Effect of laser-assisted diamond turning (Micro-LAM) on form and finish of selected IR crystals

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INTRODUCTION

In this paper we investigate the effect of laser-assisted diamond turning, hereafter referred to as µ-LAM (Micro-LAM process), on the form and surface finish of selected infrared (IR) crystals that are fabricated with the process. The µ-LAM process is a technology that enables the simultaneous use of laser emission during single point diamond turning (SPDT) [1]. The laser is passed through the diamond and the irradiance of the laser on the machining zone facilitates the cutting action of the diamond tool due to the local heating and "softening" of the material during the cut [2, 3].

The SPDT process has enabled the easy production of freeform and aspherical optics [4, 5]. These optics have found vast applications in fields of optical imaging [6, 7], illumination, etc. It is imperative for the SPDT process to produce parts with form errors less than quarter of the operating wavelength of the light.

The IR crystals chosen for the purpose of this study are single crystal silicon (Si) and single crystal calcium fluoride (CaF_2). Si has a relatively high index of refraction and low density enabling it to be a great candidate for compact and light IR optical systems [8]. CaF_2 on the other hand is highly transmissive and it's low absorption rates makes the material a good choice for the emission of high power lasers [9].

Several studies have been undertaken to understand the cutting mechanics of SPDT of infrared materials that are inherently brittle in nature [10-12]. Although these studies provide significant insights into fabrication techniques for making optical quality parts made of IR crystals, they don't offer considerably distinctive solutions, for successful machining of the IR optical materials. Indeed, those articles have done a great body of work on optimization of the conventional cutting parameters, i.e. spindle speed, tool feed, tool rake angle, depth of cut (DOC), etc.

The µ-LAM process provides a different solution for enhancing the diamond turning process, i.e. emission of a laser beam. The addition of the laser raises the question that how the presence of the laser-induced heat, would affect the process repeatability, as well as the form and finish tolerances achievable. After all, heat can introduce large temperature variations, thus reducing the precision of the diamond turning process, that usually is performed under highly controlled conditions.

EXPERIMENTAL METHOD

To study the effect of the µ-LAM process on the surface form and finish of Si and CaF_2, an experimental approach was undertaken. Two convex samples with a specific radius of curvature (ROC), were machined. The machining is done on an ultraprecise diamond turning lathe, a Precitech Nanoform® 250. Each sample is cut under identical conditions in the presence and absence of the emission of the laser of the µ-LAM system.

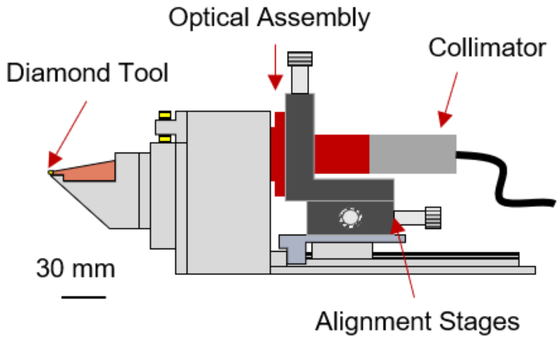

FIGURE 1. Optimus$_{T+1}$ Tool Post

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The Optimus$_{T+1}$ is a tool post that is a proprietary design of the Micro-LAM team. It incorporates an optical assembly that is designed to deliver an IR laser beam (1064nm wavelength) through the diamond cutting tool, see FIGURE 1.

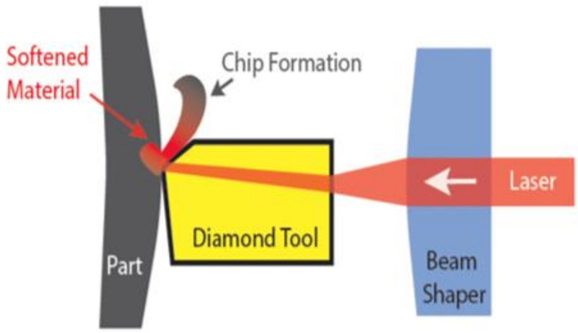

FIGURE 2. The delivery of laser emission at the cutting edge of the diamond tool

The laser delivered by the optical system within the tool post, is focused near the cutting edge of the diamond tool, see FIGURE 2. This highly focused spot of the laser at the cutting edge provides the local heat that enables the material "softening" mentioned in the introduction.

