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Step height measurement of microscale thermoplastic polymer specimens using contact stylus profilometry

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ABSTRACT

Quantitative characterisation of the dimensions of micro-scale polymer specimens imposes higher demands on stylus profilometry. Due to the weak and time-dependent mechanical properties of polymers, one of the main error sources within tactile dimensional measurement for polymeric structures comes from the surface deformation of specimens under stylus scanning with a certain probing force. In this paper, a practical elastic–viscoplastic model is proposed for modelling the (steady-state) polymer deformations during tactile surface scanning. To experimentally determine the viscous material properties of polymers necessary for the proposed analytical model, a stylus-profiling based methodology has been developed. The feasibility of the proposed methodology and a measurement error compensation model has been experimentally verified. Preliminary experimental investigation on measurement of polymeric step height specimens with currently available stylus profilometers demonstrates that the specimen deformation induced tactile measurement deviation can be evidently reduced.

1. Introduction

Owing to their unique advantages such as low cost, light weight, ease of processing and excellent optical properties, polymer materials including SU-8, PMMA and PDMS have long been employed in micro-system technology [1,2]. To date, various polymer micro-components and micro-systems have been developed, including micro-optics such as micro-lens arrays [3,4] and diffractive micro-optical elements [5], micro-actuators and -sensors such as micro-grippers [6], micro-x-y stages [7] and micro-polymer-resonators [8]. As one of the key points in quality control of these polymer micro-components and micro-systems, their geometrical dimensions have to be quantitatively characterised.

As for dimensional characterisation of structures in micro- and nano-scale, there exist already various approaches, including non-contact (optical) methods [9] and stylus profilometry [10,11]. However, due to the quite low reflectance of most polymer micro-specimens, optical approaches fail in many cases, especially when complex objects such as polymer specimens on silicon substrates have to be measured [12].

Taken into consideration that contact-based stylus profilometry is, in principle, independent of the optical properties of the specimens to be measured, it is therefore expected that polymer micro-specimens could be quantitatively determined by tactile surface profilometry. Preliminary experimental investigations [12] indicate, however, large systematic deviations when stylus profilometry is used for dimensional measurement of polymer specimens, especially polymeric structures on hard substrates (for instance, silicon wafers), since polymers have generally much weaker elastic modulus than metallic, ceramic and semi-conductor materials.

Recent research on surface deformation of polymer under tactile scanning [13,14] suggests that the systematic deviations of stylus profilometry for polymeric specimen can be modelled by a simplified elastic visco-plastic model, and then reduced by means of surface topography post-processing. Unfortunately, however, although different efforts [15–21] have been made in the past years to determine the mechanical properties of polymers used in micro-systems, the material properties of polymers, which are necessary for the aforementioned model, cannot be obtained easily and precisely, since none of the currently available testing methods for time-dependent mechanical properties of polymers has been validated [22]. In addition, it is not yet very clear how the friction between a (diamond) stylus tip and the polymer surface under test will contribute to the measurement deviation of stylus profilometry.

In this paper, our effort to improve the measurement accuracy of contact-based profilometry for polymeric step-height micro-specimens on hard substrates is reported, in which pre-knowledges of the material properties and of tip–surface friction are not necessary. Systematic measurement deviation of tactile

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profilometry is firstly analysed in Section 2, specimen preparation is illustrated in Section 3, methodology of stylus profilometry for soft specimen on hard substrates including data evaluation methods is proposed in Section 4, preliminary experimental investigation of the feasibility of the proposed model and the proposed post-processing method are detailed in Section 5.

2. Systematic measurement deviations of tactile stylus profilometry for polymers on hard substrates

Systematic measurement deviations of contact stylus profilometry are observed, when a step height specimen under measurement consists of materials with different mechanical properties [12]. Assuming the following tactile surface scanning conditions:

1. an ideal spherical stylus tip with a tip radius r_{tip},
2. a probing force F_{tip} applied on the stylus tip and
3. a surface scanning speed v_{tip},

the measured polymeric step height t_m (s.a. Fig. 1) is:

$$t_m = (t - d_{\mathrm{L}}) + d_{\mathrm{s}}, \tag{1}$$

where t is the step height at zero probing force, d_{L} the surface deformation of the polymeric layer and d_{s} the surface deformation of the substrate of the step height specimen during tactile scanning, respectively. The systematic tactile measurement deviation for polymer step height specimens can be deduced as follows:

$$\Delta(F_{\mathrm{tip}}, r_{\mathrm{tip}}, v_{\mathrm{tip}}) = t_m - t = -d_{\mathrm{L}} + d_{\mathrm{s}}. \tag{2}$$

The objective of this work is to experimentally investigate the possibility of quantitative modelling and compensation for $\Delta(F_{\mathrm{tip}}, r_{\mathrm{tip}}, v_{\mathrm{tip}})$ appearing for polymer step height specimens, and finally to improve the measurement accuracy of stylus profilometry for polymer specimens.

