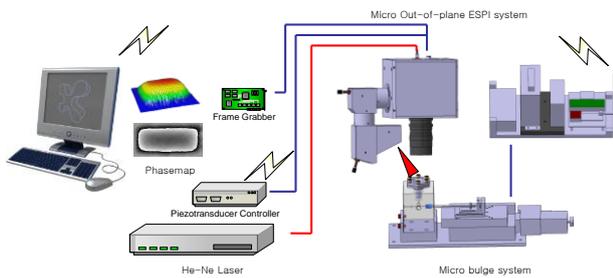

Fig. 3 Schematic diagram of the out-of-plane micro-ESPI system and bulge testing system developed in this study

3. Measurement results and discussion

3.1 Measurement of bulge shape and deformation

In order to determine the mechanical properties from the bulge test, the bulge deformation of the film specimen should be measured. In this study, the deformation was measured using the out-of-plane ESPI system shown in Fig.

3, and the copper film 18 μm thick was used. Two types of membrane windows were prepared in rectangular and square windows with the aspect ratio of b/a=4, 2.5x10 mm^2 and b/a=1, 3.5x3.5 mm^2, respectively. The film was mounted with adhesive on the specimen mounting plate with the bulge window which was installed on the pressure chamber with a fixing clamp. The pressure which was delivered through the syringe with a constant ratio was imposed on the film over the bulge window and then the film within the window started to be deformed with increasing pressure. The deformation of the 3-dimensionally bulged film could be measured with the out-of-plane ESPI system. Fig. 4 presents the typical speckle pattern of the deformation and the profile of the deformation in the longitudinal and transverse directions for the rectangular and square windows, respectively. The deformation could be visualized in the 3-dimension as shown in Fig. 5. As can be seen in Fig. 3(a) and Fig. 4(a), the deformations observed from the rectangular window was nearly uniform in the longitudinal direction except end edge region of the window and the 3-dimensional profile was considerably similar to a half-sectioned cylinder. Similarly, the 3-dimensional profile of the deformation from square window was spherical shape, as shown in Fig. 4(b) and Fig. 5(b). So, from these measured profiles, it was found that application of the thin-walled cylindrical and spherical vessel models for the rectangular and square windows are reasonable and the in-plane stress condition can be assumed for calculation of the stress..

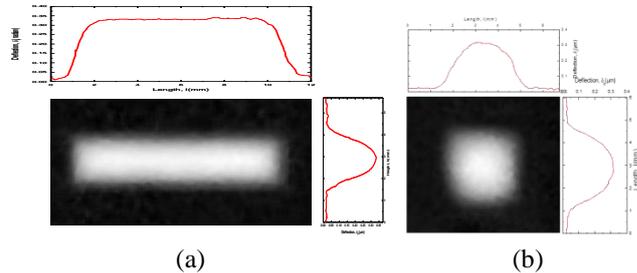(a)   (b)

Fig. 4 Typical profile of the deformation of the bulged film measured with the out-of-plane ESPI system for (a) the rectangular and (b) square window.
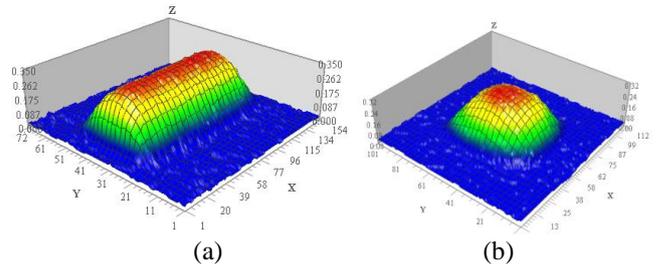

(a)   (b)

Fig. 5 3-dimensional visualization of the deformation observed for (a) rectangular and (b) square windows

