Factors Affecting Surface Finish in Diamond Turning

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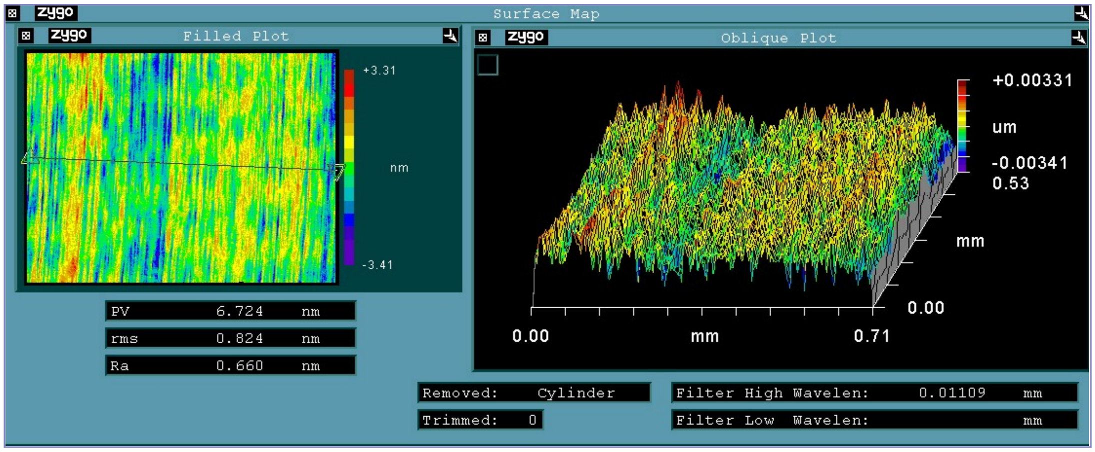
Introduction

A number of factors contribute to the final finish of diamond-turned surfaces. The complex interactions of these factors create confusion. The purpose of this technical note is to clarify the situation. Here, surface finish is defined as defects in the machined surface with length scales less than 0.8mm, such as those induced by vibration. Longer defects are categorized as form errors. This is consistent with most standards for optical surfaces. The following discussion presents each factor that significantly affects surface finish.

Workpiece Material

The first and foremost factor is the material being machined. The material must be compatible with the diamond turning process, i.e. having reasonable tool wear and enough ductility to permit clean cutting with minimal surface damage. Impurities in the material and its grain structure are also big limiters of surface finish. This is the primary reason why it is difficult to achieve better than a 3 nm Ra finish on most aluminum alloys.

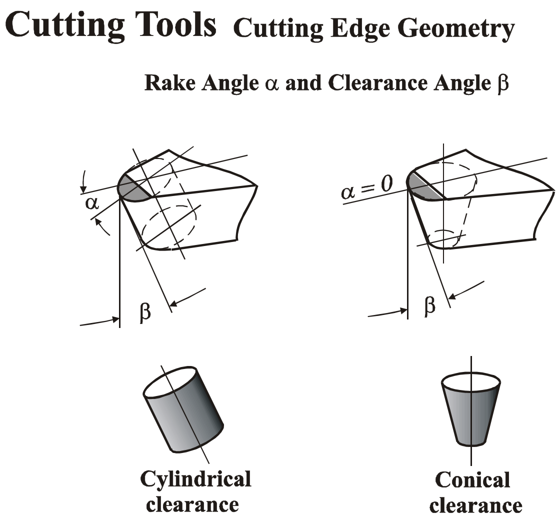


PV 6.724 nm
rms 0.824 nm
Ra 0.660 nm
Removed: Cylinder
Trimmed: 0
Filter High Wavelen: 0.01109 mm
Filter Low Wavelen: mm

Typical performance achieved with SPDT of electroless nickel plated mold pin.

In contrast, a high phosphorus content, electroless nickel plating is amorphous (no crystal structure) and can be deposited in an extremely pure form. For these reasons, it is nearly an ideal choice of material when the ultimate in surface finish is required. Finishes of better than 0.6 nm Ra have been achieved by diamond turning electroless nickel. In some materials, the surface speed during cutting and the depth of cut also influence surface finish and tool wear. Fortunately, the effect of surface speed is small for many of the common diamond-turnable materials.

