MODELING OF VIBRATION IN SINGLE-POINT DIAMOND TURNING

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INTRODUCTION

The objective of this work is to develop a model to simulate the effects of vibration on the surface finish of single-point diamond turned parts. This model can be used to optimize cutting conditions for best surface finish and to predict geometric characteristics of the surface beyond the conventional rules of thumb. These characteristics can also have a significant impact on optical surfaces that operate in the visible range by introducing coherent scatter that produces the familiar "rainbow" appearance of diamond turned surfaces in white light.

Surface finish in single-point diamond turning is primarily influenced by four factors: Geometry, vibration, material properties, and tool edge quality. The first-order geometric model using the parabolic approximation gives the peak-to-valley roughness which is determined solely by the crossfeed (*f*), and the tool radius (*R*).

$$PV = \frac{f^2}{8R} \tag{1}$$

This approximation is often used as the sole determiner for choosing radius and feedrate even though at large radii and small feeds, the predicted finish is not achievable.

VIBRATION

Assuming suitable materials are selected and the tool edge quality is high, vibration is typically the next largest factor in determining surface finish. The origin of this vibration can be from a number of sources, although the axes of the machine or the spindle are the most likely candidates. The ASG 2500 Diamond Turning Machine at the Precision Engineering Center suffers mainly from a 65 Hz vibration of the Z-axis which has a magnitude of about 30 nm. This amplitude can vary slightly depending on spindle rpm and balance. Either of these can increase this vibration. For the purposes of the following discussions and examples, the vibration of the ASG 2500 Z-slide will be used as the source of the vibration, though the technique can be applied to any source.

The impact of vibration on a diamond-turned surface is generally to degrade the surface finish. In its simplest form, a sinusoidal vibration in the normal direction would leave an RMS surface finish of 0.707 times the amplitude of the vibration. It would seem that the surface finish could never be improved beyond this value and there would be no point in slowing the feedrate or using a larger radius tool. This assumption is, however, incorrect due to interaction between neighboring grooves at small feedrates. By modeling the surface produced by a vibrating tool, it can be shown that the surface finish is no longer limited by the vibration amplitude but can be improved by moving to finer feedrates.

THE SURFACE FINISH MODEL

A number of points along the edge of the tool are calculated for each x-position in increments of the crossfeed. The depth of cut changes around the periphery of the part with the vibration environment.

$$depth = A\sin\left(\frac{\omega x}{\Omega f}\right) \tag{2}$$

where A is the vibration amplitude, ω is the vibration frequency of the tool, x is the radial position of the tool and Ω is the vibration frequency of the spindle.

As shown in Figure 1, after multiple profiles are generated, redundant points in the overlapping regions are eliminated and only the point with the largest depth at each x-coordinate is retained. Individual cross-traces at different rotational positions of the spindle can then also be assembled into 3D profiles as shown in Figure 2.

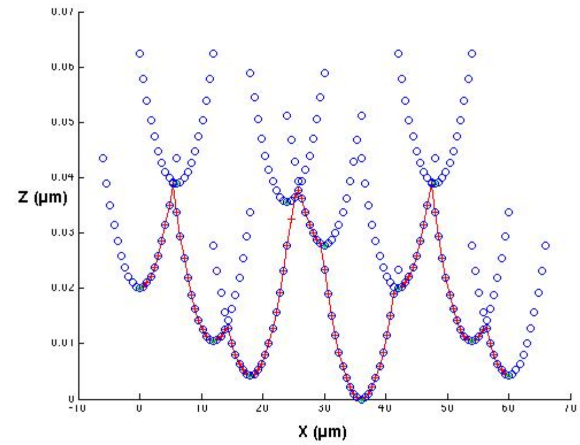

FIGURE 1. Points along multiple tool profiles, at varying depths due to vibration, produce a finished surface contour.

