STUDY ON EVALUATION METHOD OF DETERMINING YOUNG'S MODULUS USING ULTRAMICRO HARDNESS TESTER WITH SMALL BALL INDENTER

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Abstract: The aim of this study is to determine Young's modulus by means of measured indentation load, depth and elastic recovery displacement of an indenter during loading and unloading processes using a developed horizontal ultramicro hardness tester. In order to determine correctly Young's modulus of materials in narrower and shallower area of nanometer or micrometer level, authors use very small ball indenters that are made by bearing ball of a diameter in 0.3mm and 0.5mm. Several metal specimens [carbon steel, stainless steel, high tension brass and aluminum alloy] are used in test. Young's moduli of metal specimens calculated on the ball indentation theory show good agreements with that of uniaxial compression test. As a result, effectiveness of evaluation method of determining Young's modulus with a small ball indenter is confirmed.

Keywords: Horizontal Ultramicro Hardness Tester, Small Ball Indenter, Young's Modulus

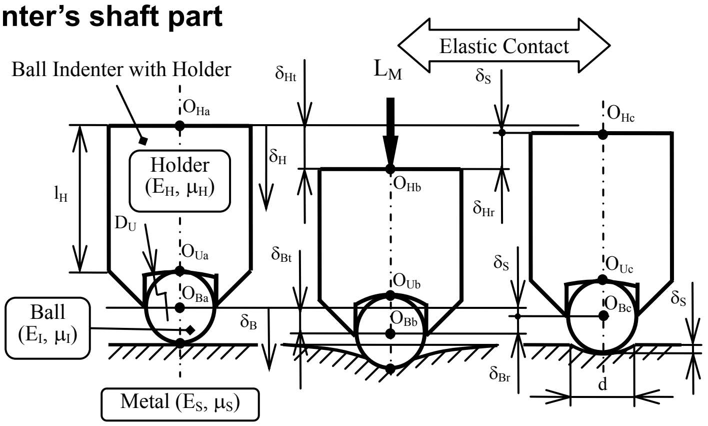
1. INTRODUCTION

Hardness testing is a simple and effective method to determine mechanical characteristics of materials. Recently, many industrial parts become smaller because of miniaturization of industrial products. Usually, the pyramidal indenter e.g. Berkovich or Vickers, have been used mainly in ultramicro hardness testing. But their tips have truncation [1], [2], so it is very hard to decide correct shape of them in the contact area. As compared with pyramidal indenters, tip shape of a ball indenter will be correct if a ball is made by a bearing ball. Therefore, a ball indenter like this may be recommended for determining mechanical characteristics of materials in narrower and shallower area of nanometer or micrometer level.

2. CALCULATION FORMULA OF YOUNG'S MODULUS USING A BALL INDENTER WITH HOLDER

2.1 Elastic deformation of an indenter's shaft part

Contact figures between a ball [D: diameter] indenter with holder [l_H: shaft length, D_U: diameter of spherical hollow part] and a metal's surface during loading and unloading are shown in Fig.1.[3] When the maximum load L_M is applied, elastic deformation δ_{U1} of the contact part between a ball and a holder's spherical hollow part is given by Eq.(1), and elastic deformation of the straight holder's shaft part δ_{U2} is given by Eq.(2).



[E_I· E_S· E_H: Young's modulus, μ_I· μ_S· μ_H: Poisson's ratio]

Fig.1 Contact Figures between a Ball Indenter with Holder and a Metal's Surface during Loading and Unloading

$\{F(E)_{IH}=(1-\mu_I^2)/E_I+(1-\mu_H^2)/E_H=I(E)+H(E)\}$

$$\delta_{U1} = \left[\left(\frac{9}{8}\right)F(E)_{IH}^{\ 2}\left\{1-\left(\frac{D}{D_U}\right)\right\}\Big/D\right]^{\frac{1}{3}}\cdot L_M^{\ \frac{2}{3}} \quad (1),\quad \delta_{U2} = \frac{I_H}{A_H\cdot E_H}\cdot L_M \quad (2)$$

