# RAKE ANGLE VARIATION IN DIAMOND TURNING

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## INTRODUCTION

When turning non-rotationally symmetric (NRS) surfaces using a fast-tool servo (FTS), the rake angle of the tool effectively changes as a function of the surface slope. As fast tool servos find ever more applications and are pushed to ever larger strokes and higher operating frequencies, the diamond tools used on them tend to encounter larger variations in rake angle. Recent experiments at the Precision Engineering Center (PEC) have pushed this envelope to variations in rake angle of up to 90 degrees. The effect on figure, finish and tool life is substantial, so a quantization of the errors is needed. The varying tool forces are the main contributor to rapidly changing cutting conditions. These tool forces have been measured in various cutting experiments with the goal of determining optimum rake angles for machining. Large negative rake angles produce large thrust forces whereas large positive rake angles require large clearance angles and, hence, fragile tools. With advance knowledge of the tool forces and the material being cut, an optimum initial rake angle may be found.

The example case studied here involves a 6 mm diameter cylinder with sine waves machined around the periphery. This part was machined at the PEC with a piezoelectric fast tool servo of 20 µm range and 1 kHz bandwidth. A magnified cross-section is shown in Figure 1. Two observations in making these parts led to this investigation of tool forces: 1) significant distortion in the shape of the sine waves and 2) abnormally high tool wear given the short cutting distances and small depths of cut.

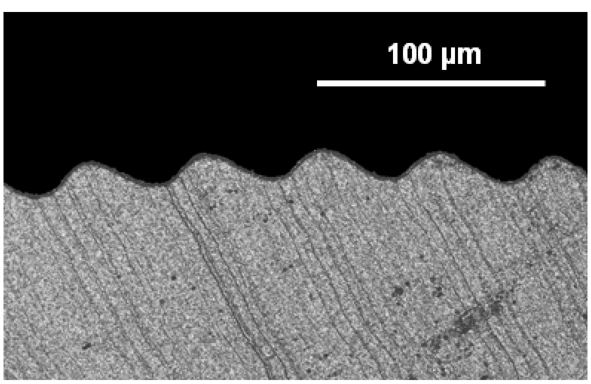


***FIGURE 1.*** *Cross-section of 360 periods of a 17 µm sine waves on a 6 mm dia cylinder*

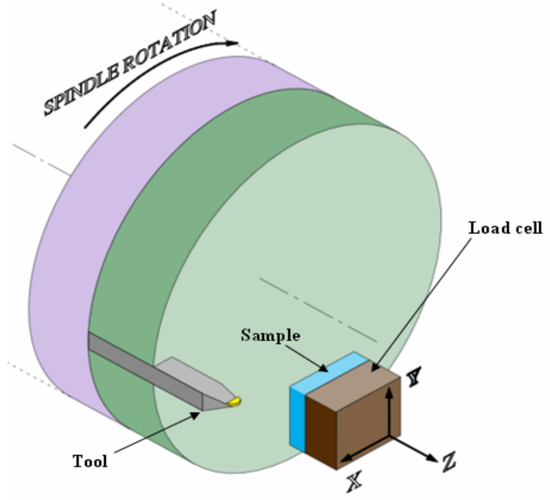


***FIGURE 2.*** *Schematic showing setup for tool force measurements.*

## TOOL FORCE MEASUREMENTS AS A FUNCTION OF RAKE ANGLE

To get an idea of the force variation involved in cutting these sinusoidally figured parts, the forces had to be measured. Previous investigations into tool forces at the PEC [1, 2] by Arcona and Drescher did not measure the effect of varying rake angles, though efforts to assess tool forces at normal (0º rake) incidence were successful.

