Good Practice Guide No 2 EMPIR project MicroProbes

Setting probing force and scanning speed of fast microprobes for non-destructive roughness and microform measurements

U. Brand[1], Min Xu[1], Z. Li[1], R. Slesinger[2]

[1] Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, D-38116 Braunschweig, Germany

[2] Czech Metrology Institute, Okruˇzn´ı 31, 638 00 Brno, Czech Republic

This Good Practice Guide (GPG) was developed during the course of the EMPIR project MicroProbes "Multifunctional ultrafast microprobes for on - the - machine measurements". Within this project fast piezoresistive silicon microprobes were developed for fast roughness measurements [1] and mechanical property measurements [2].

During fast tactile topography measurements, the inertia of the microprobe cantilever creates dynamic forces which might lead to tip flight and thus measurement errors. To prevent from tip flight, usually the highest possible probing forces are used. These are mainly given by the hardness of the surface to be measured.

The Good Practice Guide helps users of microprobes to set the probing force and the maximum scanning speed of their microprobing system for reliable topography and roughness measurements.

1. Introduction

Tactile probing systems have been used for a long time in roughness metrology since they allow reliable measurement of roughness parameters due to their robustness against different kinds of surface contamination often found in an industrial environment.

The maximum scanning speed of conventional stylus instruments is limited by the inertia of the probe system. For typical probe masses of 1 g the maximum scanning speed of such probing systems is limited to approximately 0.5 mm/s [3]. For smaller stylus masses of 5 mg scanning speeds of 2.5 mm/s were obtained supported by an analytical model describing a simple pivoting stylus [3]. This GPG uses this simple model to simulate the dynamical properties of 5 mm long cantilever type piezoresistive microprobes which might lead to tip flight.

A further measurement deviation might occur due to scratching of surfaces during measurement. To model this, an approach of Flores describing the elasto-plastic scratching of surfaces for spherical indenters [4] is used.

Moreover, this GPG assumes an optimum damping of the microprobes in such a way that no eigenfrequencies are excited.

2. Maximum probing force

For standard two-dimensional roughness profile measurements a maximum probing force of 750 µN is recommended for tip radii down to 2 µm. This recommendation is only valid for hard surfaces comparable to steel. For softer materials the probing force needs to be lower to prevent the scratching of these surfaces. Flores [4] published an empirical formula to describe the plastic scratch depth d_{pl} of metals with yield strength Y depending on the tip radius r and the probing force F:

$$d_{pl} = \frac{F}{8.1 \cdot \pi \cdot r \cdot Y} \quad (1)$$

For materials with vanishing strain hardening coefficient it can be assumed that the hardness H is approximately three time the yield strength Y [5]:

$$H \approx 3 \cdot Y \quad (2)$$

Thus, the plastic scratch depth can be estimated by

$$d_{pl} = \frac{F}{2.7 \cdot \pi \cdot r \cdot H} \quad (3)$$

The tip radius of unused silicon microprobes usually is of the order of 100 nm. But these silicon tips wear continuously during roughness measurements depending on the hardness of the samples to be measured. On steel roughness standards [6] this usually leads to more or less flat tips of some micrometer in width [1]. Thus, in order to prevent the scratching of surfaces the used tip radius and the hardness of the surface to be measured, need to be known.

Microprobes are also available with spherical diamond tips of 2 µm radius.

In this Good Practice Guide we recommend reducing the scratching depth of surfaces to less than 10^{-3} of the tip radius:

$$d_{pl} < \frac{r}{1000} \quad (4)$$

Combining Equ. (3) and (4) allows us to calculate the maximum probing force F_{max} for different hard metals and different tip radii:

$$F_{max} < \frac{2.7 \cdot \pi \cdot r^2 \cdot H}{1000} \quad (5)$$

Table 1 lists the maximum probing forces of microprobes with a tip radius of 2 µm for different metals according to Equ. (5) and Fig. 1 shows the dependence of maximum probing force versus hardness.

Table 1 Maximum probing force F_{max} versus hardness H of the material to be measured according to Equ. (5) for a 2 µm tip radius:

Material	**Hardness *H* (GPa)**	***Max. probing force F_{max}* (µN)**
Brass	0.27	*9.2*
Gold	0.3	*10.3*
Aluminium	0.3	*10.3*
Platinum	0.69	*24*
Copper	0.72	*24*
Steel	3.0	*103*
Tungsten	3.43	*116*
Iron	4.2	*143*
Invar	5.0	*170*
Nickel	5.0	170
Chromium	8.5	289

