applied optics

Closed-loop laser polishing using in-process surface finish metrology

Oliver Faehnle,[1] Rolf Rascher,[2] Christian Vogt,[2] and Dae Wook Kim[3,*]

[1]FISBA AG, Rorschacher 268, CH-9016 St. Gallen, Switzerland
[2]THD-Technische Hochschule Deggendorf, Germany
[3]College of Optical Sciences, University of Arizona, Tucson, Arizona 85721, USA
*Corresponding author: letter2dwk@hotmail.com

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This paper lays out the trail onto a closed-loop polishing process of optical elements enabling the application of the optimum polishing time needed. To that aim, an in-process testing method for monitoring an inclusive micro-surface quality (e.g., comprising surface roughness and scratch-and-dig) within the polishing spot is analyzed, and its applicability to closed-loop polishing for classical loose-abrasive full-aperture polishing as well as for computer-controlled laser polishing is experimentally tested and verified. This enables the determination of the optimum local dwell time resulting in stable and cost-optimized polishing.

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Optical lenses have been generated for more than 3400 years, as indicated, e.g., by the 1400 B.C. Minoan lenses, which were excavated on the Greek island of Crete [1]. If we analyze the development of optical fabrication technologies, and if we do so from an evolutionary point of view, we recognize that this process has been ruled by aiming on "minimum effort taken" to generate "just good enough levels of lens quality" needed; with lens quality essentially meaning shape accuracy and surface finish (comprising level of surface roughness [Sq], depth of subsurface damage [SSD], and level of scratch-and-dig [S&D]).

1. INTRODUCTION

In the author's perception, we identify three sequential phases in the evolution of optical fabrication technology overlapping each other temporally: (a) handcrafting; (b) machining; (c) processing. These three phases distinguish themselves in their general strategy to generate the required lens quality level and place the significance of the presented closed-loop technology into context.

A. Handcrafting (Lens Manufacturing Without Using Machines)

Our forefathers rubbed blank materials such as crystal surfaces by handheld tools to generate shiny objects such as ritual gadgets, tools, weapons, or jewelry. In doing so, the lens generation process (LGP) was controlled by two entities: (1) cognitive thinking based on logic and (2) intuitive sensing using human vision, audition, and the sensation of hands. This handcrafted LGP is still being applied by hobby astronomers polishing lenses without any access to machines.

B. Machining (Lens Production with Kinematics Carried Out by Machines Guided by Humans)

Step by step, parts of the LGP have been transferred to tooling and machining devices. For instance, during the development of abrasively grinding and polishing of lenses, the manual rotational movement of the lens was replaced by the use of bow-driven spindles. This type of machine resembles an early version of a lathe and has been in use for at least 1940 years, as described by Plinius 77 B.C. [2].

The combination of rotating the optical substrate (or the tool) by a machine and translating and pressing the tool (or the lens) by hand is still in existence today (e.g., foot-driven polishing machine in Fig. 1). Master opticians are capable of hand-polishing optical surfaces to shape accuracies of below 30 nm RMS deviation of the desired shape and surface roughness levels of ~0.5 – 2 nm RMS, although they are using spindles featuring lateral positioning accuracies of several 100 μm.

This craftsmanship is often referred to as "the golden hands of the opticians," which is a skill one cannot learn by rational thinking only but by training one's hand sensation and intuition while feeling the LGP *in situ*. With machinery successively taking over the kinematics of handcrafting, we have been gaining accuracy and stability. Thus, major progress has been made, e.g., feed-controlled CNC machineries reaching positioning accuracies of less than ~80 nm enabling a new process of ultra-precision machining: ductile mode grinding [3].

Fig. 1. Foot-driven polishing machine at an optics shop in Delft, The Netherlands.

C. Processing (LGP Optimized by Controlling Multiple Fabrication Parameters Without Human Interaction)

The modern optics manufacturing community has gained much progress by optimizing machines only. Nevertheless, we need to keep in mind that machines are only one part of the LGP and that, on our trail to process stabilization and full automation in optics fabrication, we need to automate the whole lens generating process itself. To that aim, LGP quality-improvement methods have been developed, which strictly distinguish between machine and process issues identifying and optimizing critical fabrication process parameters and their interrelations [4].

