Preliminary Characterization of Vortex Machining

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Abstract

Vortex Machining is a novel finishing process capable of producing localized material removal with surface quality similar to existing sub-aperture techniques. Additionally, the unique high-aspect ratio tooling, a slender fiber (7 µm diameter, approx. 4 mm long) attached to a tuning fork, could be used to finish more complex geometries than currently possible. This abstract provides an overview of the construction of a dedicated testing facility and development of analysis software. Additionally, machined footprint geometries and their corresponding surface roughness are assessed. Results obtained on polished silicon indicate Gaussian-like footprints with surface quality near that of the surrounding un-machined surface.

1 Introduction

Investigations are being carried out to quantify a sub-aperture (highly localized) material removal (MR) process. Vortex Machining is a loose-abrasive polishing process that is capable of producing smooth (and possibly low-subsurface damage) MR footprints with lateral dimensions in the tens of micrometers and depths in the tens of nanometers. In this process, the tool is a high-aspect ratio, micrometer-scale oscillating probe positioned several micrometers above the workpiece surface which is submerged within a shallow, stationary colloidal slurry bath, see Figure 1. The probe's oscillations induce vortices in the polishing slurry near the surface to be machined. The vortices accelerate polishing abrasives over the surface causing localized material removal [1]. The high-aspect ratio tool could make possible fine finishing in complex

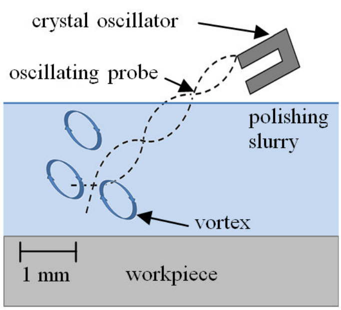

Figure 1: Schematic illustration of major features of the Vortex Machining process.

geometries such as deep channels or small holes. Such capabilities were previously unattainable with traditional polishing and other sub-aperture techniques.

2 Process Development

A dedicated process has been developed for in-depth characterization of the Vortex Machining process. The facility is designed for a short and stable metrology loop to achieve reliable collocation of the oscillating probe and workpiece, see Figure 2. The sample and probe are both secured kinematically with their relative positions controlled using an *xy* and a *z* translation stage. Three position sensors measures off the surfaces on a rectangular monolithic reference block on the slurry containment unit and, to minimize Abbe error, are positioned close to the axis of the probe. To compensate for evaporation of the fluid, an additional reflective sensor for detecting fluid height and a liquid dispenser pump has been implemented to maintain a stable slurry height. Probe stability has been achieved through the implementation of an FPGA-based lock-in amplifier and phase-locked loop. Tests have verified lateral and vertical positioning stable to ±5 µm and ±0.5 µm, slurry height stable to ±10 µm, and probe magnitude stability within 2%, see Figure 3 [1].

3 Preliminary Results

Development of the machining center has facilitated preliminary studies of the Vortex Machining process. To date, all testing has been carried out using a 4^{th} mode, 7 µm diameter carbon probe oscillating near 32.7 kHz as the tool. The tool was positioned 45° to the workpiece with a stand-off distance of 20 µm between the tool tip and workpiece surface. The polishing slurry used was a 0.05 µm colloidal alumina slurry diluted with deionized water (mixing ratio 1:1). Polished silicon <100> wafers were used in all initial tests [1]. Additionally, CNC code was written to machine footprints at equally spaced intervals of 100 µm. A Zygo NewView 5000 SWLI (Scanning White Light Interferometer) measurement of the surface is plotted in Figure 4. Another single footprint measured with a Vecco DI3100 AFM (atomic force microscopy) system is shown in Figure 5.

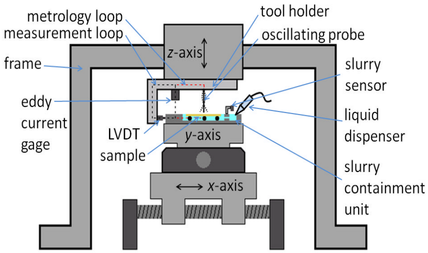

Figure 2: Block diagram of experimental testing facility. Modified from [1].

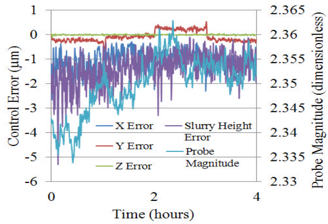

Figure 3: Plot displaying stability of the testing facility. Probe magnitude is shown on the right axis.

4 Footprint Analysis and Characterization

For characterization of Vortex Machining footprints, MATLAB™ based software has been developed. The code was written to determine the footprint geometries, surface roughness, and volumetric removal rates. AFM measurements of several footprints have been filtered and analysed in a study to determine if the process deteriorates the initial surface quality. Profiles on the machined and un-machined silicon were analysed and compared, showing roughness values on the same order of magnitude (near 0.5 nm RMS). Most of the current data shows higher roughness in the machined footprints, but more analysis is needed to confirm the physical significance of this trend. Roughness characterization will present implications on the surface quality and damage induced by this process. 3D integration to determine the volume of the measured footprints has shown removal rates near 20 $\mu m^3 \cdot hr^{-1}$ with the current process configuration and operating conditions [1]. Future research is aimed toward determination of correlations between surface roughness, removal rates, and fluidic energy density models derived from mathematical analytic solutions [2]. Testing to determine the influence of slurry composition is also planned.

5 Conclusion

Vortex Machining is a novel finishing process that has potential to fill the void left by existing sub-aperture techniques. The system is differentiated in that it can provide more localized correction with comparable surface quality. Applications are envisaged to include; machining of channels for laminar microfluidic devices, localized form correction on high-end optical components, and sub-nanometer

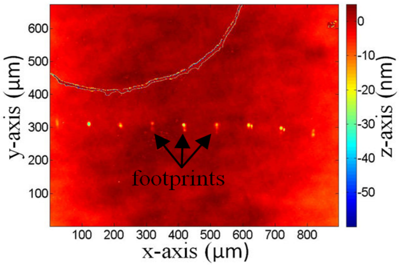

Figure 4: Contour map measured using SWLI showing multiple footprints spaced at 100 µm.

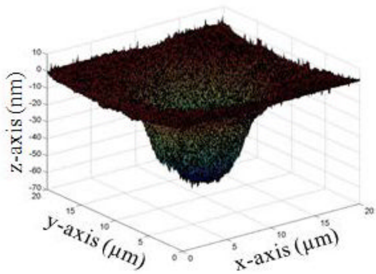

Figure 5: Surface map of footprint imaged using an AFM.

surface finishing of complex geometric features on silicon wafers. In addition to the implementation of a dedicated testing facility and analysis software, novel investigations on the machined footprints have been presented. Results to date indicate Gaussian-like geometries, roughness values near 0.5 nm RMS, and volumetric removal rates near 20 $\mu m^3 \cdot hr^{-1}$. Initial data indicates some deterioration in surface quality due to the machining process although further evaluation is necessary to determine the physical significance of these measurements.

6 Acknowledgements

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