Developing a more useful surface quality metric for laser optics

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ABSTRACT

Light scatter due to surface defects on laser resonator optics produces losses which lower system efficiency and output power. The traditional methodology for surface quality inspection involves visual comparison of a component to scratch and dig (SAD) standards under controlled lighting and viewing conditions. Unfortunately, this process is subjective and operator dependent. Also, there is no clear correlation between inspection results and the actual performance impact of the optic in a laser resonator. As a result, laser manufacturers often overspecify surface quality in order to ensure that optics will not degrade laser performance due to scatter. This can drive up component costs and lengthen lead times. Alternatively, an objective test system for measuring optical scatter from defects can be constructed with a microscope, calibrated lighting, a CCD detector and image processing software. This approach is quantitative, highly repeatable and totally operator independent. Furthermore, it is flexible, allowing the user to set threshold levels as to what will or will not constitute a defect. This paper details how this automated, quantitative type of surface quality measurement can be constructed, and shows how its results correlate against conventional loss measurement techniques such as cavity ringdown times

Keywords: Surface quality, SAD, scratch, dig, MIL-0-13830A, MIL-PRF-13830B, inspection, ISO 10110

1. INTRODUCTION

A specification for surface quality appears on the drawings or tolerance callouts of most optical components.. Often, the customer requested value for surface quality is tight enough to have some impact on component cost. Yet, in most cases, there is no clear correlation between the specified surface quality and the performance of the optic in the application. Thus, consumers are often paying optics fabricators to achieve a level of quality that has no practical value.

Throughout our economy today, manufacturers in many areas, including photonics systems and lasers, find themselves pressured to reduce manufacturing costs and lead times, while simultaneously improving product quality and reliability. Thus, it is becoming increasingly important to determine which specifications meaningfully impact system performance, and which do not. The traditional surface quality specification, in particular, is one which does not always serve the needs of modern laser manufacturers or consumers because it can increase cost without improving performance. To understand how this situation arose, it's necessary to know the history of the surface quality specification.

2. SURFACE QUALITY SPECIFICATION BACKGROUND

2.1 History of the specification

The surface quality specification used most widely today was first formally defined in the US military standard MIL-O-13830, which was published in 1954.[1] From the outset, this standard was meant to apply to the visual appearance of components (e.g. cosmetics), and never intended to relate to their performance in an optical system. Furthermore, this standard was developed long before the advent of the laser.

MIL-O-13830 provided specific definitions for the allowable number and apparent visibility of scratches and digs (pits) on an optical surface. In particular, scratches and digs were each specified with a number. The scratch number denoted how a given scratch on a component visually compared with a "standard" scratch, usually contained on a reference piece fabricated in accordance with the specifications of drawing C7641866 (produced by the US Military). The dig number represented the "mean dig diameter" in hundredths of a millimeter. Therefore, a 20 dig had a 0.20 mm mean diameter.

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However, actual inspection for digs was visually performed with reference to a standard, rather than by physical measurement of dig dimensions.

Because MIL-O-13830 specified scratch visibility, as opposed to actual physical dimensions, the viewing conditions for testing were also spelled out. These included lighting on the piece (from either a 40W incandescent bulb or a 15W cool white fluorescent lamp), viewing angle (approximately 90° from the source to achieve darkfield illumination) and even the background against which the part is viewed.

Over the years, confusion arose in the photonics industry as to the exact interpretation and meaning of the surface quality specification, especially as concerns the scratch number. In an attempt to remedy this, the drawing C7641866 was revised several times in the 1970's. Unfortunately, this simply added to the confusion. One reason for this is that a 1974 version of the drawing (revision H) specified that comparison standards be produced using scratches in which the scratch number (e.g. 80) corresponded to the width of the scratch in microns. But, only two years later, another version of drawing (revision J) stated that the scratch number represented the width of the scratch in tenths of a micron. While the original scratch masters for the specification and the underlying meaning of the specification itself hadn't changed, this caused many to misunderstand how the specification was to be properly applied. It should be noted that the current version of C7641866 specifies that, for all scratch numbers, the width of the scratch "shall be no greater than 10 µm."

In 1997, the US government released an update of the original surface quality specification called MIL-PRF-13830B. While this addressed and cleared up some of the confusion around the precise meaning of the scratches and digs, it still did not address the underlying problem with the specification. This relates to the way the surface quality specification is applied in practice.