Test Samples

Two convex samples comprised from single crystal Si and CaF_2 were used. Details on the geometry of the samples are given in Table 1.

Table 1. Test sample information

Material	Dimensions	ROC (mm)
Si	∅62 mm × 5 mm	205
CaF_2	∅25.4 mm × 15.5 mm	50

Metrology

The form measurements are done using a Taylor Hobson LuphoScan® 260-420 HD. This instrument is a multi-wavelength scanning interferometer.
The surface finish of the samples was measured using a Taylor Hobson® CCI, a scanning white light interferometer (SWLI).

Table 2. Supporting metrology information

Hardware	Data type and analysis
LuphoScan 260-420 HD	Form measurements Piston, tilt, power removed Total points measured ≈ 10^6 Metric used: Sq or RMS (nm)
Taylor Hobson CCI	Roughness measurements 4th order Chebyshev removed High-pass filter with λ = 80 µm Detector size = 1024 × 1024 pixels Metric used: peak-to-valley (PV)

Details regarding the metrology hardware, the applied processing filters, and quantification metrics used, are outlined in Table 2.

Diamond Cutting Tools

Single crystal synthetic diamond tools manufactured by K&Y Diamond® were used for all the cutting tests. Information regarding the tools used for the cutting tests can be found in Table 3.

Table 3. Tool information

Tool	Rake angle (°)	Nose radius (mm)	Primary clearance (°)
1	-35	0.3	10
2	-35	0.3	10
3	-35	0.5	10

The -35° rake angle provides the necessary compressive stresses during the cutting of the brittle crystals.

Diamond turning conditions

In each of the performed experiments two cuts were done. The first cut used the base tool path for generation of the aimed convex geometry. The second cut was done with a program that was compensated for the surface errors measured after the first cut. It should be noted that both cuts are meant as "finishing" passes.
The machining parameters were selected based on the information available in the public literature [10, 12]. The parameters are listed in Table 4.

Table 4. Machining parameters of the samples

Sample	RPM	Feed (mm/min)	DOC (µm)
Si	2000	3	6
CaF_2	4500	6	2

Four experiments were done. These tests are aimed to establish a direct comparison between the achievable form and finish of the diamond turning process, with and without the µ-LAM system. These tests are listed in Table 5.

Table 5. Cutting tests with µ-LAM and conventional diamond turning

Test	Tool	Laser power (W)
Si-1	1	0
Si-2	2	2.7
CaF_2-1	3	0
CaF_2-2	3	2.7

The Si tests were done using two different tools, i.e. tool 1 and tool 2. The reason for using the two different tools was the expected higher tool wear imposed by cutting the larger Si parts. In contrast, the diamond tool wear during the CaF_2 experiments, are expected to be negligible, due to the sample smaller size and material. To ensure that the conventional cutting experiment, i.e. CaF_2-1, was conducted under conditions with less tool wear, the CaF_2-2 test was done post the CaF_2-1 test.

RESULTS

The cutting tests of Si-1, Si-2, CaF_2-1, and CaF_2-2, (see Table 5 for the testing conditions), were done with a spindle balance of less than 1 nm PV deviations in the spindle position. In each test the surface of the samples were measured using the SWLI and LuphoScan instruments.

