In-process monitoring of grinding and polishing of optical surfaces

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A new tool with which to monitor the quality (roughness and subsurface damage) of optical surfaces during grinding and polishing, intensity-detecting total internal reflection microscopy (iTIRM), is presented. A general description of the new measurement method is given, followed by a description of the experimental *in situ* measurement setup. Experimental results of the method are presented that demonstrate that iTIRM can be used either to control the roughness-reduction process during production or to investigate the process itself. The possibility of implementing the method in an optical workshop is discussed. © 2000 Optical Society of America

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1. Introduction

In-process monitoring of the surface characteristics of optical components during grinding and polishing is a helpful tool for optical fabrication research. The information obtained can be used to optimize fabrication processes, minimizing fabrication time (processes can be automatically stopped when the desired surface quality of the optical surface is reached) and production costs [process parameters can be (automatically) adjusted during grinding and polishing]. The fact that optical fabrication processes physically alter the surface to be measured seriously interferes with *in situ* monitoring of the surface. In today's optical fabrication, the quality of optical surfaces is not monitored *in situ* during grinding and polishing. Therefore, in what follows, we present a method that is not affected by wet machining processes and thus can be applied for in-process monitoring of the surface alteration [change of roughness and subsurface damage (SSD)]. In this paper we report on the first results of experiments in which we applied intensity-detecting total internal reflection microscopy (iTIRM) to monitor grinding and polishing processes *in situ*.

2. Method

This method monitors the surface quality (roughness and SSD) of an optical component during grinding and polishing and originates from total internal reflection microscopy (TIRM),[1] which is a nondestructive testing method that is usually applied to measure SSD. In TIRM, the surface of the sample is illuminated from within the material by a laser beam at an angle exceeding the critical angle of total reflection, causing the beam to be totally reflected at the surface under investigation. Roughness of the surface and defects (e.g., cracks) at or near the surface will cause the laser light to be scattered; in TIRM this scattered light can be detected qualitatively with a microscope positioned above the surface, as shown in Fig. 1. The prism is used to couple the laser beam into the sample with an index-matching fluid between the prism and the sample to prevent reflection at the prism-to-sample interface; other coupling configurations can also be used. The scattering of light at the surface of the sample will lead to a decrease in the intensity of the reflected beam, which qualitatively indicates the existence of cracks.

Whereas in TIRM the scattered light is detected, the method presented here uses the intensity of the reflected light to detect both roughness and SSD and is therefore called iTIRM to indicate that it is an intensity-detecting TIRM.[2] Variations in the inten-

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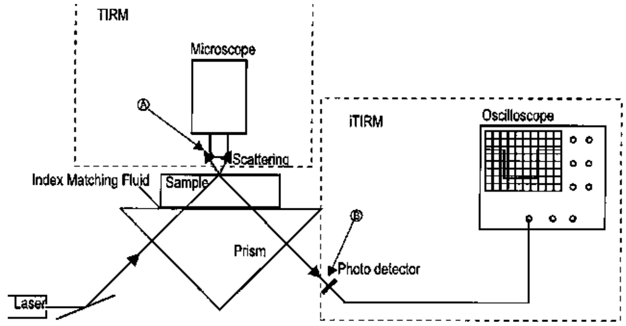

Fig. 1. TIRM compared with iTIRM. In TIRM the scattered light is detected optically at A, and in iTIRM the intensity of the laser beam is measured at B.

sity of this beam are caused by variations in the scattering and indicate a change in the structure of the surface of the sample.

In what follows, we report on experiments in which we applied iTIRM to monitor the increase in quality, i.e., reduction of roughness, of optical surfaces during grinding and polishing.

3. Monitoring of the Roughness-Reduction Process

A. Setup

The surface quality of flat glass (BK7) samples was measured in process. The roughness-reduction processes that we investigated (grinding, microgrinding, and polishing) were assumed to occur homogeneously over the entire surface of the sample. Under these assumptions the rms value of the surface roughness can be taken to be constant over the whole surface, and therefore monitoring a small area of the surface will be sufficient. Because the sample was mounted upon a spindle that was rotating within the polishing machine, the beam could not enter and leave the sample via the underside of the sample through a coupling prism. To overcome this difficulty we polished the sidewall of the flat, circular sample and let the beam enter the sample directly through the sidewall. The samples used had a thickness of 1 cm and a diameter of 5 cm, and coupling the beam via the side of the sample led to angles of incidence and reflection of approximately 80° with respect to the surface normal and thus to an elongated projected spot at the surface in the direction of propagation of the beam. The orientation of the sample with respect to the beam changed constantly because of the rotation, and the area covered by the inspection spot changed accordingly, leading to fluctuations in the measured signal and in the direction of the output beam. These fluctuations could be neglected because we accurately aligned the sample and the spindle such that the surface was perpendicular to the rotation axis. The measurement setup is shown in Figs. 2 and 3. To prevent the slurry used for grinding and polishing from flowing over the side of the sample and obstructing the beam, we attached a piece of tape to the upper rim of the cylindrical side of the sample.

