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Development and Verification of PZT Actuating Micro Tensile Tester for Optically Functional Materials

Seung-Soo Kim, Hye-Jin Lee*, Hyoung-Wook Lee, Nak-Kyu Lee,
Chang-Soo Han, and Jai-Hyuk Hwang

Abstract: This paper is concerned with the development of a micro tensile testing machine for optically functional materials such as single or poly crystalline silicon and nickel film. This micro tensile tester has been developed for testing various types of materials and dimensions. PZT type actuation is utilized for precise displacement control. The specifications of the PZT actuated micro tensile testers developed are as follows: the volumetric size of the tester is desktop type of 710mm′ 200mm′270mm; the maximum load capacity and the load resolution in this system are 1Kgf and 0.0152mgf respectively and; the full stroke and the stoke resolution of the PZT actuator are 1000μm and 10nm respectively. Special automatic specimen installing and setting equipment is applied in order to prevent unexpected deformation and misalignment of specimens during handling of specimens for testing. Nonlinearity of the PZT actuator is compensated to linear control input by an inverse compensation method that is proposed in this paper. The strain data is obtained by ISDG method that uses the laser interference phenomenon. To test the reliance of this micro tensile testing machine, a 200 μm thickness nickel thin film and SCS (Single Crystalline Silicon) material that is made with the MEMS fabrication process are used.

Keywords: Micro tensile tester, PZT actuation, automatic specimen setting system, MEMS, SCS, nickel thin film, ISDG.

1. INTRODUCTION

It is forecasted that market demands on ultra-micro sized optically functional components rapidly increase in next generation display devices or optical communication industries. Applications of optically functional components are the reflecting plate in the LCD back light unit, optical connecting array, optical rheotome, reflecting plate in LED light source, and etc. Since these high priced core components require great precision and accuracy, evaluation of reliability such as the life cycle endurance test, impact test, and residual stress test is necessary for these components. However, in practice, real reliability tests are not easy to perform due to consideration of various factors. Rather than actual testing, it would be much easier to evaluate the reliability of components by the analytical approach. Although the analytical method [1] is utilized by software tools, it is obviously necessary to acquire fundamental properties of materials through real test methods.

Test methods for fundamental properties include the tensile test, bending test, hardness test and resonance test. Among these tests, the tensile test is the most efficient method because it directly measures elastic modulus, fracture strength and Poisson's ratio without any conversion using special equations.

However, the micro tensile test requires precise alignment of the specimen and reliance of the testing machine itself because of the miniaturized specimen.

Many researchers have studied micro tensile tests in order to overcome these restrictions, especially in the case of gripping methods and tensile forcing methods. Greek and Johansson [2] made the testing machine inside the SEM chamber using a load sensor with a strain gauge and PZT actuation. Tsuchiya et al. [3] studied gripping method utilizing electrostatic force

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Seung-Soo Kim, Hye-Jin Lee, Hyoung-Wook Lee, and Nak-Kyu Lee are with the Production Technology Division, Korea Institute of Industrial Technology, 994-32, Dongchun-dong, Yeonsu-gu, Incheon 406-130, Korea (e-mails: {sskim, naltl, hwlee, nklee}@kitech.re.kr).

Chang-Soo Han is with the Faculty of Mechanical Engineering, Hanyang University, 1271, Sa1-dong, Sangrok-gu, Ansan-si, Gyeonggi-do 425-791, Korea (e-mail: cshan@ anyang.ac.kr).

Jai-Hyuk Hwang is with the Faculty of Aerospace and Mechanical Engineering, Hankuk Aviation University, Goyang-ity, Gyeonggi-do 412-791, Korea (e-mail: jhhwang@hangkong. ac.kr).

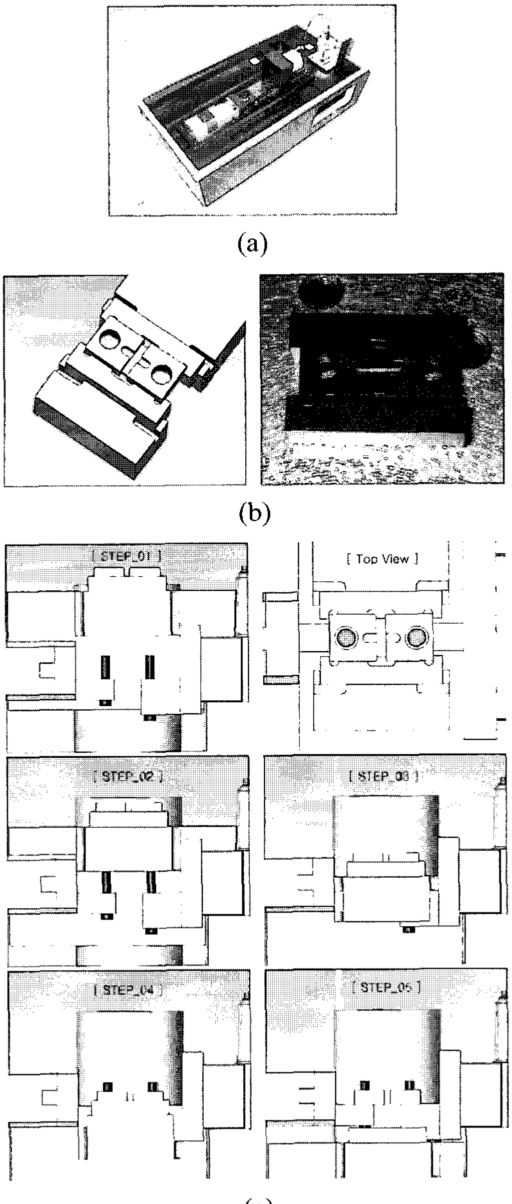
* Corresponding author.