2.2 Practical difficulties in applying the surface quality standard

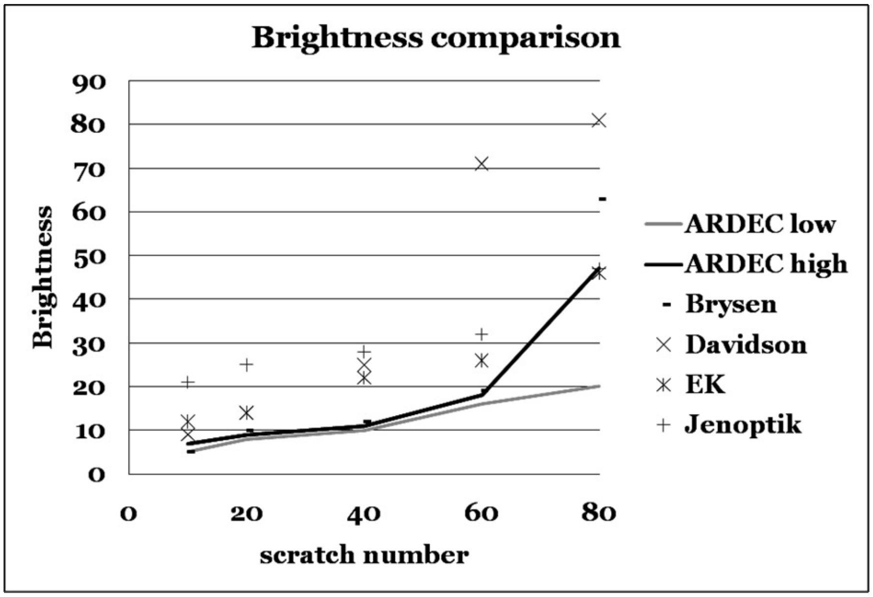

Figure 1. Relative brightness of four comparison sets. Sample 1 is FLIR/Brysen S&D 1109, Sample 2 is Davidson Optronics D-667A S/N 2431, Sample 3 is an Eastman Kodak Paddle, EKCO CM2, and Sample 4 is a Jenoptik paddle EO #53-157 CM1. [2]

At the heart of the problem with MIL-PRF-13830B is the fact that it only refers to apparent scratch visibility. No matter how well lighting and viewing conditions are standardized and controlled during testing, there will always be some operator-to-operator and setup-to-setup variations in evaluating scratch and dig values. Furthermore, the comparison is performed to a set of reference standards. These can be obtained from several different sources, but themselves show a fair degree of variation amongst different suppliers. For example, Aikens[2] found a wide range of visual appearance associated with a given scratch number on reference standards obtained from four different suppliers, as seen in Figure 1.

MIL-PRF-13830B can also be difficult for inspectors to implement in practice. Table 1 reproduces the section of MIL-PRF-13830B which details how scratches are to be classified. Just this one small set of requirements (and there are several pages of the specification that relate to surface quality) represents a fairly tall order for quality control personnel. For example, section 3.5.2.1.1 details the process for determining the maximum allowable combined length of scratches. This requires performing a mathematical operation which is difficult for the inspector to accomplish under the typical time constraints of a production environment. Section 3.5.2.4 also asks the inspector to differentiate between coating scratches and substrate scratches, yet this is usually difficult or impossible to accomplish by visual means alone.

Table 1. Section of the MIL-PRF-13830B surface quality specification which details how scratches are to be classified.[3]

> MIL-PRF-13830B
>
> 3.5.2 Scratches.
>
> 3.5.2.1 Circular element. The combined length of maximum size scratches located on each surface of an optical element shall not exceed one quarter the diameter of that element.
>
> 3.5.2.1.1 Maximum combined lengths of scratches. When a maximum size scratch is present, the sum of the products of the scratch numbers times the ratio of their length to the diameter of the element or appropriate zone shall not exceed one half the maximum scratch number. When a maximum size scratch is not present, the sum of the products of the scratch numbers times the ratio of their length to the diameter of the element or appropriate zone shall not exceed the maximum scratch number.
>
> 3.5.2.2 Noncircular shaped element. The computing diameter of element shapes other than circular shall be that of a circle of equal area. Scratches beyond the free aperture of any element as given on the optical system drawings or detail drawings shall not be considered when applying the appropriate formula specified in 3.5.2.1.1.
>
> 3.5.2.2.1 True roof surfaces on prisms. True roof surfaces on prisms shall be considered equivalent to a single surface equal to the sum of the individual roof areas for purposes of scratch and dig computation, except that the roof edge shall not be considered in the summation of the length of the allowable scratches. Scratch and dig tolerances for roof prisms are set on the basis that the equivalent surface above is viewed from the air side. (3.7.10.1).
>
> 3.5.2.2.2 Surface quality, central zone. Areas of surfaces whose specified scratch qualities are 20 or better shall have no more than 4 separate scratches in any 1/4-inch diameter circular area. This requirement does not apply for scratches smaller than number 10.
>
> 3.5.2.3 Surface quality, outer zone. Surface quality outside the free aperture of any element shall be considered 80-50, unless otherwise required.
>
> 3.5.2.4 Coating scratches. Coating scratches, scratches which do not penetrate the glass surface, shall be within the same limits specified in 3.5.2. Coating scratches shall be considered separate from the substrate scratch requirements.

