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Modeling of the dynamic machining force of vibration-assisted nanomachining process

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ABSTRACT

Nanofabrication technology is very important for many emerging engineering and scientific applications. Among different nanofabrication technologies, vibration-assisted nanomachining provides a low-cost easy-to-setup approach for producing structures with nano-scale resolution. It is very important to understand the mechanism for this nanomachining process and predict the involved machining force, so as to provide guidelines to achieve higher productivity and reduce tip wear. In this work, a machining force model for the tip-based nanomachining process was developed and validated. We analyzed the instantaneous engagement between the cutting tool (AFM tip) and the workpiece (PMMA film) during each tip rotation cycle for the vibration-assisted nanomachining process. A discrete voxel method was adopted to calculate the material removal rate at each moment, and an empirical machining force model is developed by correlating the machining force with material removal rate, which is a function of the input parameters of the nanomachining process. The machining force model was verified by experiments over a large range of machining conditions, and the coefficients in the force model were obtained by minimizing the Mean Square Error (MSE) method by comparing the predicted machining force from the model and measured machining force from the experiments. The results show a good fit between the predicted machining force and the measured machining force.

1. Introduction

Nanotechnologies have been widely applied in many areas such as physics, chemistry, biological science, and engineering. Nanoscale fabrication of master patterns and masks are critical for emerging nanotechnology. Many nanofabrication methods have been developed for fabricating nanostructures, such as X-ray lithography [1], e-beam lithography [2–4], nanoimprint lithography [5,6], etc. Although these methods can achieve high resolution, many of them still rely on photolithography or e-beam lithography to fabricate the mold or mask. The e-beam lithography systems are very expensive (typically >$ 1 M) [7], and the hourly rate for users is typical $120-200/hr [8]. Compared with expensive e-beam lithography, Atomic Force Microscope (AFM) based nanofabrication provides a lower-cost, easy-to-setup alternative to tasks mentioned above. The AFM-based nanofabrication system can only cost around $ 20–80 k USD [9] with an hourly user rate about $20-30/hr [10].

The tip-based nano-machining approach is capable of modifying the sample mechanically by cutting or plastic deformation with low cost, while the major disadvantage of this method is its low productivity. As the fabricated feature width is mainly determined by the AFM tip radius, multi-scratching steps are needed to make a larger feature. Moreover, poor process controllability is the other disadvantage of the traditional nanomachining. In direct scratching, a large normal force is required to push the tip into the sample for mechanical modification [11–13], which depends heavily on properties of the sample materials and the cantilever used. The Large normal force also causes tip wear problem. Previous researchers have demonstrated that vibration assisted nanomachining method can significantly reduce the machining force and reduce tip wear for material insensitive depth regulation [14–16], which is a potential method for low-cost high-efficiency nanofabrication method.

It is very important to understand the mechanism and the interaction force involved in the nanomachining process, so as to plan the process properly and to improve productivity and achieve better machining performance. While directly physical modeling of the machining process at the nanoscale is very difficult, at conventional scale, many force models haven been developed for different

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machining processes [17–20]. In these models, a mechanical modeling approach was adopted to predict the cutting force using the chip load, cut geometry, and other cutting conditions for many metal cutting processes. The cutting force models were used to increase the material removal rate, and predict the machining force and the associated tool deflections and surface geometrical errors [21–24]. Similar to conventional scale machining processes, some force and process models were successfully developed for micromachining processes [25–28]. In general, in these models, these resulting machining forces were correlated with the workload in the material removal process.

Modeling of processes at the nanometer scale is very complex, due to the complicated physics involved. The molecular dynamic simulation was adopted by many researchers to study the scratching-based nanomachining process, which studies the molecular interaction of the process at different process conditions [29,30]. While this method can provide predictive results for machining force and feature geometry after machining, it is computationally intensive and time-consuming, which limit its application generally to relatively simple processes. Experimental modeling was also applied for some relatively simple nanomachining process, such as nano-scratching [31], in which the effect of major scratching parameters on the nanostructure was studied to estimate the force needed to scratch features with desired dimensions.

In this article, a machining force model for the tip-based vibration-assisted nanomachining process was developed and validated. The model correlates the machining force with the instant material removal rate, which is a function of the specific machining conditions (i.e. setpoint force, xy vibration amplitude, and feed rate). We first analyzed the instantaneous engagement between the cutting tool (the AFM tip in this paper) and workpiece during tip rotation for the vibration-assisted nano-machining process. A discrete voxel method was adopted to calculate the material removal rate during the machining process. Then the machining force model was developed to correlate machining force with material removal rate. A set of machining experiments was performed at different machining conditions to calibrate and evaluate the model. The predicted force from the model fits very well with the measured machining force from the experiments.