Table 1. Micro tensile tests' results with various schemes. [Reproduced from [10] in 1999]

	Method of Measurement		Results		Specimen		
	Load	Displacement	Young's Modulus [GPa]	Fracture Strength [GPa]	Size w×t[μm]	Material	Gripping Method
Greek (1997)	Strain Gage	Optical Encoder	167	1.25	10×10	Polysilicon	Insertion
Tsuchiya (1998)	Strain Gage	Strain Gage	-	2.5	2~5×2	Polysilicon	Electrostatic
Ogawa (1997)	Load Cell	Microscope	96	0.95	300×0.5	Titanium	Screw
Chasiotis (1998)	Load Cell	AFM	132	-	50×1.9	Polysilicon	Electrostatic
Sharpe (1997)	Load Cell	Interferometry	176	0.56	200×200	Nickel	Insertion
Sharpe (1997)	Load Cell	Interferometry	168	1.21	600×3.5	Polysilicon	Glue
Suwito (1997)	Sensing Beam	Displacement Sensor	-	1.2	28×15	SCS	Glue
Yi (1999)	Load Cell	Interferometry	169	1.2	100×5	SCS	Glue

instead of adhesion. Ogawa et al. [4] made a tensile tester using a DC servo motor and Young's modulus, and the fracture strength of the micro-fabricated thin film of titanium with 0.5mm thickness using a microscope and two CCD cameras. Chasiotis and Knauss [5] marked two lines of gold on a poly silicon specimen and calculated the strain using AFM. Sharpe et al. [6-8] proposed the ISDG (interferometric strain displacement gauge) method. They used poly silicon and nickel film as a sample material and deposited a gold line marker on it. Yi and Kim [9,10] developed a tensile tester using the ISDG method and verified the tester developed using single crystalline silicon (SCS). These results are summarized in Table 1.

In this paper, a PZT actuating type micro tensile testing machine has been developed for application to various types of materials including metallic materials, polymer materials and single crystalline silicon. This tester is designed to easily test a miniaturized specimen. The 200 μm thickness nickel thin film and SCS MEMS fabricated specimens are used to test the reliability of this PZT actuated micro tensile testing machine. The PZT actuated tensile testing machine was equipped with special automatic specimen installing equipment in order to prevent undesirable deformation and misalignment of specimens during handling of specimens for testing. The control method using the inverse function of the nonlinearity curve of the PZT actuator is applied to this system to compensate the nonlinearity of the PZT actuator.


(a)

(b)

(c)

Fig. 1. (a) Micro tensile tester with PZT actuator (b) Automatic specimen-setting device (c) Automatic specimen-setting procedure (pin type grip).

2. DEVELOPMENT OF PZT ACTUATING TYPE MICRO TENSILE TESTING MACHINE USING THE COMPENSATING NONLINEARITY METHOD

The PZT actuated tensile tester is constructed in horizontal fashion as shown in Fig. 1(a). The PZT actuator generally has a very high stroke resolution in relatively small displacement range although the full stoke is almost 1mm. Since the applied voltage to the PZT produces the actuation, more precise control can be possible when the relation between voltage and displacement of the PZT is linear.

A vertical load removing system is designed using a LM guide and ball screw to prevent the deflection of specimens by their weight under horizontal testing.

Tensile testing of a micro sized specimen is difficult to perform due to the size of the specimen. It is necessary that the experimenter's dependence should be eliminated at the installation stage in order to ensure and increase the repeatability. In this paper, an automatic specimen-setting device is developed using the micro stepping motor with the resolution of 0.1μm in a vertical direction with respect to the stroke. Fig. 1(b) shows this special equipment. The procedure of the automatic specimen setting is shown in Fig. 1(c). The specification of this tensile tester is also summarized in Table 2.

PZT actuators generally have unique nonlinearity by the inversion appearance of spontaneous polarization that occurs by the electric and mechanical combination of the ferroelectricity. The PZT actuator for the micro tensile tester also has this feature as shown in Fig. 2.

Table 2. Specification of PZT actuating micro tensile testing machine.