The experimental setup used for measuring forces (Figure 2) involved placing a sample on a Kistler 9251A piezoelectric load cell and collecting force data while the sample was flycut. The interrupted cut avoided the problem of charge loss in the piezoelectric load cell, though some ringing at the beginning of each cut had to be truncated from the data. The sample was electroless nickel plated copper and was fixed while the rotating tool could be repositioned at varying rake angles. The tool clearance angle of 12º, however, limited positive rake angle

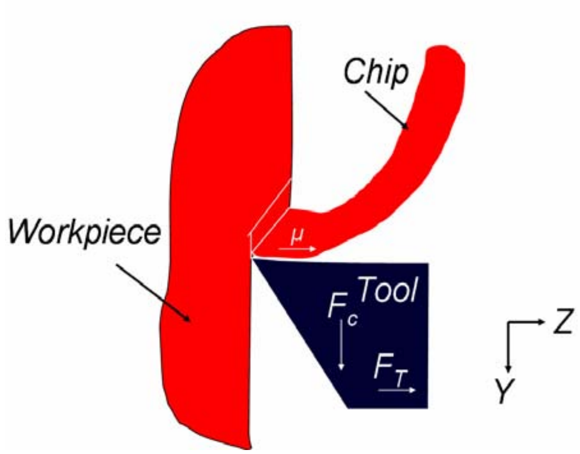


***FIGURE 3.*** *The cutting force ($F_c$) and the thrust force ($F_t$) are measured with respect to the shown axis orientations of the machine*

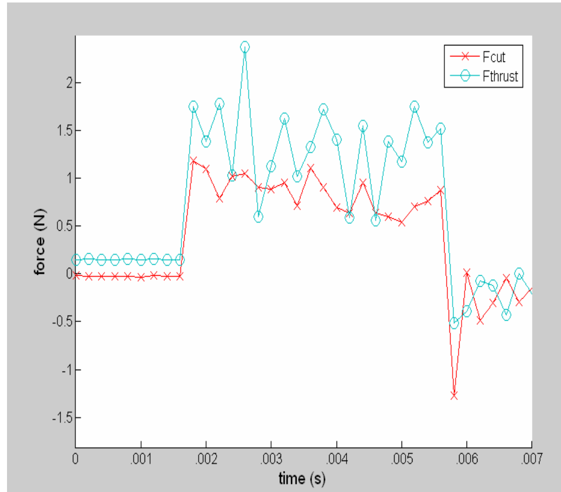


***FIGURE 4.*** *Sample force measurement at 0º rake angle.*

measurements to 10º. The measured cutting and thrust force orientations are shown in Figure 3. The force directions are fixed with respect to the surface of. the workpiece as the tool is rotated through different rake angles. A sample measurement is shown in Figure 4. The plot shows one pass over the sample at 0º rake angle. Data was collected at 5 kHz. Cuts were made with the tool positioned at 0º, 10º, -10º, -20º and finally 0º again. The freshly lapped tool had a conical nose radius of 0.5 mm. Each cut was performed with a 20 µm upfeed and a 10 µm depth of cut at 120 rpm spindle rotation. The final results for force measurements are tabulated in Figure 5. Each data point represents an average of 20 passes over the workpiece.

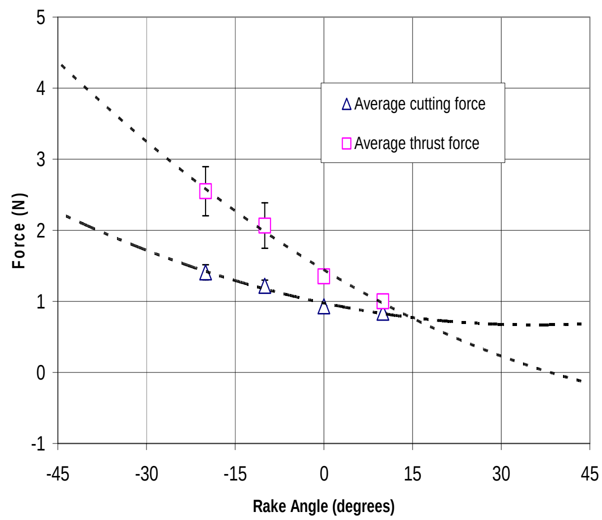


***FIGURE 5.*** *Force variation as a function of rake angle. The dashed lines are least-squares polynomial fits to the data and are extrapolated to ±45 º.*

A least-squares 2nd-order polynomial curve fit allows extrapolation to larger rake angles. Future experiments using large-clearance tools and a larger adjustment range of tool angle will actually allow data collection at rake angles larger than 20º.