The most recent stop along the "evolutionary" trail toward highly efficient and fully automated deterministic fabrication processes was the development of computer-controlled optical surfacing (CCOS) technology. Here, the tool guidance on precision machines by cognitive thinking and intuition has been completely replaced by computer numerical control machines and process optimization intelligence such as dwell-time/parameter simulation algorithms. Well known and industrially established CCOS platforms such as magnetorheological finishing (MRF) and ion beam figuring (IBF) enable the highest possible surface form qualities by using dwell-time-controlled surfacing processes without depending on an employee's education (cognitive thinking) or an optician's "golden hands."

2. IN-PROCESS METROLOGY FOR CLOSED-LOOP POLISHING

A surface finish can be measured after each iterative run using a portable phase-shifting interferometer *in situ* (e.g., micro-finish topographer [5]) or a compact scattering-based roughness sensor (e.g., *horos* [6]) mounted on a machine or robot. These highly sensitive measurement technologies provide successfully accurate surface information to guide further iterative runs.

And yet, mainly due to the lack of an in-process capability (i.e., simultaneous testing during fabrication) feedback mechanism, the process control during CCOS runs is done primarily as an open-loop process (i.e., iterative approach of fabrication-measurement-fabrication cycles without real-time feedback).

A. Closed-Loop Polishing Setup

This paper reports on a new closed-loop approach for polishing processes by introducing an in-process (and *in situ*) monitoring of lens finish levels within a single compressed-but-inclusive signal, as shown in Fig. 2.

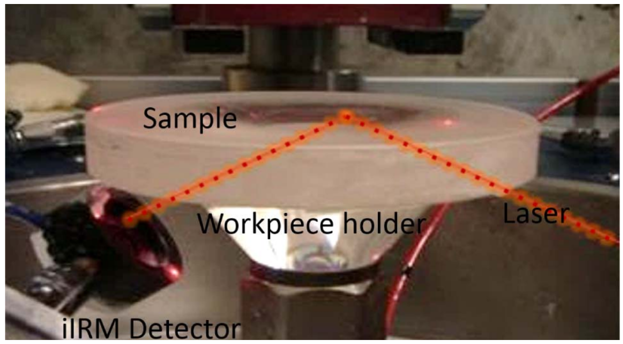

Fig. 2. iIRM: While the sample is being polished, the intensity of a laser beam is being detected, which is internally reflected from within the material at the surface under test. That way, the in-process lens's surface quality is being monitored within a single signal.

Besides the lens shaping process, polishing (the generation of the required level of surface finish) is the most expensive and time-consuming process in many optics fabrication applications. Unfortunately, in order to set up polishing times, we are still mostly relying on human intuition and experience. Besides that, surface brightness is measured neither *in situ* nor in process but off-machine by measuring two parameters separately: Sq and S&D.

In the presented approach, however, the optimum polishing time can be detected in real time within the polishing spot, thus enabling cost and time optimization of the polishing process, obtaining full automation within reach. To that aim, the recently developed method for measuring surface quality, called intensity-detecting internal reflection microscopy (iIRM) [7], as shown in Fig. 2, has been further developed and applied for in-process control of lens finish levels on machines while running traditional loose abrasive polishing process and a subaperture laser polishing process.

B. iIRM Metrology with Subnanometer Sensitivity

It has been demonstrated that, by monitoring the intensity of a laser beam that is being reflected at an optical surface within the sample while its outside is being abrasively ground and polished, the surface finish levels can be monitored in-process [7].

Any surface imperfections such as Sq, S&D, or SSD cause scattering and consequently a loss of intensity of the reflected beam (i.e., Fresnel reflection) as an inclusive single-output signal, which provides a simple but powerful closed-loop feedback system. It is important to note that it is not monitoring the scattered light distribution, which may include more information about the surface quality, but could be too sensitive to be implemented in the in-process polishing with the mechanical motions, vibrations, and polishing slurry actions. Due to its simplicity measuring only the specular reflectance signal, the iIRM is robust enough to be applied during the actual manufacturing runs, which makes it a true in-process metrology method.

