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Investigation on friction behavior and processing depth prediction of polymer in nanoscale using AFM probe-based nanoscratching method

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ABSTRACT

The present work investigates the friction behavior and machined depth prediction when scratching on a polymer material using an atomic force microscopy (AFM) tip. According to the calculated results based on the experimental tests and the proposed model, the flow stress during machining is demonstrated to be a logarithmic increase with the scratching speed increasing, and the adhesive friction coefficient has little change with the variation of the normal load and scratching speed. Finally, several nanochannels with expected machined depth are achieved on the polymer surface using the prediction method presented in this study and the deviation between the experimental and desired values is mainly less than 10%.

1. Introduction

Nowadays, due to the potential in health care, life sciences and environmental concerns, label-free assays have attracted more and more attention. In order to overcome the difficulty of using the most current label-free assays techniques to detect analytes at a very low concentration in a short span of time, some scholars proposed an approach to confine the analytes in a nanoscale space leading to analytes striking the surface of this space more frequently [1–3]. Nanochannel-based sensor has been proven to be an effective nano-confinement used in the label-free assays technique [4–6]. Therefore, the preparation of size-controllable and good quality nanochannels is essential to these research and applications. To date, many techniques, including electron beam lithography (EBL) [7], focused ion beam (FIB) [8], nanoimprint lithography (NIL) [9], and interferometric lithography (IL) [10] have been employed to fabricate nanochannels. However, these approaches usually require a complex operation procedure, a high investment for the fabrication facility and strict environmental requirements.

Due to the advantages of low cost, simple operation process, atomic-level manipulation capabilities and atmospheric environment requirement, the Atomic Force Microscopy (AFM) tip-based nanofabrication method has been demonstrated to be a powerful and feasible approach to create high quality micro/nanostructures [11]. A variety of methods have been widely used to study and perform nanofabrication based on the AFM system, such as dip-pen nanolithography [12], local anode oxidation [13], thermochemical nanolithography [14] and nanomechanical scratching method [15]. Among these methods, the nanomechanical scratching approach is the easiest and most flexible. Many scholars have employed this method to fabricate nanostructures on the surfaces of metals [16], polymers [17], and semiconductor materials [18,19]. In particular, due to owning easiness to scratch, good quality of formed features and etching resistance, polymer materials are usually selected as the substrate in the nanochannels-based sensors [20,21]. However, how to fabricate nanochannels with expected dimensions by AFM tip-based nanomechanical scratching approach on the surface of polymer material remains a challenging issue. Previous studies presented several theoretical models to predict the machined depth of the desired nanostructures on the metal and semiconductor substrates, and the authors obtained the excepted nanostructures successfully [22–24]. In these proposed theoretical model, it is assumed that the dominant mechanism of energy dissipation is plastic deformation [22]. Thus, the influence of the elastic recovery is neglected in their studies. Moreover, comparing with the adhesion component, the cutting force contributed by the deformation of the material is generally dominant, and thus, the effect of the adhesive friction force is ruled out during scratching on the surfaces of the metal and semiconductor materials. However, because the polymer is a typical time-dependent material, the elastic recovery should be considered in the mechanical scratching process [25–27]. Moreover, the influences of material pile-up, adhesive friction force and flow stress can not be neglected in the scratching process of polymer materials [28–30]. Therefore, the theoretical models developed for the metal and semiconductor materials are unsuitable to reveal the

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nanoscratching process on the polymer substrates. It is worth investigating the friction behavior and the normal load-machined depth relationship when scratching on the polymer surface by using AFM tip-based nanomechanical machining method.

In this study, a machined depth prediction model for nanochannels scratched with an AFM tip is developed. Effects of adhesive friction force, flow stress, material pile-up, materials elastic recovery and geometry of the AFM tip are considered in the theoretical model. Experiments are conducted on a typical polymer material to study the influences of the normal load and scratching speed on the material pile-up, friction force and machined depth. Based on the proposed theoretical model and the experimental results, the adhesive friction coefficient and flow stress are analyzed in detail. Furthermore, several nanochannels with expected machined depth are achieved on the polymer surface using the AFM tip-based nanomechanical machining method.

2. Theoretical model of nanoscratching on polymer material

When scratching on a polymer surface using an AFM probe, the influences of the recovery of the material, formation of the pile-up and adhesive friction force during scratching on the machining outcomes should be considered in the theoretical modelling process. In order to avoid the influence of the tip wear, a diamond tip is selected as the cutting tool for all scratching tests and the tip wear can be neglected when conducting the experimental tests on the polymer surface. Thus, in this study, the AFM probe is assumed as a rigid abrasive particle. As the geometry of the diamond AFM probe used for nanomachining is generally triangular pyramid, different scratching directions would lead to various machining results. In this study, the lateral force applied on the apex of the tip is needed to be measured to conduct the calculation of the theoretical model. In order to obtain the lateral force easily in the experimental tests, the orientation perpendicular to the long axis of the tip cantilever is selected as the scratching direction. However, due to the asymmetric geometry of the AFM probe, the pile-ups can only be accumulated on one side of the machined groove when scratching with the perpendicular to cantilever direction, as shown in Fig. 1(a) [25]. This asymmetric distribution of the pile-ups should be considered in the theoretical model. Aiming to predict the machined depth, the cutting forces during the scratching need to be analyzed first. The normal force and tangential force applied on the unit area of the probe by the material flowing can be expressed as [31]:

$$\begin{cases} d\overrightarrow{F_n} = \sigma_f dA\hat{n} \\ d\overrightarrow{F_t} = \mu_a \sigma_f dA\hat{t} \end{cases} \tag{1}$$

where σ_f is the flow stress during machining and μ_a is the adhesive friction coefficient. $\hat{n}$ is the normal unit vector, which is the perpendicular to the surface of the probe and in the oblique upward direction. $\hat{t}$ is the tangential unit vectors, which is the opposite direction of the projection direction of the tip moving on the probe surface. dA is the unit area of the interaction contact between the AFM probe and the sample surface. The normal and lateral loads can be obtained by integrating the vertical and lateral component of the cutting forces per unit area, respectively, which can be calculated as follows.

$$\begin{cases} \overrightarrow{F_N} = \iint (\sigma_f \hat{n}\cdot\hat{z} + \mu_a \sigma_f \hat{t}\cdot\hat{z}) dA\hat{z} \\ \overrightarrow{F_V} = \iint (\sigma_f \hat{n}\cdot\hat{v} + \mu_a \sigma_f \hat{t}\cdot\hat{v}) dA\hat{v} \end{cases} \tag{2}$$

where F_N is the normal load and F_V is the lateral force. $\hat{z}$ is the unit vector in the vertical direction and $\hat{v}$ is the unit vector in the lateral direction along the tip moving. In order to simplify the calculation, the axial direction of the AFM probe is assumed to be perpendicular to the machined sample surface. Moreover, the width of the machined groove is about several hundred nanometers, which is much larger than the radius of the cutting edge of the probe (about 40 nm in this study). Thus, the influence of the cutting edge of the probe is neglected in the modelling process. As shown in Fig. 1(b), the main cutting surface is denoted as *I-surface* (AOB plane). Because of the formation of the asymmetric pile-up mentioned above, the contact area between the probe and the sample should be enlarged. Thus, the total height of the contact area between *I-surface* of the probe and the sample (h_{total}) can be expressed as:

$$h_{total} = h_s + h_d \tag{3}$$

where h_s is the depth that the tip inserted into the sample surface during the scratching process, and h_d is the height of the pile-up, as shown in Fig. 2(a). h_m is the residual machined depth measured after machining, as shown in Fig. 2(b), and h_r is the recovery depth which is defined as the difference between h_s and h_m. The recovery rate (R_e) of the material is defined as the ratio of h_r and h_s [25]. The ratio between h_d and h_m is denoted as τ_p. h_s and h_d can thus be calculated as:

$$h_s = \frac{h_m}{1 - R_e} \quad , \quad h_d = \tau_p h_m \tag{4}$$

First, the probe is assumed as an ideal triangular pyramid without spherical apex. Considering the contact area between the tip and the sample material in *I-surface*, applying Eq. (4) through Eq. (1) and integrating it in this contact area, the vertical and tangential cutting forces applied on the *I-surface* of the AFM tip can be derived as:

$$\begin{cases} \overrightarrow{F_{In}} = \dfrac{(\tan\beta_1 + \tan\gamma_1)(1 + \tau_p - \tau_p R_e)}{2\cos^2\alpha_1 (1 - R_e)^2} \sigma_f h_m{}^2 \hat{n}_I \\ \overrightarrow{F_{It}} = \dfrac{(\tan\beta_1 + \tan\gamma_1)(1 + \tau_p - \tau_p R_e)}{2\cos^2\alpha_1 (1 - R_e)^2} \mu_a \sigma_f h_m{}^2 \hat{t}_I \end{cases} \tag{5}$$

where α_1 is the included angle between the axis of the triangular pyramid and the perpendicular of AB edge in the AOB plane. β_1 is the included angle between OB edge and the perpendicular of AB edge and γ_1 is the included angle between OA edge and the perpendicular of AB

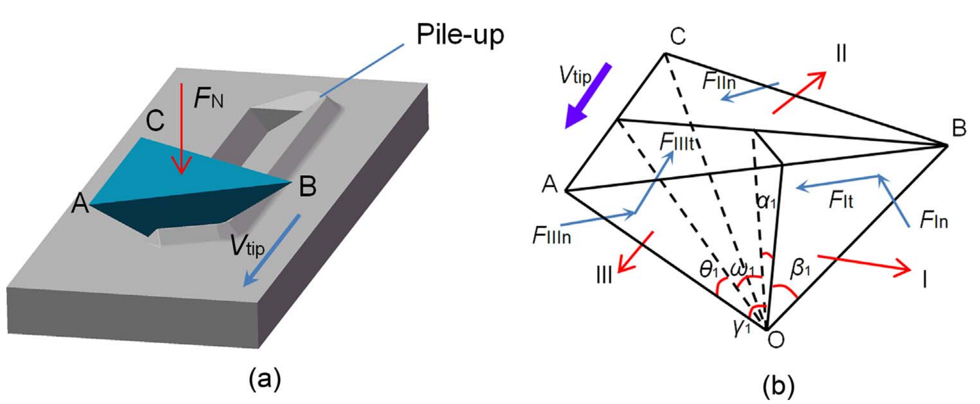

Fig. 1. AFM tip-based nanoscratching. (a) Schematic view of scratching process on polymer material. (b) Cutting forces applied on the AFM tip.