Non-destructive, real time direct measurement of subsurface damage

White Paper

Agilent Technologies

ABSTRACT

Subsurface damage control and measurement is critical on a wide range of optical elements. The amount of subsurface damage present in an optic determines its yield strength, the amount of laser power that the optic can handle, and the flatness that can be maintained during the coating process. In these days of reduced tolerance for mission failure, it is critical to have accurate knowledge of the condition of an optic before sending it into space. Destructive tests provide very accurate measurements of subsurface damage, but such testing can be time consuming and an uncertainty always remains: Does the finished part have the same subsurface properties as the measured sample? Various laser scattering techniques currently provide non-destructive measurement of subsurface measurement, but these measurements are all indirect. The laser scattering techniques directly measure the amount of laser light scattered from a surface and below, which is then correlated to an approximate depth of subsurface damage that might produce the measured amount of scattering. In contrast, the technique presented here is both a non-destructive and direct measurement of the depth and extent of subsurface damage. Because it is a direct measurement, subsurface damage depth can be reported in real time, allowing for in-process corrections and optimizations. This paper presents the measurement setup and offers an example of the experimental output provided by this new method.

Keywords: subsurface damage, non-destructive evaluation, real time measurement, laser scattering, glass fracture

1.0 The Risks And Costs Of Subsurface Damage In Optical Components

Subsurface damages such as cracks, voids, and contaminant particles are a fact of life in even the highest-quality optics. The damage may be inherent to the type or quality of the material used, or it may be produced during sawing, grinding, polishing, and other fabrication steps. Regardless of the source, subsurface damage in precision optical elements can present considerable risks of performance irregularities and even system failure, particularly in applications that involve either significant physical stresses or the use of high-power laser light. When these conditions are present and the cost of failure is high—such as in space-based systems—problems caused by subsurface damage can become critical. For instance, subsurface damage in an optical path of an optical element can cause light absorption and scattering that may lead to poor quality optical signals or heat generation that in extreme cases can cause the optical element to explode. In addition, optics with significant hidden structural damage may not survive the mechanical stress of launches and other mission events.

In addition to these critical failures, subsurface damage plays an often underappreciated role in meeting high-precision component requirements. An optic can appear to be within specifications at the end of manufacturing, but once it is exposed to the heat of the coating chamber, the subsurface cracks propagate. This causes a warping of the optic, making it nearly impossible to meet tight wavefront and flatness requirements.

Unfortunately, there is no predictable correlation between surface quality and subsurface quality in optics, as **Figure 1** indicates. The sample on the left has a smoother and flatter surface overall than the sample on the right, but the subsurface damage is significantly more extensive on the left. In other words, surface profile measurements alone can yield extremely

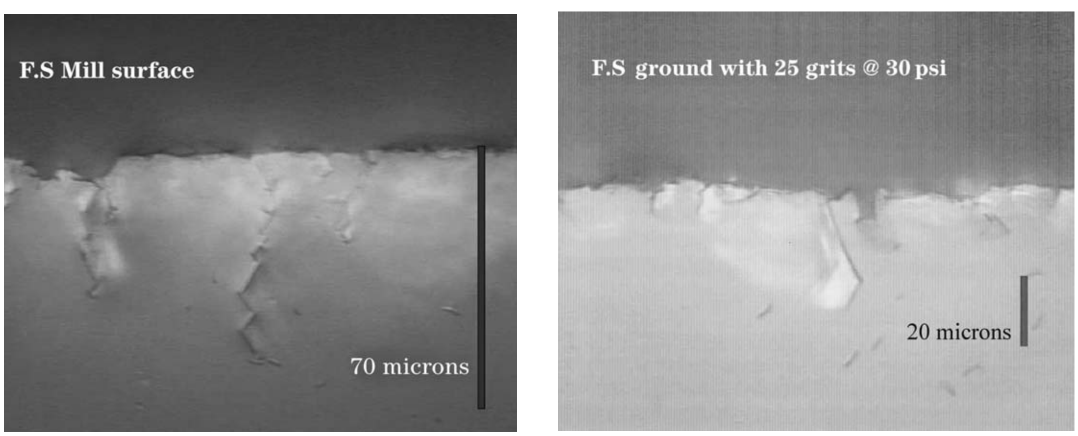

Figure 1. Surface quality is not a reliably predictable indicator of subsurface damage.

misleading answers. While some subsurface damage manifests itself as straight "pinholes" in the surface, cracks with the more characteristic "lightening bolt" shape shown in these samples are impossible to probe visually or mechanically to their full depth.