No.	Description	PZT actuation
1	Max. Load Capacity [gf]	1000
2	Load Resolution [gf]	0.0152
3	Full Stroke [μm]	1000
4	Stroke Resolution [nm]	10
5	Max. Velocity [mm/min]	1200
6	Min. Velocity [mm/min]	0.0006
7	Data Acquisition Res.	A/D:16bit, D/A:16bit
8	Environmental Factor	0°C ~ 50°C, 10%~90% RH
9	System Frame	Anodized Aluminum Frame
10	Size [mm^3]	710×200×270
11	Etc.	Anti-vibration pad Image system with CCD

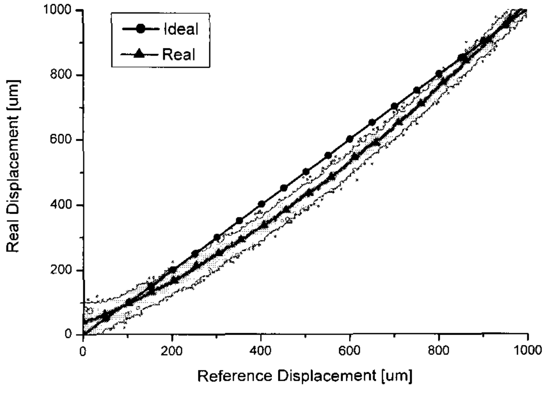


Fig. 2. Nonlinearity of the PZT actuator for the micro tensile tester.

To improve the reliability of micro tensile tests, a method for compensating nonlinearity is proposed.

This paper adopted the method that compensates the nonlinearity by using the inverse function of the nonlinearity curve of the PZT actuator as a control method.

First, in order to test the nonlinearity of the PZT actuator, a potentiometer was used as shown in Fig. 3. In the same conditions 10 tests were repeated, and the averaged nonlinearity curve was extracted from the acquired 10 test results by using the moving average method. Then the 2nd order polynomial curve fitting process was carried out in relation to the averaged nonlinearity curve.

(1) is the nonlinearity curve function of the PZT actuator for the micro tensile tester.

$$y_{real} = au_{ref}^2 + bu_{ref} + c, \tag{1}$$

where

u_{ref} = *reference displacement*,

y_{real} = *real displacement*,

$a = 0.40430$, $b = 0.58216$, $c = 0.03522$

The inverse function as a control input compensating the nonlinearity can be derived as follows

$$au_{ref}^2 + bu_{ref} + c - y_{real} = 0, \tag{2}$$

$$u_{ref} = \frac{-b \pm \sqrt{b^2 - 4a(c - y_{real})}}{2a}. \tag{3}$$

Because the minus sign is not valid, only the plus sign is used.

Therefore the control input equation using the inverse function of the nonlinearity curve function is

$$u_{ref} = \frac{-b + \sqrt{b^2 - 4a(c - y_{real})}}{2a}. \tag{4}$$

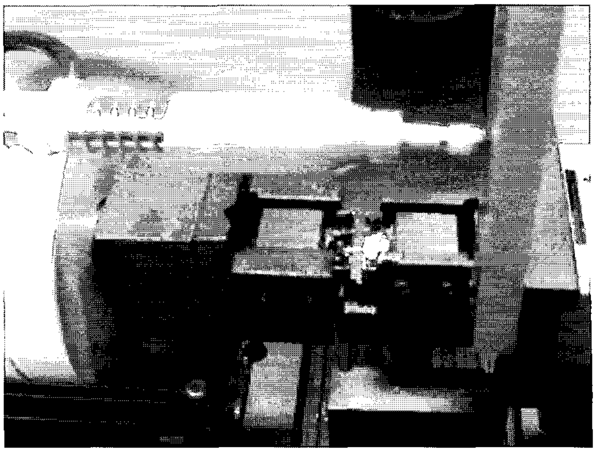


Fig. 3. Micro tensile tester configuration.

Fig. 4 shows the comparison between the compensated control input using (4) and the non-compensated one.

Fig. 5 shows that the compensated real displacement output is nearly equivalent to the ideal one.

To prove whether the real displacement output by the PZT actuator is linear or not in relation to the test speed variation, several tests have been carried out. Table 3 indicates the relationship between test speeds and the linearity of real displacement output. 10 tests have been carried out in each speed, and the averaging process using the moving average method and the linear curve fitting have been performed. As well, the coefficients and the percent error of the coefficients of the curve fitted function were presented in Table 3. Finally, the linearity of the real displacement output is independent of the test speed.

Therefore the method of compensation using the inverse function of the nonlinearity curve of the PZT actuator can be suitably applied to the micro tensile tester.

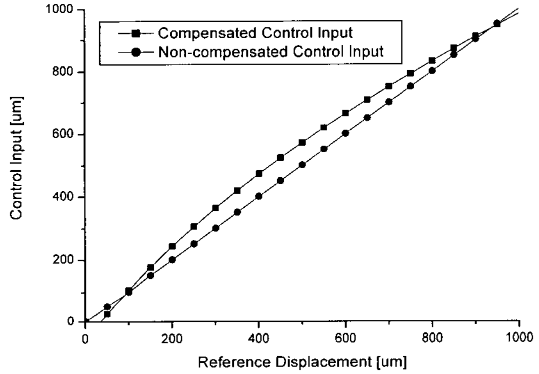


Fig. 4. Comparison of control inputs.