<u>Form measurements</u>

FIGURE 3(a), (b) depict the form errors imparted on Si sample cutting with conventional diamond turning and the µ-LAM process, respectively. The interferograms are taken post the application of the corrective tool path. The PV corresponds to the difference between the highest and lowest point on the measurement data. The measurement data of the parts closely match one another, confirming that the heat induced by the laser has minimal effect in introducing additional form errors.

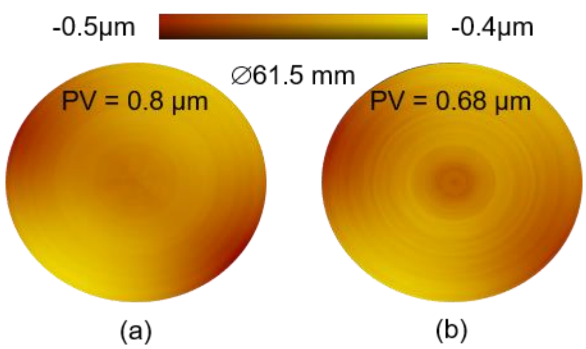

FIGURE 3. Form error measurements for the Si samples; (a) conventional diamond turning (b) µ-LAM process

The form errors imparted during the machining of CaF_2 samples are illustrated in FIGURE 4. The good agreement between the PV values of the measurements of the parts cut in the absence of the laser, i.e. FIGURE 4(a) and the presence of the laser, i.e. FIGURE 4(b), is complemented by the fact that large surface defects near the center are nearly gone on the sample machined with the µ-LAM process. These defects are speculated to be a consequence of the single crystal structure of the CaF_2 sample. Their absence on the CaF_2-2 sample demonstrates how the laser enhances the ductile cutting of the CaF_2 material.

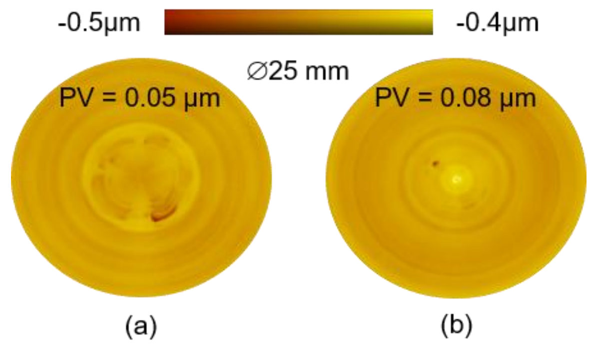

FIGURE 4. Form error measurements for the CaF_2 sample. (a) without µ-LAM (b) with µ-LAM

<u>Roughness measurements</u>

The roughness interferograms for both samples are taken near and off the center of the parts. In single crystal materials, often brittle fracture patterns at the center are observed.

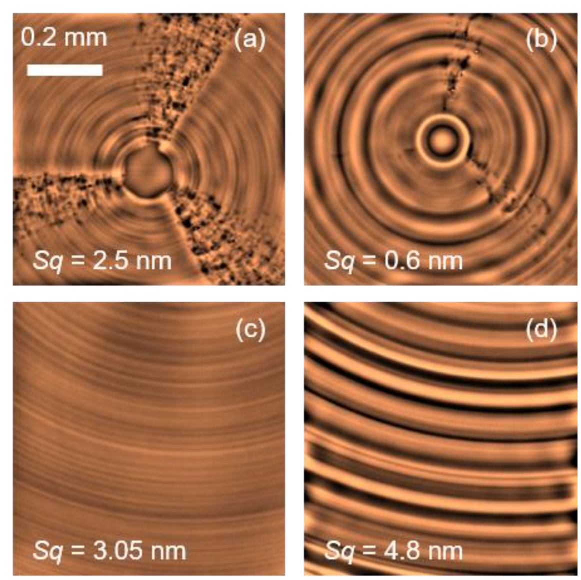

FIGURE 5. SWLI measurements on Si part (a, b) near center with and without µ-LAM respectively (c, d) off-center with and without µ-LAM respectively

For quantification of the surface roughness, the RMS of the height data, i.e. Sq, is used. FIGURE 5 shows the SWLI measurements for the Si parts. Comparing FIGURE 5(a), (b), the brittle fracture pattern near the center is far more severe when the part is machined with conventional diamond turning. FIGURE 5(c), (d), on the other hand, suggest that the waviness of the sample machined with the μ-LAM process is slightly more prominent.