To bring some certainty to the fabrication process, attempts have been made to mathematically model the quality of the optical element based on knowledge of the materials and fabrication processes employed. With an accurate model, the expected damage in a particular design can be determined. However, such models will be inaccurate if the model is based on inaccurate characterizations of the material or the fabrication process, or if effects not anticipated in the model cause damage. Furthermore, even when a model is accurate, the level of subsurface damage in individual optical elements is generally subject to variations, and a specific optical element may have more or less subsurface damage than expected.

Without a simple and reassuring way to assess quality or obtain accurate feedback during fabrication, processes generally develop based on beliefs and rules of thumb, rather than on dependable information. For instance, glass fabricators start with coarse grit, which removes material quickly but causes deep cracks. The next step is moving to a finer grit and machining long enough to remove the material to the depth of the cracks made with the coarse girt. This process is then repeated with ever finer grits. However, without accurate knowledge of the depths of whatever subsurface cracks are in the piece, fabricators more or less end up guessing how long to machine each piece. The result in either suboptimal parts or suboptimal processes–or both.

Clearly, with conventional fabrication processes, the quality of the final artifact is nearly always uncertain to some degree.

2.0 Existing Methods Of Measuring Subsurface Damage

Given the costs and risks of poor quality, numerous attempts have been made over the years to develop efficient and reliable methods of detecting and assessing quality problems below the surface. The most common techniques fall into two general categories: destructive measurements and measurements of scattered light.

2.1. Destructive measurements

In destructive measurements, a test sample is physically modified in some way to expose material below the surface. A taper grinding process, for example, cuts into samples of an optical element design to expose the subsurface damage for evaluation. Alternatively, damage at an optical surface can be enlarged or exposed using an acid etch. The acid etch generally has greater effects on cracks than on intact material, thereby permitting surface examination with a high-power microscope to detect the enlarged or exposed cracks or defects.

These destructive techniques can be used to build a model of either the materials or the fabrication processes. However, each optical element evaluated in this manner is generally destroyed or rendered unusable, which is obviously undesirable for expensive systems or elements. Also, because destructive evaluation is usually a sampling process, it only measures typical subsurface damage for a given design subjected to a given process. Consequently, some uncertainty always exists regarding those units that weren't evaluated. Further, the results of a destructive evaluation can typically take several days to obtain.

2.2. Measurement of scattered light

In the approaches that involve measurement of scattered light, laser light impinges on the surface at an angle, and a detector is positioned to receive backscatter resulting from subsurface damage. A horizontal scan is performed, and the intensity of the backscatter is recorded at each location on the horizontal plane. The intensity is then correlated with depth through a lookup table, resulting in estimates of subsurface damage. However, no direct vertical measurement is made.

2.3. Other methods

Among the other methods that have been developed are acoustic measuring techniques that combine Hertzian Acoustic Emission Indentation (HAEI) and a Line Focus Acoustic Microscope (LFAM). This approach can examine the surface condition and fracture toughness of an optical element, but it has trouble detecting defects larger than about 10 µm and also requires expensive equipment and a significant amount of skill, training, and technical support.

3.0 A New Non-Destructive, Real Time Subsurface Measurement System

A new non-destructive method has been developed that combines direct subsurface measurements with real-time graphical analysis of subsurface defects. This technique adapts a confocal scanning laser microscope system typically used in surface-scanning applications (such as assessing surface topographies of platters in optical disk drives) but directs the focal plane into the optic element, rather than scanning the surface. **Figure 2** offers a schematic of the system, and **Figure 3** shows one specific implementation.

As indicated in **Figure 2**, the focal plane of the microscope is adjusted vertically to various depths within the optical element. Given the confocal microscope's ability to block returned light from above and below the focal plane, this approach achieves visual resolution of 150 nm up and down the vertical axis (in the case of this particular microscope). The system conducts a three-dimensional internal scan of the test article through optical sectioning, stacking a collection of horizontal focal planes between the minimum and maximum depths set for the test. A complete 3-D profile is created in a matter of seconds for a typical optical element, providing the real-time answers needed to ensure both product and process quality.

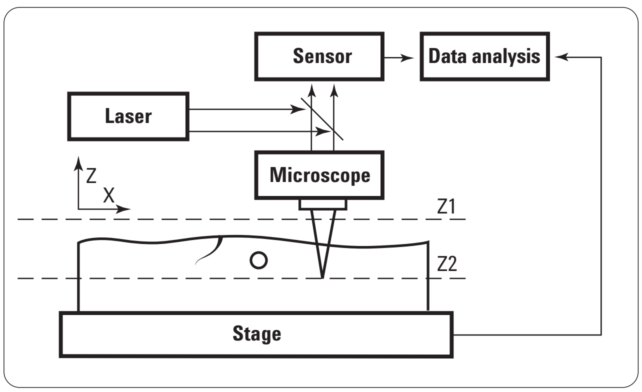

Figure 2. Schematic representation of non-destructive, real time subsurface measurement system

Figure 3. Scanning laser microscope used in subsurface measurement system.