In the case that hard materials like silicon be used as the substrate of a polymeric step height specimen, the substrate deformation d_{s} under a practical tactile scanning condition will be in the elastic region, and therefore can be explicitly expressed by the Hertzian solution as follows:

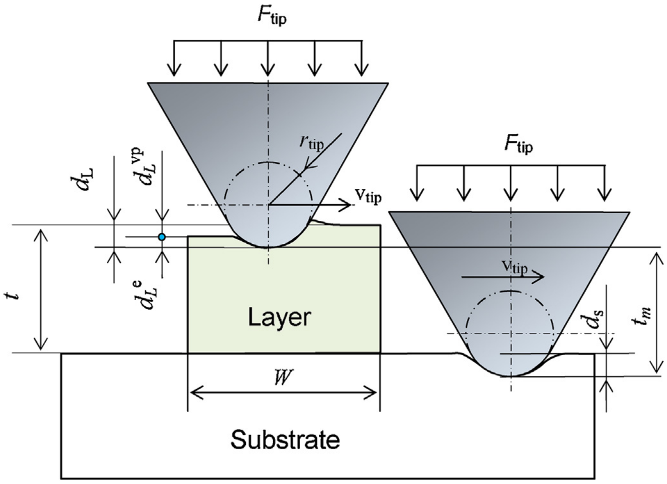

Fig. 1. Theoretical analysis of the systematic measurement deviations of a tactile profilometer for a polymer step height specimen, where t is the thickness of the polymer layer at zero-probing force, t_m the measured layer thickness (step height) under a probing force F_{tip} and a tip radius r_{tip}.

$$d_{\mathrm{s}} = \left(\frac{F_{\mathrm{tip}}}{\frac{4}{3} E_{\mathrm{s}}^{*} \cdot r_{\mathrm{tip}}^{\frac{1}{2}}} \right)^{\frac{2}{3}}, \tag{3}$$

where E_{s}^{*} is the effective modulus of the substrate.

Therefore, the key task of determining the systematic deviation Eq. (2) is essentially to quantitatively model the polymer surface deformation under given scanning conditions, i.e.

$$d_{\mathrm{L}} = \Psi(F_{\mathrm{tip}}, r_{\mathrm{tip}}, v_{\mathrm{tip}}, MP_{\mathrm{s}}, MP_{\mathrm{L}}), \tag{4}$$

where MP_{s} and MP_{L} are the mechanical properties of the substrate and those of polymer layer under investigation, respectively. Obviously, there exists generally no explicit solution for Eq. (4), especially when the layered structures are composed of time-dependent materials, and the material properties of substrate would also contribute to d_{L} in case of large surface deformation.

It is already known that the influence of the substrate's material properties on the surface deformations of structural layers will be quite small, when $d_{\mathrm{L}} < \frac{1}{10} t$ [23,24]. Further investigation [25] reveals that the substrate effect becomes fully negligible when the contact radius a_c within a tip–surface interaction is less than one tenth of the layer thickness t. In addition, numerical and experimental investigations of spherical scratch tests on polymers [27] have indicated that the tip–surface-sliding contact will get into steady-state status when the tactile scan length is larger than 2–3 times of the tip radius.

To simplify the modelling work, it is therefore rational to assume that the following pre-conditions hold during each tactile surface scan:

1. the tactile scanning parameters F_{tip} and $\mathrm{v}_{\mathrm{tip}}$ remain constant,
2. $d_{\mathrm{L}} \ll t$, so that no substrate effect has to be taken into consideration,
3. polymer structural width $W \gg 5 r_{\mathrm{tip}}$, so that steady-state tip–surface interaction can appear,
4. the contact pressure $\max\left(\frac{F_{\mathrm{tip}}}{\pi r_{\mathrm{tip}} d_{\mathrm{s}}}\right) \ll Y_{\mathrm{s}}$, where Y_{s} is the yield strength of the substrate.

Under the aforementioned assumptions, Eq. (4) can now be simplified to

$$d_{\mathrm{L}} = \Psi(F_{\mathrm{tip}}, r_{\mathrm{tip}}, v_{\mathrm{tip}}, MP_{\mathrm{L}}). \tag{5}$$

For structures made of polymer materials, and thermoplastic photoresists in particular, the corresponding specimen surface deformation d_{L} can be further described by a linear superposition of (recoverable) elastic deformations $d_{\mathrm{L}}^{\mathrm{e}}$ and strain-rate dependent visco-plastic deformation $d_{\mathrm{L}}^{\mathrm{vp}}$, as illustrated in Fig. 1.

Let the averaged sliding contact pressure $\sigma_{\mathrm{c}} = F_{\mathrm{tip}} / \pi r_{\mathrm{tip}} d_{\mathrm{L}}$. Within the purely elastic deformation region, i.e. $d_{\mathrm{L}} \equiv d_{\mathrm{L}}^{\mathrm{e}}$, we have

$$\sigma_{\mathrm{c}} = E_{\mathrm{c}}^{*} \cdot \varepsilon_{\mathrm{c}} = \frac{4}{3\pi} C_1 E_{\mathrm{L}}^{*} \cdot \varepsilon_{\mathrm{c}} = \frac{4}{3\pi} \tilde{E}_{\mathrm{L}}^{*} \cdot \varepsilon_{\mathrm{c}}, \tag{6}$$

where E_{c}^{*} is the sliding contact modulus, E_{L}^{*} the effective instantaneous elastic modulus of the polymer under test, the contact strain

$$\varepsilon_{\mathrm{c}} = \sqrt{\frac{d_{\mathrm{L}}}{r_{\mathrm{tip}}}}, \tag{7}$$

and the coefficient C_1 is generally material dependent [27,28]. For convenience, here the effective sliding elastic modulus $\tilde{E}_{\mathrm{L}}^{*} = C_1 E_{\mathrm{L}}^{*}$ is defined and introduced to Eq. (6).