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Technical Paper

Predictive modeling of feature dimension for tip-based nano machining process

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ABSTRACT

The tip-based vibration-assisted nanomachining process can fabricate three-dimensional (3D) features with nanometer scale resolution. To control the feature dimension accurately in process planning, we need to understand the relationship between feature dimension and machining parameters including set-point force, XY vibration amplitude and feed rate. In this article, we conducted full factorial experiments to analyze the relationship between feature dimension and machining parameters. Based on analysis of variance (ANOVA), we determined the significant factors in determining the feature dimension. The feature width is mainly controlled by XY vibration amplitude, and the feature depth is controlled XY vibration, setpoint force and feed rate. In order to predict the feature dimension in nanomachining and provide instructions for machining parameter selection, a semi-empirical mechanical model was built first. Then simplified regression models were also investigated, with all models displaying good predictive capability. The results show good fit between predicted feature depth and measured feature depth, for most machining conditions. These models provide good capability in process planning for implementation of this process.

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1. Introduction

Machining process modeling have been heavily studied in conventional scale, with many of these studies examining the modeling of cutting force and the prediction of the feature dimension after machining. Researches on modeling of dynamic metal cutting process is summarized [1], mechanical modeling approach has been used to predict the cutting force for the ball end milling processs [2]. Cutting force models have been used to increase the material removal rate [3], and mechanistic methods have been widely applied for the force predictions and prediction of the associated tool deflections [4] and surface geometrical errors [5].

Besides mechanical modeling, simulation methods have also used in the study of machining process. A surface topography simulation was studied to simulate the finish profile generated after a turning operation [6]. Finite element (FE) simulations were applied to analyze the orthogonal cutting process [7]. Predictions of machining induced micro hardness and grain size are performed by using 3D finite element (FE) simulations of machining and machine learning models, which have been adapted to predict machining induced micro hardness and grain size [8]. Finite element simulation has applied to predict cutting force, tool stress and temperature in high-speed flat end milling [9]. Cutting force and chip formation under different tool edge geometry in the orthogonal machining process was analyzed with finite element method [10].

Statistical modeling approach has also been widely used to study the machining processes. Statistical models and artificial neural networks have been compared for predicting tool wear in hard machining [11]. Optimal cutting conditions for surface roughness were investigated using response surface methodology [12]. Cutting conditions for the hard turning process was optimized using analysis of variance (ANOVA) and experimental design methods [13].

Processing modeling at nanomater scale is very difficult, due to the complex physics involved in the process. Molecular dynamic simulation is a useful method to study the machining process from the aspective of molecular responses to the process input. At the nanometer scale, the nanomachining of copper was simulated with molecular dynamics method [14]. Molecular dynamics simulation was also used to study the chip formation process during nanomachining [15], while this method can give predictive results for feature dimension after machining, it is computaional intensive and time consuming, which limit its application to relatively simple

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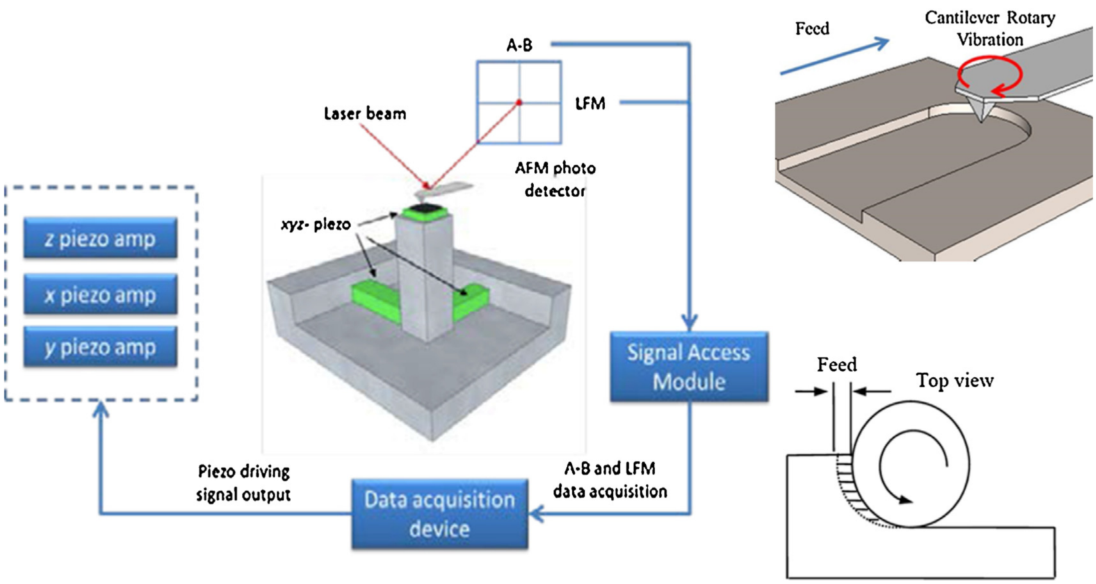