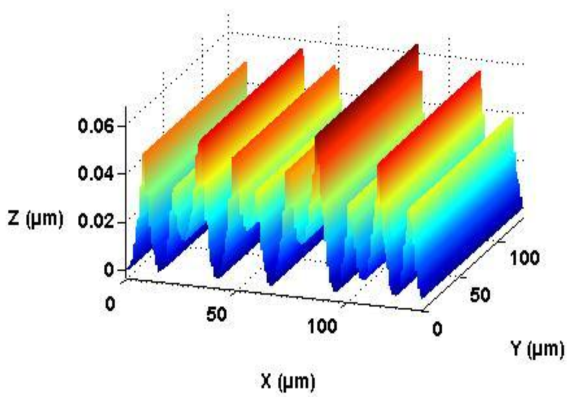

FIGURE 2. Multiple simulated surface profiles assembled into a 3-D surface.

It is at lower feedrates that the effects of tool vibration on a diamond-turned surface become interesting as illustrated in Figure 3. The illustration shows the surface left at small feedrates where the crossmarks show the tool location at each pass in the profile. A number of passes are not represented at all in the finished surface, leaving only the most extreme passes and, hence, a smoother surface than would be expected if all cuts were represented.

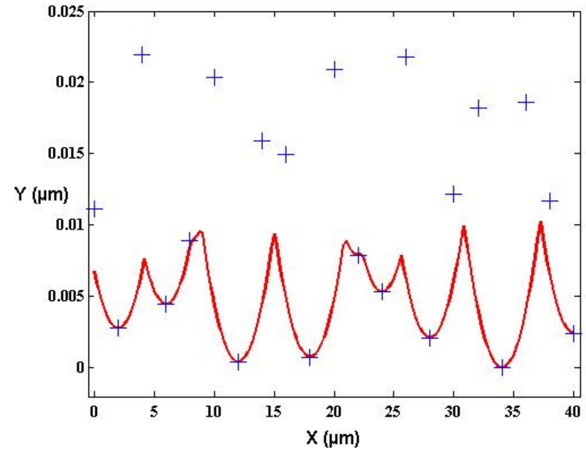

FIGURE 3. At fine feedrates, some passes of the tool (+) are not represented in the finished surface. This produces a better finish than would be expected from the RMS of the vibration alone.

EXPERIMENT

To verify the simulations, a plated copper sample was machined with the same feedrates used in the simulations. Machining experiments were performed on an ASG 2500 DTM using a 505 rpm spindle speed and a 0.5 mm radius, zero rake natural diamond tool. The laboratory temperature was controlled to 20 ±0.05°C. Petroleum oil cutting fluid (Mobilmet Omicron®) was used for lubrication and chip removal.

Eight 2 mm wide bands were machined on the 50 mm diameter sample with crossfeeds of 0.6, 0.9, 1.9, 2.7, 6.1, 8.6 and 19.1 µm/rev. The surface was ultrasonically cleaned and then measured on a Zygo NewView 5000 Scanning White-Light Interferometer (SWLI) using 50X magnification. The measurement area is 108 µm X 144 µm. Figures 4 and 5 show the typical profile measurement result. The effects of vibration on groove depth can clearly be seen in the profile at this large feedrate. The depth varies seemingly randomly as the tool traverses the part. Note a small chip is visible in the tool edge as a repeatable defect from each pass. At finer feedrates, this portion of the tool does not, however, have an effect.

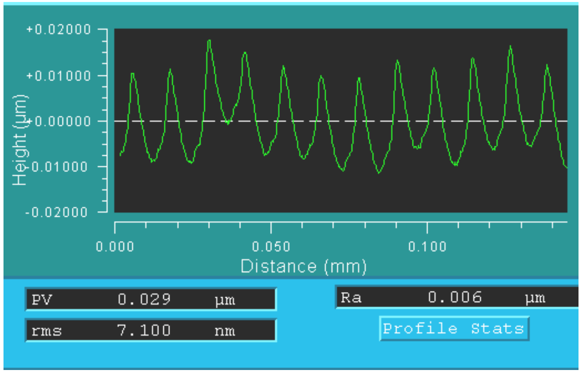

FIGURE 4. Typical surface profile measurement illustrating the depth change as a result of vibration with large feed rate of 12 µm/rev.