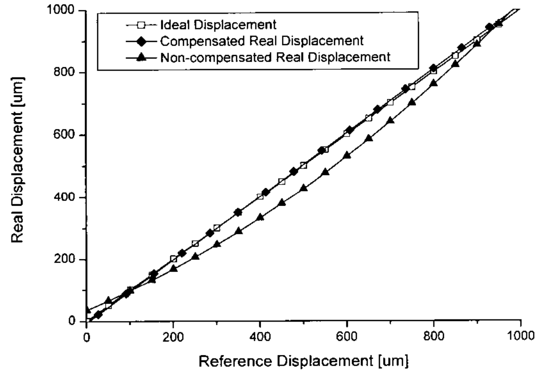


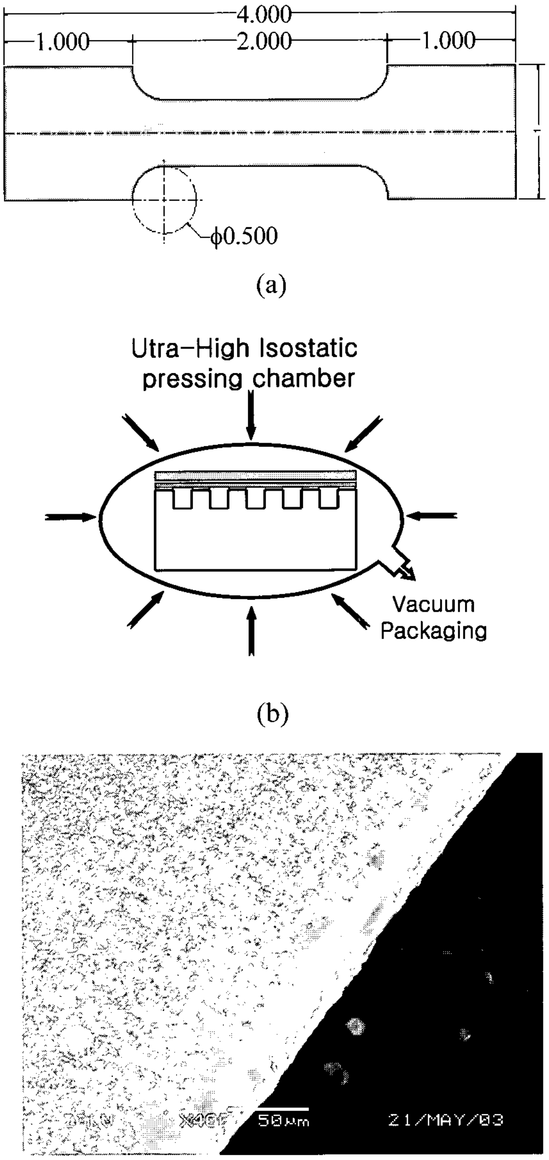
Fig.5. Comparison of real displacement outputs.

Table 3. Relationship between test speeds and the linearity of real displacement output.

Test Speed [mm/min]	Slope	Error [%]	Y Axis Intercept	Error [%]
0.01	1.01917	1.9	-0.00627	-0.6
0.1	1.02163	2.2	-0.00626	-0.6
1	1.01225	1.2	0.00936	0.9

3. MICRO TENSILE TESTING FOR NICKEL THIN FILM

Micro tensile testing has been carried out with a nickel film, which has been widely used for an optically functional material in recent years. The film for the test is fabricated by electro-deposition with 200μm thickness. The dimension of the specimen is shown in Fig. 6. The specimen is made by the burr-less mechanical pressing process under the vacuum package and ultra-high isostatic pressure of 3000 bars. The side edge of the specimen indicates a clean surface without any burrs. This method is useful for the mass production of a specimen.



(a)

(b)

(c)

Fig. 6. (a) Dimension of nickel specimen (b) Schematic view of specimen fabrication process (c) Surface of the fabricated specimen.

To test precisely, we designed a gripper having a specimen holding adapter in glue type as shown in Fig. 7. This gripper can enable fine alignment of specimen setting by adjusting the specimen holding adapter. This specimen holding adapter makes it easy to set and separate the specimen. Micro tensile testing has been carried out with 0.01mm/min tensile testing velocity.

Load-displacement curves for nickel film are shown in Fig. 8 and maximum loads and their displacements from the two tests (compensated and non-compensated) are presented in Table 4.

In the non-compensated case, as supposed, the initial part of the load-displacement curve also includes nonlinearity. It is presumed that this is due to affection of the PZT nonlinearity.

As a result of the nonlinearity of the load-displacement curve, the elastic region is unclear. Therefore it is certain that the non-compensated case is not reliable. On the other hand, it is shown that the linearity of real displacement output is well reflected in the compensated case.

Fig. 7. Gripping method of nickel specimen.

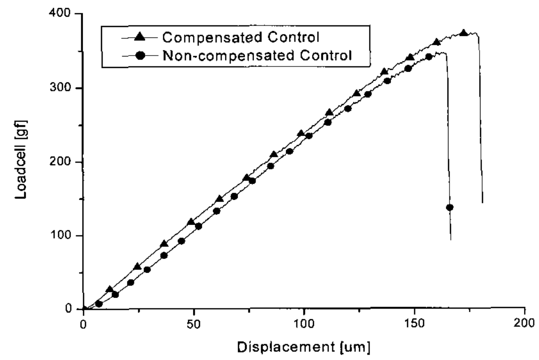


Fig. 8. Test graph of nickel film specimen.

