Micro-Finish Topographer: surface finish metrology for large and small optics

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ABSTRACT

The MicroFinish Topographer (MFT) is the result of an interest in directly measuring the surface roughness of large optics without the need for using replicas that may degrade the measurement data and that contaminate the surface. Once the MFT proved itself on large optics it was immediately suggested that a similar device should be designed for small optics. All this really took was turning the original MFT upside down and placing small specimens on a holder. This one device tests samples from 10 mm diameter to 10 m with phase measuring interferometry that does not need vibration isolation. Further, the MFT form factor makes it ideal for use in doing on-machine surface finish metrology.

Keywords: Surface finish, optical metrology, phase shifting interferometry,

1. INTRODUCTION

The motivation for this work on micro-finish topography, or surface roughness, began because of the difficulty of measuring finish on large optics, anything that would not fit on the stage of a conventional surface roughness measuring microscope. For large optics, about the only way of measuring roughness is to make a replica and then measure the replica. This replica approach, unfortunately, has a number of drawbacks, not the least of which is contamination of the surface in the vicinity of where the replica was taken.

In addition, making replicas is a cumbersome process because of the time and skill needed to prepare the replica, but also the time needed for curing. Removal of the replica is a delicate step and the finished replica may not be a faithful indication of the finish.

For these reasons it seemed a good idea to think through the idea of directly measuring the finish of large optics by setting the roughness topographer directly on the surface to be measured. Since most microscopes are not designed with this concept in mind, it meant starting with a clean slate to come up with an approach that would be a suitable solution.

This paper describes the thought process in coming up with a design for a direct surface roughness measuring interferometer, and the further evolution into a device that would also measure small optics. Once the design is described, the advantages of the approach will be analyzed. Finally we give some examples of typical results obtained with the Micro-Finish Topographer (MFT), the name we gave the new device.

2. UNDERLYING DESIGN FLAW WITH A STANDARD MICROSCOPE

As background to the thinking on a microscope that would sit directly on the surface to be measured, it is useful to look at the mechanical design of a typical microscope used for surface roughness measurement such as the one in Fig. 1. The microscope itself, including the PZT phase shifter and often heavy light source tube, are supported by an “L” shaped frame via a vertical focusing stage. The sample to be measured sits on top of a 2 to 4 axis stage. The stage interfaces and the lack gussets on the “L” shaped frame mean that the critical distance between sample and interferometric objective is prone to changing minute amounts due to vibration introduced to the microscope through its base. In imaging, this is not much of a problem particularly at the low magnifications typically used for surface roughness measurement. A change of 10 to 100 nm is barely noticeable in an image but will cause fringes created between the sample and objective to move up to a third of the fringe spacing assuming illumination at 635 nm., even more if shorter wavelengths are used. This means the microscope must be vibration isolated to get good surface roughness data.