As a result, elastic deformation δ_U of an indenter's shaft part is the sum of δ_{U1} and δ_{U2}.

$$\delta_U = \delta_{U1} + \delta_{U2} = C_1\cdot L_M^{\ \frac{2}{3}} + C_2\cdot L_M \quad (3)$$

when loading-unloading indentation test is carried out, measured displacements δ_{Ht} and δ_{Hr} are displacements of the machine frame. Therefore, relationships between displacements δ_{Ht}, δ_{Hr} of a machine frame O_H and displacements δ_{Bt}, δ_{Br} of a ball center O_B are given by Eq.(4)

$$\left.\begin{aligned}\delta_{Bt} &= \delta_{Ht} - \delta_U\\ \delta_{Br} &= \delta_{Hr} - \delta_U\end{aligned}\right\} \quad (4)$$

A relationship is shown in Fig.2.

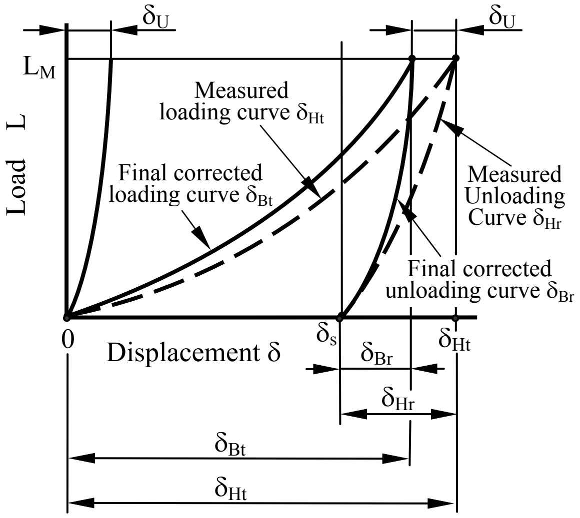


Fig.2 Relationships between δ_{Ht}, δ_{Hr}, δ_{Bt} and δ_{Br}

2.2 Calculation formula of Young's modulus using a ball indenter with holder

From Hertz's elastic contact law [4] between a ball and a spherical hollow metal's surface, a relationship between load L_M, contact diameter d, elastic recovery displacement of a ball center δ_{Br} and elastic parameter $F(E)_{IS}$ $\{=(1-\mu_I^2\}/E_I+(1-\mu_S^2)/E_S=I(E)+S(E)\}$ is given by Eq.(5), and contact diameter d is given by Eq.(6). [5]

$$L_M = \left(\frac{2}{3}\right)\frac{d\cdot\delta_{Br}}{F(E)_{IS}} \quad (5),\qquad d = 2\left[D\left\{\delta_{Bt} - \left(\frac{\delta_{Br}}{2}\right)\right\}\right]^{\frac{1}{2}} \quad (6)$$

Rearranging Eq.(5) and Eq.(6) with respect to E_S, the calculation formula of Young's modulus E_S of a metal specimen is obtained as

$$E_S = \left(1-\mu_S^{\ 2}\right)\Big/\left[\left(\frac{4}{3}\right)\left(\frac{\delta_{Br}}{L_M}\right)\left\{D\left(\delta_{Bt} - \frac{\delta_{Br}}{2}\right)\right\}^{\frac{1}{2}} - I(E)\right] \quad (7)$$

3. EXPERIMENTS

3.1 Indenter and testing machine

In this test, two indenters that have different diameters 0.5mm and 0.3mm are prepared. The cross section of an indenter is shown in Fig.3. The tip part of an indenter is made of a ball-point's tip.