Fig. 1. Experimental setup. (a) The vibration assisted tip-based nano machining system. The AFM system was customized, and signal feedback system was added. (b) Schematic illustration of tip movement in the XY plane. (c) The top view of machining process.

process. Exprimental modeling has slo been applied for nanomachining process. The effect of major scratching parameters on the nano structure was studied to estimate the force needed to scratch features with desired dimensions [16].

In this research, feature dimension prediction models of tip-based nanomachining process are developed and validated. We first use analysis of variance (ANOVA) method to determine statistically significant factors that influence feature dimensions, and then built a semi-empirical model to describe the relationship between feature dimension and machining parameters. Then simpler linear and nonlinear regression models were built to be compared with semi-empirical model. The effectiveness of these models was verified using experimental data.

2. Machining setup and experimental design

2.1. Machining setup

The experimental setup includes a commercial AFM, Park XE-70 (Park Systems Corp®), and a customized nano-vibration system, as shown in Fig. 1(a). The detailed description of the nanovibrator has been previously reported [17]. The Signal Access Module from the Park Systems obtain the normal and lateral forces during nanomachining process, which are measured by cantilever deflection and torsion from the photo detector. The machining force measured from cantilever deflection and torsion are acquired by LabVIEW during machining through a data acquisition device (NI USB-6259), which is also used to generate a synchronized sinusoid signal with 90° phase difference to control the vibration of XY-piezoactuators as shown in Fig. 1. A tapping mode cantilever with a nominal stiffness of 48 N/m and resonant frequency of 190 kHz is used in this study. The sample is mounted on the top of the nanovibrator, which is vibrated in the XY plane with the frequency of 2 kHz. In our experiment, vibration-assisted nano machining is applied to (PMMA) film. The PMMA film (950PMMA A4 as a 2% dilution in anisole) is spin-coated on a cleaned silicon substrate for 40s at 4000 RPM, and baked at 180 °C for 90 s. The thickness of PMMA is 40 nm and the machinable area is 2 μm × 2 μm.

During the machining process, the force applied by the tip to the sample is determined by setpoint force of the AFM, which corresponds to the deflection of cantilever. The larger setpoint force induces the larger interaction force between AFM tip and sample surface, which will produce the larger feature depth. As shown in Fig. 1(b), the sample was actuated by the nanovibrator to provide a XY in-plane vibration, thus the width of the feature is regulated by XY vibration amplitude. With high frequency circular XY-vibration, only a thin slice of material is removed in one machining cycle, which greatly enhances the machining speed and reduces tip-sample interaction force. Diameter of the virtual tool is controlled by the XY-vibration amplitude, which directly regulates the feature width that can be machined in one single machining path. Feed rate is the relative velocity of the AFM tip in the direction of machining. With larger feed rate, the AFM tip moves faster on the sample surface, and more material (feed per rotation) is removed in a revolution. The purpose of this study is to determine the relationship between feature size and machining inputs parameters.

2.2. Experimental design

To fully understand the relationship between feature dimension and machining input parameters, a full factorial design was developed. The machining input parameters include the setpoint force, the XY vibration amplitude and feed rate. From our preliminary experiments, we determined the feasible range of each parameter to machine an observable feature. For each input parameter, we set three different values corresponding to low, medium and high values of the parameter, yielding a 3^3 full factorial design. The full experimental design is given in Table 1 below. The machined features are scanned with the same AFM, and for each feature, we measure 10 times from randomly selected positions, with the mean values used for our analysis.

Table 1
Full factorial 3^3 experimental design.

Factor	Levels
Setpoint force (nN)	120, 140, 160
XY vibration amplitude (mV)	35, 50, 65
Feed rate (μm/s)	0.6, 1.0, 1.4

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