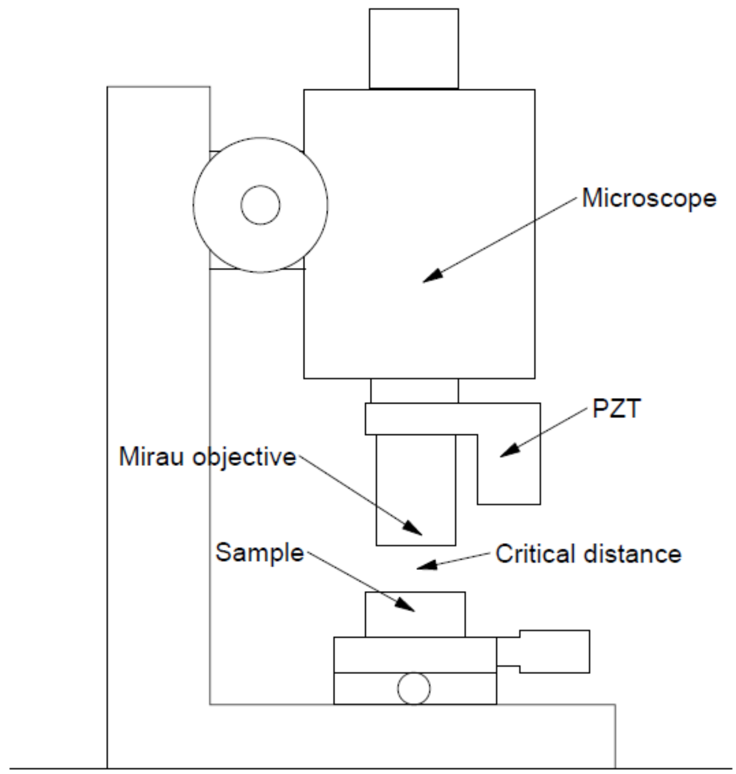

Fig. 1 Mechanical design of a typical microscope

A first clue as to how to improve the design comes from an inverted microscope where the sample stage is much more closely coupled to the objective. Of course, the inverted design has the objective pointed in the wrong direction but this idea will re-surface in our overall design approach. The main idea here is to closely and stiffly couple the objective to the surface being measured.

3. DESIGN FOR LARGE OPTICS

In a commercial microscope, the microscope body and light source is a fairly massive assembly. This is partly due to the need for a bright, polychromatic light source that is also a big source of heat. None of these attributes would make it easy to mount a standard microscope above the sample being measured. Instead, we decided to begin with the commercially available Point Source Microscope (PSM)[1] that is generally used for the alignment of optical systems. Its advantages are its light weight, small package size, center of mass in line with the optical axis and built-in, solid state, light sources.

When the PSM is combined with a short coupled frame into which is is built a kinematic, 3 degree of freedom stage it produces a package like that shown schematically in Fig. 2. The center of mass sits centered on a short, circular base coupled via 3 fine pitch adjustment screws to a ring that sits on the sample via 3 nylon balls. The adjustment screws are constrained in “V” grooves directly above the nylon balls so no moments are introduced in the ring. The straight thorough coupling makes for a stiff connection between the microscope objective and the sample being measured so the critical distance is maintained fixed to the few nm level even in the presence of vibration introduced through the sample. The entire system moves together, sample and MFT so the fringes remain stable.

In practice, the MFT looks like the photograph in Fig. 3 where the MFT is measuring the roughness of the first 8.4 m diameter Giant Magellan Telescope off-axis primary mirror segments at the Steward Observatory Mirror Laboratory[2]. The weight of the MFT is 1.6 kg and it has a form factor of about 150 mm in diameter by 240 mm tall.