## IMPACT ON FIGURE ERROR

While tool forces are always present in machining, constant forces usually have little impact on figure error, particularly in ordinary turning applications when stiff toolposts are used. Fast-tool servos typically are limited in their static stiffness, however, and varying forces can cause them and the workpiece to deflect. Particularly on small parts, compliance in the material can be significant, causing a figure error. Test parts were structured with a 16µm sine wave with ±45° rake angle variation. The

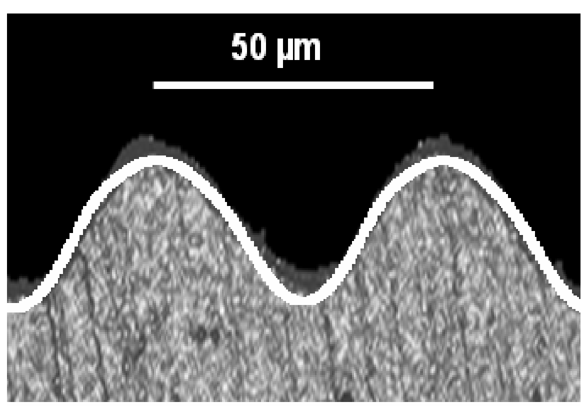


***FIGURE 6.*** *The calculated perturbed tool path from Figure 7 superimposed on a section of Figure 1*

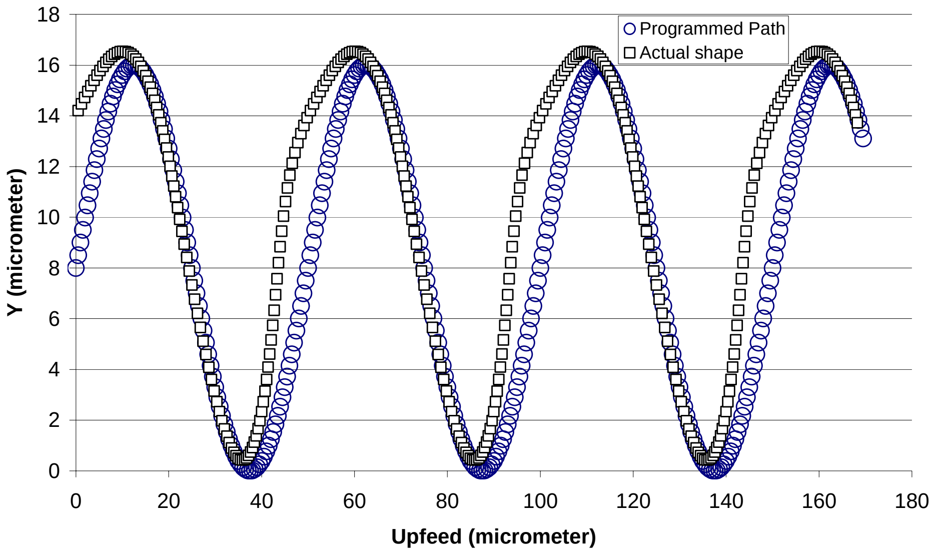


***FIGURE 7.*** *Preturbed shape of the sine waves machined on a 6 mm diameter, 20 mm long brass cylinder. The programmed ideal path is shown for reference.*

part was a 6 mm dia electroless Nickel plated brass cylinder. Modeling the cylinder as a cantilever beam with a length of 20 mm, the deflection can be calculated from the experimentally obtained tool forces. Calculating deflection from this and correlating to the measured forces yields a perturbed sine wave as shown in Figure 7. This distorted sinusoidal shape is very similar to that shown in Figure 1 and when superimposed onto the measured data follows the shape of the actual part. This is illustrated in Figure 6.