1. Micro-Roughness Monitoring Using iIRM

An iIRM experimental study has been performed using two BK7 samples. The flat BK7 samples (1 in. diameter each) have been polished down to optical qualities using

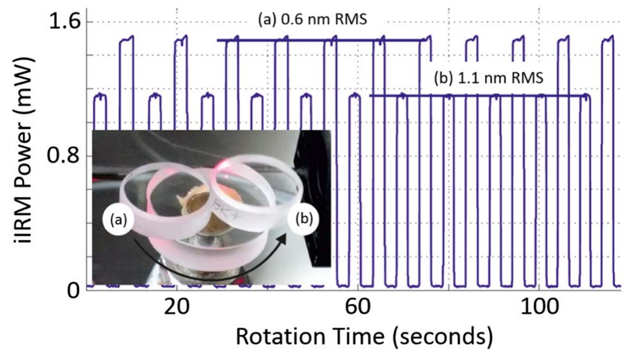

Fig. 3. Experimental iIRM measurements setup for sample (a) with Sq = 1.1 nm RMS and sample (b) with Sq = 0.6 nm RMS. The measured iIRM power as a function of spindle rotating time is plotted in the graph. (Note: The reference [absolute] surface roughness values were measured using a white light interferometer).

cerium-oxide-based slurries on a traditional spindle machine, and their surface roughness values have been measured by white light interferometry as a reference.

Both samples were mounted on the polishing machine spindle, as shown in Fig. 3, and the iIRM signal has been monitored (applying an angle of 5 deg between the laser beam and the surface normal) while the setup is rotating. As the iIRM measures sample (a) and (b) alternatively, the recorded signal in Fig. 3 clearly demonstrates distinguishing subnanometer levels of surface roughness levels, e.g., 0.6 nm rms from 1.1 nm rms.

2. Scratch-and-Dig Sensing Using iIRM

The iIRM's sensing capability to detect S&D was experimentally verified by measuring three sample sleeves. The microscopic image of the sleeves is shown in Fig. 4. A wide range of polishing defects from 900 nm deep brittle scratch to 100 nm sleeves without any brittle cracking present were detected as presented in Fig. 4.

Consequently, iIRM is a comprehensive solution to achieve a closed-loop optics finishing by monitoring both surface finish levels (Sq and S&D) using a single feedback control signal *in situ* and in process.

3. CLOSED-LOOP LOOSE ABRASIVE POLISHING

A. Real-Time Process Monitoring

The iIRM closed-loop concept was first applied to a traditional LASF31 lens polishing process. Figure 5 shows a typical iIRM signal characteristic, which was measured on a traditional load-controlled spindle polishing machine *in situ* and in process. As the lens surface finish level improves during polishing, less light is being scattered at the surface under test, and the iIRM signal rises until the polishing process reaches (in this example after approximately 150 min) the ultimate level of lens surface quality achievable by the applied set of fabrication parameters. This is indicated by the iIRM signal reaching its final plateau. It is important to note that, after about half an hour of polishing, the polishing process became contaminated caused S&D and a dip (red circle in Fig. 5) in the signal, which subsequently was polished away again. This highlights the real-time feedback loop capability of the iIRM-based polishing technology.

Contrary to traditional methods, where setting up a polishing time is based on an empirical estimation (i.e., open-loop), employing iIRM in process, the exact moment is being detected at which the final plateau has been reached. From here on, continued polishing no longer improves the lens finish level and can be stopped for saving cost and machining time. Also, if necessary, the next manufacturing phase (e.g., IBF or MRF) can be started depending on the final target specification.

B. Comparative Experimental Demonstration

As a comparative demonstration of the iIRM's capability to be applied for a closed-loop fabrication process control sensor, in Fig. 6 two independent BK7 lens polishing processes were monitored and compared.