The detector was connected to a digital oscilloscope that plotted the intensity of the reflected beam as a

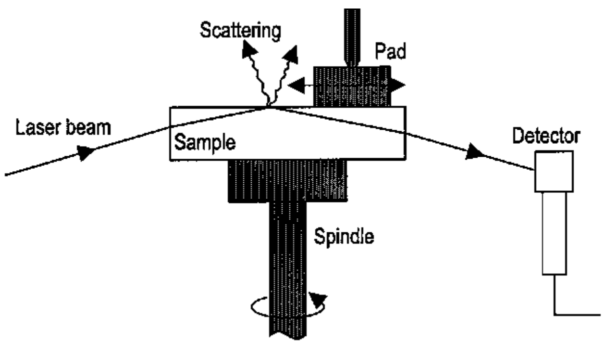

Fig. 2. Setup of iTIRM measurement system on a polishing machine. The detector is connected to an oscilloscope.

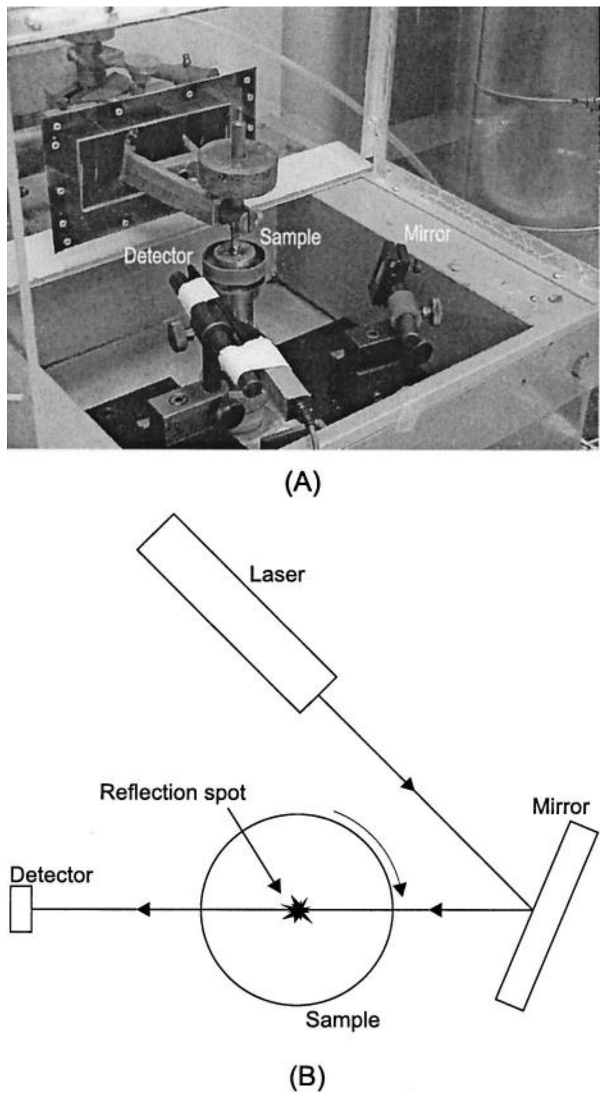

Fig. 3. (A) Polishing machine with the iTIRM measurement system. The laser beam enters the polishing machine from the rear and is reflected by the mirror toward the sample. (B) Top view of the measurement setup.

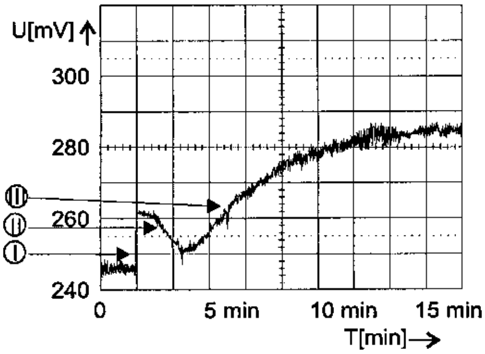

Fig. 4. Intensity of the reflected beam when a previously ground sample (with #400 abrasives) is further ground with #800 abrasives.

function of time during the roughness-reduction process and was capable of storing the measurement results to a floppy disk.

B. Experiment

We tested the iTIRM measurement method in several grinding and polishing processes to detect transitions between roughness levels related to different states of fabrication. The purpose of making the measurements was to demonstrate the capability to detect a change in surface quality during the roughness-reduction processes with iTIRM; relating the intensity of the reflected beam to specific surface-roughness parameters such as the rms value of surface height or correlation length was not considered in this investigation but will be the subject of further research.

