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DIAMOND REFRACTIVE OPTICS FABRICATION BY LASER ABLATION AND AT-WAVELENGTH TESTING

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Abstract

The next generation light sources will require x-ray optical components capable of handling large instantaneous and average power densities while tailoring the properties of the x-ray beams for a variety of scientific experiments. Diamond being radiation hard, low Z material with outstanding thermal properties is proposed for front-end prefocusing optics applications. Euclid Techlabs had been developing x-ray refractive diamond lens to meet this need. Standard deviation of lens shape error figure gradually was decreased to sub-micron values. Post-ablation polishing procedure yields ~ 10nm surface roughness. In this paper we will report on recent developments towards beamline-ready lens including packaging and compound refractive lens stacking. Diamond lens fabrication is done by femtosecond laser micromachining. We had been using this technology for customization of other beamline components.

INTRODUCTION

Significant increase in average synchrotron beam brightness is projected for numerous facilities as they upgrade to diffraction limited storage rings. For ultrafast experiments, x-ray free electron lasers produce 10 orders of magnitude larger peak brightness than storage rings. It is therefore extremely important to develop next generation x-ray optics for these new light sources. Diamond is a "go to" material for high heat load applications. Single crystal diamond is an excellent material for x-ray optics due to its high x-ray transmissivity and uniform index of refraction [1]. For compound refractive lens (CRL) application there is an additional benefit from the single crystal material of choice for the lens because small angle reflections on defects and voids, typical for polycrystalline materials, are minimized and the x-ray beam quality is preserved [2, 3].

It is, however, a challenging task to manufacture complex shapes out of diamond. We use femtosecond laser cutting technology to manufacture a compound refractive lens, the most popular x-ray optics element, from a single crystal diamond. A femtosecond laser pulse duration is extremely short: material is ablated while pulse heating effects are minimized. In the past 3 years we have developed a fs-laser ablation procedure that yields diamond refractive parabolic lenses with shape error of 0.8 µm r.m.s. with surface roughness on the order of 200-300 nm Ra and polishing procedure that brings surface roughness into 10-20 nm Ra region but increases the figure error to 1.4 µm r.m.s.

DIAMOND LENS FABRICATION

For diamond lens production we developed a femto-second laser ablation system. It consists of a fs-laser operating at the second harmonic (515 nm), a motorized lens that allows moving the position of the focal spot ± 2 mm and a set of computer-controlled mirrors paired with a large aperture final-focus lens. Using this setup a laser beam can be steered at large speeds in the focal plane of the lens. The work surface is mounted on a linear stage for sample examination under a microscope for an in-line metrology.

We developed ablation scripting to minimize surface roughness and achieve high degree of shape fidelity. A typical lens parameters that we ablate is 450 µm aperture with radius of curvature 100 µm. Given the difference in refractive decrement such lens is roughly equivalent to an industry standard beryllium lens of the same aperture and R=50 µm.

As-ablated lenses have roughness on the order of 200-300 nm. For x-ray applications we are developing post-ablation chemical – mechanical polishing procedure. In this procedure a conformal bit is lowered into the diamond lens along with fine sub-micron diamond slurry and spun inside for anywhere from 4 to 8 hours. Large number of factors make this procedure quite complicated: uneven pressure distribution, not equal linear velocity at different parts of the polishing bit, different diamond crystal orientation along the paraboloid surface and some others. We are able to polish full lens surface to 10-20 nm Ra roughness. Figure 1 shows a comparison of polished and un-polished lens along with the residual plots of the paraboloid fit.

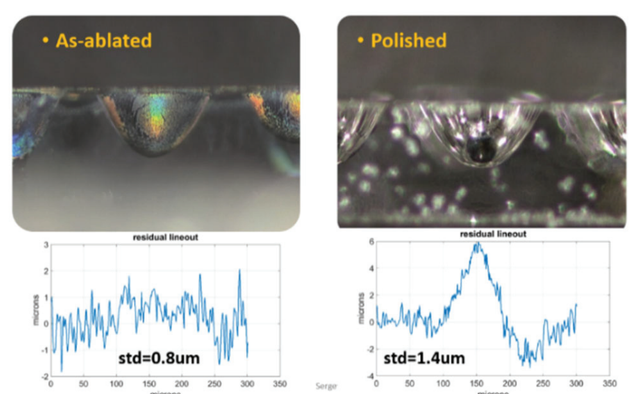

Figure 1: Top: Optical image through a polished side of the diamond plate. Left: as-ablated lens. Right: Polished lens. Bottom: corresponding lineouts of paraboloid fit residuals.

