Micro Force Transfer Standards

L. Doering [1], J. Frühauf [2], U. Brand [1]

[1] Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

[2] Chemnitz University of Technology, Faculty of Electrical Engineering and Information Technology

Introduction

The measurement of material properties and dimensional metrology are often carried out by mechanical probing using small spherical probing balls. Well-known instruments, such as microhardness measuring instruments, atomic force microscopes, stylus instruments and coordinate measuring machines operate in this way. With increasing miniaturisation and high precision requirements for measurement, these probing systems become ever finer, i.e. the radius of the probing spheres used becomes ever smaller. It therefore is necessary to increase the resolution and accuracy of the measurement. This reduction of the probing sphere diameter leads to the reduction of the probing forces required in order not to destroy the surface of the workpiece to be measured. Small probing forces are needed in particular, when soft materials are measured, i.e., in the ideal case, the probing force should be zero. In reality a force is, however, necessary to deflect the stylus tip and to ensure permanent contact between the stylus tip and object measured. These small probing forces below a few mN therefore have to be measured very exactly. For these purposes, different kinds of silicon bending beams or cantilevers, respectively, have been examined. Two types of micro force sensors were investigated: active and passive sensors. Passive sensors, which consist of calibrated bending beams can be used as micro force calibration standards. Active sensors also consist of Si bending beams but with integrated piezoresistive strain gauges for measuring the beam deflections during probing. Commercially available cantilevers, which were originally produced for application in atomic force microscopes and cantilevers manufactured by the Faculty of Electrical Engineering and Information Technology of the Chemnitz University of Technology [1] were investigated as micro force transfer standards and sensors.

Experiments

Micro force calibration

The experimental setup [2] essentially consists of a piezoelectric 1d-fine positioning device (PIFOC [3]) and a precise compensation balance. The whole experimental setup is called "Micro Force Measuring Device" (MFMD). The cantilever to be measured is mounted on the piezoelectric translation unit. When the piezoelectric device moves downwards, the tip of the micro force sensor is pressed onto the balance stamp. As the balance uses a compensation method, a contra acting force is generated lifting the balance stamp to its original level and the value of this force is indicated. Both, the movement of the PIFOC and the force values were measured and controlled with a personal computer. For better stability of the temperature, the experimental setup was build up in a thermally isolated box.

Results for and discussion on a micro force sensor

- **Calibration of a micro force sensor**

A commercial silicon AFM cantilever [4] was investigated. The stress signals upon deflection of the Si beam are generated by piezoresistive elements on the bending beam (see figure 1). At the fixed end of the bending beam to which the greatest mechanical stress is applied, the elements are arranged forming a Wheatstone bridge to measure the change in resistance upon deflection. To calibrate a micro force sensor, the stress signals and the probing force are measured simultaneously (Fig. 2). This force sensor shows a relatively linear characteristic curve for larger deflections, corresponding to constant stiffness.

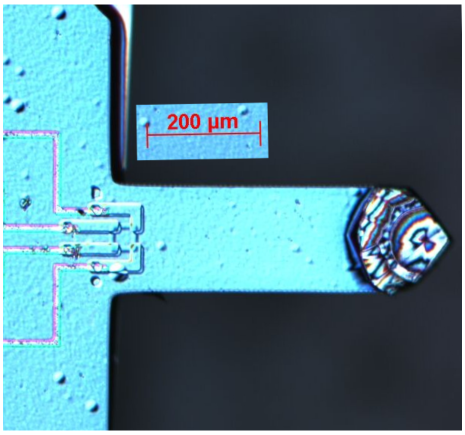

Fig. 1 AFM cantilever with piezoresistive Wheatstone bridge (stiffness = 462 N/m with a standard deviation of 1 N/m)