As predicted by Preston [8], for 4 kg load (i.e., higher polishing pressure) traditional polishing reaches its final level of lens finish quality earlier than if a 1 kg load was applied. Therefore, monitoring the lens Fresnel reflection change applying iIRM, polishing can be stopped at the most efficient moment when the signal reaches its final plateau.

It is worth noting that one of the major limitations, especially in the industrial optics manufacturing process, has been the absence of in-process (i.e., real-time feedback during a

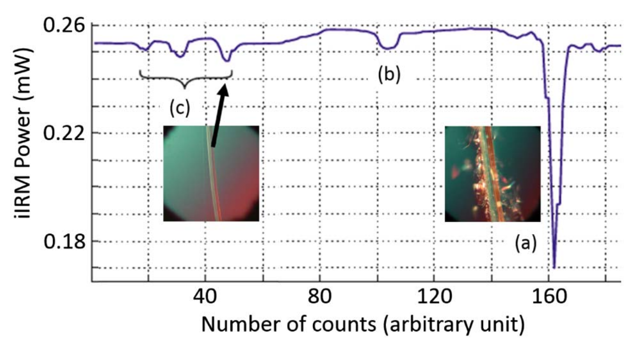

Fig. 4. iIRM measurement as it goes through generated sample grooves of (a) 900 nm deep brittle scratch, (b) 150 nm deep ductile sleeve, and (c) three polishing sleeves; the smaller ones of which are about 100 nm deep. (Note: All grooves were measured by white light interferometry as a reference to know the dimensions of S&Ds).

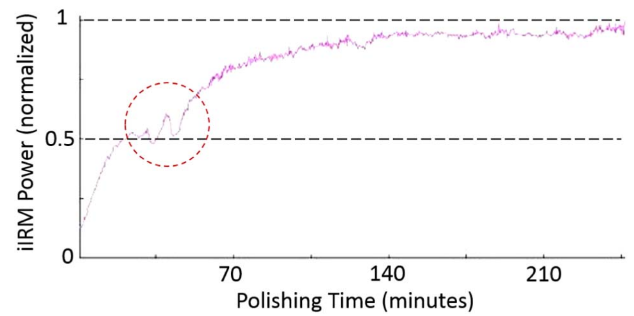

Fig. 5. iIRM: While the sample lens (LASF31) is being polished, the intensity of the reflected laser beam is being monitored. As lens finish level improves, less light is being scattered at the surface under test, and the iIRM signal rises until the polishing process reaches after approximately 150 min the ultimate level of lens finish level achievable by the applied set of fabrication parameters.

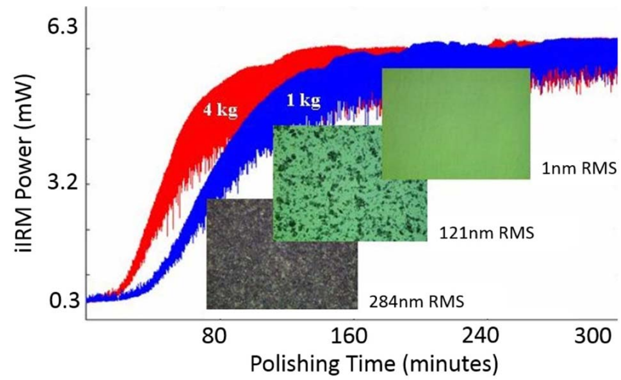

Fig. 6. Comparative closed-loop polishing processes for ground BK7 lens with different polishing loads of 1 kg and 4 kg. (Note: Nomarski microscopy images of the surface in different phases of the process are inserted with their respective RMS surface roughness values).

polishing run) metrology sensing the creation/polishing/removal of S&D. In order to check surface quality status, the machine had to stop for a measurement or inspection. The measurement might be an *in situ* approach, but it is still not a real-time. This often causes severe manufacturing efficiency and throughput issues. The same statement is applied for the real-time monitoring of surface roughness quality. As shown in Fig. 6, using the in-process metrology feedback, a nonstop polishing run can be continued as a single run (i.e., closed-loop) until the surface quality meets the requirement without stopping (i.e., conventional "polish-stop-measure-polish" open-loop) the machine.