2.3 ISO 10110 – A quantitative approach

In an attempt to overcome the limitations of MIL-PRF-13830B, the International Standards Organization developed a more quantitative standard for surface quality. Specifically, ISO 10110 details a classification system for surface defects based on their actual physical sizes and frequency of occurrence over a given part area. There is no attempt in this specification to relate to defect visual appearance or a quantitative measure of defect scatter loss. However, the ISO approach eliminates the need to maintain a master defect standard and to reproduce this standard for use by manufacturers. Instead, inspecting to the ISO standard ideally involves the ability to accurately measure the absolute size and number of defects over a region of interest on a surface.

Unfortunately, accomplishing this in practice is difficult and time consuming. Defects which are readily apparent to the eye when viewed under darkfield conditions can be just a few microns or less in actual physical width. Actually measuring defects of this scale is best accomplished with a calibrated microscope system. But, a microscope with sufficient magnification to properly resolve such small defects will necessarily have a relatively small field of view. This can make it difficult to image the entire length of a scratch, which is necessary in order to properly classify it in accordance with ISO 10110. Additionally, visualizing the entire surface of even a fairly small part may require sequentially looking at multiple fields of view. This is time consuming and problematic in a production fabrication environment, especially since there is no automated equipment currently commercially available for performing this task. Like MIL-PRF-13830B, the ISO 10110 specification also details the total number of allowable defects of a given size, so, again, this must be tracked on the fly by the inspector.

Because of these factors, real world implementation of ISO 10110 inspection is often performed visually. Typically, a range of defects are measured on a witness sample, and then these are used by inspection personnel to gauge scratch sizes on production parts. Of course, this just reintroduces many of the operator and illumination dependent limitations of the MIL specification.

3. ALTERNATIVE MEASUREMENT METHODOLOGIES

The two primary existing ways of specifying surface quality both have their limitations. Namely, the MIL specification is too subjective, operator dependent and reliant on inconsistent reference standards, and the ISO standard, while quantitative, is difficult to implement in practice. And, for the laser manufacturer, both pose an additional more important problem. This is that neither measures a parameter that is directly correlated with laser performance.

The performance of a laser resonator is clearly affected by scatter losses from its intracavity components. Thus, directly measuring scattered light, or the effect of light scatter, is a useful metric for the laser manufacturer. Since neither MIL-PRF-13830B nor ISO 10110 provide a practical framework for accomplishing this, we must look for other methods. Two approaches worth examining are cavity ringdown and total integrated scatter (TIS).

3.1 Cavity Ringdown

Cavity ringdown directly measures the effects of all losses in a laser type resonator setup. To perform cavity ringdown, a resonator is built using two (or more) mirrors. One of these has already been characterized, and the second is the component under test. A laser beam is introduced into the resonator (typically matched in size with the lowest order transverse mode of the cavity), and the light exiting the cavity through one of the components is measured. When this reaches a set threshold level, the laser is suddenly switched off, and the decay time of the output is monitored. Anything (transmission, scatter, absorption) which removes light from the cavity effects the storage time of the resonator, making this a very sensitive technique for gauging loss. Furthermore, since this test configuration is similar to the actual use conditions for intracavity laser optics, the results of ringdown measurements can be well correlated with performance of the final optical system. In practice, the transmission and absorption characteristics of the optic under test are measured using other techniques so that the ringdown measurement can be used to isolate solely the effects of scatter (due to both surface roughness and defects).