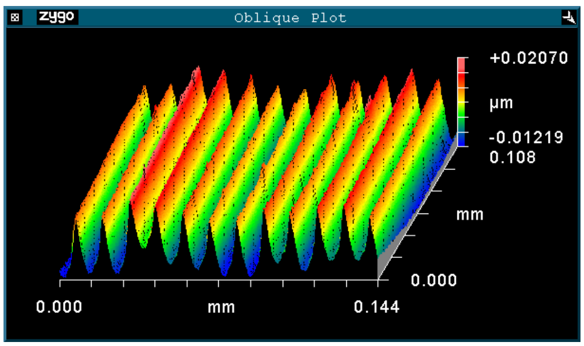

FIGURE 5. A typical measurement result in oblique plot form. This is the same machined surface shown in Figure 4.

Figure 6 shows the results for a series of simulations and cuts performed to verify the model. The plot also shows the line that represents the theoretical finish approximation for a parabolic surface.

$$RMS = \frac{f^2}{26.6R} \qquad (3)$$

Clearly, the surface finish can improve significantly beyond the RMS 7.7 nm limit of a simple sinusoidal vibration. The finish also continues to improve with finer feedrates between 2 and 5 µm, when they already deviate significantly from the theoretical approximation.

ENVIRONMENT

As the results displayed in Figure 6 show, at theoretical finishes below 2 nm RMS, the model does not predict the surface finish. At these extremely fine finishes, other factors begin to take effect such as environmental effects and material anisotropies. While the temperature in the laboratory is controlled to less than 0.1°C, even such small temperature fluctuation can have an impact. At small feedrates, the long-period fluctuations of the temperature over 1-8 min can have an impact on finish, as shown in Figure 7.

The Z-axis deadpath on the ASG 2500 interferometer was approximately 250 mm at the position where the sample was machined.

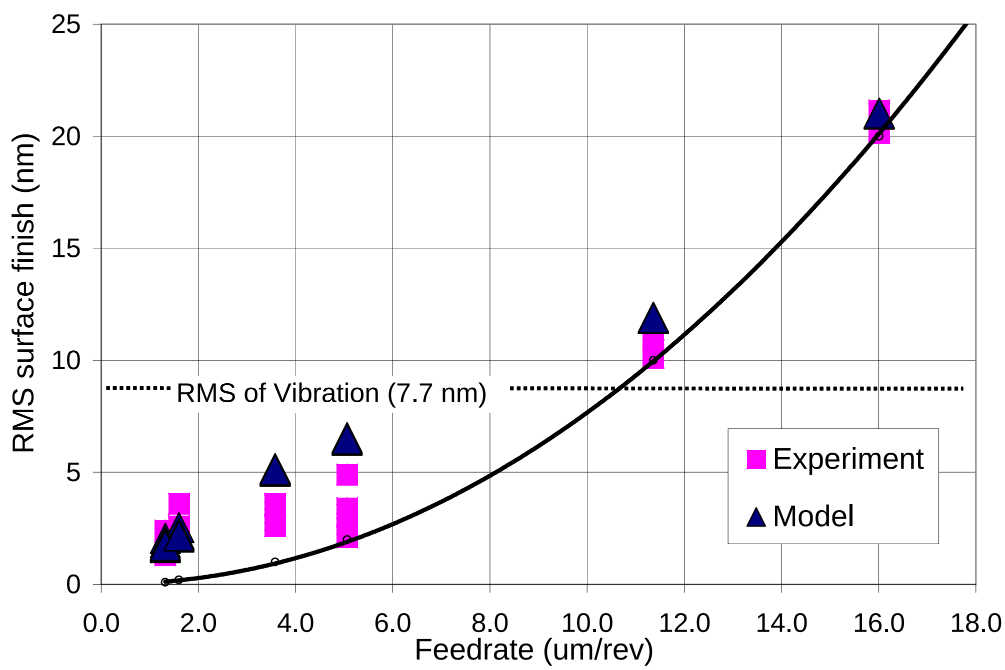

FIGURE 6. Triangles show the simulated finish with vibration and the squares show the machining results. Variation in roughness around the periphery is shown in both model and experiment.