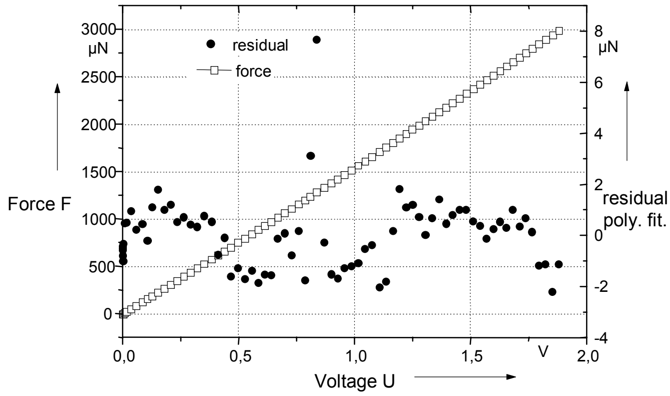

Fig. 2 Probing force F versus output voltage U of an AFM cantilever type micro force sensor. The residuals from a second order fit are shown on the right ordinate

The measurements for calibration are repeated four times. The graph in figure 2 shows that the shape of the curve is linear. The assumption that the curve is better described by a polynomial of second order, supplies more conformity and residuals are in the range of ±2 µN. Results are shown in table 1.

Force F [µN] = A + B1*U[V] + B2*U[V]^2 (1)

Measurement No.	A	B1	B2
m1	-9.0	1496.6	50.7
m2	-3.5	1491.5	53.7
m3	-5.1	1485.1	56.0
m4	-1.8	1483.3	53.5
average	-4.8	1489.1	53.5
sd	3.1	6.1	2.2

Table 1: Repeatability of the force-voltage sensitivity of a micro force sensor (see fig. 2)

How this sensor is used: The most important point using these micro force sensors is the fact that the sensor deflection under constant load is dependent on the location of the point of loading. The force leads to a deflection and thus to a change of the sensor signal. As the measured voltage is directly proportional to the force, the force can easily determined by measuring this voltage. The repeatability of the force output voltage sensitivity was measured (see table 1). From the variation of the linear coefficient a repeatability of the measured force of about 1% can be concluded.

- **Application of a micro force sensor for probing force calibration of a CMM fiber probe**

For the deflection experiments with a fiber probe (fig. 3) mounted on a coordinate measuring machine [7], the fiber probe was moved to a position close to the tip of the cantilever but not touching it. Then the fiber probe was moved in the direction of the cantilever.
Figure 4 shows the deflection of the fiber probe and the corresponding electrical signal U from the Si cantilever. The fiber probe was deflected in steps of 1 µm. The micro force sensor emitted a signal of (2.00 ± 0.02) mV/µm.

Fig. 3 The fiber probe (top) and the micro force sensor (bottom)

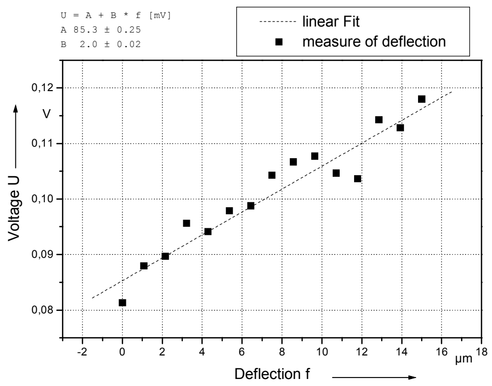

Fig. 4 Micro force sensor output signal U (voltage) measured over deflection f of a CMM fiber probe

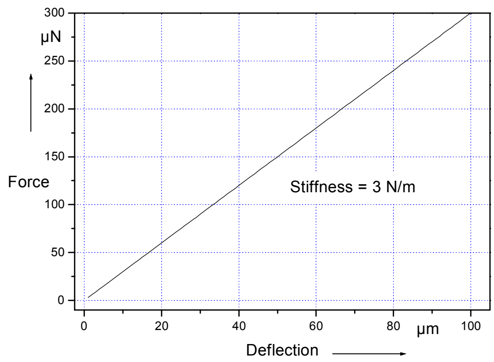

Fig. 5 Resulting graph for probing force over deflection

This corresponds to a fiber probe stiffness of 3 N/m. With a typical deflection of half a ball diameter of approximately 50 µm of the fiber probe a probing force of 145 µN results (see fig. 5).