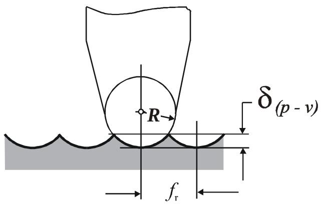
Diamond Tool



The diamond tool plays a major role in surface finish as well. It must be sharp and free of chips on the nanometer scale. The tool rake angle, and sometimes the tool radius, must be optimized for a given material and workpiece, in order to achieve the best finish. Proper tool lubrication is also critical to achieving good surfaces, and provisions must be made to cleanly remove the chips coming off the tool. Chips dragging on the freshly cut surface are a frequent problem. The forces generated in the cutting process can excite vibrations in the workpiece and in the diamond tool. Consequently, the diamond must be rigidly bonded to a stiff tool shank, such as carbide, that then must be rigidly clamped to a stiff tool holder. The workpiece must be well supported if it is thin, and then be rigidly attached to the diamond turning machine.

Assuming an ideal material, tool and machine, there is still a theoretical limit to the achievable finish in diamond turning. This theoretical finish is due to the cusps left after feeding a circular shaped tool across the workpiece. These tool marks are readily evident under microscopic inspection, except in the cases where the defects in the material dominate the surface structure. The cusp height is given by the square of the feed-per-revolution, divided by eight times the radius of the tool. The theoretical finish can be made arbitrarily small by slowing the feedrate. In production, however, feedrate is a key factor determining the cost of diamond turning.

Finish = function of tool radius and feed rate



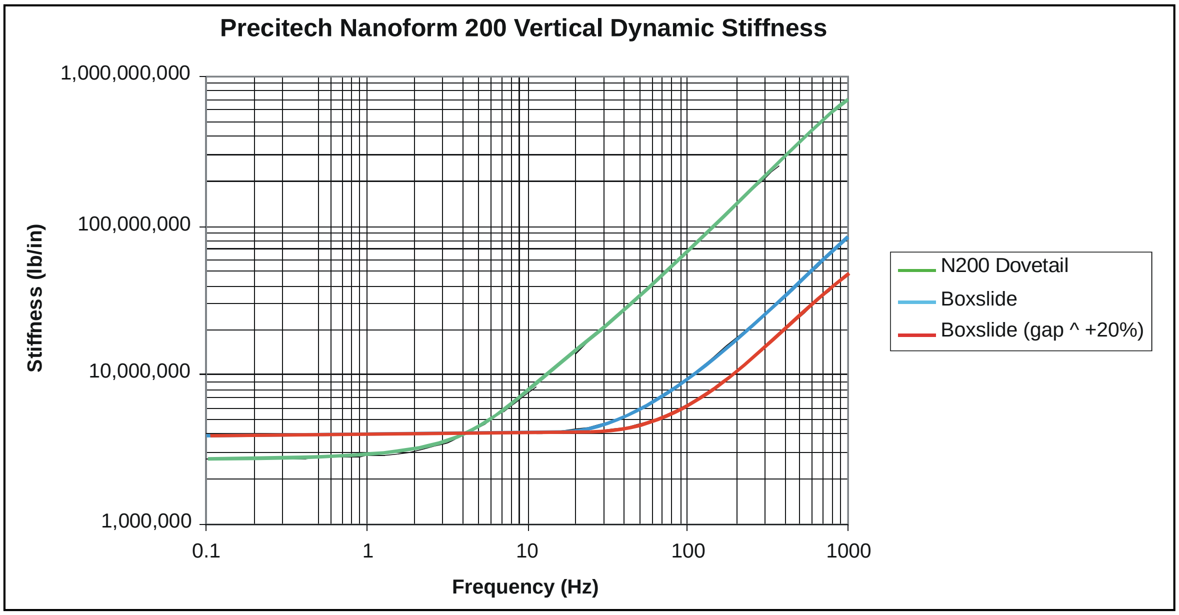
$$\delta_{(p-v)} \cong \frac{f_r^{\,2}}{8R}$$

$$\delta_{rms} \cong 0.0373\,\delta_{(p-v)} = 0.0373\frac{f_r^{\,2}}{R}$$

Cutting Forces and Dynamic Stiffness

All the factors mentioned above are independent of the characteristics of the diamond turning machine itself. Rigidity of the machine is important, but usually not because of the dynamic cutting forces. During most finishing operations, these forces are so small, and of such a high frequency, that they can only excite significant vibrations in the small inertias of the tool and workpiece. According to Newton's Law, the relatively large inertia of the machine components will move much less in response to the same force. Of course, the static component of the cutting forces will cause a static deflection, which only affects form error, and not finish.