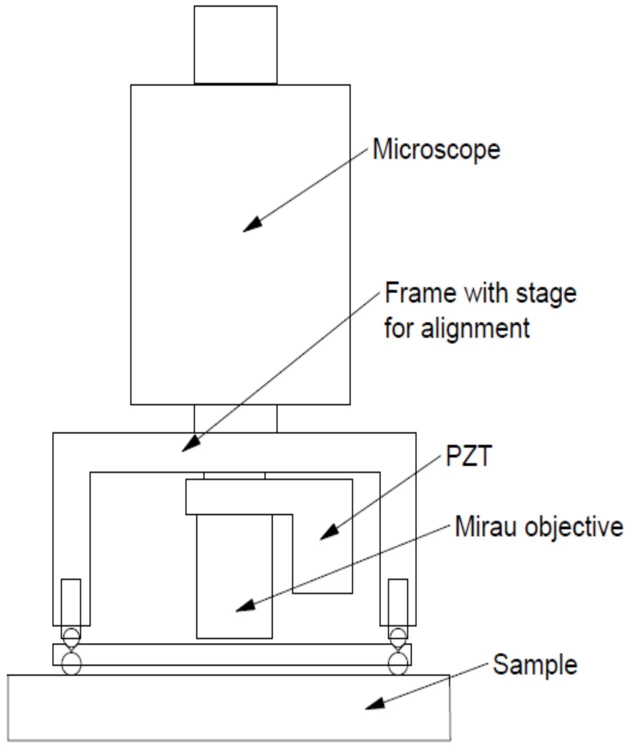

Fig. 2 Schematic design of the Micro-Finish Topographer

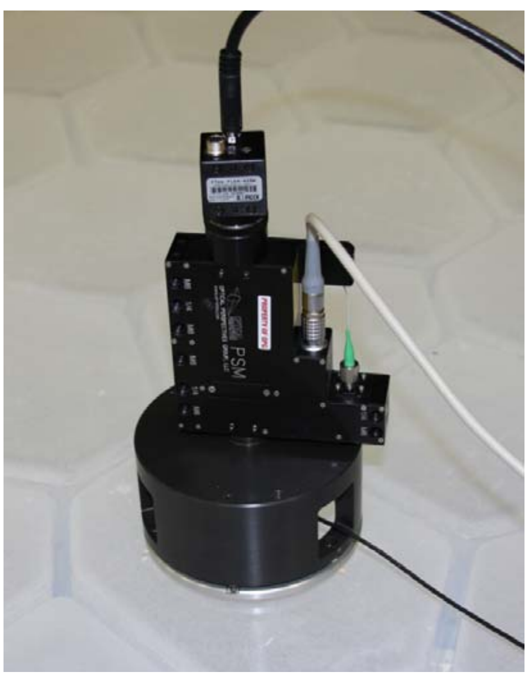

Fig. 3 MFT sitting on the 8.4 m Giant Magellen Telescope primary mirror at the Steward Observatory Mirror Lab (Photo John Davis)

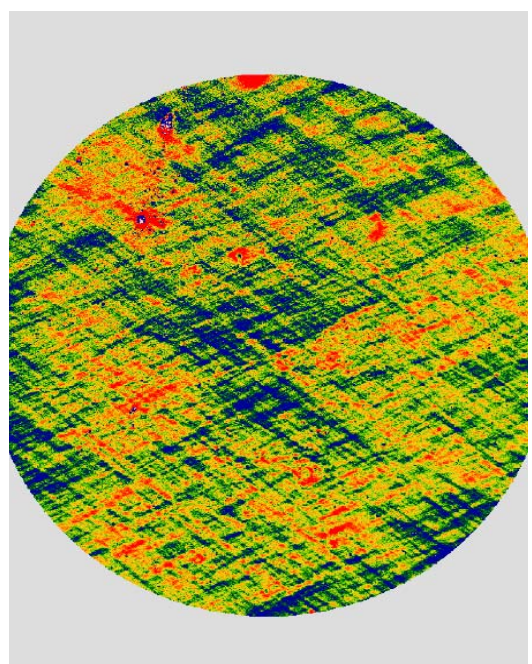

Fig. 4 Data from the GMT mirror in Fig. 3. The roughness was 1.7 nm rms after removing the form error terms

A typical measurement of roughness at the coarse figuring stage of polishing is shown in Fig. 4 where the form errors have been removed to give a value of 1.7 nm rms. The cross hatched pattern of roughness is typical of the finish left by the large stressed lap being used for polishing.

Another aspect of this design that makes the MFT easy to use in this mode is that once fringes are obtained by focusing and tilting with the 3 fine adjustment screws, the fringes barely move as the MFT is picked up, or slid, to a new location on the surface. This is because the MFT is being located by the surface directly rather than by some intermediary datum. This speeds up the measurement process and makes it easy to take data at many locations quickly.

4. DESIGN FOR SMALL OPTICS

No sooner than we had gotten the MFT designed for use on large optics a colleague asked what about small optics? This was clearly a good question, but it took only a moment to remember the idea of the inverted microscope. A frame was made to hold the entire unit upside down and a plate was made to support samples kinematically relative to the objective. This idea is shown schematically in Fig. 5 and in practice in Fig. 6. Now samples as small as 10 mm diameter can be measured with the same MFT that is used for large optics. The switch over from one configuration to the other takes about 5 minutes.