4. CLOSED-LOOP CO_2 LASER POLISHING TECHNOLOGY

Among the various subaperture polishing techniques of glass, laser polishing [9,10] distinguishes itself by its scalable polishing spot size as well as by the absence of any physical contact between the tool and workpiece. Polishing is achieved by local absorption of laser power within the polishing spot (i.e., footprint) causing the surface and its subsurface region to melt and flow, thus reducing surface roughness, defects, and removing subsurface damage (SSD) as long as the necessary depth is molten.

To that aim, setting up process parameters is a trade-off between continuous wave at lower laser power values and the application of a pulsed laser illumination at a high-power level. Lower laser power gently melts the surface and near surface regions but risks the generation of shape deviations and mid-spatial frequencies due to material flow. The application of a high-power pulsed laser avoids changes in mid-spatial frequency surface shapes but risks high surface and subsurface tension caused by the high temperature gradients generated, which might even cause local cracking. In both cases, the risk of vaporization of material exists, which might cause redeposition of material by the laser beam being scanned along the surface. Thus, in-process surface quality monitoring becomes a critical component to guide and optimize a laser polishing process.

A. CO_2 Laser Polishing Experimental Setup

The iIRM method is applied for the determination and control of optimum local polishing dwell times, enabling a closed-loop laser polishing process called control of LASer surface optimization (C-LasSO).

The experimental C-LasSO setup to guide the laser polishing process of a fused-silica sample is shown in Fig. 7. The iIRM He–Ne (wavelength $\lambda = 0.633$ μm) laser is being reflected from the sample surface, and the reflected beam intensity is being monitored. The internal local subaperture surface area under test is collocated at the exact laser polishing active area melting its surface locally. The closed-loop experimental configuration and setup parameters are summarized in Table 1.

Because the fused silica is not transparent at the operating wavelength of the applied CO_2 polishing laser (wavelength $\lambda = 10.6$ μm), the intensity of the reflected He–Ne intensity can be monitored without any interfering signals. This unique C-LasSO configuration enables real-time direct monitoring of the active laser polishing zone in process using a set of laser

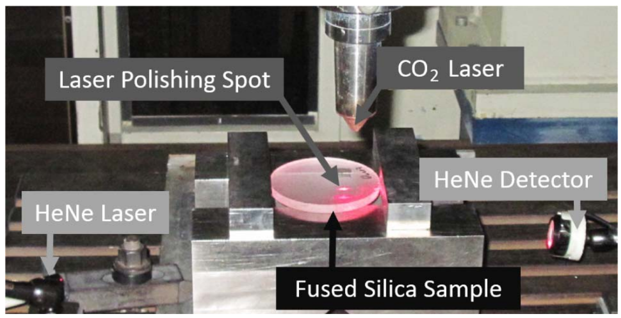

Fig. 7. C-LasSO setup for a closed-loop CO_2 laser polishing process at the Technische Hochschule Deggendorf, Germany. While the fused-silica sample is locally laser polished, the local surface roughness within the laser footprint is being monitored by detecting the intensity of a He–Ne laser reflected right in the collocating CO_2 laser footprint zone.

Table 1. Closed-Loop CO_2 Laser Polishing Configuration

	Specification	Extra Reference
CO_2 laser	120 W at $\lambda = 10.6$ μm (2000 W Max)	Coherent-ROFIN CO_2 Slab laser
Polishing coverage/speed	12 × 12 mm area in ∼1 min	E.g., 2 of 15 × 15 mm areas in Fig. 8
iIRM laser[a]	He–Ne laser $\lambda = 633$ nm	or Diode laser 2 mW at $\lambda = 650$ nm
iIRM detector[a]	Silicon Photodiode λ:400–1100 nm	Thorlabs PM16-120
Substrate type	Fused silica	Fine ground with 5–7 μm SiC grit

[a]This is a typical laser and detector configuration for a standard iIRM setup. However, any other laser–detector pair can be used as long as it produces a repeatable and stable outcome signal, as shown in Fig. 3.