Results for and discussion on a probing force standard

- **Calibration of a probing force standard**

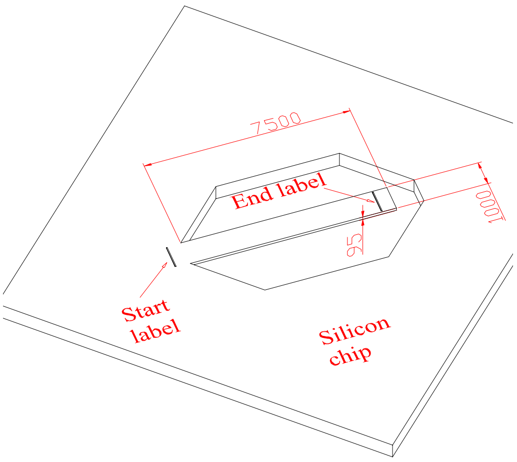

Fig. 6 Sketch of a probing force calibration standard (typical dimensions in micrometer)

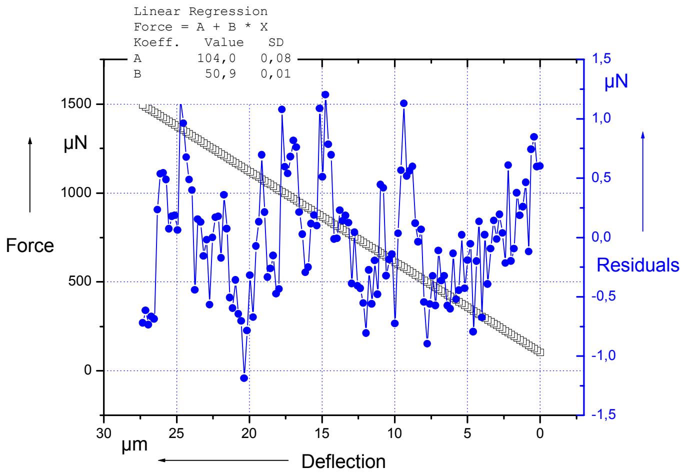

Fig. 7 Force and residuals of a linear fit versus deflection

The passive sensor was etched from a silicon chip without further electrical contacts (fig. 6). The dimensions of the bending beam can be changed within a wide range. Several alignment labels are located on the sensor. The calibration was carried out by applying a known deflection to a well-known point and measuring the resulting force [5]. The contact point was chosen close to the centre of the end label of the standard (see fig. 6). Figure 7 shows the calibration curve of a micro force transfer standard. On the right ordinate the residuals from a linear fit are plotted. These deviations amount to ±1 µN over a range of probing forces up to 1500 µN.

- **Application of a probing force transfer standard for probing force calibration of a stylus instrument**

The simplest way to determine the probing force consists in placing a balance underneath the equipment. But this often is not possible because the balance is too large. The probing force calibration of the stylus instrument was therefore performed with the standard described above by making a scan over the centre line of the standard. Figure 8 shows the profile measured. The start and end labels are shown in the diagram. The profile shows a vibration of the bending beam behind the end label. This will be discussed later. The probing force of the stylus instrument can be evaluated either by measuring the deflection and by calculating the probing force using the calibrated stiffness [5], [1] or using a new method called "difference method".

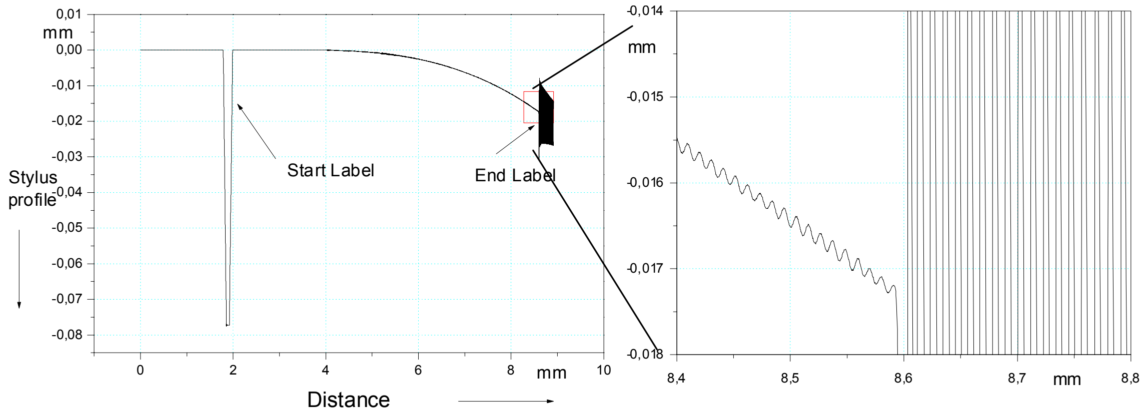

Fig. 8 Stylus instrument profile measurement on the probing force calibration standard

