

## Ductile Regime Nanocutting of Silicon Nitride

John A. Patten, Wei Gao, Ronnie Fesperman, University of North Carolina at Charlotte

Research has been carried out to evaluate the ductile regime machining of silicon nitride. The Nanocut II device, an experimental cutting instrument, was used to produce cuts in silicon nitride with single point diamond tools (-45 degree rake angle). This device controls the depth of cut to within a nanometer, and measures the cutting and thrust forces (in mN) with sub-mN resolution. Actual depths of cut ranged from 250 to 600 nanometers, and the corresponding forces were less than .2 N. From this data the force ratios ( $F_c/F_t$ , the apparent coefficient of friction) were calculated. These values ranged from 1.7 to 4.

Keywords: silicon nitride, ductile machining, ductile-brittle transition, CMP, vibration assisted machining.

### Introduction

Ductile cutting of ceramics in general, and silicon nitride in particular, is possible by either controlling the depth of cut (below the critical ductile to brittle transition) or by thermally heating the material to soften and possibly toughen its response to deformation (Shin, 2000). The goal of this present research is to perform controlled depth of cut experiments while simultaneously monitoring the cutting and thrust forces. This data, depth of cut and forces, together with tool geometry, cutting conditions (speed, feed) and material property data are being used in a collaborative research project to model and simulate the machining of ceramics (Hocken, 1999).

### Results

All cuts in this range, actual depths of cut as measured on an AFM of 250 to 600 nm, resulted in purely ductile material removal with no evidence of brittle fracture. Subsequent cutting test on a commercial diamond turning machine (DTM) indicated that the ductile to brittle transition threshold for this material was approximately 10 micrometers (Patten, 2000b). The resulting surface finish of the cuts was comparable to the as received polished conditions of 25 to 100 nm Ra.

### Discussion

Three different types of cuts were performed: Cuts were made in room air (Figures 1 & 2), vibration assisted cuts, and cutting with chemical-mechanical polishing (CMP) slurries (Figures 3 & 4). The cuts made in air resulted in the highest cutting forces compared to vibration and slurry assisted machining (Figures 1 & 3). Vibration assisted machining involved vibrating the sample, normal to the tool, with a PZT stack, at 200 Hz with amplitude of 1 to 2 nm. The vibration assisted machining resulted in reduced cutting and thrust forces compared to non-vibrating cuts made in room air (Figures 3 & 4). Cuts made with CMP slurries showed a reduced cutting force and increased thrust force (Figures 3 & 4). Cutting tests with combined vibration and slurry assisted cutting resulted in forces in-between those of just vibration or fluid alone (Figures 3 & 4). The (as received) silicon nitride samples were polished to a surface roughness of 25 to 100 nm Ra.

This relatively rough surface, and the corresponding porous polycrystalline structure of the material, made it difficult to obtain accurate depth of cut comparisons between the various cutting processes. Therefore the origins of the reduced forces associated with vibration or slurry assisted machining, compared to cutting in air, can not at this time be positively determined. The reduced forces could be due to material or process condition changes. The material's behavior, such as yield strength, or the chip formation process, including shear and friction processes, could have changed as a result of the vibration or CMP slurry. Alternately, the depth of cut may be different, even though the programmed depth of cuts were the same (the results are indicated for programmed depth of cut of 1000 nm and 1500 nm, but the actual depth of cut, as measured on an AFM were between 250 nm and 600 nm). The latter could arise if the material's response to the vibration or slurry resulted in a change in surface characteristics, such as hardness. Future tests on a nanoindenter and DTM will shed some additional insight into the observed phenomena.

### **Conclusions**

Ductile regime cutting of silicon nitride is possible in the nanometric range. Cutting forces can be significantly reduced by employing vibration and/or fluid assisted cutting action. Vibration assisted cutting also lowers the thrust force, while fluid assisted cutting raised the thrust force compared to dry cutting in air. This latter phenomenon is similar to that experienced with deforming silicon (Patten, 2000a). The combination of vibration and fluid assisted machining resulted in intermediate effects for the thrust force, i.e. the thrust forces for combined vibration and fluid assisted machining fell in-between those cuts using just vibration or fluid alone. The force ratio  $F_c/F_t$ , the apparent coefficient of friction (Figure 5), was greatest for the vibration assisted machining and least for the fluid assisted machining. This former result is influenced most by the significant decrease in thrust force during vibration assisted machining. It is possible, that the vibration acted to "break-up" the surface and thus reduce the thrust force. (the vibration is in the thrust direction and not the cutting direction). The lower force ratios obtained with the fluid may be due to lubricity associated with the slurry provided at the contact surfaces. The combination of vibration and fluid assisted machining, by reducing the cutting force, should result in reduced tool wear. The one unanswered question is why the fluid alone caused a decrease in the cutting force but an increase in the thrust force. One possible explanation, is that the fluid increased the apparent hardness of the material, resulting in less penetration and a corresponding smaller depth of cut which would subsequently reduce the cutting force.