Dovetail/Boxslide in Relation to Dynamic Stiffness



Notes:

- Low frequency stiffness (<5-10Hz) is equivalent to static stiffness.
- Various sources of dynamic impulses on diamond turning machines (ex motor electromagnetic dynamics, spindle etc.) occur in the frequency range of 10 - 1000 Hz.
- Compliance (flexure) and inertial response (mass) of components are not included in this model.

However, there are many other dynamic (time-varying) forces acting on a diamond turning machine that are much larger than the cutting forces, and they are discussed in the following sections. A machine's ability to resist these dynamic forces is one of the key characteristics that determine its surface finish capability. This characteristic is called dynamic stiffness. Unfortunately dynamic stiffness is much more difficult to measure than static stiffness. Typically, a machine's dynamic stiffness is determined by its inertias, its damping, and its natural frequencies.

Spindle

Some of the largest dynamic forces acting on a diamond turning lathe are due to the spindle. Most of these forces are synchronous with the rotation of the spindle, such as imbalance, or from the poles of the spindle motor. Because these forces repeat every revolution of the spindle, and because they usually have negligible components greater than 12 times per revolution, they only affect surface finish within two to three millimeters of the center of rotation. Outside this small center region, the spindle induced errors fall into the form regime. This is a common misconception.

Oftentimes, the spindle exerts forces that have an asynchronous component as well. These are usually due to electrical noise in the motor amplifier or air pressure pulsations. Because these forces do not repeat every revolution, they do contribute to surface finish. A dynamically stiff spindle and machine can resist these forces, but a high quality amplifier with low noise cables is the best solution.

Environment and Peripheral Devices

There are a number of other dynamic forces acting on the machine. Some of these are due to the machine environment. It has been shown that sound pressure due to slamming doors, loudspeakers, fans and other noisy, nearby machinery can excite machine vibrations. Another source is vibration induced by seismic forces, which are usually below 30 Hertz, such as floor-mounted machinery, footsteps and outside road traffic. Measures can be taken to isolate these environmental influences, such acoustic enclosures or pneumatic vibration isolators; but they are only necessary if the machine has a low dynamic stiffness. If the machine's dynamic stiffness is high enough, it can be impervious to these environmental influences and needs no isolation. Again, this is a common misconception.

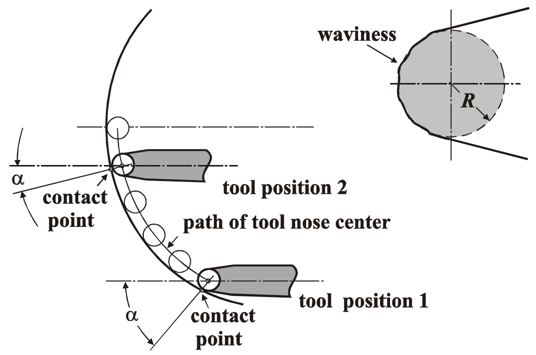
Even when environmental influences can be completely eliminated, a machine needs dynamic stiffness to resist other forces that are on board the machine. These can include fans, compressors, pumps, motors, transformers, hoses and cables between moving components, way covers or other sliding friction forces, and side forces from the actuators used in the machine's slides. All of these can contribute to surface finish if the machine is dynamically compliant.