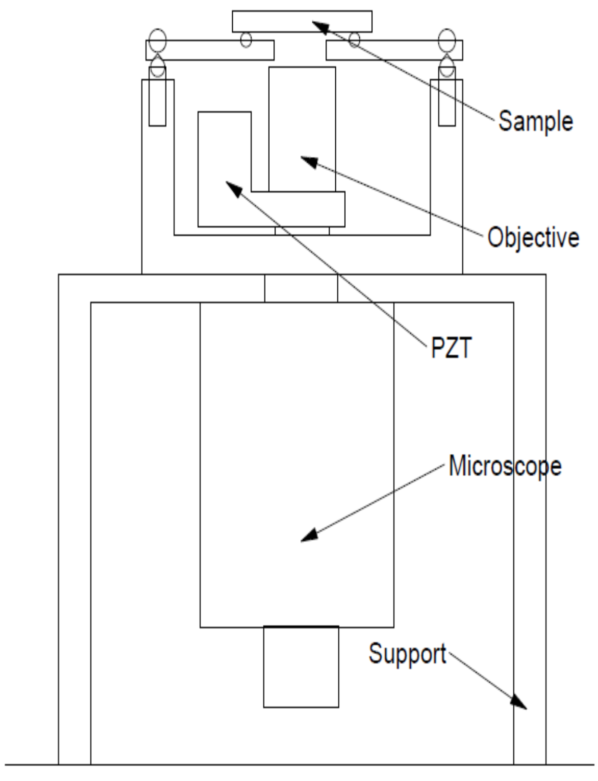

Fig. 5 The MFT supported for small optics measurement

Fig. 6 Photograph of the MFT in its inverted roughness configuration with a small sample on top

In the inverted version of the MFT, the sample rests on 3 nylon balls on a plate that is supported by the 3 adjustment screws so the same direct coupling between sample and objective is present in this version. All the same advantages apply as in the case of the large optics scheme; the system is largely immune to vibration, and because the sample is supported off the surface being measured, once fringes are found and broken out, sample after sample of the same radius can be measured without having to touch the focus and tilt adjustments. This is a great time saver over traditional systems where the sample is supported on its backside so that variations in thickness and wedge mean re-adjustment for focus and tilt with every sample.

5. DESIGN FOR ON-MACHINE METROLOGY

Another aspect of the MFT design is that the whole instrument is so light and small that it is possible to mount the MFT on diamond turning (DT) machines to do in-situ surface finish metrology and machine control diagnostics. Fig. 7 shows the MFT with a right angle attachment to reduce the length of the MFT ready for installation on a DT lathe along with an example of fringes from a turned part. As shown in Fig. 7 the PZT attachment is incorporated in the package. However, because of the built-in isolation and the resolution of the control systems on DT machines, the machine itself can be used to do the phase shifting or ramping to obtain surface roughness and contour information.

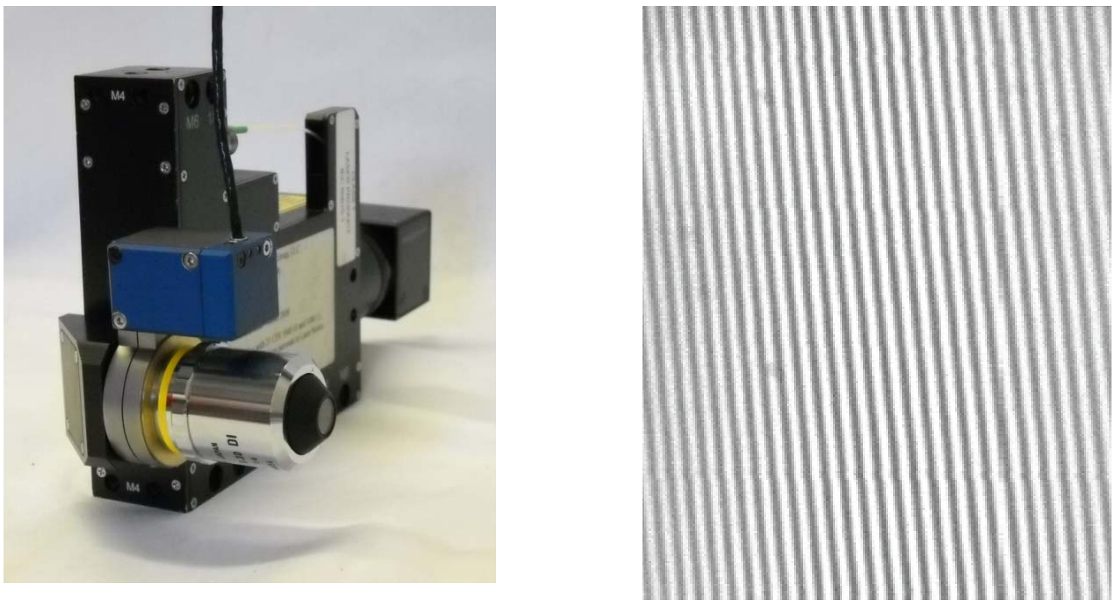

Fig. 7 MFT including a PZT objective shifter ready for installation on a DT machine (left) and fringe pattern obtained from a part on the DT machine (right)

The on-machine capability has two major functions, it can be used by the machine builder as a diagnostic system in the tuning of the machine before, and potentially, after delivery, and for the user of assuring the part finish meets specification before removing the part from the machine. Since it is tedious to remount a DT'ed part, knowing that it will meet spec while it is still mounted on the machine is a major benefit. As can be seen in the fringe pattern there are minor short spatial frequency errors after long stretches where there no errors. Understanding how these errors were produced would lead to methods of eliminating them.

6. DESIGN ADVANTAGES

As is obvious from the descriptions of the designs, nothing is different optically from any other micro-roughness profiler. The difference is in the mechanical design and that leads to a number of advantages over a design based on a traditional microscope. The fundamental advantage is that by supporting the microscope directly on the sample for large samples, or by supporting the sample directly on the microscope for small ones, the critical distance or measurement loop of the interferometer is largely immune to vibration. This makes it possible to measure the roughness of large samples without resorting to time consuming and contaminating replicas.

Another advantage that directly goes along with this design approach is that the alignment between the sample and the microscope is fixed since the sample is referenced off the surface being measured. This means that the adjustment for tilt and focus can be done once, and will remain the same sample after sample. This substantially speeds the measurement of multiple samples of the same curvature. Finally, the small package size and weight of the MFT makes it suited for mounting on a machine tool to measure surface finish and contour prior to removing the part from the machine. This added capability to a machine tool adds value because of the built-in inspection resource.

7. RESULTS OF MEASUREMENTS

The MFT uses 4D Technology 4Sight software[3] to drive the PZT and analyze the fringe data. The software runs on a desktop computer and work is in progress to migrate to a laptop system to increase the flexibility of the MFT. All of the results in this paper are based on 4Sight analysis.

Surface roughness measurement, like surface form error measurement, can never be less than zero, and any noise source will only make the apparent roughness or form error worse than it really is. In addition, at the roughness scale surfaces are not completely isotropic so the roughness varies with location on the sample. Thus it is difficult to put an absolute number on how smooth a surface is. A perfect example is that a roughness measurement will continue to get better and better the more measurements are averaged or filtered. One can model this behavior and show there is an asymptote but this is seldom done except possibly in a research lab.

What can be done is to show the repeatability of roughness measurements under various filtering options and environmental conditions. There is not much in the way of examples other than company literature showing how filtering affects results and what repeatability can be expected under certain levels of vibration isolation. We used a smooth SiC sample (<0.2 nm rms) and a 10x Nikon Mirau objective that had an rms reference mirror of less than 0.2 nm rms. The MFT was able to show repeatability of less than 0.06 nm rms time after time *without* vibration isolation. While we do not have instrumentation to measure our environment, from the qualitative descriptions of vibration criterion curves, we estimate our environment to be about 200 μm/sec[4]. To get this kind of repeatability on other roughness instruments an environment of 12.5 μm/sec or better is recommended[5].

Fig. 8 is an example of a typical measurement of the SiC sample mentioned above. This average consists of an average of 30 separate measurements without moving the sample between measurements. Each measurement was a burst of 25 measurements averaged as 1. The reference was not subtracted since the point of the exercise was to determine repeatability. All terms through spherical aberration were removed since we were interested in roughness over the 0.96 by 0.78 mm sample area. There was 1 bad pixel out of a nominal 786,432 and no filtering of any sort. Another interesting feature is that there were a few large excursions in that the P-V was 63.3 nm while the PVq was 1.75 nm. The profiles show the smoothness of the surface except for the very localized features that are rather symmetric about the mean. The detail in the surface is emphasized by using the maximum contrast feature of the software.

At the moment the MFT is strictly a temporal phase shifting interferometer. It is our intension to add a white light scanning mode in the future when software is available to support that mode. As it is, the MFT 4Sight software will successfully unwrap 8 μ" rms (200 nm rms) surfaces on a GAR S-22[6] surface roughness standard.

