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Tribology of Manufactured Optical Surfaces

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Abstract

Optical components of non-planar geometry require special machining to produce. Single point diamond turning is the manufacturing method of choice to produce these surfaces. Three main factors contribute to the quality of these surfaces. Machine accuracy has shown improvements with the increased use of air bearings. Tool wear and design are shown to be effected by the crystal orientation of the diamond used for cutting. Material and coatings also play a role in producing high quality optical surfaces.

Measuring these surfaces is critical for characterizing the surface in question. Atomic force microscopy, contact profilometery and laser interferometry are shown as appropriate methods for measuring the surface profile of the diamond turned surfaces.

1. Introduction

Optical components are used in many applications in engineering. Surfaces of these components must have specific tribological characteristics to perform as optical components. Various methods are employed to achieve optical surfaces. The method of focus for this report is diamond turning. The single point diamond turning process has become widely used in the past two decades. This is due to its ability to create optical surfaces suitable for both infrared and visible light applications. [1] Diamond turning solves the specific problem of creating optical surfaces with curvature. Flat surfaces are much easier to obtain by various manufacturing methods. One such method would be lapping.

This report will focus on three main areas of research in this area. Machine accuracy is the first and most influential factor effecting optical surface characteristics. Tool design and geometry also affect the surface. Base material has a major affect the surface finish obtained from diamond turning. Finally, along with base material, coatings are used to improve optical characteristics of the base materials. These three factors are the major contributors to the optical surface obtained from diamond turning.

2. Machine Accuracy

2.1 Cutter Run-out or Eccentricity

Machine accuracy can be adversely affected by cutter run-out or eccentricity. This problem manifests itself in premature tool wear as well as increased surface roughness of the optical component. [2] Machining is performed be moving a tool with respect to the rotating optical component in question. Movement is performed both radially and axially to produce the desired curvature in the piece. If the tool is not precisely located at the center of spherical surface being generated, error from cutter eccentricity has occurred. [1] Figure 1 shows the affect of tool eccentricity.

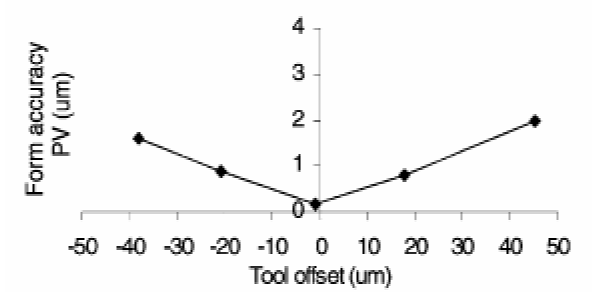

Figure 1: Experimental results by Schmitz, et al. showing component form accuracy vs. tool eccentricity. [1]

To a lesser extent, tool height error also has an effect on the optical surface produced. Figure 2 shows these effects:

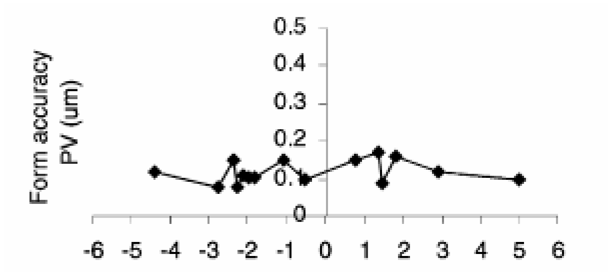

Figure 2: Experimental results by Schmitz, et al. showing component form accuracy vs. tool height error. [1]

This figure shows that there is little effect from tool height error in comparison to tool offset or eccentricity. The following equation shows theoretically why this is the case:

$$x(\rho) = \rho - \frac{\Delta H^2}{r} - \frac{\Delta H^4}{r^3} - .... - \Delta T \qquad (1)$$

where x is the radial coordinate with respect to the machining plane, ρ is the distance from the cutting point to the centerline of the part, r is the radius of curvature of the generated surface, ΔH is the tool height error and ΔT is the eccentricity error. [1] Since all the tool height error terms are divided by the radius of curvature, they become much less of a factor in determining surface accuracy. Tool eccentricity, denoted by ΔT becomes the dominant factor in the equation.