Table 4. Comparison of displacements at maximum load and maximum loads.

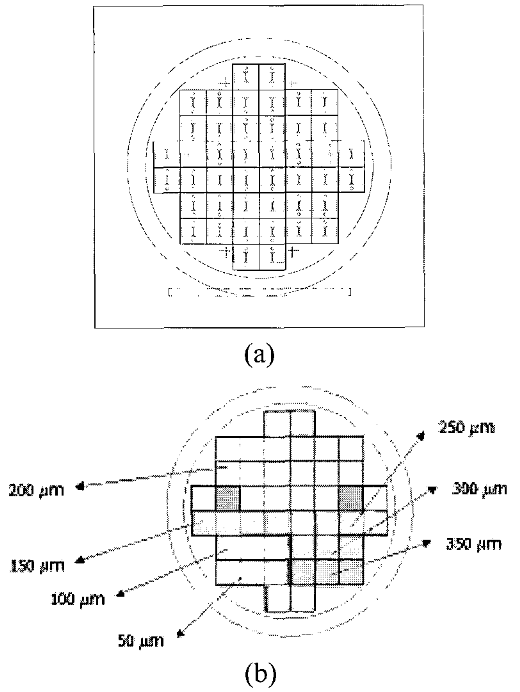
	Compensated	Non-compensated
Displacements at Maximum Load	178.0 um	163.5 um
Maximum Loads	373.7 gf	347.3 gf

As indicated in Table 4, differences between the compensated and the non-compensated test are the result of the nonlinearity. Finally, it is certain that the compensated control input test is well performed.

4. MICRO TENSILE TESTING FOR SCS MATERIAL

The micro tensile testing specimen of SCS (Single Crystalline Silicon) material is made with the MEMS fabrication process. This specimen is fabricated from the boron doping p-type single crystalline silicon wafer. The photo mask for the MEMS fabrication process is shown in Fig. 9.

The MEMS specimen has the shape and dimensions shown in Fig. 10. The parallel length is 2000 ㎛, width of the parallel part is 200 ㎛, width of the gauge



(a)

(b)

Fig. 9. (a) Photo Mask for micro tensile specimen (b) Lattice (Numbers are parallel part widths of micro tensile specimens).

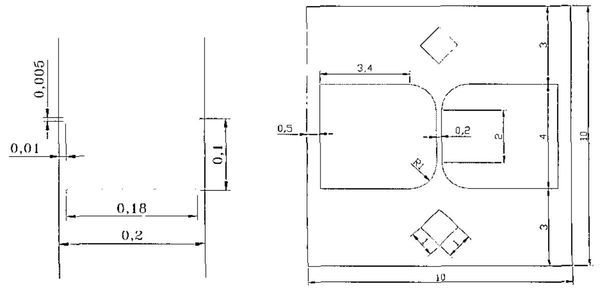


Fig. 10. Dimensions of micro tensile specimen and aluminum gauge mark.

mark is 5 μm, the gauge length is 100 μm, length of the gauge mark is 180 μm, height of the gauge mark is 2 μm and thickness of the specimen is 250 μm. The fabrication process flow chart to make the MEMS specimen is shown in Fig. 11.

The ISDG (Interferometric Strain / Displacement Gage) method is used to obtain the strain data. Gage length for the ISDG is indicated on the parallel part of the MEMS specimen using aluminum marking. The ISDG is the strain measurement method, which uses the irradiated He-Ne laser on the aluminum marking. This laser light is diffracted and interfered because of the double-slit interference phenomenon. Then we can get an interference pattern (fringe) in Fig. 12 that appears when two diffraction patterns are overlapped with each other.

This interference pattern changes to displacement data by the PSD (Position Sensitive Detector) sensor. As distance between the double aluminum marking is extended for the tensile test, the interference pattern moves to a specific direction. As such we can obtain moving position data of the maximum intensity spot in the interference pattern. The ISDG method theory uses the Young's interference phenomenon that is shown in Fig. 13.

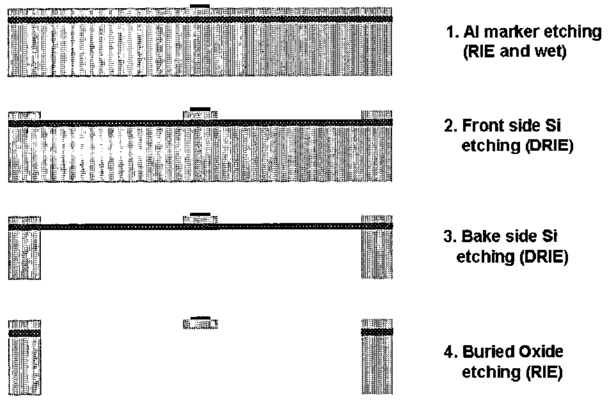


Fig. 11. Fabrication flow chart of micro tensile specimen.