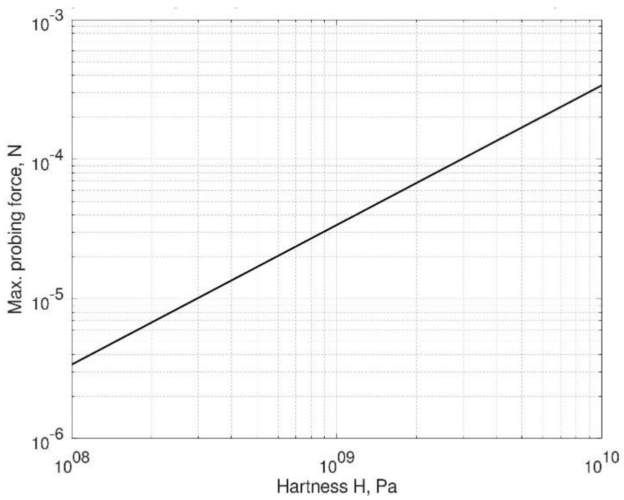

Fig. 1 Maximum probing force versus hardness of the material to measured according to Equ. (5) for a 2 µm tip radius

Maximum permissible probing forces range from 9 µN on soft metals like gold and brass to 289 µN on hard metals like chromium.

3. Maximum scanning speed

Morrison [3] modelled the maximum scanning speed of a stylus instrument with pivoting stylus. His model considers sinusoidal surface profiles with surface wavelength λ and amplitude A_1. The inertial mass m_i of the microprobe mainly consists of the mass of the cantilever with length L, width w, thickness d and density ρ. For microprobes with diamond tip the mass of the tip has to be added to the inertial mass m_i. For microprobes with silicon tip the mass of these tips can be neglected.

Thus, the inertial mass for microprobes with silicon tip can be calculated as:

$$m_i = L \cdot w \cdot d \cdot \rho \tag{6}$$

Dynamic forces created at steep slopes of the profile lead to tip flight. Thus, not the static cantilever mass has to be considered, but the effective mass of the cantilever m_{eff} [7]:

$$m_{eff} = \frac{33}{140} m_i \tag{7}$$

For standard CAN50-2-5 microprobes from CiS [8,9] with 5 mm length, 200 µm width and a thickness of 50 µm an effective mass m_{eff} of $0.27 \cdot 10^{-7}$ kg results.

Morrison's equation for the maximum scanning speed of pivoting styluses on sinusoidal surfaces can be described by:

$$v_{max}(F) = \sqrt{\frac{3 \cdot \lambda^2 \cdot (2F + m_{eff} \cdot g)}{8 \cdot \pi^2 \cdot A_1 \cdot m_{eff}}} \tag{8}$$

For sinusoidal surface profiles it is assumed that the minimum surface wavelength λ_{min} that can be measured is larger than four times the tip radius:

$$\lambda_{min} > 4 \cdot r \tag{9}$$

Thus, for a tip radius of r = 2 µm the smallest measurable surface wavelength is λ_{min} = 8 µm. Assuming further a surface amplitude A_1 = 0.1 µm then the maximum scanning speed v_{max} can be calculated according to Equ. (8) (s.

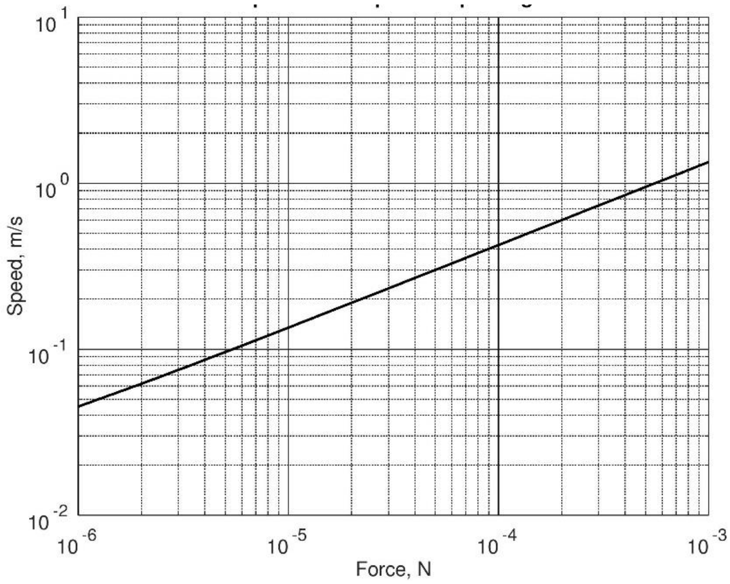

Fig. 2 Maximum scanning speed versus probing force for 5 mm long piezoresistive microprobes with 2 µm tip radius on sinusoidal surface profiles with 0.1 µm amplitude and 8 µm surface wavelength

).