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These lenses are packaged now into a tight tolerance aluminium-bronze disk for precision stacking (Fig. 2). Alternatively, an ultra-compact CRL can be produced by stacking individual diamond plates. This type of packaging does not require a heavy-load bearing stages for CRL alignment.

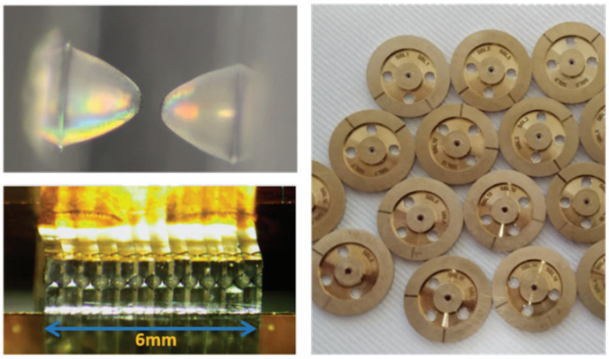

Figure 2: Top left: Side view of a double-sided lens. Bottom left: ultra-compact CRL made of diamond plate stack. Right: diamond lenses packaged in an aluminum-bronze holder.

AT-WAVELENGTH METROLOGY

Right after laser ablation we employ laser scanning confocal microscopy for metrology in-house. However visible light metrology does not give consistent results primarily due to the transparency of diamond samples and parabolic shape of the surface (these methods rely on light coming back to the sensor). Also, these methods do not probe the presence of any structural features inside the optical element that are sampled by x-rays.

X-ray metrology at the design operational energy (at-wavelength) is the best way to characterize diamond lenses. We had recently characterized a set of polished and un-polished lenses at the European Synchrotron Radiation Facility (ESRF) beamline BM05. At-wavelength metrology had been done using the x-ray speckle vectorial tracking (XSVT) technique at 17 keV. A speckle pattern is produced by inserting a membrane diffusor into the x-ray beam. When the lens is inserted after the diffusor the speckle pattern is changed due to x-rays refracting on the lens. Tracking these changes allows to reconstruct the lens profile. This technique is described in detail in [4, 5].

Ten polished and fourteen as-ablated lenses were characterized. Each measurement is fitted with a paraboloid of revolution, - a perfect lens shape. The residual of the fit is referred to as lens figure error (Fig. 3, Top). The goal of lens production is to minimize this figure error. The residual can be decomposed into Zernike polynomial to identify primary aberrations (Fig. 3, Bottom). This information can be used to improve fabrication process or plan correction optics for the diamond lens stack [6].

Average values for radius of curvature and figure errors are presented in the Table 1 along with other lens parameters.

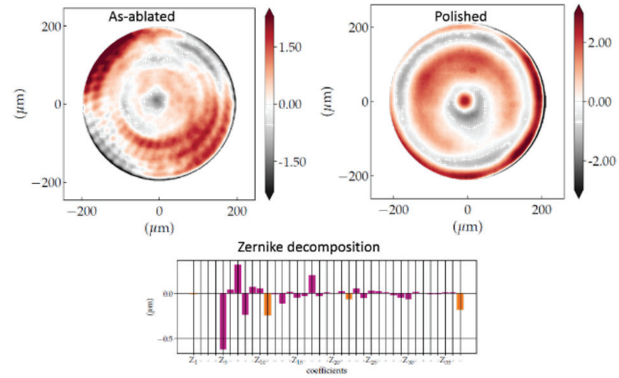

Figure 3: Top: Left: a typical figure error of as-ablated lens. Right: figure error of the polished lens. Bottom: Figure error decomposition into Zernike polynomials.

Table 1: Two-Sided Diamond Lens Metrology

Margin	Optical	17 keV
R(apex)	95.35 μm/side	48.1 um, (96.2 μm/side)
Aperture, $2R_0$	420 μm	400 μm
Figure error for A=350 μm	0.64 μm / side	1.19 μm total
Figure error polished for A=350 μm	0.91 μm/side	1.09 μm total
d, neck	19.7 μm	
Roughness, Sa	300 nm	
Polished, Sa	20 nm	

CONCLUSION

Diamond refractive lenses have been systematically characterized at the ESRF by means of x-ray speckle vectorial tracking. These results show that figure errors achieved for diamond lenses are approaching beamline requirements and compatibility with industry standard lenses.

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