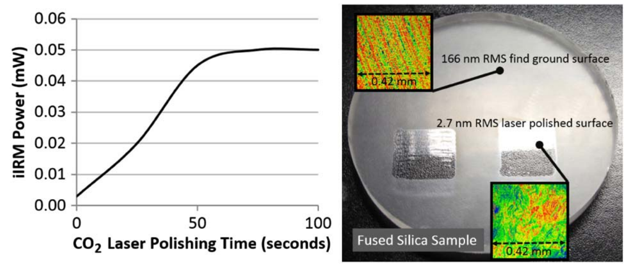

Fig. 8. (left) Measured iIRM signal in the C-LasSO set up. The signal was simultaneously recorded during the laser polishing process on a fine ground fused-silica sample. (right) Two square regions were polished and both the initial ground surface and the final polished area were measured using a white light interferometer.

polishing parameters such as dwell time and applied laser power.

B. Real-Time CO_2 Laser Polishing Process Monitoring

Figure 8 (left) presents the history of measured iIRM signal monitoring the surface finish quality during the closed-loop process using C-LasSO. A fine ground fused-silica sample (~166 nm RMS surface roughness) was laser polished, as shown in Fig. 8 (right). As the surface roughness is improved due to the melting process, the C-LasSO signal increases until the final surface quality has been reached at about 2.7 nm RMS surface roughness, and the C-LasSO signal reaches a plateau. From that point on, the closed-loop polishing process stops because any further laser polishing no longer increases surface quality and may worsen the surface quality.

5. CONCLUDING REMARKS

Developments in the field of optical fabrication technology throughout history have been analyzed from an evolutionary point of view, identifying basically three sequential phases overlapping each other temporally: (a) handcrafting; (b) machining; and (c) processing. While essential progress has been made optimizing machines only, enabling technologies such as ductile mode grinding, the next step is the optimization of fabrication processes themselves, including machineries being one tessera within the whole process.

Following that trail, the process of monitoring optical surface finish during surface polishing has been proposed and analyzed. The first experimental results toward the closed-loop approach controlling the CO_2 laser polishing process have been presented.

The iIRM, a compressed single Fresnel reflection measurement approach, has been adapted to monitor surface roughness and defect changes within the active polishing spot. This concept was experimentally verified by setting up a closed-loop polishing process. Based on the iIRM signal being monitored in process, the polishing run can be stopped at the optimal moment of meeting the surface finish specification to save machining time and cost.

The suitability of this closed-loop approach to both traditional loose abrasive polishing and laser polishing has been demonstrated, and the experimental data have been reported. For traditional polishing, its capability of real-time detection of the very moment when no further surface finish improvement will occur was confirmed. In addition, by applying the C-LasSO method, it is possible to determine the optimal dwell time for a local laser polishing spot. Consequently, C-LasSO enables the optimization of laser polishing by avoiding excessive local dwell times and minimizing the risk of generating shape deviations such as mid- to high spatial frequency errors and a possible vaporization of the glass. Also, this technology can be utilized for a laser polishing parameter set optimization by (e.g., CO_2 laser power) monitoring the real-time surface quality evolution.

For the lens manufacturing case in Fig. 2, both surfaces are polished, and the iIRM laser beam was delivered through the bottom surface. If it is a mirror fabrication case, the same technique can be still applied because the back surface is often polished prior to the front (i.e., mirror) surface for mounting-fixtures requiring a stress-free flat back surface. However, thanks to the noncontact laser polishing process, C-LasSO (patent pending) is currently being tested in a mode sensing the polishing spot from the outside of the material instead of testing the internal reflection within the material. There is no more requirement for a polished bottom surface. Moreover, it will enable the development of an enhanced laser polishing process for strongly curved ground or polished optical surfaces.

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