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Numerical Analysis of the Ultraprecision Machining of Copper

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INTRODUCTION

Modeling of the ultraprecision machining process can aid in the understanding of the relative importance of various process parameters and ultimately lead to improved methods of generating ultraprecision surfaces such as those required for metal optics and single crystal microelectronics substrates. Any modeling method should be verified by direct comparison to experimental data. Until recently it has been difficult to accurately measure the cutting edge, or sharpness, of a diamond tool; and therefore, most models have assumed a infinitely sharp cutting tip. With the relatively new technology of the Atomic Force Microscope (AFM), the cutting edge of single crystal diamond tools can be quantitatively described. Ultraprecision machining experiments using an AFM characterized cutting tool and orthogonal geometry have been performed. These experiments [1] have resulted in measured cutting and thrust forces for different depths of cut in copper (Te-Cu: 99.4-99.5% Cu, 0.5-0.6% Te, 4-5 micron grain size, 225 MPa yield strength) with a well characterized diamond tool. By using this actual tool tip geometry we have been able to develop a model that can predict cutting and thrust forces for depths of cut on the order of the sharpness of the tool. Forces predicted by this numerical model are compared to the experimentally measured forces.

NUMERICAL APPROACH

We used the Eulerian finite element code Mantle as our basic computational tool. The code, which uses quadratics in 6-node
triangles to represent velocity and temperature fields, has been well-tested and validated on plane convective flow problems [2] as well as on a conventional orthogonal machining problem. The reader is referred to [2] and [3] for detailed information about the code; here we describe features of Mantle that were implemented to study the ultra-precision machining problem. The use of a flow code makes unnecessary an artificial tension release algorithm to simulate the material separation at the tool tip commonly used in other numerical approaches to the machining problem; in our method we calculate the actual stresses and strain rates at the point of separation.

Our numerical procedure uses a viscoplastic constitutive model as the relationship between strain rate and deviatoric stress while the pressure field is developed from the incompressibility requirement on the viscoplastic strain rates. The material viscosity $\mu$ relates the strain rate and deviatoric stress and is taken to be of the form

$$
\mu = \begin{cases} 
\sigma_y \frac{\varepsilon}{\sqrt{3}} + \bar{\mu} & \text{if } \dot{\varepsilon} \geq \dot{\varepsilon}^* \\
\mu_{\text{max}} & \text{if } \dot{\varepsilon} \leq \dot{\varepsilon}^*
\end{cases}
$$

where $\sigma_y$ is the material yield stress and $\dot{\varepsilon}^* = \sigma_y / \sqrt{3} (\mu_{\text{max}} - \bar{\mu})$ is an effective viscoplastic strain rate. This material model approximates perfectly plastic flow at constant yield stress $\sigma_y$ for large strain rates while for small strain rates the flow is nil simulating rigid behavior. The parameters $\bar{\mu}$ and $\mu_{\text{max}}$, which come into play for very large and very small strain rates respectively, were set by the requirements of acceptable convergence rates and to not affect the numerical solution in the deforming region around the tool tip.

The configuration of the chip and the shape of the workpiece surface as they are deformed by the cutting operation were determined using the shooting method to maintain these surfaces on streamlines of the material flow [3]. A constant coefficient of friction was maintained on all contact surfaces between the tool and workpiece by iterating on the Robin coefficient, which relates linearly the relative tangential velocity and the frictional stress at
the contacting surfaces. Finally, the frictional stress was limited in value to be no greater than the material maximum shear stress (taken to be $\sigma_y/2$).

Two cutting tools ("new" and "worn") were used in the experimental and numerical investigations. The effective edge radii of the two profiles were approximately 0.1 micron and 0.25 micron, respectively (note, however, that the actual profiles were not circular). A picture of a typical finite element mesh used in the Mantle machining simulations is shown in Fig. 1. This mesh shows the work material shape after Mantle iteratively repositioned the mesh's free surfaces. Different meshes had to be created for each depth of cut, and for both of the cutting tool profiles. The true depths of cut (defined as the distance from the top surface of the incoming work material to the top surface of the exiting work material) ranged from 0.024 to 1.45 micron.

RESULTS AND DISCUSSION

The cutting and thrust forces calculated by Mantle are plotted in Figs. 2 and 3. The experimentally-measured forces are also shown in these figures. Data for both the new and the worn tool profiles is included (thus, there are four curves on each plot).

For depths of cut above approximately 1 micron, there is little difference between the new and worn tool profiles, for both the cutting and thrust force. At depths of cut much larger than the effective radius of the cutting tool, the difference between a new and a worn tool profile becomes negligible, and the forces depend only on the depth of cut.

The cutting force is approximately linearly proportional to the depth of cut over the entire range of depths of cut. However, the thrust force, especially the thrust force for the worn tool profile, shows two different regimes: for small depths of cut (below approximately 1 micron), the thrust force (especially for the worn tool profile) is nearly constant, whereas above approximately 1 micron, the thrust force is approximately linearly proportional to the depth of cut.
Above a depth of cut of 1 micron, the ratio of the thrust force to the cutting force is nearly constant (approximately 0.3). Below this depth of cut, the ratio increases rapidly for the worn tool profile, but only slowly for the new tool profile. The thrust force on the worn tool profile is greater than the cutting force for depths of cut less than approximately 0.2 microns, but the thrust force on the new tool profile is never greater than the cutting force. The difference in the ratio of the thrust force to cutting force between the new and worn tool profiles may be explained by considering the length of contact on the clearance face of the tool. The worn tool profile is in contact with the work material over a longer length on the clearance face than the new tool profile, but both profiles have approximately the same contact length on the rake face of the tool. A longer clearance-face contact length results in a greater thrust force on the cutting tool; however, this effect is only noticeable for small depths of cut, because for large depths of cut the clearance-face contact length (for the new or worn tool profile) is much smaller than the rake face contact length.


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Fig. 1. Finite element mesh for 0.044 micron depth of cut simulation with the worn tool profile.

Fig. 2. Measured and calculated thrust force for new and worn tool edge profiles.