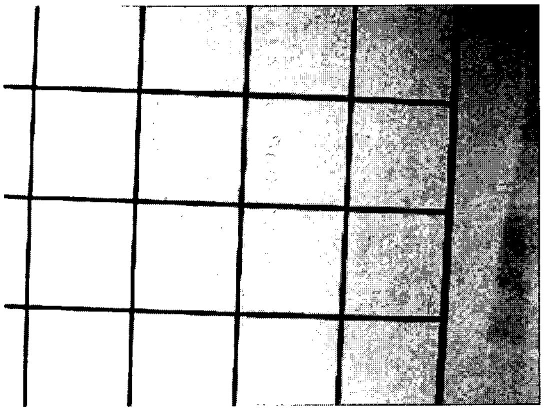


Fig. 12. Fringe pattern from laser diffraction and interference.

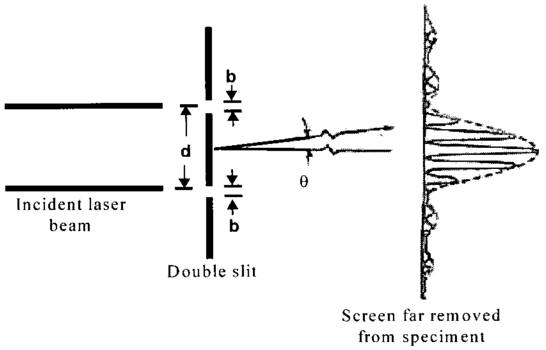


Fig. 13. Schematic of the double-slit interference phenomenon (b: width of slit, d: distance between double slits, θ: angle between incident light and spot on the screen).

The light diffraction phenomenon occurs when a ray of light passes through a small slit. When the distance between the screen and the double slit is larger than d, light intensity on the screen is

$$I = I_0 \sin^2 \beta / \beta^2 , \tag{5}$$

where I_0 : initial intensity of ray of light and

$$\beta = \pi b \sin\theta / \lambda , \tag{6}$$

where λ : wave length of ray of light

This equation means that light intensity changes according to position (θ) of the screen by light diffraction. When $\beta = \pm\pi$, light intensity has the first minimum value and from (6), width of the diffraction pattern is

$$\sin\theta = \lambda / b . \tag{7}$$

In this ISDG system, reflected light on the micro sized aluminum mark is used in compensation for a ray of light that passes through a small slit. Light intensity on the screen is

$$I = I_0 \sin^2 \beta / \beta^2 \times \cos^2 \gamma , \tag{8}$$

where

$$\gamma = \pi d \sin\theta . \tag{9}$$

Maximum angle of diffraction pattern is decided by λ/b and angle interval of the interference pattern is decided by λ/d. Therefore distance between the double aluminum mark can be measured from the interval of the interference pattern. This distance data between the double aluminum mark is a gauge length at arbitrary times during the tensile testing. Finally the engineering strain data measured from the distance data is indicated in (10).

$$\varepsilon = \frac{l - lo}{lo} \tag{10}$$

where

l : gauge length at arbitrary time
l_0 : initial gauge length

Micro material testing system for the SCS MEMS specimen can be constructed with the ISDG module. The system is installed in a darkroom to prevent outside interference and to measure the precise strain data. This system is shown in Fig. 14.

To test the SCS MEMS specimen precisely, the gripping method shown in Fig. 7 is used. The picture of gripper and the SCS MEMS specimen in which the laser is illuminated on the gauge mark is shown in Fig. 15.

Micro tensile testing has been carried out with 0.01mm/min tensile testing velocity. Laser wavelength of the ISDG is 632.8nm and power of the He-Ne laser is 10mW. Two pictures of before and after testing are presented in Fig. 16. These pictures are captured by CCD camera with high magnification lens.

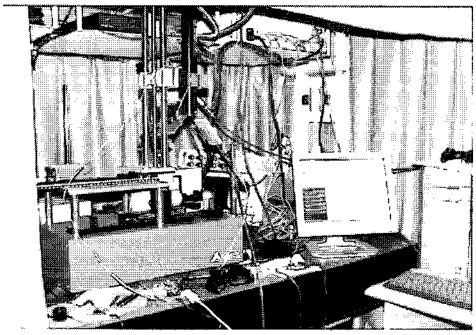


Fig. 14. Photograph of developed micro tensile test system with ISDG system.

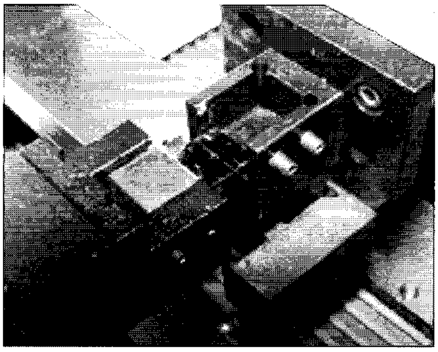
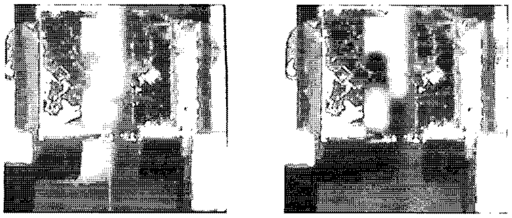


Fig. 15. Gripper of the micro tensile tester and illuminated SCS MEMS specimen.



(a) (b)

Fig. 16. Pictures of specimen (a) Before test (illuminated by laser) (b) Fractured specimen.

The load-displacement curve of the tensile test in the elastic region is shown in Fig. 17. In this graph the displacement is the compensated control displacement. The displacement data from the PSD sensor is indicated in Fig. 18. Each raw data of the PSD sensors are converted to displacement by (9) and the summed result is a curve that is pointed to ΔL at gauge length. To obtain a stress-strain curve, this result is put into (10) to finally achieve a stress-strain curve in Fig. 19.

As a result, the elastic modulus of the boron doped p-type SCS specimen is 79.6GPa in this tensile testing data. This value is similar with the result of 73.1GPa in the paper published by Bhushan and Koinkar.

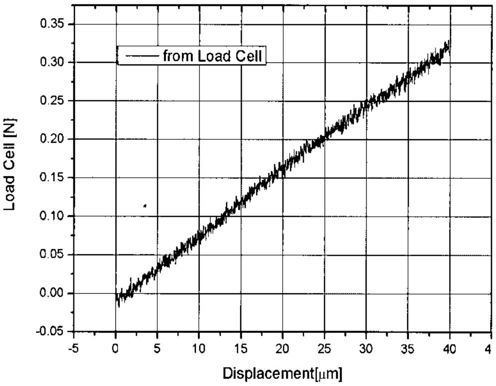


Fig. 17. Load-displacement curve of micro tensile test.

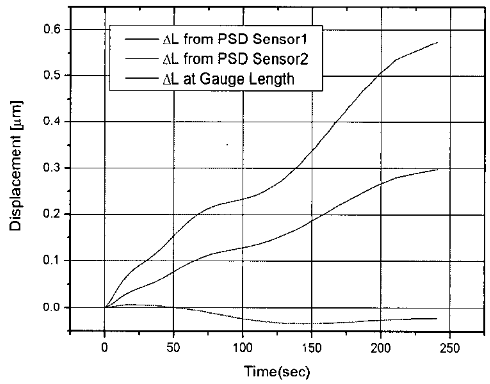


Fig. 18. Displacements from PSD sensor with respect to time.

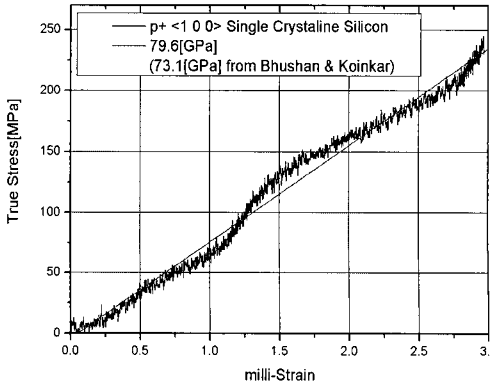


Fig. 19. Stress-strain curve for p-type SCS.

5. CONCLUSION

Micro tensile testing machines have been developed for various types of materials including metallic materials, polymer materials and SCS. The PZT type micro tensile testers are developed considering a load and an elongation limit of materials. Special automatic specimen installing equipment is adopted in order to prevent undesirable deformation. Tests of nickel film and SCS material were carried out in this PZT actuated micro tensile tester that was developed in this paper. PZT actuator that is used in this micro tester has a nonlinearity so linear input can't have a linear output performance. In this paper as a control method, the method which compensates the nonlinearity by using the inverse function of the nonlinearity curve of the PZT actuator was adopted. The linearity of real displacement output is well reflected in the compensated material tensile testing. ISDG method was applied to measure the strain of SCS MEMS specimen. And the result is similar to the results in the paper of Bhushan and Koinkar. The PZT actuating micro tensile tester that uses compensating nonlinear control is well constructed systematically. More various optical material will be applied to this system and the PZT actuated micro tensile tester will be modified in the further study.

REFERENCES

[1] Y. A. Jeon, K. S. No, J. S. Kim, and Y. S. Yoon, "Characteristics of ZnO thin film deposited on various metal bottom electrodes," *Metals and Materials Int.*, vol. 9, no. 4, pp. 383-387, August 2003.

[2] S. Greek and S. Johansson, "Tensile testing of thin film microstructures," *Proc. of SPIE*, vol. 3224, pp. 344-351, 1997.

[3] T. Tsuchiya, O. Tobato, J. Sakata, and Y. Taga, "Specimen size effect on tensile strength of surface-micromachined polycrystalline silicon thin films," *J. Microelectromech. Syst.*, vol. 7, pp. 106-113, 1998.

[4] H. Ogawa, K. Susuki, S. Kaneko, Y. Nakano, Y. Ishikawa, and T. Kitahara, "Measurement of mechanical properties of microfabricated thin film," *Proc. of IEEE Micro Electro Mechanical Systems Workshop*, pp. 430-435, Nagoya, January, 1997.