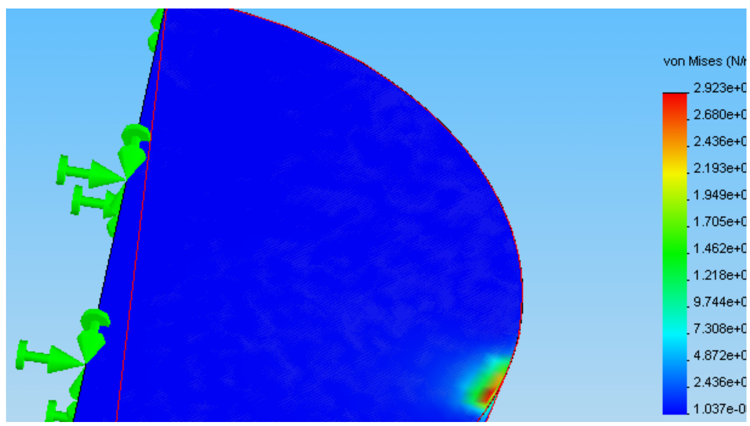

***FIGURE 8.*** *Simulated stresses in the diamond tool calculated using FEA and measured forces. Maximum stress at 0º is 2.9 GPa*

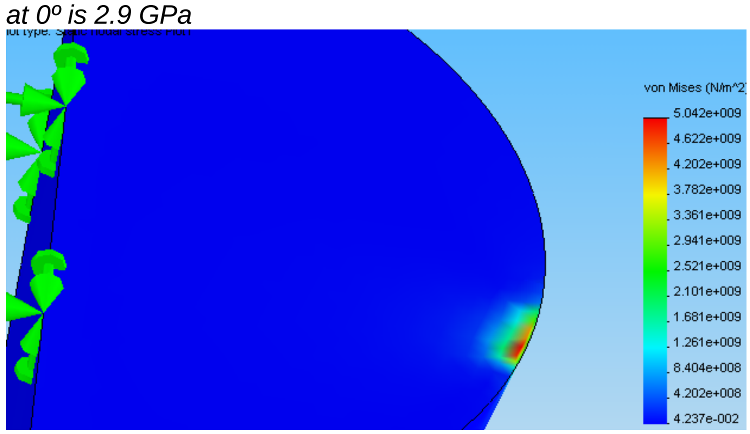


***FIGURE 9.*** *FEA as in Figure 8 performed at 20º rake angle. Maximum stress is 5 GPa.*

## TOOL LIFE

Significant wear was noted on the tool used to machine the sine wave parts. The distance cut was less than 500 m, surface roughness was impacted significantly. Ordinarily, this sort of cutting distance in nickel would not lead to appreciable wear or chipping of the tool, but with the extreme clearance angle of 50° used, the edge becomes quite fragile. This geometry was based on the conventional non-ferrous metal turning practice of using a 0° rake angle tool. Hence, the included angle on the tool is only 40° whereas most conventional tools have included angles around 80°. Taking another look at this practice, however, say we have a requirement of ±45° as in the described part. While the clearance angle must be at least 45°, the initial rake angle could be anywhere from 0 to –45°. While increasing the rake angle increases the cutting forces substantially, it also decreases stress in the part. Finding an optimum geometry will be based on applying tool force data to different tool geometries and evaluating the internal stresses in the diamond. Initial assessments using COSMOS Finite element modeling software and the experimental force results shown in Figure 5 show that, while tool forces may decrease for more positive rake angles, the internal stresses in the tool actually increase as shown in Figures 8 and 9. Additionally, internal shear stress increases significantly as the clearance angle is increased.

## CONCLUSIONS

The role of rake angle variation in machining free-form optics is rarely addressed. As tool excursions and, hence, surface slopes increase, however, the impact of rake angle variation cannot be ignored. Both static deflection of the workpiece and tool as well as the life of the tool can be be impacted significantly. The preliminary results presented here represent merely the first step in an effort to understand the impact of varying rake angles in diamond turning. The resulting knowledge will lead to methods for combating the negative effects of this phenomenon, ultimately, better more cost effective free-form optics.

## REFERENCES


[1] Arcona, C., “Chip Formation and Surface Finish in Diamond Turning”. PhD Dissertation 1996.

[2] Drescher, J. P, “Tool Force, Tool Edge and Surface Finish Relationships in Diamond Turning”, PhD Dissertation 1992.