2.2 Machine Chatter

Vibration in diamond machining is another source that affects optical surface quality. Compliance in the tool holder can cause vibration. Spindle dynamics can also be a source of vibration in the machining process. Advances in air bearing technology has helped reduce the affects of machine chatter. [3]Extensive simulations on machine chatter have been conducted by Marsh and Schaut [4]. Their simulations compared well to the experimental results of machining chatter. The result of their work is a simulation program that can be used to predict the effects of machine vibrations. An interesting finding was that increasing the tool cutter radius resists machine chatter.

For flat optical surfaces, machine chatter is also a problem. The effects of spindle dynamics are studied by Marsh, et al. [5] The main effect of spindle wobble is waviness of the surface generated. This directly affects the optical quality of the surface.

2.3 Typical Diamond Lathe Finish Specifications

Typically roughness, scratch-dig, form and reflectivity are the specifications associated with a mirror. The specifications will be specified for specific wavelength ranges, for different wavelengths of light are more sensitive to surface characteristics than other wavelengths.

The roughness of a mirror directly affects the diffusion of light reflecting from the surface. Typically 50 Ǻ can be achieved with standard diamond turning and no polishing. For large flat surfaces, 10 Ǻ may be achieved.

The scratch-dig specification refers to local errors or local imperfections in the substrate. These are typically a function of tool wear and more so, improper substrate chip removal. Chip removal can be facilitated by using cutting fluid. A typical scratch-dig specification, such as 60-40, is a measure of the optical surface, as compared to a set of manufactured standards. This is in accordance with the Mil Spec for The Inspection of Optical Components, MIL-O-13830-A.

Form, sometimes called surface accuracy, is a relation of how close a manufactured surface correlates to the nominal surface. This is typically a macroscopic specification for surface quality. A typical specification for an optical component is ¼ wavelength (typically a 632nm source illuminates the surface) and a 1/10 wavelength is considered precision. An optical window placed against the test surface is used to determine the wavelength.

Reflectivity is simply the amount of light transmitted from an optical surface. This can be controlled by utilizing different substrates and coatings for the mirror. [10]

3. Tool Design and Wear

Tool wear is usually an issue reserved for economics of machining processes. Increased tool wear simply means the tool needs to be sharpened or replaced more frequently. However, in diamond turning, tool wear can be the difference between a quality optical surface and an unusable surface. If a tool can wear during the course of machining a optical surface, the surface quality will change over the course of manufacturing. Polishing and grinding have been used as mask the effects of tool wear as a post processing step. However, these methods are time consuming and costly. It is desirable to avoid these steps if possible. [6] Research has been conducted around optimizing tool wear based on design. Crystal orientation of the diamond tool is critical in reducing tool wear. [1] Figure 3 shows the relation between crystal orientation and the forces required for machining. Reduced cutting force will result in a slower wear rate of the tool. In order to achieve the nanometer scale surface roughness required for optical surfaces, the diamond used for the tool must be of the single crystal variety. [3]

