CONTINUOUS PHASE PLATE POLISHING USING MAGNETORHEOLOGICAL FINISHING

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INTRODUCTION
Magnetorheological Finishing (MRF®) methods and systems have been developed to imprint complex, continuously varying topographical structures onto 430 x 430 millimeter optical surfaces. These optics, known as continuous phase plates (CPPs) are important for kilojoule- and megajoule-class laser systems requiring precise control of beam-shape, energy distribution and wavefront profile. MRF’s sub-aperture polishing characteristics make it possible to imprint complex computer generated topographical information at spatial scale-lengths approaching 1 millimeter and surface peak-to-valleys as high as 22 millimeters to within 30 nanometers of design specifications.

High-powered laser systems utilized for inertial confinement fusion research, such as the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), Laser MegaJoule (CEA) near Bordeaux, France, and OMEGA at the Laboratory for Laser Energetics require precise characterization and control of the laser beam illumination at the target plane. A major portion of this work centers upon developing and engaging state-of-the-art technology to set the stage for creating nuclear fusion in a laboratory setting. Continuous phase plates (CPPs) form the vital and enabling portion of the optics chain used in these kilojoule- and megajoule-class laser systems because they make it possible to manipulate and control laser beam-shapes, energy distributions, and wavefront profiles [1, 2]. This prescribed beam characteristic control is made possible via manipulation of the incoming wavefront by the CPPs. CPPs function in combination with a focusing element to define the size and shape of the beam at focus, the wavefront characteristics (uniformity) at the focal plane, and the intensity of the beam within the focal spot.

As illustrated in Figure 1, a focusing element such as a lens results in laser light focused to a diffraction limited far-field spot of about 15 µm in diameter at the focal plane (about a 30,000 times reduction in size). Even though the focused beam possesses high intensity, it is too small to use for illumination of large areas (about 1 mm in size) with high intensity coherent light. Additionally, it has a highly non-uniform intensity profile due to the limitations of the focusing element and light diffraction, which result in non-uniform illumination. Attempting to increase the spot size to about 100 µm by defocusing the lens, which one would think could be a course of action, does make the far-field spot larger, but its shape and intensity profile remain ill-conditioned. Introduction of a CPP into the optics chain that is specifically designed to yield the required far-field spot size and intensity uniformity in the focal plane solves the problem. CPPs fall into the category of diffractive optics where we take advantage of the apparent bending of light waves in response to small topographical changes on an optical surface. CPPs are made by imprinting a continuously varying phase profile onto an optical surface, as shown in Figure 2.
FIGURE 2. Continuously varying topographical CPP pattern with an 8.6 µm peak-to-valley imprinted onto a 430 x 430 x 10 mm fused silica substrate using MRF.

MANUFACTURING CPPs
Manufacture of CPPs to the extreme tolerances required for use in high-power laser systems demands state-of-the-art technology for topographical imprinting. Magnetorheological Finishing (MRF®) polishing technology is a highly versatile and precise process for polishing surface topography into optical surfaces. MRF is a deterministic polishing process; that is, the end result can be predicted and repeatedly achieved. MRF greatly enhances product quality and repeatability while providing a quantum leap in throughput, productivity, yield, and cost effectiveness by replacing the art of optic polishing with science and technology. [3]

MRF is an advanced optical finishing process combining interferometry, precision equipment, and computer control [4]. It utilizes a sub-aperture polishing tool, or removal function, generated by the interaction of a magnetic field and an iron-based Magnetorheological fluid containing microscopic abrasive particles such as ceria or nano-diamonds as shown schematically in Figure 3.

FIGURE 3. MRF polishes optics by creating a sub-aperture polishing tool using magnetic media and an electromagnet. Material is removed in the area where the optic is immersed into the fluid ribbon. Surface polishing is accomplished by rastering or rotating the optic over the ribbon. The fluid is continuously recycled.

A MRF tool removes material from an optical surface when the optic is positioned at a fixed distance from a moving spherical wheel. An electromagnet located below the wheel surface generates a magnetic field in the gap between the wheel and optic. When the MR fluid is delivered to the wheel, it is pulled against the wheel surface by the magnetic field gradient and becomes a sub-aperture polishing tool. A sophisticated computer program determines a schedule for varying the translation velocity of the optic as it sweeps through the polishing zone, in a raster pattern. Because the removal function is interferometrically characterized and highly stable, the system can efficiently deliver high precision parts. Other advantages are that the polishing tool is easily adjusted, and conforms perfectly to the optical surface, enabling topographical polishing. The deterministic nature of the MRF process makes it possible to correct optical figure over a large area using a small controllable removal function. In its normal operating configuration, MRF uses the removal function and dwell time to differentially remove material from areas of an optic so that the desired surface or wavefront properties are obtained. Imprinting of surface topography onto an optical surface such as that required for CPPs is a non-traditional application of this technology. The distinct difference is that instead of removing the waviness or imperfections from the optical surface, MRF is applying surface structure in a deterministic fashion. For short spatial periods, one can think of the process as imprinting or correcting a number of small geometric errors, or lenses, present on a large piece of glass. Here, the size of the removal function becomes important in attaining the desired topographical fidelity. The MRF system software provides the mechanism to perform this task by using a solving algorithm that performs a deconvolution of the removal function shape and the incoming surface structure measured via interferometry or mathematically supplied by the user. In a typical raster-polishing application, the MRF software uses the existing surface figure as a starting point and a flat surface as the desired end-point. The algorithm attempts to converge to a solution that minimizes the rms of the surface via the removal function/existing surface deconvolution. For imprinting, the process must be inverted. It must start with an existing surface figure and end with a surface possessing desired topography. This is
accomplished by adding the height-inverted topographical imprint map (negative image) to the starting metrology. The solving algorithm converges this virtual surface towards flatness. This results in the proper removal of material from the initial optical surface even though the software output is a plano surface. The process is shown in Figure 4.