At each observation point within the test zone, an increase in the intensity of reflected light indicates scattering or reflection from a defect or damage at that point within the component. The area over which defects extend and the intensity of the light provide indications of the severity of the damage.

A scanning laser microscope is intended for measuring surface features, and once the microscope penetrates the optical surface, the index of refraction of the material causes the apparent depth to differ from the actual depth. The first order approximation of this relationship is shown in **Figure 4**.

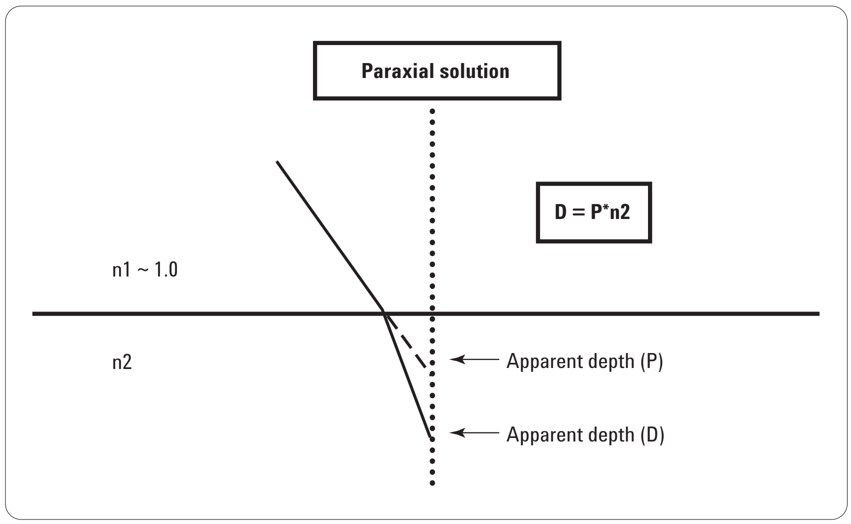

Figure 4. Determining true depths of subsurface imperfections by factoring in the refractive index of the material being tested.

4.0 Experimental Demonstration

We have conducted a number of experiments to verify the validity and accuracy of this new direct, real-time technique method for assessing subsurface damage by comparing it with a conventional destructive examination. The procedural steps were as follows:

1. Prepare a test sample that can be first analyzed using this non-destructive technique and then examined again using a destructive approach; **Figure 5** shows the preparation of the test sample, based on the method developed by Anderson and Frogner[1].
2. Locate a crack along the seam using the scanning microscope and measure its full extent (the deepest point at which it scatters light).
3. Scale the measurement from Step 2 as needed by the refraction index of the test material
4. Separate the test sample halves and rotate one half 90 degrees and locate the same crack (which is now stretching horizontally along the exposed surface); measure the length of the crack through direct observation
5. Compare the measurements from Steps 2 and 4.

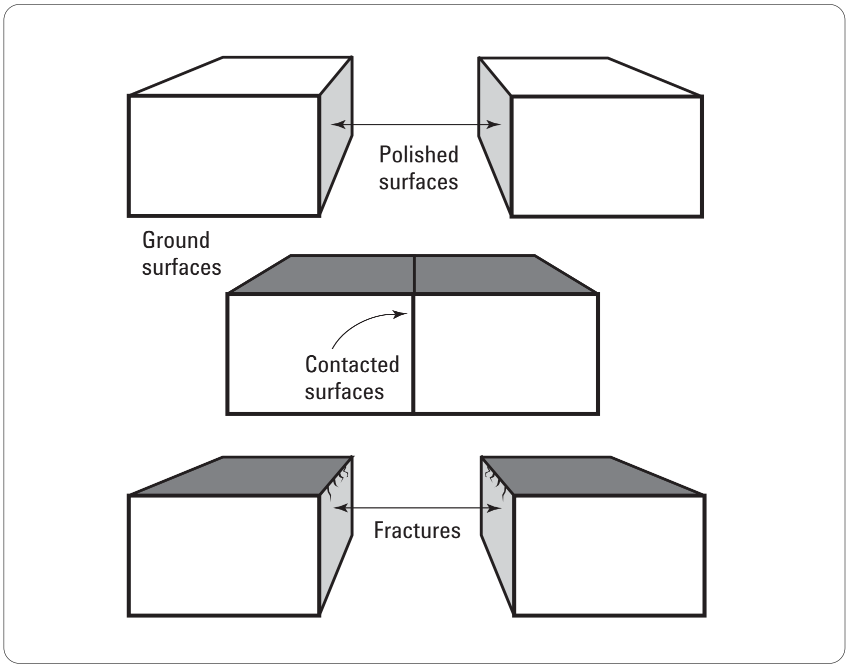

Figure 5. Preparing the test sample, following Anderson and Frogner.