The cylindrical vessel model simulating a rectangular membrane is infinitely long in the longitudinal direction, the deflection of the membrane in the transverse direction is a parabola. So the deflection w(x) can be written as:

$$w(x) = \frac{h_0}{a^2}(a^2 - x^2) \qquad (2)$$

with the origin of the x coordinate in the center of the rectangular membrane.[4,5] The height of the membrane deflection measured as in Fig. 4 and 5 can be checked to be a parabola in the transverse direction of the membrane. Fig. 6 represents the comparison of the measured heights of the membrane deflection at the different differential pressure levels to those fitted according to Eq.(2), Here, the symbols and lines indicate the measured values and fitted values, respectively. It can be seen that the bulge height can be excellently described by a parabola over the overall region except the membrane boundary edge region.
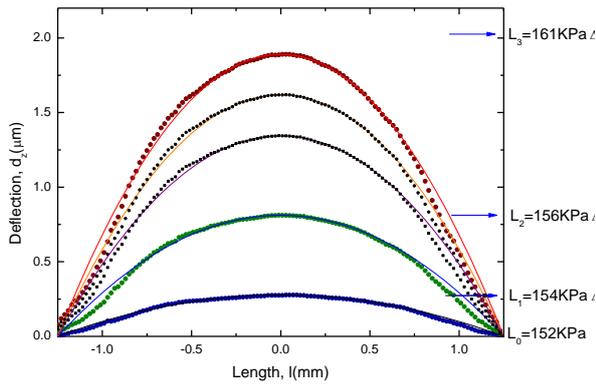

Fig. 6 Comparison of the measured heights of the membrane deflection with those fitted to Eq. 2 at the different differential pressure levels.

In this bulge test, the membrane deformation increased with increasing differential pressure. So, the increment of deformation was consequently measured as shown in Fig. 7. The speckle patterns could be observed at the different pressure levels, and the patterns was converted to the relative increment of the bulge height at the respective pressure levels, as mentioned before. These consequent observations of the speckle patterns can be driven to the pressure-deformation curve as shown in Fig. 8.
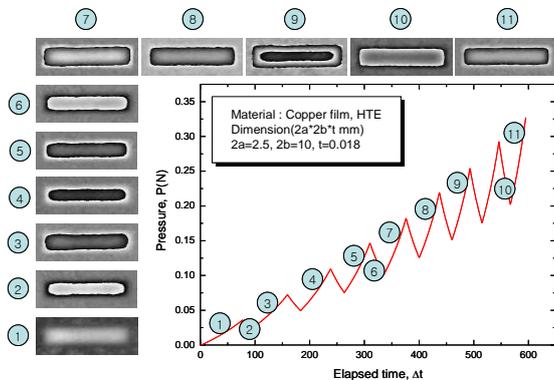

Fig. 7 Pressure-time curve and interferometric speckle patterns corresponding to the respective loading and unloading steps for Copper film
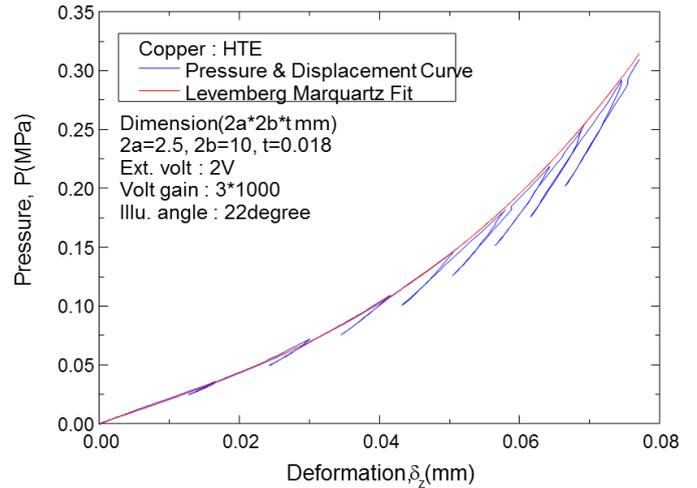