[5] I. Chasiotis and W. Knauss, "Mechanical properties of thin polysilicon films by means of probe microscopy," *Proc. of SPIE*, vol. 3512, pp. 66-75, 1998.

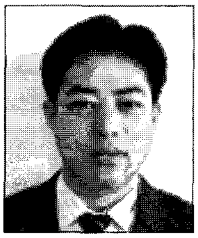
[6] W. N. Sharpe Jr., "An interferometric strain/ displacement measurement system," *NASA Technical Memorandum 101638*, August 1989.

[7] W. N. Sharpe Jr., B. Yuan, and R. L. Edwards, "A new technique for measuring the mechanical properties of thin films," *J. Microelectromech. Syst.*, vol. 6, pp. 193-199, 1997.

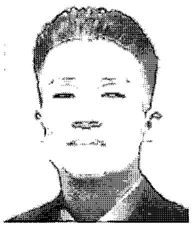
[8] W. N. Sharpe Jr., D. A. LaVan, and R.L. Edwards, "Mechanical properties of LIGA-deposited nickel for MEMS transducers," *Proc. of Int. Conf. Solid-State Sensors and Actuators*, pp. 607-610, 1997.

[9] T. Yi and C. J. Kim, "Microscale material testing: Etchant effect on the tensile strength," *Proc. Int. Conf. Solid-State Sensors and Actuators*, pp. 518-521, Sendai, June, 1999.

[10] T. Yi, Lu Li, and C. J Kim, "Microscale material testing of single crystalline silicon: Process effects on surface morphology and tensile strength," *Sensors and Actuators A: Physical*, vol. 83, no. 1-3, pp. 172-178, May 2000.

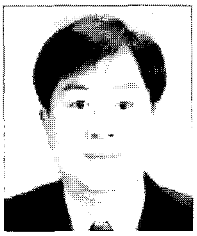


Seung-Soo Kim received the B.S. degree in Die and Mould Design from Seoul National Polytechnic University and the M.S. degree in Production Engineering from Hanyang University. He is currently working towards his doctoral degree in the Department of Mechatronics Engineering at Hanyang University. Since 1991, he has been working at the Korea Institute of Industrial Technology, Incheon where he is currently employed as a Principal Researcher on the Micro Forming Technology Team. His main research interests are mechanical machine design, manufacturing process design and mechatronics.

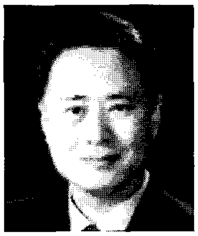


Hye-Jin Lee received the B.S. and M.S. degrees in Dynamic System and Control Design from Hankuk Aviation University. He is currently working towards his doctoral degree in the Department of Dynamic System and Control Design at Hankuk Aviation University. Since 2004, he has been working at the Korea Institute of Industrial Technology, Incheon as a Researcher on the Micro Forming Technology Team. His main research interests are design and control of mechanical machines and mechanical property measurement systems. He also researches piezo actuating precision system design and control, manufacturing process design, and mechatronics.

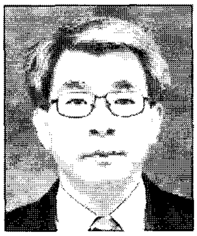
Hyoung-Wook Lee received the B.S., M.S., and Ph.D. degrees in Mechanical Engineering from KAIST, Daejeon Korea, in 1995, 1997, and 2003, respectively. Since 2003, he has been with the Korea Institute of Industrial Technology, Incheon where he is currently employed as a Senior Researcher on the Digital Production Processing Team. His main research interests include mechanical machine design, finite element analysis, micro tensile testers, and digital manufacturing.



Nak-Kyu Lee received the B.S. in Mechanical Engineering from Han Yang University and the M.S. and Ph.D. degrees in Mechanical Engineering from KAIST, Daejeon Korea in 1987 and 1992. Since 2001, he has been working at the Korea Institute of Industrial Technology, Incheon where he is currently employed as a Principal Researcher on the Digital Production Processing Team. His main research interests are metal forming, structural analysis, and micro mechanical design.



Chang-Soo Han received the M.S. and Ph.D. degrees in Mechanical Engineering from the University of Texas at Austin. He worked in the Rockheed Austine Division from 1987 to 1988. In 1990, he joined the Faculty of Mechanical Engineering at Hanyang University, where he is currently employed as a Professor. He was a Visiting Professor at UC Berkeley University in 1996. His main research interests include micro/nano manipulators, service robots, and auto guide vehicles.



Jai-Hyuk Hwang received the B.S. degree from Hankuk Aviation University in 1980, the M.S. from KAIST (Korea Advanced Institute of Science and Technology) in 1982 and the Ph.D. from the University of California, Berkeley in 1990. He worked as a Research Engineer from 1982 to 1986 at KAIST. Since 1990, he has been with the School of Aerospace and Mechanical Engineering at Hankuk Aviation University where he is presently employed as a Professor. His primary research interests are in vibration control, dynamics and control of vehicles, and micro/nano manipulators. He is a member of AIAA, KSME, KSASS, and KSNVE.