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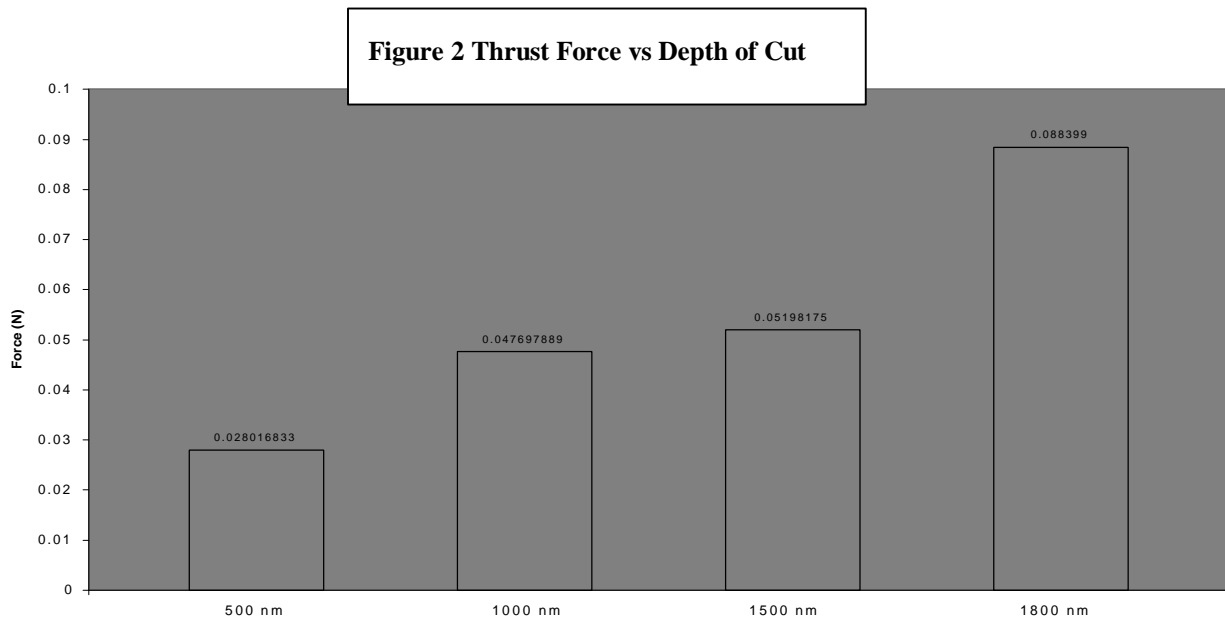
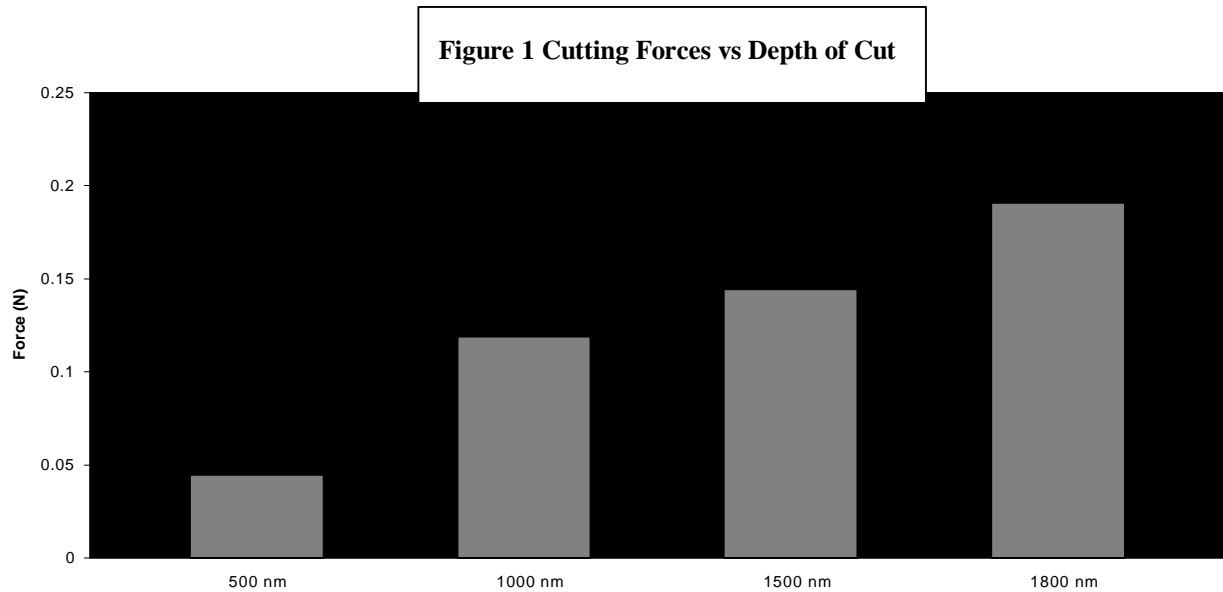
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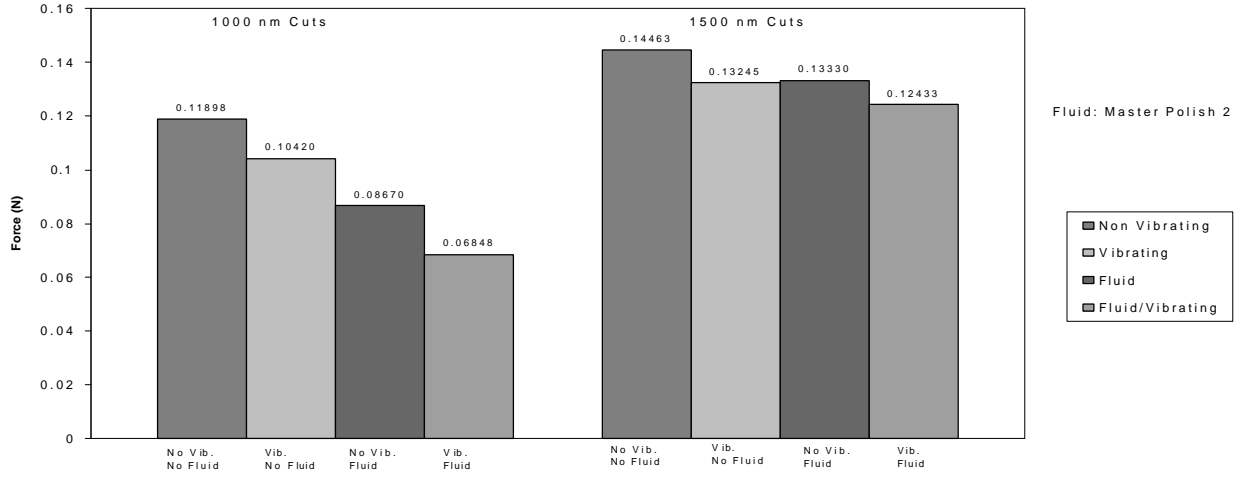
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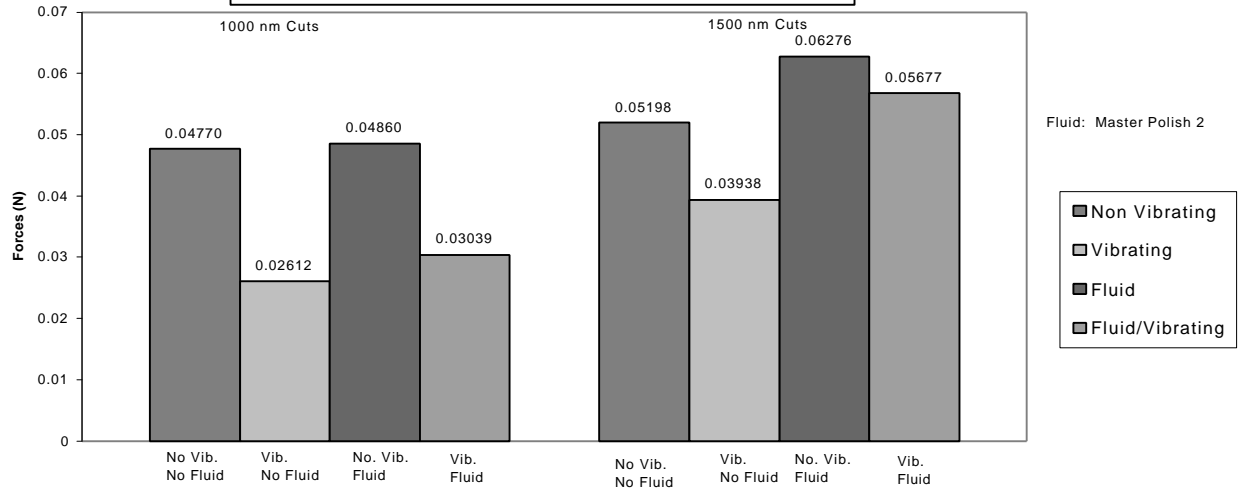
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**Figure 3 Cutting Force, Depth, Vibration and Fluid**



**Figure 4 Thrust Force, Depth, Vibration and Fluid**



**Figure 5 Apparent Coefficient of Friction, Depth, Vibration and Fluid**