Given a maximum temperature variation of 0.1º C, the calculated resultant deadpath error using the Edlén equation[1] is 25 nm. This limitation reflects the need to reduce deadpath, compensate for environmental fluctuations with a refractometer, operate in a vacuum, or use another means of position feedback such as a linear encoder. While linear encoders do not eliminate errors due to thermal fluctuations, expansion of the scale due to temperature changes tends to have a much longer period, so errors move into the figure error regime rather than roughness.

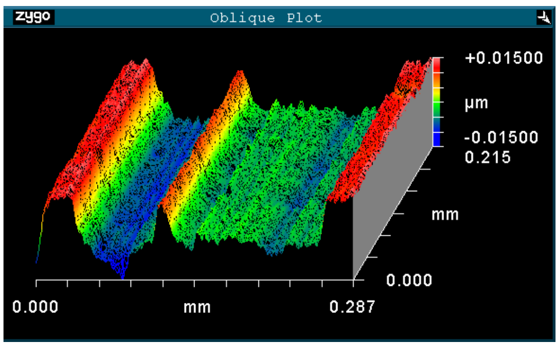

FIGURE 7. Temperature fluctuations at low feedrates can produce surface finish degradation due to deadpath error in the DTM laser interferometer.

MATERIALS

Material effects, such as inclusions or grain boundaries have a much larger impact in materials such as 6061 Aluminum[2], though apparently there are still defects even in the plated copper used as shown in Figure 8.

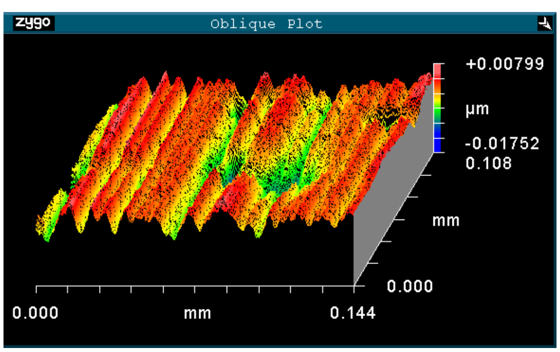

FIGURE 8. 3D surface profile of a plated copper surface machined at fine feedrates showing pits in the surface due to material defects.

The final contribution to a degraded surface finish is from errors in the control of the axes. In the case of the ASG, tests of the custom, DSP-based, controller showed tracking errors of less than 10 nm Peak-to-Valley [3]. While of some significance, the effects of this tracking error are still not as significant as those due to temperature variations and material defects.

CONCLUSION

Understanding what determines surface finish enhances the ability to improve surface finish in the most efficient manner. It also allows us to exploit all of the capabilities of a diamond turning machine to achieve the best possible finish for that machine. The conventional wisdom that there is little point in machining at lower feedrates beyond the point where the measured surface finish is worse than the theoretical finish (obtained from the parabolic approximation) simply does not hold. Ever finer feedrates continue to reduce the impact of vibration to a point where it does not impact the surface finish any more and material or environmental effects take over. In the particular case of the PEC's ASG 2500 DTM, lower feedrates than 2 µm using a 0.5 mm radius tool do not improve the surface finish. Factors other than vibration dominate below this feedrate. Until these the impact of these factors is reduced, smaller feedrates simply add time to the machining effort with little gain.

FUTURE WORK

In another application, the model can be used to perform the same analysis with the tool vibrating parallel to the surface. The advantage of this action is that the normally regularly spaced grooves formed in diamond turning that turn the surface into a diffraction grating can be randomized. This could reduce coherent scattering that produces undesirable structure in the optical output that often makes diamond-turned optics unsuitable for visible applications.

REFERENCES

[1] Alexander H. Slocum, "Precision Machine Design" 1994 John Wiley, New York.
[2] John P. Schaefer, "Progress in Precision – Single Point Diamond Turning (SPDT) of Optical Components" ASPE Proceedings 2001 Spring Topical Meeting Presentations DVD.
[3] T.A. Dow, L. Lamonds, Fabrication of Optical Surfaces and Fiducials, 2005 PEC Annual Report, pg 81.