2. Experimental setup for vibration-assisted nanomachining process

The experiments setup of the nanomachining process includes a commercial AFM, Park XE-70 (Park Systems Corp®), and a customized nano-vibration system. The nano-vibrator provides the relative vibration between the tip and the sample to be machined to facilitate the nanomachining process. The detailed description of the nano-vibrator has been reported in our previous study [15]. During nanomachining, the normal deflection and torsion of the cantilever are measured by the four-quadrant photodetector in the AFM as A-B and C-D signal, which can be accessed by the Signal Access Module from the Park Systems. The cantilever deflection and torsion signals from the photodetector represent the normal force and the lateral force in nanomachining and are acquired in LabVIEW during machining through a data acquisition device (NI USB-6259). The same data acquisition device is also used to generate synchronized sinusoid signal with 90° phase difference to drive the xy-piezo actuators to generate the controlled vibration in xy-plane (Fig. 1).

In this paper, to study the cutting force during nano-machining, vibration-assisted nano-machining is applied to a PMMA film. The PMMA film (950PMMA A4 as a 2% dilution in anisole) is spin-coated on a cleaned silicon substrate for 40 s at 4000 RPM and baked at 180 °C for 90 s. The thickness of the resulting PMMA film is about 40 nm as the sample for nanomachining. A tapping mode cantilever with a nominal stiffness of 48 N/m and the resonant frequency of 190 kHz is used in this study.

The sample is mounted on the top of the nanovibrator, which is actuated to vibrate in the xy plane at the frequency of 2 KHz. The amplitude of the xy vibration is used to control the width of the machined trench in one machining pass. With the xy vibration, the material removal is distributed to every rotation cycle. For each cycle, only a small slice of material is removed, which can effectively reduce the tip-sample interaction force in machining. By selecting a higher vibrational frequency, we can achieve a higher machining speed with reduced interaction force between the tip and the sample.

3. Modeling of dynamic machining force

Modeling of the tip-sample interaction force is very important for achieving high performance and throughput in the tip-based vibration assisted nanomachining. The cantilever deflection and torsion from too large force can potentially introduce form error of the machined feature. Moreover, the larger forces will likely shorten tool life. The physical modeling of the nanomachining process is extremely complex. In this study, an empirical mechanics model incorporating the time-varying geometry of the cut was explored to describe the correlations between the machining force and the process inputs. The machining forces for the vibration assisted nanomachining are directly related to the instant tip-sample engagement in each vibration cycle. Unlike direct scratching with almost constant tip-sample engagement, in this nanomachining process, the tip only removes a slice of material in each cycle as shown in Fig. 2(a). The tip-sample contact keeps changing as the tip rotates. Intuitively, the interaction force between the tip and the sample will depend on the instant tip-sample interaction, which induces a time-varying force.

To model the dynamic machining force in the tip-based nanomachining process, we first analyzed the geometry of the engagement between the AFM tip and the sample during each vibration cycle. Then a discrete voxel method was developed to calculate the volume of the tip-sample engagement and material removal rate at each instant from the feature width and depth, which in turn are the function of the machining conditions. Finally, a machining force model was developed, which can predict the machining force from the input parameters of the machining process.

3.1. Estimation of the instant material removal rate

In tip-based nano-machining, the AFM tip as the cutting tool is intrinsically blunt with negative rake angle, and the dimension of the tool is comparable to the material removed, which is quite different from conventional scale machining process using tools with the sharp cutting edge. Although it is very difficult to measure the exact geometry of the cantilever tip, in our modeling, we assume the cantilever has a semispherical tip with a fixed radius of 30 nm (measured by the Scanning Electron Microscope), and the depth of cut is smaller than the AFM tip radius. In the vibration assisted nanomachining, the sample is vibrated in a circular path in xy-plane. Thus in one rotation cycle of the tip, the tip-sample engagement will depend on the rotational angle of the tip and other related machining condition, such as machined patterns, depth, and width of the features.

When cutting a slot in the vertical direction, the top view of in-plane AFM tip movement during one machining cycle is shown in Fig. 2(a). In one rotation cycle, AFM tip starts machining from