MAGNETORHEOLOGICAL (MR) JET FINISHING TECHNOLOGY

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ABSTRACT

Conformal (or freeform) and steep concave optics are important classes of optics that are difficult to finish using conventional techniques due to mechanical interferences and steep local slopes. One suitable way to polish these classes of optics is by using a jet of abrasive/liquid mixture. In doing so, the energy required for polishing may be supplied by the radial spread of a liquid jet, which impinges a surface to be polished. Such fluid flow may generate sufficient surface shear stress to provide material removal in the regime of chemical mechanical polishing. Once translated into a polishing technique, this unique tool may resolve a challenging problem of finishing steep concave surfaces and cavities. A fundamental property of a fluid jet is that it begins to lose its coherence as the jet exits a nozzle. This is due to a combination of abruptly imposed longitudinal and lateral pressure gradients, surface tension forces, and aerodynamic disturbance. This results in instability of the flow over the impact zone and consequently polishing spot instability. To be utilized in deterministic high precision finishing of remote objects, a stable, relatively high-speed, low viscosity fluid jet, which remains collimated and coherent before it impinges the surface to be polished, is required. A method of jet stabilization has been proposed, developed and demonstrated whereby the round jet of magnetorheological fluid is magnetized by an axial magnetic field when it flows out of the nozzle. It has been experimentally shown that a magnetically stabilized round jet of MR polishing fluid generates a reproducible material removal function (polishing spot) at a distance of several tens of centimeters from the nozzle. In doing so, the interferometrically derived distribution of material removal for an axisymmetric MR Jet, which impinges normal to a plane glass surface, coincides well with the radial distribution of rate of work calculated using computational fluid dynamics (CFD) modeling. Polishing results support the assertion that the MR Jet finishing process may produce high precision surfaces on glasses and single crystals. The technology is most attractive for the finishing of complex shapes like freeform optics, steep concaves and cavities.

Key words: Optical, finishing, jet, magnetorheological (MR), polishing, sub-aperture

1. INTRODUCTION

In traditional polishing, particularly in chemo-mechanical polishing (CMP), material removal results from the polishing slurry particles’ mechanical interaction with a chemically reacting workpiece surface, resulting in material removal on the atomic or molecular level [1]. For example, in glass polishing, the chemical activity of water lowers the energy needed to break the silicon-oxide bonds, whereas the mechanically activated abrasive particles perform work in removing the silica glass basic unit (silica tetrahedron), and transporting the debris away from the workpiece surface. Further, in this particular case, the rate of the bond-rupture reaction depends not only on chemical environment, but also on the magnitude of the applied mechanical stress [2]. Different methods are used to supply mechanical energy to the workpiece surface, thus providing a mechanical interaction between polishing particles and the workpiece surface to be polished [3]. Considerable recent attention has been focused on the techniques where such energy is supplied by fluid flow, which may generate sufficient surface stresses to provide material removal in the regime of CMP. The advantage of this approach lies in the fact that, in contrast to conventional “contact” polishing, the surface normal stress and the surface indentation are not dominant in the process of material removal. This results in the absence of a subsurface damaged layer.

In magnetorheological finishing (MRF), the mechanical
energy required for material removal over a portion of the workpiece surface is generated by the magnetically controlled hydrodynamic flow of a magnetorheological polishing fluid. A fundamental advantage of MRF over existing technologies is that this sub-aperture polishing tool conforms to the local surface shape and does not “wear” since the state of the re-circulated fluid is continuously monitored and maintained, heat is removed and polishing is done inside a stable magnetic field. MRF can produce surface accuracy on the order of 30 nm peak-to-valley (p-v) and surface micro-roughness less than 1 nm rms [4].

A method called “Hydroplane Polishing” is based on the phenomenon of hydrodynamic lubrication [5]. In this process, material removal is achieved by way of hydrodynamic flow of abrasive particle/fluid mixture. Multiple inclined surfaces are formed in a circumferential direction on a circular plate, which then rotates in fluid. Hydrodynamic pressure that is generated through the fluid wedge balances the normal load. The workpiece floats above the plate surface and is polished by the abrasive particles, which pass through the converging gap with the fluid.

A hydrodynamic principle is also used to provide high precision polishing in “Elastic Emission Machining” [6]. In this technique, a loaded elastic polyurethane ball polishes the workpiece as it scans over the part surface. The ball is rotated rapidly in a polishing fluid and, due to hydrodynamic forces, floats above the workpiece surface. The floating gap, which is created by an elasto-hydrodynamic lubrication state, is much larger than the diameter of the abrasive particles but is still very small. The mechanism proposed for this process is an elastic bombardment of the surface by the polishing particles.