8. CONCLUSION

The MicroFinish Topographer (MFT) was originally designed to be a surface finish measuring interferometer for use on large optical surfaces where there is presently little option but using replicas to measure surface roughness. While the MFT fulfills this application admirably, its use for measuring small optics predictably and rapidly without the need for vibration isolation is an obvious complimentary use that it performs well. Further, the MFT form factor means the MFT is ideally suited for on-machine metrology of surface finish and contour.

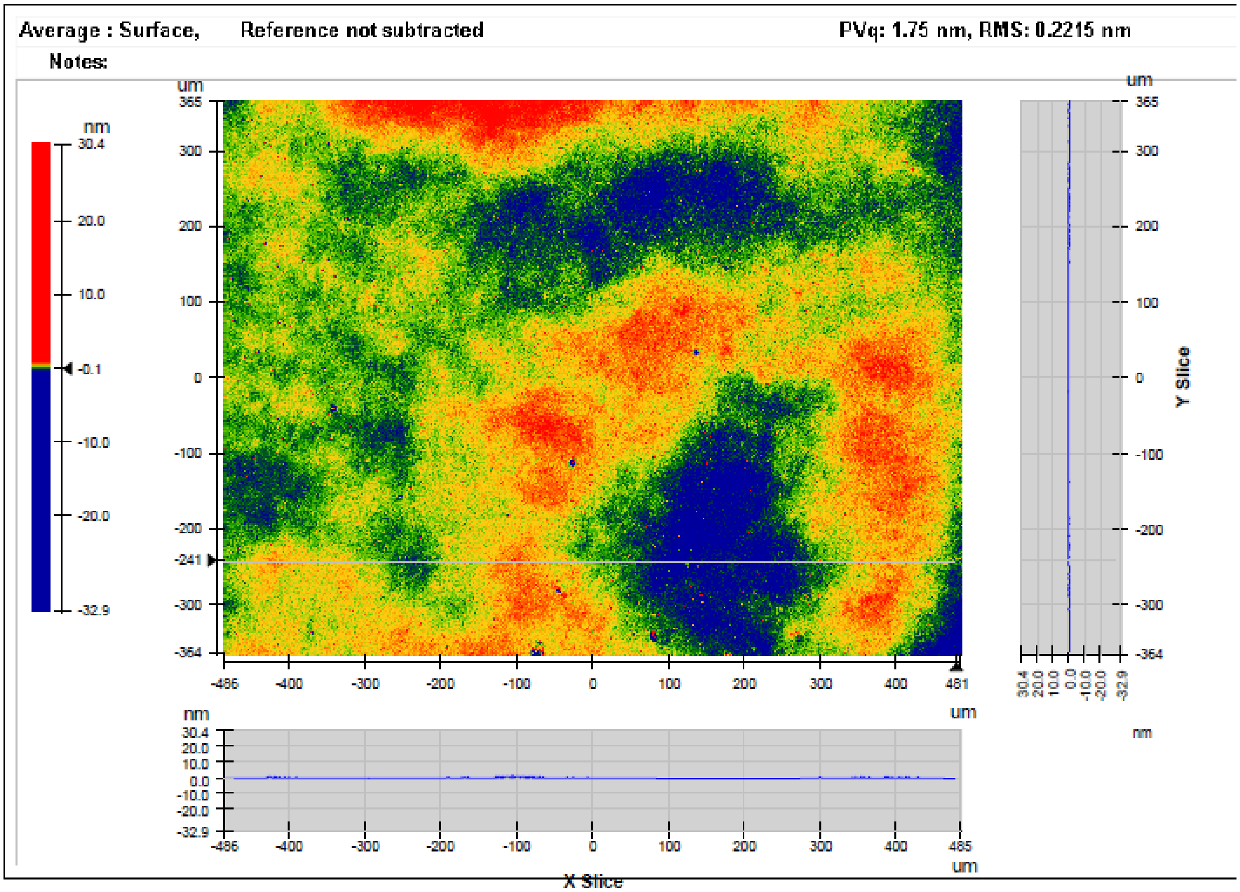

Fig. 7 Typical MFT measurement result using 4D Technology 4Sight software
The sample was a super smooth SiC artifact and the reference was not removed.

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