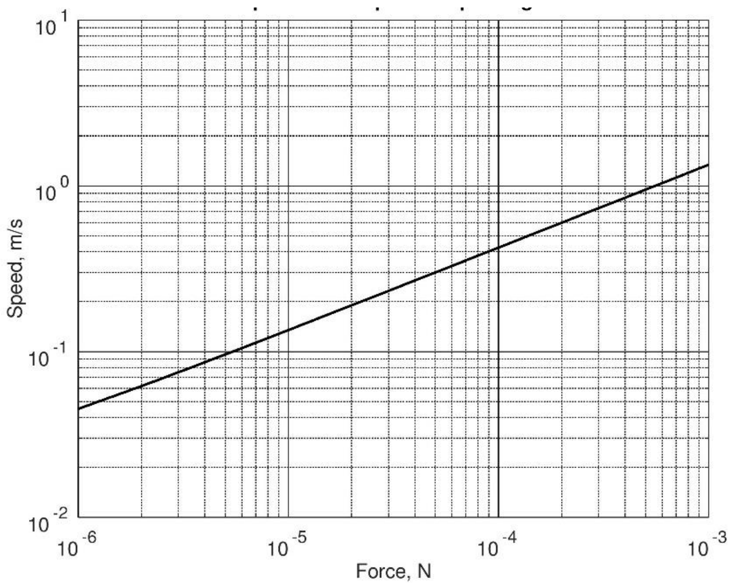

Fig. 2 Maximum scanning speed versus probing force for 5 mm long piezoresistive microprobes with 2 µm tip radius on sinusoidal surface profiles with 0.1 µm amplitude and 8 µm surface wavelength

Thus, for sinusoidal surface profiles down to 8 µm surface wavelength and up to 100 nm amplitude probing forces in the range from 10 µN to 300 µN lead to maximum scanning speeds of the microprobe with 2 µm tip radius from 70 mm/s to 350 mm/s (s. Table 2).

Table 2 Maximum scanning speed v_{max} of 5 mm long piezoresistive microprobes with 2 µm silicon tip radius on sinusoidal surface profiles with 0.1 µm amplitude and 8 µm surface wavelength

Material	**Hardness *H* (GPa)**	***Max. probing force F_{max}* (µN)**	***Max. scanning speed v_{max} (m/s)***

Brass	0.27	*9.2*	*0.129*
Gold	0.3	*10.3*	*0.137*
Aluminium	0.3	*10.3*	*0.137*
Platinum	0.69	*24*	*0.208*
Copper	0.72	*24*	*0.208*
Steel	3.0	*103*	*0.430*
Tungsten	3.43	*116*	*0.457*
Iron	4.2	*143*	*0.507*
Invar	5.0	*170*	*0.553*
Nickel	5.0	170	*0.553*
Chromium	8.5	289	*0.721*

For larger sinusoidal amplitudes A_1 the scanning speed reduces inversely proportional to the square root of A_1 (s. Equ. (8)).

Often the surface roughness but not the surface amplitude is known. The arithmetic mean roughness R_a of a sinusoidal surface profile with wavelength λ and amplitude A_1 is:

$$R_a = \frac{2A_1}{\pi} \quad (10)$$

Inserting this into Equ. (8) leads to a maximum scanning speed v_{max}

$$v_{max}(F) = \sqrt{\frac{3\cdot\lambda^2\cdot(2F+m_{eff}\cdot g)}{4\cdot\pi^3\cdot R_a\cdot m_{eff}}} \quad (11)$$

Thus, the maximum scanning speed of a microprobe with 2 µm tip radius on a nickel surface (s. Fig. 3) varies from 4 m/s for mirror like smooth surfaces (R_a = 1 nm) to 40 mm/s for very rough surfaces (R_a = 10 µm).

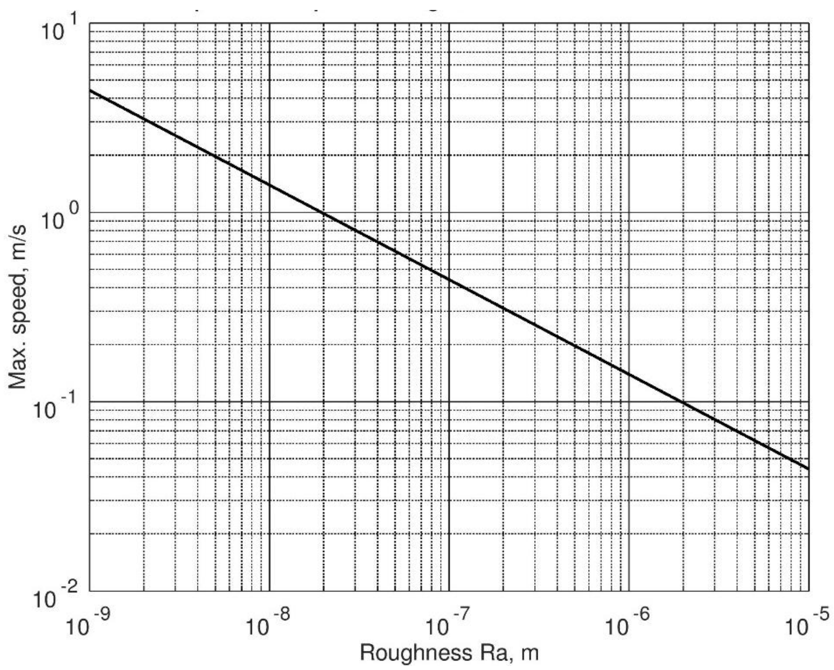

Fig. 3 Maximum scanning speed of a microprobe with 2 µm tip radius on a nickel surface (H_{Ind} = 5 GPa) versus roughness of the nickel surface

4. Summary

Two properties of fast tactile silicon microprobes are investigated in this Good Practice Guide: scratching and tip flight. To prevent tip flight of the microprobe the highest static probing force possible should be used. This is determined by the hardness of the surface to be measured to prevent a scratching of the surface. In this GPG the permissible scratch depth is set to 0.1 % of the tip radius used.

For sinusoidal surface profiles with surface wavelengths down to 8 µm and amplitudes up to 100 nm probing forces of 10 µN result for soft metals like gold and 290 µN for hard metals like Chromium. These static probing forces limit the permissible scanning speed of silicon microprobes with 2 µm tip radius on soft surfaces like gold to 140 mm/s and on hard surfaces like Chromium to 700 mm/s.

The Good Practice Guide allows to calculate the maximum permissible probing force and scanning speed of silicon microprobes with different tip radii on surfaces with different hardness, different minimum surface wavelength and different roughness.

Acknowledgement

The 17IND05 MicroProbes project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.

Literature

1. Brand, U.; Xu, M.; Doering, L.; Langfahl-Klabes, J.; Behle, H.; Bütefisch, S.; Ahbe, T.; Peiner, E.; Völlmeke, S.; Frank, T.; et al. Long Slender Piezo-Resistive Silicon Microprobes for Fast Measurements of Roughness and Mechanical Properties inside Micro-Holes with Diameters below 100 µm. *Sensors* **2019**, *19*, 1410, doi:10.3390/s19061410.
2. Fahrbach, M.; Friedrich, S.; Behle, H.; Xu, M.; Cappella, B.; Brand, U.; Peiner, E. Customized Piezoresistive Microprobes for Combined Imaging of Topography and Mechanical Properties. *Meas. Sens.* **2021**, *15*, 100042, doi:10.1016/j.measen.2021.100042.
3. Morrison, E. The Development of a Prototype High-Speed Stylus Profilometer and Its Application to Rapid 3D Surface Measurement. *Nanotechnology* **1996**, *7*, 37.
4. Flores, S.E.; Pontin, M.G.; Zok, F.W. Scratching of Elastic⁄Plastic Materials With Hard Spherical Indenters. *J. Appl. Mech.* **2008**, *75*, 061021–061021, doi:10.1115/1.2966268.
5. Cahoon, J.R.; Broughton, W.H.; Kutzak, A.R. The Determination of Yield Strength from Hardness Measurements. *Metall. Trans.* **1971**, *2*, 1979–1983, doi:10.1007/BF02913433.
6. Doering, L.; Brand, U.; Bütefisch, S.; Ahbe, T.; Weimann, T.; Peiner, E.; Frank, T. High-Speed Microprobe for Roughness Measurements in High-Aspect-Ratio Microstructures. *Meas. Sci. Technol.* **2017**, *28*, 034009, doi:10.1088/1361-6501/28/3/034009.
7. Skrzypacz, P.; Nurakhmetov, D.; Wei, D. Generalized Stiffness and Effective Mass Coefficients for Power-Law Euler–Bernoulli Beams. *Acta Mech. Sin.* **2020**, *36*, 160–175, doi:10.1007/s10409-019-00912-8.
8. Frank, T.; Doering, L.; Heinrich, G.; Thronicke, N.; Löbner, C.; Steinke, A.; Reich, S.; others Silicon Cantilevers with Piezo-Resistive Measuring Bridge for Tactile Line Measurement. *Microsyst. Technol.* **2014**, *20*, 927–931.
9. CiS Forschungsinstitut Für Mikrosensorik GmbH, Piezoresistive Mikrotaster CAN50-2-5.