- **The difference method**

To calculate force F producing deflection f of a cantilever, the formula

$$F = \frac{3EJ}{L^3} f \qquad (2) \qquad \text{with} \qquad J = \frac{bh^3}{12} \qquad (3)$$

is usually used (if the cross section of the cantilever is rectangular). E is Young's modulus, L is the distance between the fixed site of the cantilever and the working point of the force, and b and h are the width and the height (thickness) of the cross section, respectively.

The probing force is dependent on the third order of L and h. Hence the accurate determination of these dimensions is very important. An accuracy of 1 ‰ is needed to achieve an accuracy of 1% for the force. To meet these demands, the cantilever can be designed to have the length L and the width b in the mm range but the height h must be in the 100 µm range. The thickness of the beam must therefore be measured with an accuracy of 100 nm.

Nevertheless, cantilever forces determined by equation (2) deviate using a balance by up to 10% from the values measured by independent methods. One reason is the influence of the clamping location, which is not infinitely stiff. To overcome this complication we assume an increased effective length of the cantilever which is composed of an unknown part ΔL and a measurable length L_i ending at the working point of the force. Using two measurements in which the load is located at positions L_1 and L_2

$$F = \frac{3EJ}{(\Delta L + L_1)^3} f_1 \qquad \text{and} \qquad F = \frac{3EJ}{(\Delta L + L_2)^3} f_2$$

the quantity ΔL can be eliminated, which leads to eq. (4):

$$F = 3EJ \frac{\left(\sqrt[3]{f_2} - \sqrt[3]{f_1}\right)^3}{(L_2 - L_1)^3} \qquad (4)$$

Now the force can be calculated on the basis of the difference of the two load positions. The scan measured with a stylus instrument contains a lot of pairs of values f_i, L_i. Combining pairs with the same distance (L_1 - L_2) a constant force should result. But this is really true only for large values of L_1 and L_2 (towards the end of the scan). On short cantilevers the effective length model is not suitable. However, analysing the last 500..1000 µm of the scan the calculated force is in good agreement with the values measured using a calibrated stiffness in a defined loading position (end label) [1], [5].

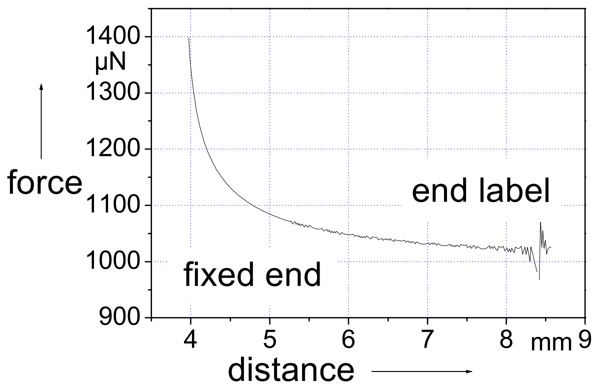

Fig. 9 Typical graph of the probing force of a stylus instrument calculated with the difference method

Results

- **Force calibration of a stylus instrument with the probing force calibration standard**

In the first step, two standards as described above were calibrated on the MFMD [2] and their stiffness was determined. The second step was the determination of the probing force of a stylus instrument [1], [6] by different methods. A typical graph of the described difference method over the whole range is shown in figure 9. Close to the end label, the calculated force changes are very small. The experiment was repeated twice. The evaluation by the difference method over the last 500 µm of the beam shows minor differences of force values. Table 2 contains first results including force value calculated using the simple cantilever equation (2).

