Enhancing Precision Manufacturing Through In-Situ Metrology

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Introduction

Production methods for generation of artifacts with nanometer level dimensions and tolerances include modifications of traditional tools plus the development of new manufacturing methods. These can be classified as reductive and additive. Reductive methods are represented by conventional machining, abrasive processes (belt and rigid wheel grinding), third body abrasion (including chemically assisted), etching, electrolysis and ion beams. Additive methods include the broad variety of deposition processes such as electro deposition, plasma sprays, sputtering, e-beam and magnetron deposition etc. We are concerned in these investigations with the identification of the optimal means of increasing precision and accuracy of manufactured components produced using multiple processes. In particular, we will be seeking to enhance the manufacturing precision of reflective optical elements. Currently, these are made by diamond turning and polishing of mandrels, replication by deposition and removal of metallic coatings followed by a final sputtering of highly reflective coatings (iridium).

Manufacturing processes aim towards the minimization of the ratio of volume error of the component to the removal/deposition rate. Precision and accuracy of manufacture is, ultimately, limited by the repeatability of all processes that impart features over spatial wavelength scales relevant to the functional geometric tolerances. For example, polishing can be used to create surfaces with a superfine surface finish (short surface wavelengths) and nanometer level dimensional control of surface removal. However, it is not possible to simultaneously control short and long-range (or profile) features on the surface. This limited ability to control spatial wavelengths and low removal rates lead to a low manufacturing ‘efficiency’. On the other hand, diamond turning can be used to produce geometric features with short wavelength geometry limited to the tool’s tip dimensions over spatial wavelengths comparable to the working volume of the machine. However, the resolution of the tool control is limited by both the resolution of the laser scale and the repeatability of the slide error in each axis. Currently, the diamond turning machines available to this project use laser scales with a resolution of 2.5 nm, a slide straightness of the order 0.25 μm per 100 mm of traverse, display scale resolution of 10 nm and axial alignment error of the order of a few arc seconds. Typically, temperature control to within ±0.1 C is maintained during a machining cycle.

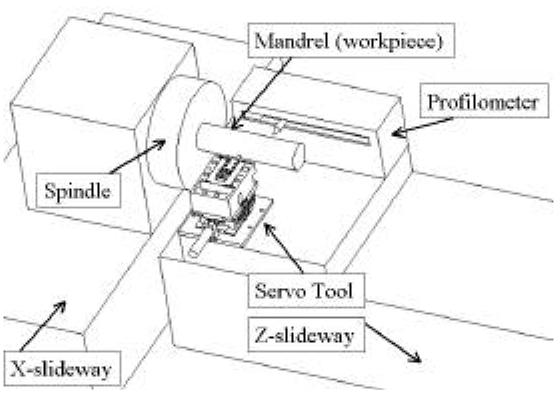

Figure 1: Modified diamond turning center

In this paper we present a modified diamond turning center that includes a precision tool servo for nanometer level control and a profilometer for in-situ metrology, Figure 1. In a typical machining cycle the specimen will first be cut to the nominal profile but over-size. The specimen will then be measured using the profilometer and deviations from the desired shape computed. These errors will then be removed by the fine tool servo in a second and final cut to net shape, this second cut being of the same depth as the first.

Technical approach

Traditionally, at higher precisions, dimensional metrology has taken place in temperature and humidity controlled laboratories, often housed away from the manufacturing process. Even for routine measurements it is often necessary to remove the work-piece from the machine or, at best, stop the process. Within this project, a portable, robust surface profiler will be designed and built. This will utilize technologies previously developed[i] for the Nanosurf family of profilers[ii]. In particular, we plan to exploit the precision motion slideway design integrated with newly developed drive couplings[iii] and stylus probe systems[iv]. Such a profiling instrument will enable a study of the implementation of local error correction using measurement at the limits of precision[v] as well as an assessment of the issues associated with the integration of nanometer metrology into manufacturing processes.

In an effort to improve the precision of machine tools, error compensation is commonly used. Typically, the errors between the position measured by the machine scales and actual position of tool relative to the specimen are mapped using a metrology system of higher precision and accuracy. This information is then used to develop (usually) software compensation that operates by effectively ‘lying’ to the controller so that the control set-point corresponds to the ‘true’ desired position. Clearly, such a compensation strategy is limited to the resolution and stability of the motion control and measurement capability of the machine. However, the potential compensation is limited only to the repeatability of the machine. Hence to exploit this potential it is necessary to either increase the precision of the scales and controller or add an additional, fine motion system. It is this latter approach that is currently under development.

Additionally, the relationship between the repeatability of the machine and the error compensation is not clear. In general, it is known that a conventional machine tool slide can exhibit nanometer level repeatability over short traverse ranges for short periods of time. However, under closed loop position control the machine tool will be working to compensate additional errors of the measuring scales, primarily measurement noise. Clearly, the resolution of the scales and the repeatability of successive cuts are independent. Hence it is possible that, while active compensation can reduce errors, it is possible that this also randomizes the residuals. This random error may be greater than the original repeatability of the uncompensated machine. Such issues will be assessed using the profilometer developed in this study.

To assess the limits of precision in diamond turning, it is necessary to calibrate the process using a method of considerably higher accuracy and precision. The precision of the profilometer will be derived from the slideway and probe technologies. Accuracy of the profiling capability will be assessed using reversal methods[vi]. These will be implemented in-situ using a probe mount design that enables precise 180 degree rotation of the stylus while maintaining lateral registration between the straight edge and stylus tip.

Hence, for the diamond turning and post processing of x-ray optical elements, this study will assess the necessary conditions for inter-process compensation in terms of process stability and repeatability.

Other technical advances that will be necessary within this project are the implementation of cascade, or ‘nested’, controllers in precision machines and the design of low cost, high precision dedicated machine tools.

In summary, the main attributes of this approach to error compensation are

1. The effects of workpiece distortion due to machining forces are included in the compensation.
2. It may be possible to achieve a precision governed by the repeatability of the slideways therefore representing the physical limit.
3. Repeatability may be enhanced by using fewer closed loop controls.

Design of a stylus profilometer

This instrument will be used to measure the profile of components throughout the manufacturing process. For replicated optics, it will be necessary to measure surface profiles of both the replicating mandrel during diamond turning and post polishing, the replica after deposition and separation and the final surface form after finish coatings (iridium) have been applied. To use this profiler at all stages in the manufacturing process, it needs to be both portable and sufficiently robust to function satisfactorily at the location of each process.

Conceptually, this design will follow that of most other profiling systems in which the stylus probe is traversed along a datum surface that is aligned to be parallel to the specimen[vii]. During this traverse the stylus is maintained in contact with the surface and variations in this motion are measured and interpreted as the surface profile. For an ideal traverse and stylus probe the output signal will be an accurate representation of the surface profile of the interface between probe tip and specimen. If the interface pressures and frictional forces are low, the measured profile will correspond to the free surface of the specimen. In practice, these requirements can be adequately satisfied to produce profile measurements with sub-nanometer repeatability. Key components of such a profilometer comprise the slideway, drive mechanism and probe head. These are briefly discussed in the following paragraphs.

Slideways used in the Nanostep family of profilometers have also been applied to larger measuring machines as well as the bearing system on the ultra-precision grinding machine Tetraform[viii] with unsurpassed performance. While this clearly exhibits the ability to provide nanometer level repeatability with high stiffness and load bearing capacity, this bearing technology has not been applied to the design of robust metrology systems for integration within manufacturing environments. In this design, the carriage supporting the stylus probe will traverse over a vee slide made up of two optical flats. A composite polymer/bronze bearing[ix] will be used to maintain a constant height during motion. A motor-gearbox combination will drive a feedscrew which in turn will be coupled via a nut to the carriage. Motion of the nut will be transmitted by a patented decoupling mechanism to attenuate motion errors of the drive[x]. When used to assess diamond turned mandrels, it may be desirable to use the *z*-axis traverse to drive the carriage, again via the decoupling mechanism. A linear scale providing 50 nm resolution over 100 mm traverse will be used to measure motion of the carriage relative to the instrument frame.

Dual probes will be necessary to assess both surface finish and profile. Surface finish will be assessed using a metrological constant force probe based on a measuring principle similar to that used in atomic force microscopes[xi]. Profile measurement will be carried out using a simple stylus arm on a flexure pivot. The difference between the two measurements is the tip radius (1.0 μm for surface finish 0.5 mm for profiling) and sensor bandwidth (200 and $\approx$ 10 Hz respectively). In both cases, displacement of the probe tip will be measured using custom-built capacitance gages utilizing a digital lock-in amplifier and ratio transformer preamplifier. Each probe will be fastened onto the carriage with a mount that enables reversal of the probe so that standard reversal techniques can be applied to implement slideway error separation[xii]. Probe calibration will be performed using high resolution laser interferometry developed at UNCC[xiii].