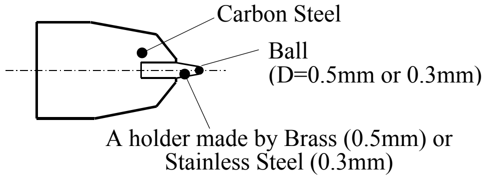


Fig.3 Specifications of an Indenter

Horizontal ultramicro hardness tester is developed as shown in Fig.4. Measurement part of load and displacement is shown in Fig.5. It is possible to compensate for inclination of an indenter by using two linear sensors. This machine moves horizontally, therefore vibration noise caused by gravity is smaller than the machine moves vertically. [6]

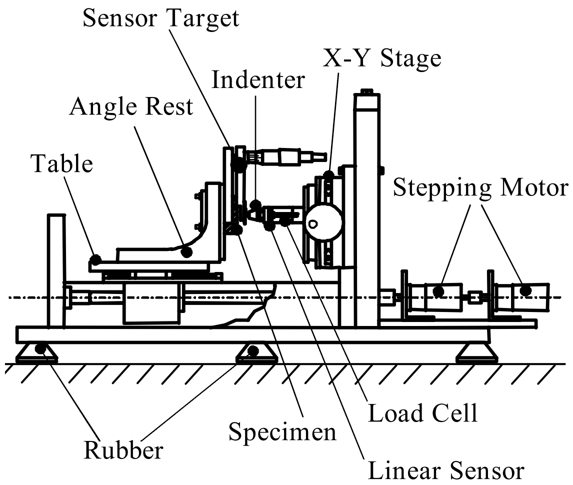


Fig.4 Horizontal Ultramicro Hardness tester (Side View)

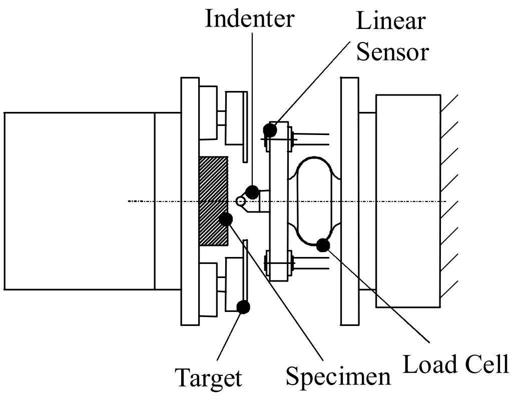


Fig.5 Top View of Measurement Part and Specimen

3.2 Specimens and calibration specimen

Several metal specimens [carbon steel (S45C), stainless steel (SUS304), high tension brass (HB), aluminum alloy (AA)] are prepared. Every specimen's surface is polished by No.2000 Emery paper and by buffed to specular condition. In order to determine experimentally elastic deformation δ_U [Eq.(3)] of an indenter's shaft part, HB specimen [E_S = 101 GPa] is used as a calibration specimen.

4. RESULTS AND DISCUSSIONS

4.1 Indentation curves

An example of the original data is shown in Fig. 6. In Fig.7 and Fig.8, indentation curves for S45C specimen are shown.

4.2 Elastic deformation δ_U of an indenter's shaft part

Loading-unloading indentation tests are firstly carried out for the calibration specimen HB, then elastic deformations δ_U of an each indenter's shaft part with respect to the maximum load L_M are determined experimentally using Eq.(3) as follows.

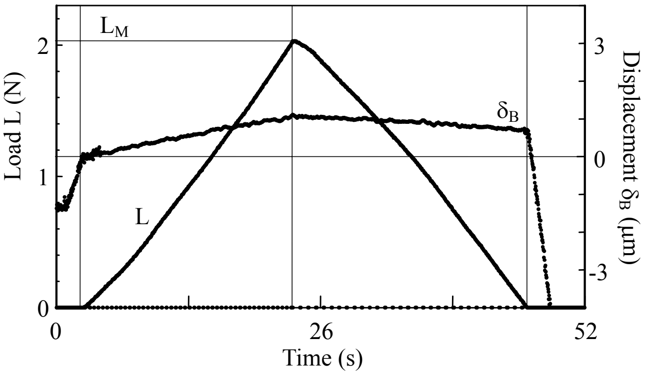


Fig.6 Original data (D=0.5mm)