![Diagram](image)

**FIGURE 4.** The MRF imprinting process integrates interferometry, computer generated prescriptions, and custom-designed software to create machine instructions to deterministically enable topographical imprinting on CPPs.

Imprinting large-aperture CPPs requires specialized MRF instruments capable of imprinting topographies on large-aperture optics. An integral part of our efforts for making CPPs a reality involved a large-aperture MRF tool. This machine is used to perform final finishing on CPP substrates and to imprint the necessary topography to manufacture a CPP. The large-aperture MRF system uses two wheels for efficiency, one large (370 mm diameter) and the other small (50 mm diameter), with optimized computer algorithms that together provide a greatly increased range of finishing options and range of topographical feature sizes that can be imprinted. The MRF process provides for a high level of versatility and speed in CPP manufacture as topographical polishing can be conducted by combining computer generated CPP and/or interferometric profiles with large MRF volumetric removal rates (~1 mm³/min). Additionally, the process seamlessly fits into the advanced manufacturing process technology for production of large-aperture optical components possessing high-ultraviolet damage resistance.

CPP imprinting of large-aperture optics typically utilizes both the large and the small wheels to take advantage of the different material removal functions sizes (bandwidth). The imprinting utilizes a multi-pass approach to obtain the desired topographical fidelity using superposition to provide for process breakpoints necessary for testing. To start the process, computer generated hitmaps containing the CPP topographical pattern and the existing wavefront in the substrate are introduced to the MRF machine. The initial passes during the MRF imprinting process use the 370 mm wheel and large MRF removal functions to imprint long spatial period features into the optical surface. Iterative raster scans are used with smaller removal functions to imprint smaller spatial period features into the optic and to refine the gradients present in the pattern. These passes begin with the 370 mm wheel and moderately sized removal functions and end with the 50 mm wheel and small removal functions. This strategy maximizes material removal over the topographical frequencies being imprinted. Each iteration is conducted using the CPPs measured transmitted wavefront from each MRF pass. This in-process interferometry is used to track imprinting progress and to optimize phase front corrections in the CPPs topography. The iterative process is complete when the optic transmitted wavefront converges to the required specification. We routinely attain 20-30 nm rms difference between the CPP prescription presented to the MRF and the final optic transmitted wavefront. With over a total of 82 large-aperture CPPs imprinted, we have only found 1 MRF related artifact that was of concern. This artifact was a polished localized lenslet on the optic surface arising from a drop of MR fluid that was not cleaned off during the imprinting process. Additionally, we have shown that CPPs can be manufactured for use in the ultraviolet (351 nm) portions of a laser system at fluences up to 14 J/cm² at 3 nsec pulse length by extending our capability of manufacturing laser damage resistant optics using MRF to CPP imprinting. This is due to the fact that MRF polishing removes subsurface damage, which is a major source responsible for initiating damage in optics at high laser fluences.

The MRF imprinting process is the only proven process that can make ultra-precise large-aperture CPPs. From the size standpoint, this process can routinely manufacture high performance plates up to 1000 x 750 mm in size.
MRF is also very efficient with respect to the fabrication time required to complete a CPP imprint. For a 430 x 430 mm CPP, MRF can complete an imprint in 56 hrs. This puts MRF imprinting into a high-throughput manufacturing category where plates can be manufactured at rates 3 to 7 times faster than other technologies.

RESULTS
In March 2006, we imprinted a 134 mm diameter CPP for the JANUS laser system at LLNL for high-powered short-pulse laser experiments, Figure 7. The JANUS laser has produced the highest irradiance (power per unit area) ever recorded: two sextillion (2 x 10^21) watts per square centimeter.

**FIGURE 7.** Near-field interferogram (left) for a 135 mm diameter CPP fabricated for use on the JANUS laser system imprinted using MRF with a peak-to-valley of 11.7 μm. The resulting far-field spot (right) has a 710 μm diameter at 95% encircled energy. The far-field spot is uniform to within 4%.

We are currently using large-aperture MRF polishing to manufacture ultraviolet laser damage resistant main debris shields and CPP substrates for use on the NIF laser system at a rate of 10 optics per month. In addition to imprinting CPPs, we developed MRF polishing techniques to a point where we routinely use it to manufacture large-aperture 430 x 430 mm plano fused silica optics to less than 125 nm peak-to-valley flatness that can withstand laser fluences of greater than 14 J/cm² at 351 nm, 3 nsec pulse width without damage.

Over the past year, our team has engaged large-aperture MRF polishing on 940 mm and 800 mm diameter BK-7 grating substrates for use on the OMEGA, VULCAN (Great Britain), TITAN, and NIF ARC petawatt-class laser systems and laser system upgrade projects. The extreme precision of the MRF tool enables us to polish these substrates to less than 100 nm peak-to-valley flatness over the entire optical surface so that high-efficiency gratings can be subsequently applied. These optics are used as laser beam pulse compressors.

SUMMARY
Manufacture of CPPs to the extreme tolerances required for use in high-power laser systems demands state-of-the-art imprinting technology to be successful. To meet this challenge, we engaged in the development of Magnetorheological Finishing (MRF) technology to arrive at a highly versatile and precise process for polishing surface topography into optical surfaces. MRF is an advanced optical finishing process combining interferometry, precision equipment and computer control, has brought the optics fabrication industry to new levels of precision in recent years.

REFERENCES