Previous work has shown that water jets can be used to polish materials such as glass, diamond, ceramics, stainless steel and alloys [7]. The surface quality strongly depends on the size and impact angle of the abrasive grains. Surface roughness of Ra ~130 nm on glass has been achieved after processing. An appropriate adjustment of process parameters such as jet velocity, abrasive size and concentration makes reduction of surface roughness on glass to Ra = 1.2 nm possible [8].

A fundamental property of a fluid jet is that it begins to lose its coherence as the jet exits a nozzle, due to a combination of abruptly imposed longitudinal and lateral pressure gradients, surface tension forces, and aerodynamic disturbance. The destabilizing aerodynamic disturbance is dramatically increased with jet velocity. This causes the high-speed liquid jet, which is the prime interest for finishing, to break into droplets and progressively spread out. For this reason, the diameter of a water jet used for cutting for example, is very small to provide precision machining and high unit pressure. Also, a nozzle is situated as close to the workpiece to be cut, as it is practically possible. Typically, such cutting jets contain abrasive particles with a high enough kinetic energy capable of sputtering (chipping) material away from the surface in the impact zone. Although a flow regime where the jet can polish rather than cut requires lower jet velocity, the problem of jet stability still persists. As this takes place, the jet irregularity increases progressively with the distance from the nozzle. That results in instability of the flow over the impact zone and consequently polishing spot instability, which is unacceptable for deterministic, high precision finishing. A reduction of jet velocity in order to obtain a coherent jet is impractical because it results in low impact energy, and therefore, low material removal rate. Increasing jet stability with fluid viscosity proportionally increases the resistance to fluid flow in the delivery system and consequently, the pumping power required to deliver the fluid to the nozzle. It makes impractical a high speed, high-viscosity jet for polishing.

To be utilized in deterministic high precision finishing, a stable, relatively high-speed, low-viscosity fluid jet, which remains collimated and coherent before it impinges the surface, is required. Such a unique tool may also resolve a challenging problem of high precision finishing of steep concave surfaces and cavities.

2.0 MAGNETORHEOLOGICAL JET POLISHING
2.1 Jet Stabilization

In contrast to known jet polishing methods [7,8] where material removal relies on the kinetic energy of impacting particles, the technique discussed in this paper is based on an assumption that the energy required for polishing may be supplied by the radial spread of a liquid jet over a surface to be polished [9]. Such fluid flow may generate sufficient surface stress to provide the regime of material removal, which is characteristic to polishing. As it was mentioned above, the liquid jet breaks down at a very short distance from the nozzle (a few nozzle diameters) resulting in instability of the impinging flow, which in this case, is highly sensitive to the nozzle-offset distance. As applied to polishing, this limits configurations where the removal function is stable resulting in significant restrictions on finishing of complex shapes.

A method of jet stabilization has been proposed, developed and demonstrated whereby the round jet of magnetorheological fluid is magnetized by an axial magnetic field when it flows out of the nozzle [9,10,11]. Such local magnetic field induces longitudinal fibrillation and high apparent viscosity within the portion of the jet that is adjacent to the nozzle resulting in suppression of all of the most dangerous initial disturbances. As a result, the MR fluid ejected from the nozzle defines a highly collimated, coherent jet. The stabilizing structure induced by the magnetic field within the jet gradually begins to decay while the jet passes beyond the field. However, remnant structure still suppresses disturbances and, thus consequent stabilization of the MR Jet can persist for a sufficient time that the jet may travel up to several meters (depending on the jet diameter) without significant spreading and loss of structure.

The foregoing is illustrated in Fig. 1. In the case of water, the jet remains stable only for ~2 nozzle diameters (transparent section of the jet at the outlet). MR fluid has higher viscosity and therefore the coherent portion of the jet extends on ~7 - 8 diameters. Initial disturbances (visible in the form of ripples

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on the surface of the coherent part of the jet) eventually result in the jet breakdown and rapid spreading. Magnetized at the outlet, the jet of MR fluid remains coherent for more than 200 diameters. The MR fluid jets shown in Fig. 1 have the same fluid viscosity and jet velocity. This means that with the magnet off, the viscosity is too low and the velocity is too high to provide a stable jet of fluid. With the magnet on, the same low-viscosity, high-velocity jet of MR fluid is stabilized by the application of the magnetic field.

2.2 Experimental Set-up

An MR Jet polishing system, a portion of which is shown in Fig. 2, has been constructed using a 5-axis CNC platform and polishing control software developed by QED Technologies. The delivery system is comprised of a mixing vessel to disperse the solids in the MR fluid, a pump, means to maintain temperature and viscosity of the fluid and pressure and flow sensors to monitor the system conditions. An MR shaper that uses the properties of the MR fluid and a magnetic field to stabilize the MR Jet is located beneath the spindle of the CNC platform. With the magnet activated, a collimated jet is directed vertically upwards to the part held by the spindle. Finally, means have been implemented to contain, collect and re-circulate the MR fluid after it impinges upon the part surface.

2.3 Removal Function

Typical MR Jet removal functions (or polishing “spots”) are shown in Fig. 3. These two spots were taken at different jet velocities by dwelling the 1.5 mm diameter jet upon the stationary flat fused silica surface for a prescribed period of time.
The distance between the nozzle exit and the part surface (the stand-off distance) was 50 mm for both. The spot on the left had a moderate fluid jet velocity giving a peak removal rate of 1.44 μm/min and volumetric removal rate of 0.033 mm$^3$/min. The spot on the right was created with an identical setup; only a more aggressive jet velocity was used giving a peak removal rate of 18.6 μm/min and volumetric removal rate of 0.51 mm$^3$/min. This demonstrates the ability to adjust material removal rate by more than an order of magnitude using the same set up. It is possible to vary removal rate further with appropriate system adjustments.

The dashed white line in Fig. 3 shows the orientation of the profile shown in Fig. 4. Notice from this figure that there is no removal in the center of the spot. This is because the material removal is due to shear flow, which is zero at the center. This will be discussed in greater detail in later sections.

The stability of the removal function is demonstrated in Figs. 4 and 5. Figure 4 shows removal function profiles (the scan along the spot diameter) typical for MR Jet polishing spots. The two spot profiles given in this figure were taken with two different stand-off distances (the distance between the part surface and the nozzle exit as shown in Fig. 2). The two distances were 50 mm (filled markers) and 150 mm (open markers) resulting in the same spot profile as shown in the figure. This is further emphasized in Fig. 5, where the maps of the material removal distribution are subtracted. The maximum variation in these removal maps is only 6.5%, even though the separation between the part and the nozzle changes by 100 mm. This quality is particularly important when considering precision finishing of steep concave (or freeform) optics.

Polishing spot stability is the most important characteristic required for high precision deterministic finishing. Evaluation of MR Jet polishing spot stability was performed as follows. Four spots were taken in succession at different locations on the same pre-measured part (see Fig. 6a). The variance between the four spots (the standard deviation) is shown in Fig. 6b. The error in this map is only 4.2 nm p-v and 0.54 nm rms, for 100 nm deep spots. These results demonstrate an exceptional MR Jet removal function stability and versatility making it a valuable tool for high precision finishing of complex surfaces.

2.4 Polishing Performance

2.4.1 Flats

Given the stable spot, QED control software, and CNC control, MR Jet can be used to accurately correct surface figure. Figure 7 shows the results of polishing a flat fused silica part with 0.47 μm p-v of primarily power error. The error was reduced to 32 nm p-v in a single iteration, and as low as 13 nm p-v after the second iteration. Furthermore, the MR Jet process has regularly demonstrated the ability to achieve roughness values much better than 1 nm rms. Figure 8 shows an example of one of these roughness maps of fused silica glass and an accompanying profile plot.

2.4.2 Conformal Optics

The unique qualities of the MR Jet process enable the manufacture of conformal optics. This important class of optics is made up of designs such as domes and other steep concaves where the shape of the optic is driven by such considerations as the aerodynamic requirements instead of the optical requirements. Since the optics have to work in transmission, the internal, concave surface must be polished as well as the external surface. This is a challenging problem for most polishing processes because of the deep sag of these surfaces. MR Jet
offers a solution to reach into the center and figure correct this internal surface as demonstrated above by the insensitivity to stand-off distance.

A small, concave glass insert was placed inside an aluminum shell that approximates a nose cone ogive (Fig. 9a). The radius of the concave surface was 20 mm and the diameter was 23 mm. The part was polished in a rotational mode, rotating on axis and sweeping around its center of curvature to keep the jet normal to the optical surface (Fig. 9b). Excellent polishing results were obtained. Figure 10 shows the figure error of the concave surface before and after MR Jet. Both the symmetric and asymmetric error was corrected, leaving a peak-to-valley of less than 50 nm (a 5x improvement from the initial conditions). In addition, the rms was improved by more than 8x.

3. MODEL VALIDATION

3.1 Theoretical Considerations

The proposed model of jet polishing assumes that the energy for abrasive particles/surface mechanical interaction is provided by the radial laminar flow, which occurs as a result of impingement of the coherent liquid column with the surface. Also, the process of material removal is considered in the context of the fundamental Preston’s statement that “the rate of polishing of the glass (that is, the rate at which material is removed) is proportional to the rate at which work is done on each unit area of the glass” [12].

To put it another way,

\[ \dot{R} \sim \dot{W} \]  \hspace{1cm} (1)

where \( \dot{R} \) is material removal rate and \( \dot{W} \) is the rate of work done at the surface.

Generally, the rate of work done by the fluid at the control surface is [13]:

\[ \dot{W} = - \int_{S} \bar{F} \cdot \bar{V} \, dA \]  \hspace{1cm} (2)

where is \( \bar{F} \) the vector fluid stress applied to the element \( dA \) of the control surface and \( \bar{V} \) is the vector fluid velocity. The fluid stress can be divided into components perpendicular to \( dA \) and in the plane of \( dA \),

\[ \bar{F} = \bar{s}_n + \bar{\tau}_x \]  \hspace{1cm} (3)

where \( \bar{s}_n \) is the normal stress and \( \bar{\tau}_x \) is the shear stress. These considerations imply that \( \dot{W} \) can be expanded as follows:

\[ \dot{W} = - \int_{S} \bar{\tau}_x \cdot \bar{V} \, dA - \int_{S} \bar{s}_n \cdot \bar{V} \, dA \]  \hspace{1cm} (4)

The fluid shear stress can arise only from viscosity, whereas the normal stress can result from both pressure and
viscosity. However, in the case under consideration when there is no normal fluid velocity component at the surface, \( \hat{s}_n \) will be dominated by the compressive stress of fluid pressure:

\[
\hat{s}_n = -p\hat{n}, \quad \text{but} \quad \hat{s}_n \cdot \hat{V} = 0 \quad \text{(5)}
\]

where \( p \) is the fluid hydrostatic pressure and \( \hat{n} \) is the normal to the surface. The rate of work at the surface then becomes:

\[
\dot{W} = -\int_{S} \hat{s}_x \cdot \hat{V} dA \quad \text{(6)}
\]

the case under consideration, the local rate of the work done at the surface will be:

\[
\dot{W}_r = \tau_r V_r \quad \text{(7)}
\]

From (1) and (5) follows that the local removal rate is proportional to the local shear stress times local fluid velocity.

As would be expected, the same qualitative result follows from Preston’s classical expression:

\[
\dot{R} = kPU = k\frac{L}{S}U = k\frac{F}{\mu S} = k\frac{\tau U}{\mu} = k\frac{W}{\mu} \quad \text{(9)}
\]

where \( L \) is the normal load, \( S \) is the surface area on which wear occurs, \( F \) is the frictional force between the glass and the polishing lap, \( \mu \) is the coefficient of friction, \( \tau \) is the surface shear stress, \( W \) is the rate of work done per unit area (the power input), \( k \) is the Preston coefficient, which is process dependent and combines surface chemistry, abrasion effects and specifics of part-polisher interaction.

### 3.2 Model Verification

An effort was made to find the correlation between the experimental removal function and the theoretical model described above. A normalized experimental radial removal rate profile was compared with the normalized radial distribution of the rate of work done at the surface calculated using a commercially available CFD package [14]. Due to the fact that the MR fluid is not affected by the magnetic field at the impingement zone, an assumption is made that it can be modeled as a Newtonian fluid. This assumption is validated by Fig. 11, which shows the flow curve of an MR fluid in the absence of the magnetic field. The small deviation from Newtonian behavior at low shear rate can be ignored for the flow regime considered in this model.

Results of the flow modeling are show in Fig. 12. Experimental data for removal rate (square markers) were taken at three jet velocities (15, 20 and 27 m/s) with a jet diameter of 2.4 mm. The solid lines in Fig. 12 represent the...
radial distribution of the computed rate of the work done at the surface under the same conditions. The open triangles show the calculated pressure profile. Note that this plot represents half of the removal profile shown in Fig. 4. Very good correlation is observed between the removal rate profile and distribution of the rate of work done at the surface providing strong support for the model presented above. It is also worth noting that the position of the peak removal rate corresponds to the position of minimum pressure whereas no removal occurs at maximum pressure. It means that the normal stress does not contribute in material removal as the model suggests. This gives strong support to our assertion that a shear mode of material removal is indeed responsible. In Fig. 13, the normalized peak of removal rate (markers) and calculated normalized local rate of work at the position of peak removal (solid line) are plotted against the jet velocity. Again, there is a very good correlation between the predicted and experimental results. According to Fig. 13, the cubic dependence of removal rate on jet velocity prevails.

4.0 SUMMARY

It has been demonstrated that impingement of a magnetically stabilized, collimated jet of MR fluid induces radial surface flow, which results in generation of the polishing spot. In numerous experiments with different process parameters (jet velocities, nozzle diameters, fluid viscosity) it was shown that material removal in the polishing spot closely correlates with the computed rate of work done at the surface by the fluid. This agrees with the fundamental basis of Preston’s model. It was also established that MR Jet finishing can produce high precision surfaces on the order of tens of nanometers p-v with roughness < 1 nm rms. Due to insensitivity to the offset distance this technique may be valuable in finishing complex shapes especially those with steep concaves and parts with a variety of cavities.

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6.0 REFERENCES