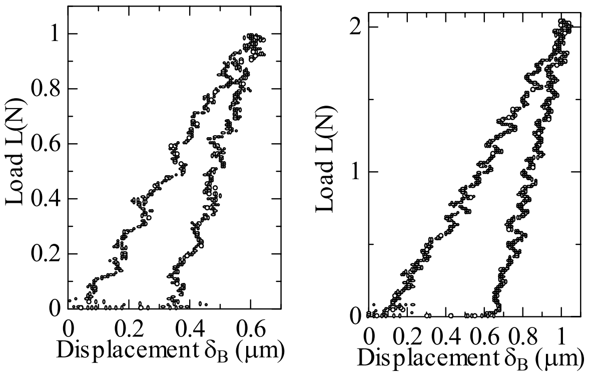


Fig.7 Test results of S45C (D=0.5mm)

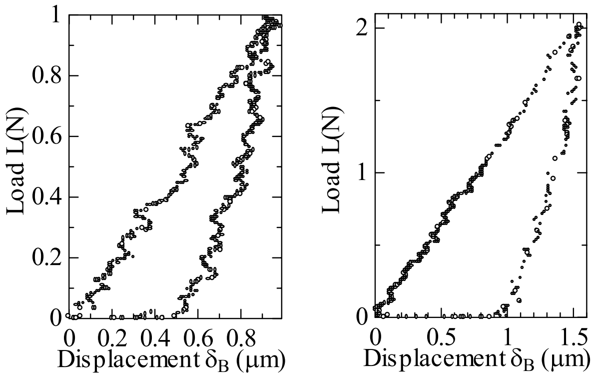


Fig.8 Test results of S45C (D=0.3mm)

(1) For S45C + Brass holder (D=0.5mm); C_1 =0.269(μm/$N^{2/3}$), C_2 =almost zero

(2) For S45C + SUS holder (D=0.3mm); C_1 =0.715(μm/$N^{2/3}$), C_2 =almost zero

4.3 Calculated Young's modulus of specimens

Using measured values of L_M, δ_{Bt} (= δ_{Ht} - δ_U), δ_B (= δ_{Hr} - δ_U) and known value I(E) =1.57×10^{-3}(1/GPa) , calculated Young's moduli of specimens are shown with respect to L_M in Fig.9 to Fig.11. Young's moduli obtained by uniaxial compression test using strain gauges are also shown in figures with horizontal continuous line and broken lines show the range of ±5%. White marks designate each experimental value and black mark is the mean value of them. Although calculated Young's moduli about specimens are scattered, mean value of them are close to those of uniaxial compression test. The cause of this tendency is presumed as follows: (1) roughness of a specimen's surface (2): scatter of measured value.

Concrete experimental and calculated values are listed in Table 1 and Table 2.

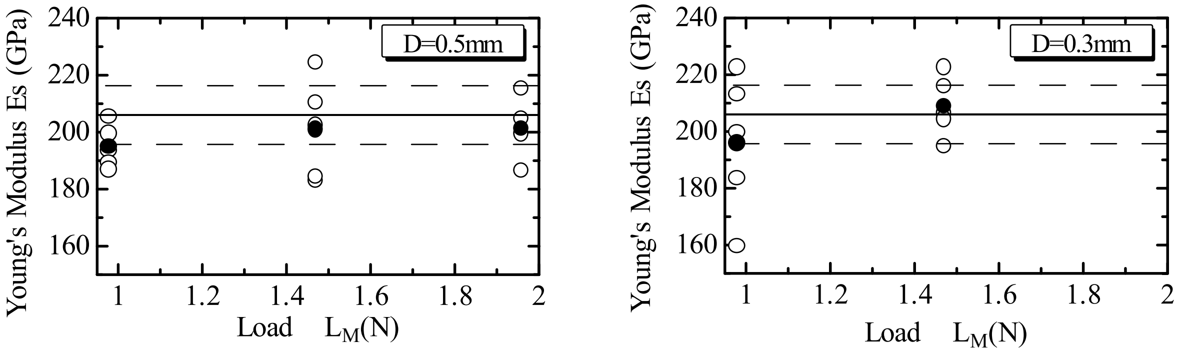


Fig.9 Relationship between the maximum Load L_M and Young's modulus E_S of S45C specimen

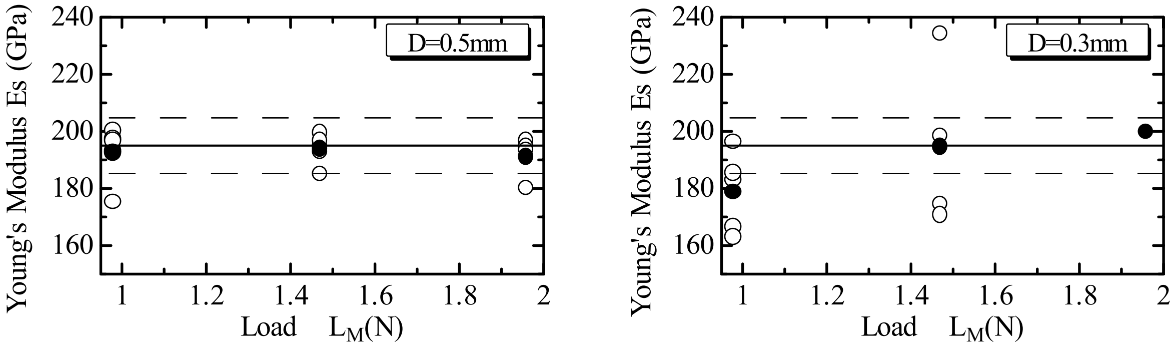


Fig.10 Relationship between the maximum Load L_M and Young's modulus E_S of SUS304 specimen

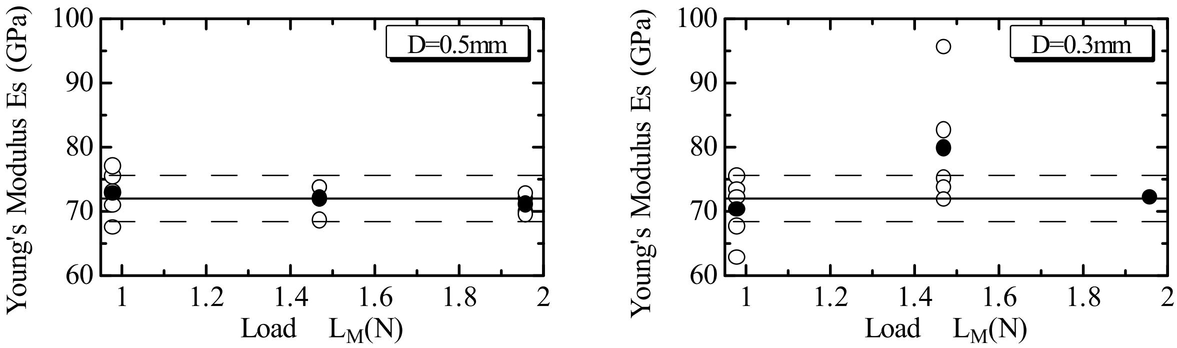


Fig.11 Relationship between the maximum Load L_M and Young's modulus E_S of AA specimen

4.4 Calculated contact diameter, comparison of depth and contact area

Calculated contact diameter d using Eq.(6) are listed in the most right column of Tables.