Fig. 8 Typical pressure-deformation curve for copper film

3.2 Measurement of mechanical properties of the film
From the respective cylindrical or spherical vessel models simulating rectangular or square membrane window shown in Fig. 4 and 5, the stress σ_x in the transverse direction can be expressed as a function of the differential pressure and membrane deflection. The stress and strain relationship can be expressed as follows;

$$\sigma = \frac{Pa^2}{2ht} \qquad \text{for the rectangular window} \qquad (3)$$

$$\sigma = \frac{Pa^2}{4ht} \qquad \text{for the square window}$$

$$\varepsilon = \varepsilon_0 + \varepsilon_{\text{bulge}} = \frac{\sigma_0}{M} + \frac{2h^2}{3a^2} \qquad (4)$$

Here, σ_0, M, P, t, h present residual stress, biaxial elastic modulus, applied pressure, thickness of the film, bulge height, respectively.
Using Eq. (3) and (4), stress and strain values could be determined and then the stress-strain curve could be constructed as presented in Fig. 9. Fig. 9 is the biaxial stress-strain curve for the copper film used in this study. From this curve, the elastic modulus and residual stress could be determined, where residual stress, σ_0, was 96.1 MPa and the elastic modulus was obtained 73.2 ± 1.1 GPa assuming the Poisson ratio of 0.34. The modulus was found to be identical to the value determined from micro-tensile test[6].

4. CONCULUSIONS AND SUMMARY

The bulge deformation of the copper film 18 μm thick was measured during bulge test using the out-of-plane ESPI system developed in this study.
1. The bulge profiles of the membrane with rectangular and square window were visualized in 3-dimension from the

speckle patterns observed using the out-of-plane ESPI system and verified to be simulated with cylindrical and spherical vessel model.

2. The pressure-deformation curve of the film could be obtained by consequently acquiring the speckle patterns of the bulged membrane and the stress-strain curve could be determined from the pressure-deformation curve using the stress and strain relationships based on the cylindrical and spherical vessel models,

3. From the stress-strain curve of the film, the elastic modus of the copper film was determined 73.2 ± 1.1 GPa which was identical to the value determined from micro-tensile test.
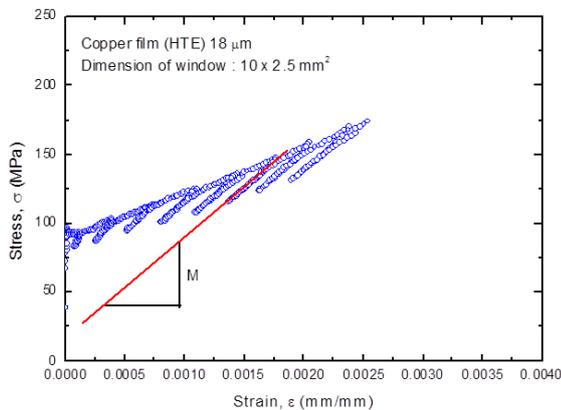

Fig. 9 Stress-strain curve for the copper film

5. REFERENCES

[1] Mohamed Gad-el-Hak, The MEMS Handbook, CRC Press, 2002.

[2] Y.-H. Huh, D.-I. Kim, D.-J. Kim, H.-M. Lee, S.-G. Hong, J.-H. Park and C.-D. Kee, "Measurement of Mechanical Properties of Thin Film by Membrane Deflection Test", Exp. Mech. Vol.50. no. 4, pp. 429-435, 2010

[3] D. I. Kim, Y. H. Huh, C. D. Kee, Out-of-plane Micro-ESPI System for Measurement of Mechanical Proper-ties of Film Materials, Key Engineering Materials, 321-323, (2006) 116-120, 2006

[4] J. J. Vlassak, W. D. Nix, A new bulge test technique for the determination of Young's modulus and Poisson's ratio of thin films, J. Mater. Res. 7(12), pp.3242-3249, 1992.

[5] J. J. Stoker, Non-Linear Elasticity ~Gordon and Breach, London, 1968

[6] Y.H. Huh, D. I. Kim, C. D. Kee, Measurement of Continuous Micro-Tensile Strain Using Micro-ESPI Technique, Key Engineering Materials, 297-300, (2005) 53-58