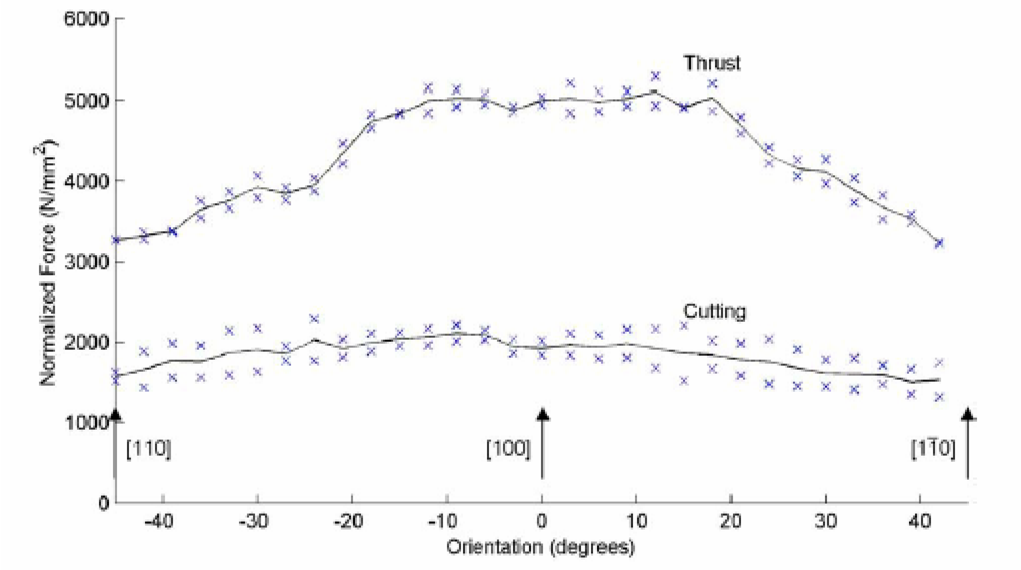

Figure 3: Experimental results of cutting force and crystal orientation. [6]

3. Base Material and Coatings

Base materials will affect the cutting performance of the diamond turning process. Different base materials require different cutting parameters to obtain the optimal surface. Diamond turning works well with materials such as aluminum, copper and nickel as the base material. [3]

Coatings such as aluminum and silica are used over the aluminum, copper and nickel to improve the reflectivity of the surfaces, over a range of wavelength. These coatings also reduce the chance of surface corrosion while creating a hard metal layer on the substrate. This reduces surface degradation of the optical surface. The coatings are typically deposited on the substrate using vacuum deposition.

Further coating layers can be deposited to further ensure surface protection. Disilicon Trioxide (Si_2O_3) is typically used in conjunction with an aluminum coating for further protection. A silver deposited coating will provide the best reflectivity for a given surface, however, silver is more delicate than aluminum and prone to scratching. [9]

4. Optical Component Surface Measurement and Characterization

Characterizing an optical surface allows an engineer to determine the effectiveness of difference surface preparation methods. Optical and stylus based profilometry are standard methods of classifying diamond turned surfaces. Atomic force microscopy may also be used. The later is the subject of a paper by Brinksmeier, et al. Figure 4 shows the principles behind atomic force microscopy. The cantilever is deflected by the very small tip at the very end. This deflection is detected optically by using the laser diode and the position sensitive photo diode. [7]

A proposed method by Wang and Mi involves illuminating the surface in question with a laser. The reflected beam is reflected and measured on a CCD. This measurement gives the slope information of the surface. By integrating this result, the authors were able to characterize the surface profile. Figure 5 shows the basic layout of their method. [8]