Table 2 Comparison of methods to measure probing forces using passive cantilevers as standards

Standard No.	Meas-urement No.	Stiffness from MFMD	Deflection measured with stylus instrument	Probing force using difference method F1	Force from MFMD F2	Force (eq. 2) F3	F2-F1	F2-F3
15-41	1	52.4 N/m	3.5 µm	186 µN	185 µN	179 µN	-1 µN	6 µN
15-41	2	52.4 N/m	3.6 µm	186 µN	191 µN	185 µN	5 µN	6 µN
6-39	1	14.3 N/m	13.3 µm	196 µN	190 µN	179 µN	-6 µN	11 µN
6-39	2	14.3 N/m	12.8 µm	198 µN	183 µN	171 µN	-15 µN	12 µN

During the experiments a number of possible deviation sources were found. In table 3 some measured variables are listed. Particularly the first three sources of possible deviations lead to inaccurate measurement values.

Table 3 Sources influencing the accuracy of the force measurement using micro force calibration standards

Sources of deviation	**Leading to**
Variable thickness of the cantilever along its length	Change of the effective moment J
Zero-load bending due to the cantilever's own weight or internal stresses	Incorrect z-position

Directional deviation of the scan or the load point from the centre line of the standard	Torsion and thus increased deflection as well as invalidity of the model
Variation of scanning speed (constant speed is assumed)	Incorrect x-position if no position measurement is available
Vibrations of the cantilever during scanning	Spread of the calculated force values
The deflection of the cantilever is too large	The model leading to equations (2), (4) is not valid

Conclusions

The stiffnesses as well as the output signals of several micro force sensors were determined using a micro force measuring device (MFMD). Then these sensors were tested by measuring the probing forces of different instruments: a stylus instrument and a micro probing system of a coordinate measuring machine. The reproducibility of the measurements was 1%. The described difference method was used to calculate probing forces from stylus profiles and compare them with the forces determined using the measured stiffness. Deviations between these values were found. The deviation sources must be minimised or eliminated to make the design and manufacture of sensors for specific measuring ranges and small uncertainties possible. The measuring accuracy presented was the best result we have obtained up to now. In further publications the effects of some deviations as described above will be presented and discussed. To get statements about the accuracy and reproducibility of the measurement results, it will be necessary to repeat the measurements. The investigations carried out up to now have shown that these sensors are most suitable for micro force measurements in the range from 10 to 3000 µN. The expected measurement uncertainties are in a range of a few µN.

Acknowledgements

We gratefully acknowledge the financial support from the Deutsche Forschungsgemeinschaft (SFB 516 “Konstruktion und Fertigung aktiver Mikrosysteme”). We also thank H. Schnädelbach and L. Yu of our PTB group and E. Gärtner of the TU Chemnitz group for their work and for helpful discussions.

Literature

[1] J. Fruehauf, H. Trumpold: Silicon Standards for Assessment and Calibration of Stylus Probes. 52nd CIRP General Assembly, San Sebastian, Spain, 18-24 August 2002, S/2 accepted for publication in CIRP Annals 2002

[2] L. Doering, U. Brand: Proc. Nanoscale Conf. 21. November 2001, Bergisch-Gladbach, Si-cantilevers with integrated piezo resistive elements as micro force transfer standards, PTB-F-44, Physikalisch-Technische Bundesanstalt Braunschweig und Berlin, ISBN 3-89701-840-3, 185-192

[3] PIFOC, type P-721.20, Physik Instrumente (PI) GmbH & Co, 76337 Waldbronn (Germany)

[4] AFM cantilever, type Pi-NC-8, NANOSENSORS GmbH & Co. KG, IMO Building, Im Amtmann 6, D-35578 Wetzlar-Blankenfeld (Germany)

[5] W. Hoffmann, S. Loheide, T. Kleine-Besten, U. Brand, A. Schlachetzki: Method of characterising micro mechanical beams and its calibration for the application in micro force measurement systems. MicroTec 2000, Hannover, 819-823

[6] Dektak 3, Veeco Instruments GmbH, Janderstrasse 9, D 68199 Mannheim

[7] U. Brand, T. Kleine-Besten, H. Schwenke: Development of a special CMM for dimensional metrology on microsystem components, ASPE 15th Annual Meeting in Scottsdale (Arizona), 22-27 October 2000, 542-546