Designed into the instrument frame will be kinematic mounting points so that the complete instrument can be readily moved and relocated within any process.

Development of a tool translation mechanism

In general, as currently developed, the servo tool provides a translation range of 3 μm with a resolution of 1 nm[xiv]. Adapting a high precision servo tool and profilometer system into a diamond turning center is a challenging design task. Considering that the workpiece and servo tool may be doused with an oil or air bath, a thin walled environmental shell is utilized to prevent any oil from entering the carriage chamber and disrupting the electronics, Figure 2.

A monolithic, tool translation flexure, Figure 3, rigidly mounts to the top of a vertical carriage platform. Four leaf flexures are designed on each side of the tool mount to provide high axial stiffness and moderately high resonant frequency. Additionally, there are two further flexures underneath the carriage that are squeeze clamped to the platform. Consequently, the base flexures restrict the carriage from tilting about the *X* axis. A combination of conventional milling and wire EDM were used to produce the monolith. The tool carriage is designed with approximately 4 MN m^{-1} stiffness and a 500 Hz natural frequency. A piezoelectric (PZT) stack actuator provides a single linear motion and uses capacitance gauging for closed loop control, Figure 4. In this design, the capacitance gage directly measures the local tool motion due to PZT expansion or contraction.

A piezoelectric (PZT) stack actuator provides a single linear motion and uses capacitance gauging for closed loop control, Figure 3. The PZT stack has a maximum range of 17 micrometers with an applied potential of 150 V. The use of capacitance sensor for closed loop control significantly reduces the hysteretic effects. In this design, the capacitance gage directly measures the local tool motion due to PZT expansion or contraction. The capacitive sensor consists of two aluminum coated glass slides. The base glass slide is approximately 1 mm in thickness and the central region is etched with a 20 μm step prior to coating of aluminum electrodes. A second slide bridges across the base plate and epoxy is applied to each corner. Glass slides of 0.2 mm thickness and aluminized on one face are chosen as the top slide to

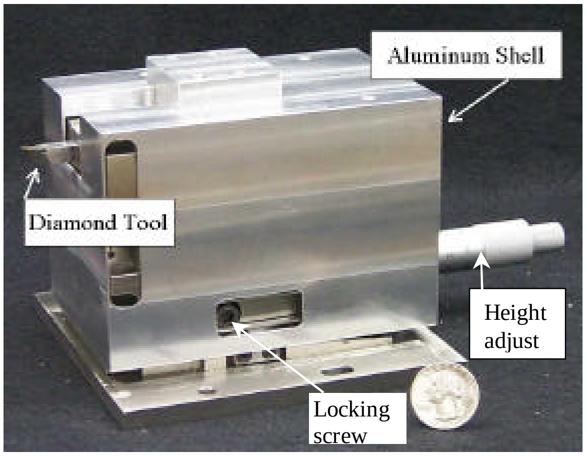

Figure 2: Assembled fine tool translator with aluminum cover

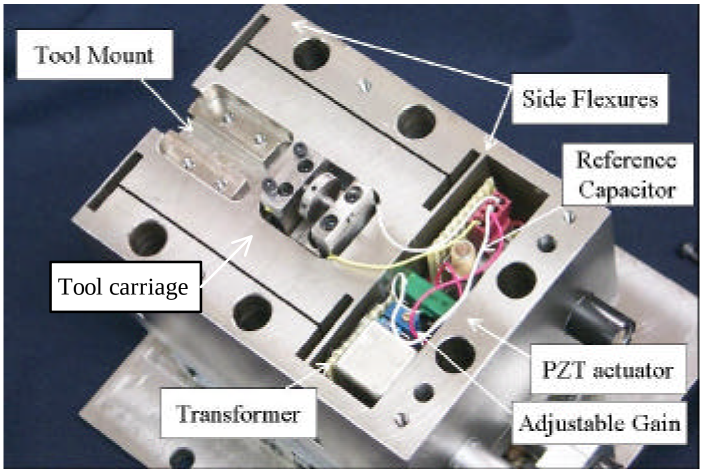

Figure 3: Tool translation flexure and capacitor electronics

provide low stiffness. A ruby sphere is bonded with epoxy to the top slide to provide a contact point for transferring motion of the carriage to displacement of the thin glass slide electrode. The capacitance assembly mounts into a flexure tilt stage. A differential screw accommodates a fine adjustment mechanism and, with feedback, this can be controlled to better than 2 μm. The complete capacitor assembly and fixture is placed through a clearance hole in the tool carriage and bolts to the carriage platform. Fine differential adjustment is then utilized to bring the ruby sphere of the capacitance sensor into contact with the tool carriage. The contact is aligned with the diamond tool axis in order to minimize Abbe offset.