Positioning System

Another significant factor affecting surface finish is the motion control system of the machine. The motion control system starts with bearings and actuation mechanisms that are free of stick/slip. To achieve high dynamic stiffness in the drive direction, a high servo bandwidth is necessary, which is then dependent on the machine's resonant frequencies, the servo update rate and the response time of the position sensor. Timing errors in the controller also impact surface finish, as does the point spacing and the number of significant digits used to program the tool path. As in the case of the spindle motor, the electrical noise from the power amplifier and the cables for the slide actuator can greatly affect surface finish.

Tool Contact and Edge Geometry

Radius and waviness of tool contour are to the order of 10 nm (rms)



The amount of structure between the position sensor and the tool tip, and between the sensor and workpiece, also has an effect. This includes the lateral offset (normally called Abbe offset), which can affect form and finish, but also the offset in the sensing direction. Dynamic forces can deform any of the structures in the tool-sensor-workpiece loop, including the sensors and their mounts, the workpiece, the slides, the spindle, the base, and the tool. This deformation causes the control system to think that the relative position of the tool to the workpiece is different than it really is. A common example of this effect is vibration in the sensor mounting. The control system detects this motion and drives the slide to cancel it, even though the slide itself is not even moving.

Sensor Resolution

Finally, the slide of a diamond turning machine can only hold position as well as it can sense it. Therefore, the position sensing system must have low noise. The noise level of a position sensor is often called its resolution. With recent developments in sensor technology, it is now possible to have a very fine resolution out to very high frequencies. However, high levels of interpolation between grating lines on a scale are often required to do this. These interpolation techniques themselves are imperfect and can cause other finish problems, but this is different than electrical noise. The marketing trend in the sale of diamond turning machines often times promotes the misconception that finer sensor resolution always translates to better position control, and thus improved surface finish. However, when resolution reaches levels below 5 nm, its contribution to surface finish is indiscernible in comparison to the other factors discussed here.

In the realm of diamond turning, sensor resolution is several orders of magnitude smaller than the accuracy of the sensors over their full travel, or of the rest of the machine (e.g. straightness and thermal errors can be several 100 nanometers in magnitude). In the past, or with cheaper machine tools, the sensor noise was large enough that it made a measurable contribution to the overall accuracy of the machine. This is another common misconception about diamond turning machines. Because the sensor noise/resolution is so small, it only affects surface finish in diamond turning, and even here it only has a small effect.

Averaging

All of the above factors can contribute to surface finish, but they cannot be added up directly because some of these factors will partially cancel others. As in form error budgets, a good approach is to use the root-sum-square of the standard deviation of each error source. This will give an estimate of the RMS surface finish, which is commonly referred to as Rq. This estimate will often be larger than in practice. The reason is due to the averaging effect that the diamond turning process can have on machine-induced finish errors. When the feed rate is slow enough and vibration is present, the diamond tool does not cut every revolution. The tool will only cut at the low end of each vibration cycle. At the high end, the tool will cut air because it is still so close to the pass when the tool was low. The averaging effect increases with slower feed rates and higher frequencies of vibration.

In many finish cuts the theoretical tool finish will be less than 1 nm PV, which is known as Rmax. Under these conditions the averaging effect will be very significant. For example, it is often possible to have 40 nm of relative movement between the tool and workpiece and still achieve a 10 nm Rmax surface finish, which can then equate to a 1 nm Ra finish. In cases such as this, an individual factor (such as sensor resolution) with a 4 nm PV amplitude will increase the finish by only 0.5%, or to 1.005nm Ra. Theoretically, more and more averaging will occur, the slower the feed-per-revolution is; but in practice other low frequency error sources will start contributing to finish, such as temperature cycling or the leveling response of pneumatic isolators. Therefore, there will exist an optimum feedrate for minimizing machine-induced finish errors. Of course, the material properties of the workpiece will present a fundamental limit in surface finish that the averaging effect cannot influence.

Conclusion

The roles that a number of factors play in producing surface finish in the diamond turning process were discussed. The best surface finish that is obtainable is a measure of the noise floor of the machine system, but this should be taken in combination with all of the other factors in deciding what is the 'best' machine for a particular use. The 'best' machine comes not from the stiffest spindle, lowest resolution, or newest controller. The 'best' machine will be the one where the various parts have been brought together in a seamless package, where all parts function together properly and harmoniously, allowing high quality optical components to be made quickly either individually or in production.