Table 1 Test Results by Horizontal Ultramicro Hardness Tester (D=0.5mm)

Metal	Maximum Load L_M(N)	Indentation Depth δ_{Bt}(μm)	Elastic Recovery δ_{Br}(μm)	Young's Modulus E_S (GPa) (a)		(b)	Contact diameter d (μm)
Aluminum	0.98	1.131	0.486	72.7			42.1
Alloy	1.47	1.658	0.637	71.9	Avg.		51.8
AA	1.96	2.052	0.760	71.0	71.9	72	57.8
Carbon	0.98	0.635	0.290	196.9			31.3
Steel	1.47	0.917	0.339	200.7	Avg.		38.7
S45C	1.96	1.135	0.398	201.3	199.6	206	43.3
Stainless	0.98	0.951	0.220	192.3			41.0
Steel	1.47	1.345	0.292	193.4	Avg.		49.0
SUS304	1.96	1.784	0.363	191.1	192.3	195	56.6

(a) : by Ultramicro Hardness Tester (b) : by Uniaxial Compression Test

Table 2 Test Results by Horizontal Ultramicro Hardness Tester (D=0.3mm)

Metal	Maximum Load L_M(N)	Indentation Depth δ_{Bt}(μm)	Elastic Recovery δ_{Br}(μm)	Young's Modulus E_S (GPa) (a)		(b)	Contact diameter d (μm)
Aluminum	0.98	1.520	0.559	70.2			38.6
Alloy	1.47	2.168	0.689	79.7	Avg.		46.8
AA	1.96	3.320	0.756	72.0	74.0	72	59.4
Carbon	0.98	0.910	0.331	178.3			29.9
Steel	1.47	1.162	0.410	194.3	Avg.		33.9
S45C	1.96	1.490	0.468	199.8	190.8	206	38.8
Stainless	0.98	1.183	0.278	195.5			35.4
Steel	1.47	1.693	0.327	208.7	Avg.		42.8
SUS304	1.96	2.121	0.385	204.6	202.9	195	48.1

(a) : by Ultramicro Hardness Tester (b) : by Uniaxial Compression Test

In Table 3, characteristic values (indentation depth and projected contact area) are listed to compare the results obtained by a ball indenter and a Berkovich triangular pyramidal indenter.

Table 3 Comparisons about indentation depth and contact area between a ball indenter and a Berkovich triangular pyramidal indenter

		Ball indenter (D=0.5mm)			Berkovich indenter (α=115°)				
Load	Metal	Indentation depth	Contact diameter	Projected contact area	Indentation depth	Contact side length	Projected contact area	ratios	
L_M (N)		δ_{Ball} (μm)	d (μm)	$A=\left(\frac{\pi}{4}\right)d^2 (\mu m^2)$	δ_{Berk} (μm)	S (μm)	$A=\left(\frac{\sqrt{3}}{4}\right)S^2 (\mu m^2)$	$\frac{\delta_{Berk}}{\delta_{Ball}}$	$\frac{A_{Berk}}{A_{Ball}}$
0.98	AA	1.131	42.1	1395	5.30	39.4	672	4.69	0.48
	SUS304	0.951	41.0	1321	4.46	33.2	477	4.69	0.36

In this table, ratios of contact area (A_{Berk}/A_{Ball}) are 0.483(=1/2.1) to 0.361(=1/2.8), however ratios indentation depth ($\delta_{Berk}/\delta_{Ball}$) are 4.7. Therefore, evaluation method of determining material characteristics using a very small ball is more effective for shallower area of materials than that using pyramidal indenter.

5. CONCLUSIONS

(1) In order to evaluate Young's modulus of metals, the calculation formula for hardness tester using a ball indenter with holder was clearly shown.

(2) Experiments were carried out for several metal specimens using the developed horizontal ultramicro hardness tester with very small indenters. Data of load and displacement were continuously measured by load cell and linear sensors during loading and unloading processes.

(3) Indentation curves were obtained by these data and Young's moduli of specimens were calculated by the calculation formula reported in this paper.

(4) Calculated Young's moduli existed within 5% range of that obtained by uniaxial compression test.

(5) For smaller area of materials, effectiveness of evaluation method to determine Young's modulus of specimen with the very small ball indenter was confirmed as compared to the results of the pyramidal indenter.

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