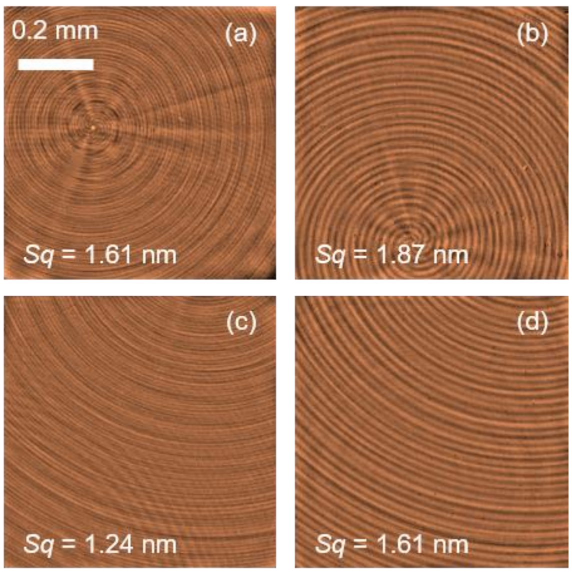

FIGURE 6. SWLI measurements on CaF_2 sample; (a, b) near center with and without μ-LAM respectively (c, d) off-center with and without μ-LAM respectively

The roughness measurements for CaF_2 sample is shown in FIGURE 6. The data suggests an increase in the waviness in the measurement data, similar to what was observed on the Si sample. No additional damage pattern was present near the center of the part.

DISCUSSION

As reported in the previous section, the key conclusion of the results is that the μ-LAM process doesn't add any complexity to the machining of IR crystals in terms of achieving desired form and finish. This result was expected since the heating of the sample during the machining happens in a very localized manner (<200 μm in radius). Furthermore, due to the very shallow depth of cuts during diamond turning, the heating effects of the laser on the part are expected to be quite repeatable. The repeatable nature of the heating effect implies that the correction program can compensate for any variations as a result of the heating.

On both sample materials cut with conventional diamond turning, clear defects and zones exhibiting brittle fractures were seen. The improved surfaces of the materials with the addition of the μ-LAM system, implies that the local heating of the laser, facilitates the ductile cutting of the IR crystals under study. This result confirms the material "softening" effect of the laser, on the workpiece.

Lastly, it should be noted that the μ-LAM process, had a minor negative effect on the extent of the waviness induced by the machining process. This is speculated to be not a significant issue. The reason behind the increase in waviness, is attributed to the absence of a B-axis of the machining center. The tool orientation with respect to the workpiece surface is continuously changing during the machining. As a corollary, the laser spot and its power density will be susceptible to variations as the cutting progresses. These variations are thought to be the main cause of the enhanced waviness on the samples. Many articles do address the importance of the waviness error on visible light optics [13-15]. However, the extent of the added waviness doesn't affect the optical performance of the crystals in the IR wavelength significantly.

CONCLUSION

The capability of machining IR materials that are inherently brittle in nature using the μ-LAM process was compared with conventional diamond turning. Even though the laser, a significant heat source, is propagated through the diamond tool, the μ-LAM can achieve and maintain the desired form on the machined materials. In addition, while not reported in this paper, the μ-LAM process has shown to enhance the tool life in cutting the brittle IR crystals nearly two times.

As future efforts of the R&D team in μ-LAM, testing on additional IR crystals will be continued. Furthermore, a deeper study into the effect of the laser on the sample waviness and solutions for the reduction of the waviness, in the absence of a B-axis will be conducted.

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