Performance Testing

The servo tool has been calibrated using a Hewlett Packard laser interferometer. During calibration, the demodulated capacitance voltage is compared to the laser displacement reading and a second order polynomial is used to fit the measured data. Next, the tool is tested to determine the fastest response time or limiting bandwidth. The response time is determined from the output from the capacitance gage when a step demand is fed into the PID controller. The servo's settling time is optimized by adjusting the three terms of the PID controller while monitoring the response in real time. Currently, the servo's optimal settling time is determined to be 12 ms, Figure 4.

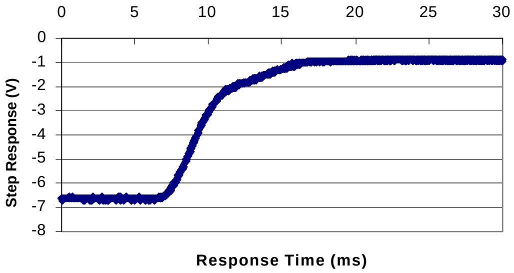

Figure 4: 12ms servo settling time under closed loop control

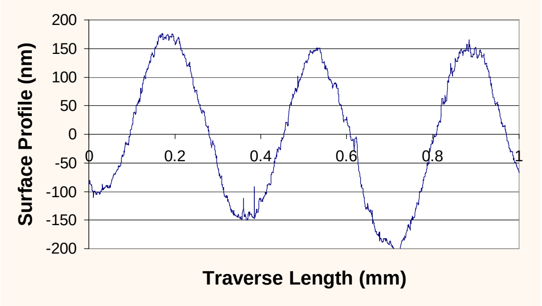

Figure 5: Sinusoidal profile of 300 nm pk-pk amplitude

Recent investigations include cutting step and sinusoidal profiles across the face of 4" diameter aluminum blanks. First, the tool servo is mounted into a Precitech diamond turning center with the PID controller and Capacitor lock-in located to the side of the Z-axis slide. These tests involve first facing the sample piece in several cutting passes until a P-V surface finish of between 50-100 Å is achieved. In the final pass, the *Z*-axis slide is translated towards the blank for a nominal depth of cut of 0.5 μm and *X*-axis feed is slowed to 2 mm per minute. A sample is cut with a sinusoidal profile having a wavelength of 0.33 mm^{-1} successive increases in depth of 20 nm after three cycles, Figure 5. A Talystep was used to measure the subsequent surface profile. Current sample measurements indicate minimal overshoot during the tool's step response. Presently, less than 60nm amplitudes have been produced, figure 6.

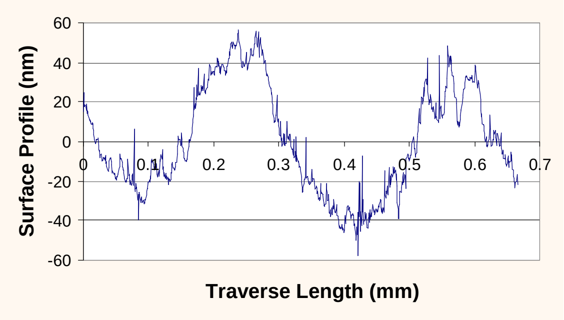

Figure 6: Profile of sinusoidal profile≈ 60 nm pk – pk amplitude.

Design of component specific machine tools

Currently, the diamond turning machines to be used in this study have been designed for commercial manufacture of components of arbitrary geometry. This versatility, while desirable from a commercial standpoint, reduces the stiffness, dynamic response and thermal/temporal stability of the machine tool and is not necessary to produce simple shapes. Per chance, the profiling system linear bearing and fine tool translator also represent the key components for a compact diamond turning machine capable of producing replication mandrels. An ultimate goal is the design of fast, stiff, compact, inexpensive, component specific diamond turning machines. Such machines would comprise a minimum number of axes each shaped to translate the tool in specified paths with nanometer level error compensation.

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