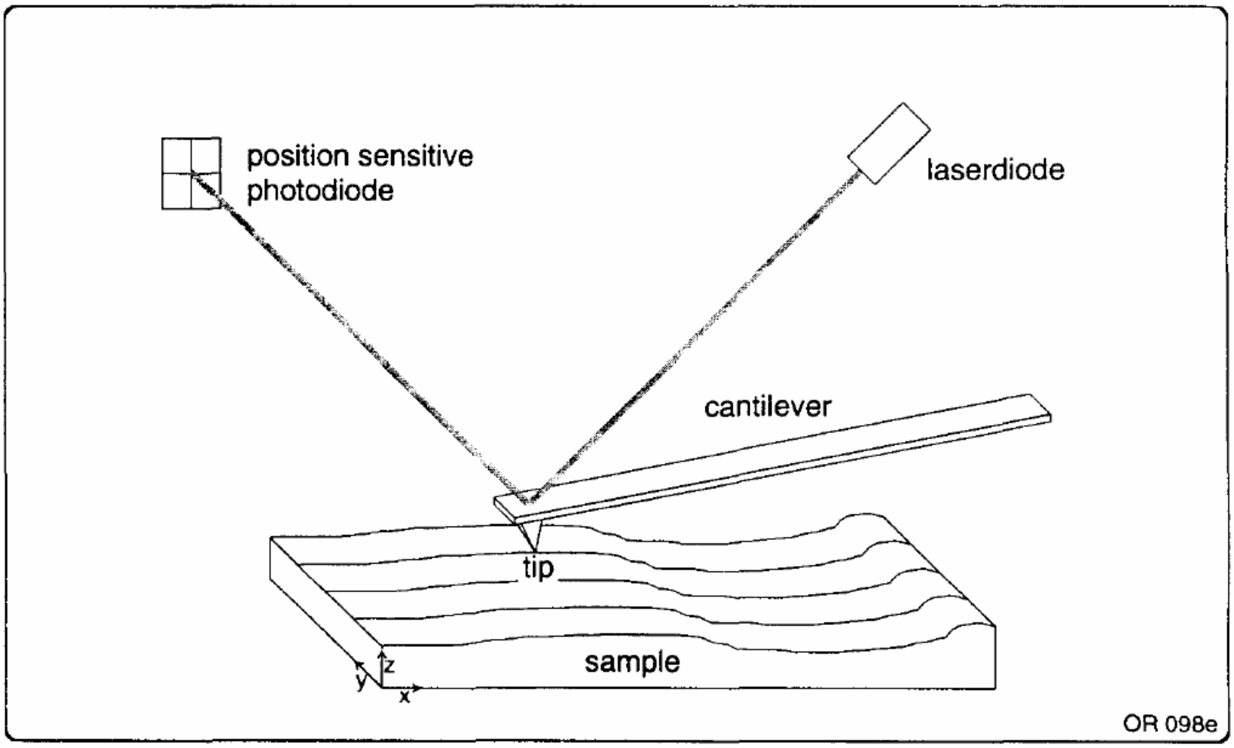

Figure 4: Principles of the Atomic Force Microscope [7]

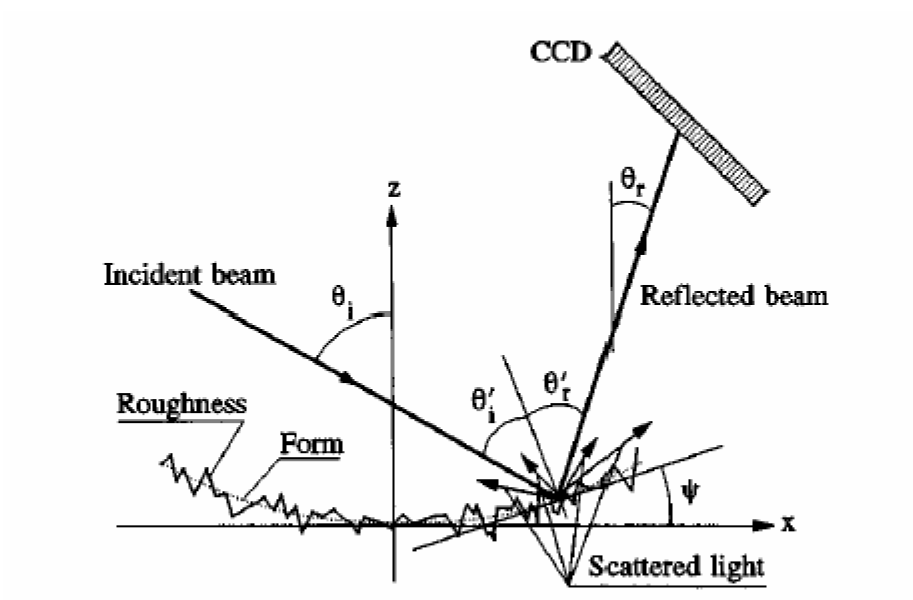

Figure 5: Light scattering and angular deflection method [8]

5. Conclusions

Diamond turning is the machining process of choice for non-planar optical surfaces. In order to obtain quality optical finishes, three main areas need to be addressed. Machine accuracy greatly influences the surface finish produced. Tool wear and design also affects the optical component produced. Finally, base and coating materials have an effect on the resultant surface.

In order to characterize these surfaces, various methods of surface measurement have been discussed. Atomic force microscopy can be used to measure the surface to the level required for optical applications. A method involving light scattering and angular deflection has also been shown to measure to the appropriate levels.

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