Figure 6 shows a representative sample of the graphical measurement output of the confocal scanning system, illustrating Step 2 in the experimental procedure. The photographic image is of one specific focal plane within the piece. The solid horizontal white line superimposed on the image indicates where a vertical cross section was measured down through the piece. The line graph positioned below the solid white line shows one pass of the scanning depth measurement across this vertical plane. The average baseline of the graph represents the surface of the optical element; peaks extending above this baseline are indications of contamination or imperfections on the surface and are ignored for our purposes here. Valleys extending below the baseline are indications of defects or damage beneath the surface.

Looking at the graph, we can then position a measurement cursor (the horizontal dashed line) at the deepest valley, as indicated by the numerical readout of 127.23 µm. To convert this observed depth to the actual depth, we follow the scaling procedure from **Figure 4** to accommodate refraction. The fused silica material used in this particular test, for instance, has an index of 1.47 at this wavelength, yielding an actual depth of 187 µm.

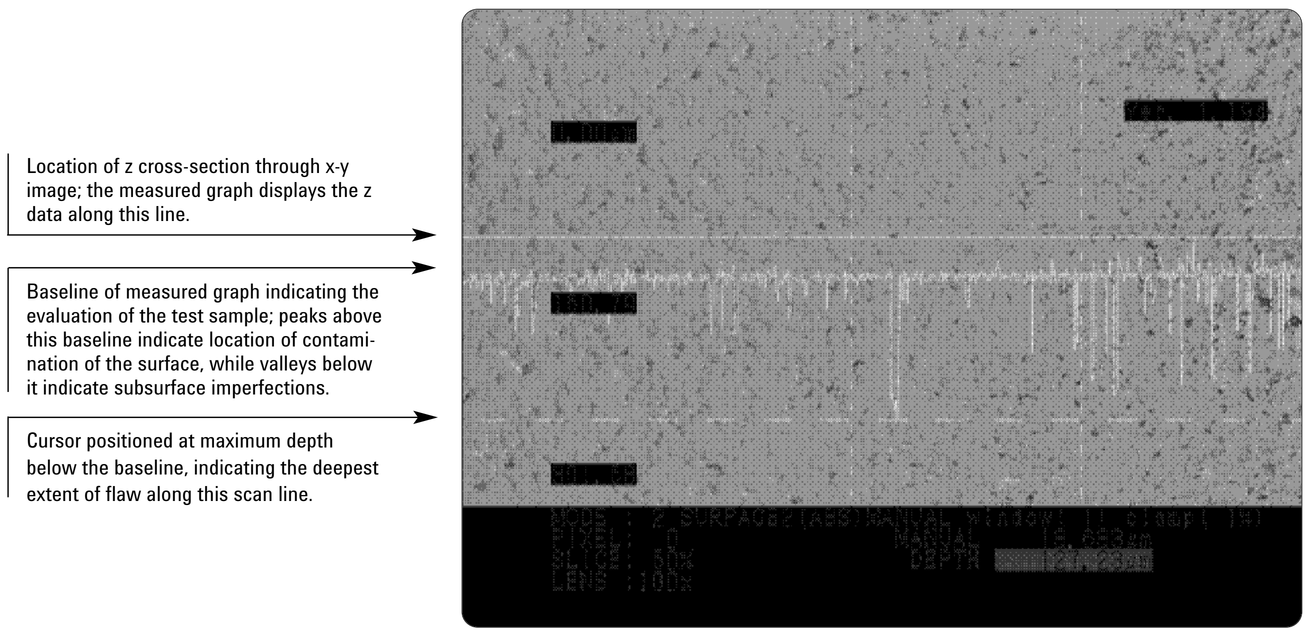

Figure 6. Measurement result using new subsurface scanning method.

Conclusion

This new technique for measuring subsurface defects and damage has proven effective in allowing Agilent Technologies to rapidly optimize and characterize manufacturing processes in order to create optics with the desired level of subsurface integrity. The close correlations observed in experimental comparisons on a variety of samples between this new approach and conventional destructive test methods offer a new level of confidence in the performance and dependability of optical elements destined for use in critical applications and demanding environments.

References

[1] David S. Anderson and Michael E. Frogner, *"A Method for the Evaluation of Subsurface Damage,"* Spectra-Physics, Inc., Mountain View California.

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Revised: 09/14/06

Product specifications and descriptions in this document subject to change without notice.

Printed in USA, September 28, 2006
5989-3090EN

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