The first experiment was carried out on an optical flat (BK7) that was previously ground with a water-based slurry containing 10% #400 SiC abrasives. Subsequently this surface was ground with a water-based slurry containing 10% #800 SiC abrasives; the angular speed of the workpiece was 2π rad/s, and the pressure was approximately 10^4 Pa. The change in surface quality was monitored in process. The result of the experiment is shown in the oscilloscope trace in Fig. 4. Point (I) in the trace is related to a decrease in scattering at the surface when the slurry is added to the sample. The liquid layer reduces the contrast and thus the scattering by the rough surface. After approximately 1 min this effect has disappeared, probably because the grinding tool has spread the slurry over the workpiece surface into a thin liquid film. This thin layer will no longer cover all the peaks in the surface structure, and the interface at which the light will reflect will appear rough again, thereby increasing the scattering [point (II) in Fig. 4]. The phenomena mentioned above are due to the optical properties of the slurry on the surface and are not caused by changes in the surface itself. After $\sim$2 min the intensity of the reflected beam starts to increase [point (III)] owing to the reduced roughness, the reduced SSD level, or both. The increase is highest initially because the sharpest peaks on the surface are removed first and these peaks contribute the most to the initial roughness of the surface. After this stage, the roughness-reduction rate decreases until the maximum smoothness that can be obtained with this process is reached, as shown by the horizontal ending of the trace. The iTIRM method can thus be used for optimization of optical fabrication by minimization of process time; i.e., it can be monitored when the end roughness is reached.

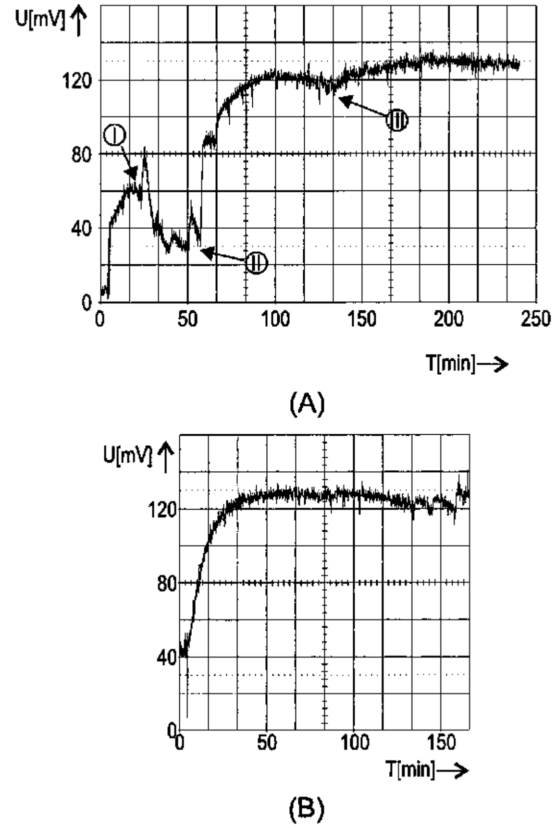

Fig. 5. Intensity of the reflected beam during the polishing of a previously ground optical flat (#800 abrasives): (A) with a slurry deficit during the polishing process, (B) with a sufficient amount of slurry during the polishing process.

In the second experiment, an optical flat (BK7) that was previously ground with a water-based slurry containing #800 SiC abrasives was polished with a water-based slurry containing cerium oxide abrasives. Oscilloscope traces of two of these experiments are shown in Fig. 5; the trace in Fig. 5(A) shows a long interruption of the expected curve. Initially a slight decrease [point (I)] in the measured intensity is visible, followed by an irregular part with low intensity [point (II)]. This interruption occurred because there was insufficient slurry on the surface and the process was running dry, creating scratches on the surface. After new slurry was added, the process returned to its expected path. A decrease [point (III)] in the intensity detected at a later stage was used as a warning signal to add new slurry to the polishing process. The result of a noninterrupted polishing experiment is shown in Fig. 5(B); here a sufficient amount of slurry had been added in process. The irregularities at 130–160 min are due to a decrease in the amount of slurry on the surface (running dry) followed by the addition of more slurry. It can thus be stated that iTIRM is a measurement tool for monitoring surface-roughness reduction and that it is sensitive to the amount of lubrication present, creating the possibility for a warning signal to be given when the surface is insufficiently lubricated; i.e., it can be used as sentinel.

4. Conclusions

The iTIRM measurement method is capable of monitoring grinding and polishing processes *in situ*, but its use is restricted to transparent workpiece materials. Its capability for *in situ* measurements makes it a valuable tool for investigating roughness-reduction processes in an optical workshop and for process control of roughness-reduction processes. Processes can be stopped as soon as the intensity has reached a certain calibrated level or when the intensity ceases to increase, which corresponds to the situation that the final roughness has been reached. Because of these properties, the iTIRM method can be used to reduce processing time. The polishing experiments showed that iTIRM can also be used to detect when new slurry must be added to the process, thus minimizing fabrication cost.

An iTIRM measurement system that is integrated with a polishing machine can simplify and automate the fabrication of optical elements to reduce production costs by minimizing fabrication time and avoiding lubrication problems.

The need for a polished side on the processed optical component and the necessity for preventing the slurry from obstructing the optical path can be obviated by integration of the laser and the detector in a rotating sample holder. In this way the measurement setup can be built in a more stable way and measurement noise induced by the rotation of the sample can be suppressed.

The iTIRM method inspects only a small area of the total surface, which is reasonable because the roughness-reduction processes are assumed to be uniform over the whole surface. The inspection method is thus not restricted to optical flats; convex and concave surfaces can also be inspected if the small inspection area is taken near the horizontal top of the curved surface, as long as the incident angle of the laser beam exceeds the critical angle for total internal reflection.

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