Design and Implementation of a High-Power Machining Facility for Investigations in Vortex Machining

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Abstract

Investigations into this sub-aperture polishing process have been carried out over the past two years. Initially, a low-power testing facility utilizing small-scale tooling was designed and implemented for experimental studies. While interesting results were observed, limitations due to process contraints and scale were found to inhibit a full analysis. As a result, a larger scale, high-power machining facility to be used in parallel with its lower power counterpart was developed and is capable of operating with different rod diameters, frequencies, and amplitudes while being less sensitive to forces from the slurry. These operating parameters will provide a broader range of settings allowing further analysis of the process. This abstract will discuss the design, implementation, and resulting observations of the high-power facility.

1 Introduction

Vortex Machining is a loose-abrasive polishing process that utilizes high-velocity fluid flow of a polishing slurry to deterministically remove material from a workpiece. As shown in Figure 1(a), a high-aspect ratio cylindrical rod (or fiber) is inserted into a shallow pool of slurry with the tip positioned at a fixed standoff distance above a workpiece of interest. When the rod is oscillated in a direction perpendicular to its axis, stationary vortices are developed within the slurry causing material to be removed from the workpiece in a highly localized region [1]. Understanding these interactions and the related mechanisms of material removal has been the primary focus of research to date. Over the past two years, significant developments have been made to

![Figure 1: Principle of operation in Vortex Machining.](image-url)
study the process which include: theoretical models to parameterize relationships of the rod diameter, frequency, and amplitude with energy density of the polishing medium; an experimental test facility utilizing 7 µm diameter fibers oscillating at a fixed frequency near 32 kHz as the machining tool (herein called low-power machining facility) [2]; and custom software for analysing volumetric removal rates, shape parameters, and roughness of footprints machined from experiments [1]. Utilizing these developments, it has been shown that the process is capable of producing low-roughness, rotationally symmetric Gaussian features with lateral dimensions and depths in the tens of micrometers and nanometers respectively [1].

2 Development of high-power machining facility

While experimental results were interesting, the low-power facility has some inherent limitations. The high-aspect ratio fiber is susceptible to fluid meniscal forces which affect both machining location and the resulting fluid energy [1,2]. The process is also only capable of operating at a fixed rod diameter and frequency with low oscillation amplitudes, limiting analysis of fluid energies. These process limitations and uncertainties have led to the design and development of a system capable of oscillating larger diameter rods at higher amplitudes. The high-power machining facility, shown in Figure 2, is comprised of a substantial frame designed to minimize disturbances from the actuator. Located below the frame is a z-axis stage with sub-micrometer feedback for vertical displacement of the workpiece relative to the rod. Utilizing this system, the amplitude, frequency, and diameter of the rod can be chosen to investigate correlations between specific energy densities and footprint geometries.

![Figure 2: Schematic of high-power machining facility (a) and physical implementation with close-up of actuation system shown in box (b).](image-url)
2.1 Actuation system
The actuation system used to provide rod oscillations, see box in Figure 2(b), was implemented through design and development of three main sub-systems: the flexure actuator, capacitive amplifier, and laser sensor. The flexure actuator was produced from solid aluminum stock and is composed of a symmetric array of four leaf-type flexure springs and a central mass. From mobility analysis, this design is inherently over-constrained but has been used in practice to provide a single degree-of-freedom. The flexure geometry, stiffness, and mass were optimized to provide up to 15 μm of linear displacement with a first mode natural frequency just above 10 kHz. A piezoelectric actuator is used as the driving mechanism for the flexure. It was realized early on that limitations exist in capacitive amplifiers commercially available for driving such actuators, with large-signal bandwidths of less than 250 Hz commonly found. Since it was desired to drive the flexure actuator at frequencies up to its first natural mode, a custom amplifier was designed and constructed. The amplifier design consists of an open-loop, hybrid class-AB architecture. After integration of the amplifier and flexure actuator, the complete system was found to have a large-signal (90 V_{pk-pk}) bandwidth of approximately 5 kHz, with almost half of the displacement amplitude still being transmitted up to 10 kHz. The final sub-component of the actuation system, the laser knife-edge displacement sensor, was integrated for real-time measurement of rod oscillations. The sensor allows data collection of rod displacements during experiments and measurement of rod-to-workpiece contact phenomena for determining the relative position between the rod and workpiece.

2.2 Z-axis stage
Results from the low-power testing facility have shown that maintaining a stable rod-to-workpiece orientation is required for repeatable experimental testing [1,2] and correlations with fluid models. The z-axis, shown in Figure 2, is comprised of a screw-drive, scissor-type stage for coarse positioning and a two degree-of-freedom, piezoelectrically actuated stage for fine positioning. The fine stage is actuated by way of two, two-bar lever-type flexures with translational and angular ranges of approximately 140 μm and 63 mrad, respectively. Measurement is provided by three capacitance gages; two are attached locally to the fine stage for angular feedback and one is attached to the machining facility frame for global translational feedback.
Sensor arrangement was designed to minimize the size of the measurement loop. Validation testing of the z-axis stage under closed-loop control has shown that translational and angular control errors have standard deviations of approximately 32.5 nm and 250 nrad over the entire vertical translation range.

3 Results/Analysis

Results show the high-power machining facility is capable of producing footprints at up to 100 times the volumetric removal rate when compared with the lower power facility. A footprint representative of the process, shown in Figure 3, was machined using a 500 µm rod at 270 Hz in a mixture of 50% water and 50 nm colloidal alumina polishing slurry. Preliminary analysis indicates that features inside the footprint have the same level of roughness as that of the un-machined material. This finding is in agreement with analysis of recent footprints machined using the low-power facility. While meant to provide a platform for further experimental analysis, the high-power facility may show further applications of Vortex Machining to large scale surface modification and/or contouring.

![Figure 3: Measurement of footprint machined on silicon workpiece over 2.5 hours illustrated as contour plot (a), line profile (b), and roughness of profile (c) calculated using zero-order Gaussian regression filter with 2.5 µm cut-off (Rq = 0.054 nm).](image)

References:
