APPLICATION OF MAGNETORHEOLOGICAL JET (MR JET®) IN PRECISION FINISHING

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INTRODUCTION
Abrasive jets provide a useful tool in machining operations for fabricating challenging designs. However, applying this technology for fabrication of precision optical components introduces a number of technical challenges. A fundamental property of a fluid jet is that it will begin to lose its coherence once it exits the nozzle. This instability results in an unpredictable removal rate of the fluid jet, which makes it unsuitable for use in a deterministic finishing process. This can be avoided by using a magnetorheological (MR) fluid and applying a magnetic field where it flows from the nozzle exit. The success of this approach has been demonstrated and implemented into the Magnetorheological Jet (MR Jet) finishing process. The magnetically stabilized jet of MR polishing fluid produces a stable and reproducible material removal function (polishing spot) at a distance of several tens of centimeters from the nozzle making MR Jet an attractive technology for the finishing of complex shapes such as free form optics, steep concaves, cavities and molds. Recent results show diverse application of this technology that includes precision finishing of optical designs that range from flats and spheres to aspheres and even conformal shapes. This includes the ability to deterministically finish optics < 1 mm in size to high precision and work with materials such as glass, metals, and ceramics such as sapphire.

MAGNETORHEOLOGICAL JET (MR JET®) FINISHING
Jet Stabilization
In contrast to conventional abrasive jet polishing methods 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. [1-6] Such fluid flow may generate sufficient surface stress to provide the regime of material removal, which is characteristic of polishing. As mentioned above, a typical liquid jet breaks down at a very short distance from the nozzle (a few nozzle diameters), making regular, jet-based polishing techniques highly sensitive to the nozzle-offset distance. This limits polishing configurations to those in which the removal function is stable, significantly restricting the 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 [1-6]. This local magnetic field induces a structure within the fluid [7] and high apparent viscosity [8] within the portion of the jet that is adjacent to the nozzle, resulting in the 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 as the jet passes beyond the field. However, the remnant structure still suppresses disturbances and, thus, consequent stabilization of the jet can persist for a sufficient time that it may travel up to several meters (depending on the jet diameter) without significant spreading or loss of structure. For nozzle sizes on the order of 1 mm in diameter coherent jets of 0.5 meters are routinely achieved.

FIGURE 1. Jet snapshot images

a. Water  b. MR Fluid Field off  c. MR Fluid Field on
This is illustrated in Figure 1. In the case of water, the jet remains stable only for ~ 2 nozzle diameters (note transparent section inside dashed circle at the outlet of Figure 1a). MR fluid has higher viscosity and therefore, the coherent part of the jet extends on ~ 7 - 8 diameters. Initial disturbances (visible in the form of ripples on the surface of the coherent part of the jet in Figure 1b) eventually result in the jet breaking down and rapid spreading. However, when magnetized at the outlet, the jet of MR fluid remains coherent for more than 200 diameters (i.e. ~ 0.4 meters for the case shown in Figure 1c).

**Experimental Set Up**

A MR Jet finishing system, a portion of which is shown in Figure 2, has been constructed using a 5-axis CNC platform and polishing control software. The delivery system comprises 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. A magnetic field optimized for the properties of the MR fluid is located beneath the spindle of the CNC platform and stabilizes the jet. With the magnet activated, a collimated jet is directed vertically upwards to the workpiece held by the spindle. Used fluid is collected and recirculated.

**Removal Function**

Figure 3 shows a model of the fluid flow as the jet impinges normal to the workpiece surface. One of the benefits of working with a collimated jet is that as the jet meets the surface, the fluid flows radially outward as opposed to simply bombarding the surface with kinetic energy. It is this radial shear flow that leads to the material removal. [9] As indicated in Fig. 3, there is no removal in the center, where the jet impinges the surface, but instead the bulk of the removal occurs outside of the area of impingement as the fluid radiates outward. Additional unique attributes of using a collimated jet is that it provides a stable and predictable removal function. This is true whether the jet impinges normal to the surface or at angle and provides a great deal of flexibility in the applications that MR Jet can address.

![FIGURE 3. Model of the flow as the MR Jet impinges on the workpiece surface.](image)

**Results on Novel Geometries**

**Cavities**

MR Jet has been demonstrated to achieve extremely high precision on a wide range of applications, from flats to spheres, aspheres and spherical domes [1,5,6]. In addition to these shapes, jet finishing has been applied to novel geometries described below.

![FIGURE 4. Schematic of a cavity that was finished with MR Jet.](image)

One unique geometry that has been finished with MR Jet is shown in Fig. 4. In this case, a flat optical surface at the bottom of a ~10 mm deep cavity was polished, which is nearly impossible to accomplish with most finishing techniques. The results are shown in Figs. 5a and 5b. MR Jet was able to finish this surface to improve the figure from >73 nm rms to ~6 nm rms.
Millimeter-Sized Optics

Another unique attribute of jet finishing technology is that it can be scaled to address millimeter-sized apertures (like the lens shown in Fig. 6). There was an objective to print an aspheric shape with only a 1.3 mm diameter and ~2.5 um of aspheric departure into a flat glass surface. The blue line in Fig. 7 shows the desired final shape of the surface, and the magenta line shows the result of printing the figure into the surface. The agreement between the Desired and Actual profiles demonstrates the ability of the system to reliably polish such complex shapes into extremely small aperture sizes. Clear apertures as small as 0.8 mm have been polished to within 25 nm P-V of the target shape.

Conformal Shapes

The unique attributes of MR Jet provide a great deal of flexibility in the geometries that can be finished and the ability to correct a conformal dome shape (see Fig. 8) has recently been demonstrated. The radius of curvature varies from ~200 mm to ~10 mm across the surface, increasing the degree of difficulty of this job. The MR Jet process has been developed to account for these difficult challenges.

The initial figure error of the exterior of the dome profile is shown in Fig. 9a [10] (28 um P-V and 8.9 um rms) and the figure error after correcting with MR Jet is shown in Fig. 9b (3.4 um P-V and 1.1 um rms). The figure was improved from 8.9 um rms to 1.1 um rms. This shows that the conformability and stability of the MR Jet provides the means to account for such a wildly changing surface and correct the figure in a deterministic fashion. This result is an important milestone in the precision manufacture of conformal shapes and opens up numerous possibilities to the optical designer for incorporating increasingly complex designs in their systems.
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 stable, predictable polishing tool. The scalability of jet finishing provides a tool to deterministically correct the figure of optics smaller than 1 mm in size. Due to the insensitivity to the offset distance, MR Jet provides a versatile tool for finishing complex shapes to high precision, ranging from conventional geometries such as flats, spheres and aspheres to increasingly complex shapes like conformal domes.

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REFERENCES


[10] Figure was characterized using the PGI 1250A from Taylor Hobson.