The main limitation of ringdown is that the laser spotsize is small, and surface quality is typically specified by the consumer over the entire part aperture. For example, a ringdown spot size might be 100 μm, while the part aperture might be 5 mm. Thus, the technique doesn't sample much of the part, unless the beam is scanned in order to deliver "spatially resolved" ringdown data (in which multiple spatial locations are sampled). Also, the equipment to perform ringdown requires some expertise to utilize. This makes it difficult to implement in a production setting. However, it's a very useful and sensitive approach for setting benchmark values for surface quality, or for verifying the results of other methods.

3.2 Total Integrated Scatter

TIS directly measures light scatter from an optic. This is typically accomplished using an integrating sphere with three ports. The optic under test is mounted into the sampling aperture. A laser beam is introduced into the integrating sphere through the input aperture, and the specularly reflected beam usually exits back out the system through this same port. The third aperture contains the detector for measuring the scattered light.

While this is a conceptually simple approach, it can be difficult to implement in practice. In particular, it's often difficult to effectively reject all the specularly reflected light without losing too much of the scattered light. Additionally, mounting each component under test into the system is time consuming, and there are currently no automated systems based on TIS measurements available for production use.

4. PRACTICAL SCATTER MEASUREMENT FOR LASER MIRRORS

While both cavity ringdown and TIS deliver reliable, repeatable, quantitative data, the practical limitations of both techniques mean that neither is well suited for use in a production environment. What fabricators and users of intracavity laser optics need is an instrument which produces the same quality data as these techniques, yet is also fast, simple to use, and well-suited for automated operation. Figure 2 shows one possible approach for quantitative measurement of scatter which achieves these ends by directly imaging scattered light from defects.

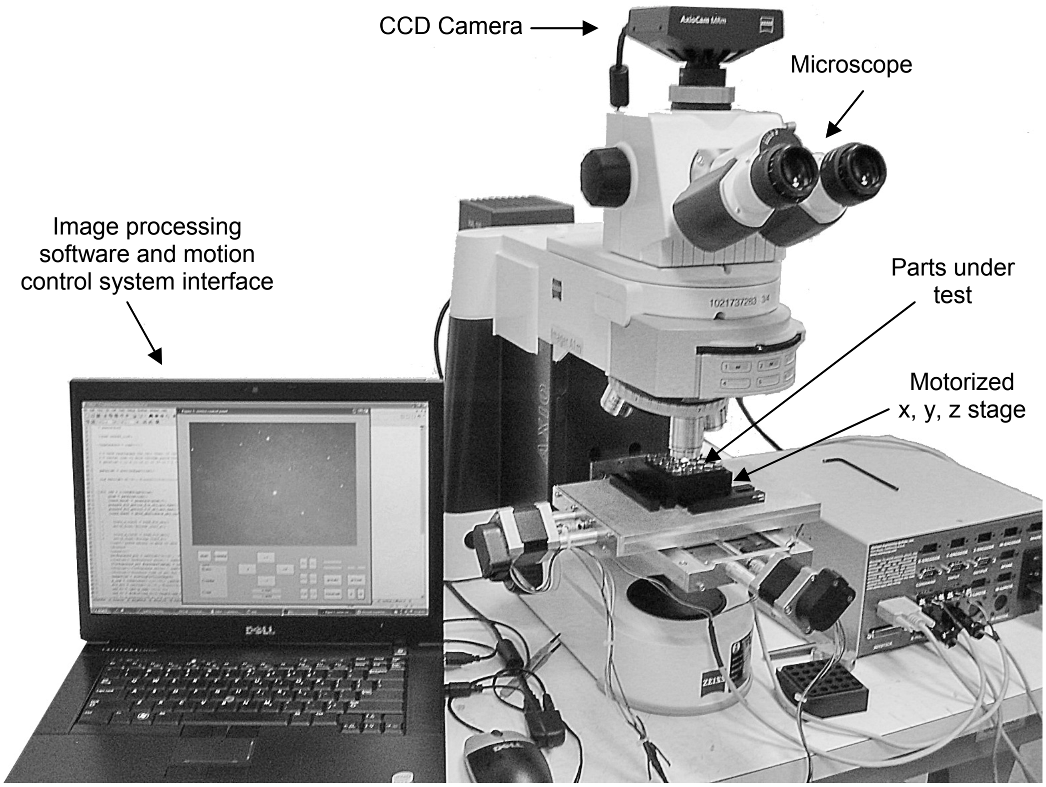

Figure 2. An automated surface quality inspection system which utilizes a microscope optical system and CCD camera to measure the brightness of light scattered from defects under darkfield illumination conditions.

In this system, optics under test are lit using a standard microscope darkfield illumination system. The optics can be mounted into the system individually; alternately, several components can be mounted and indexed for viewing using a motorized stage, as shown in the figure. Additionally, automated part loading and unloading can even be added to the system. Light scattered from defects is imaged by the CCD camera, showing up as bright features against a dark background. A host computer, containing camera control, image processing and motion control software receives and analyzes the data. Several aspects of this system merit further discussion.

4.1 Microscope field of view

One of the main limitations mentioned previously in connection with cavity ringdown is that it only samples a small area of the component clear aperture in a single measurement. While the quantitative scatter measurement instrument described here utilizes microscope optics to view the part, it does so at relatively low magnification – typically either 5X or 20X. This low magnification is possible because the system doesn't need to actually resolve the defects themselves (which may be just microns or less in dimension), but rather, it only needs to image the light scattered from these defects. This pattern of scattered light is easily viewed at lower magnifications.

With a typically sized CCD sensor, the result of this low magnification is an instrument field of view of about 2 mm in diameter. This enables small optics (less than 10 mm diameter) commonly used in laser resonators to be examined relatively rapidly, especially given that the exposure times for these fairly bright images are usually less than one second. Even when multiple images of each part are required to cover the entire clear aperture, the system can approach the speeds necessary for practical use in a production setting. Only for larger clear apertures, say over 25 mm, do 100% inspection times start to become too long to be practical.

4.2 Image processing

The goal of the optics and image processing system in the automated surface quality measurement instrument is to deliver a number for the total integrated brightness of all scattering defects on the part. In practice, the logarithm of this number is most useful because the raw quantity ranges over several orders of magnitude for typical parts. This number is obtained through a series of image processing steps, illustrated in Figure 3.

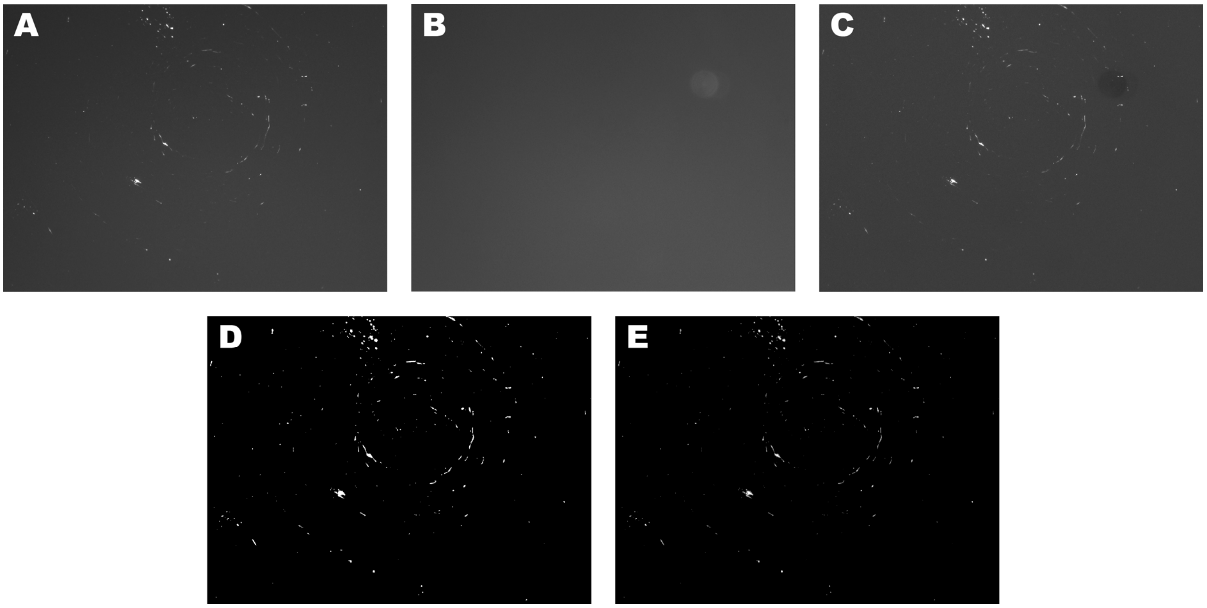

Figure 3. Image processing sequence in the automated surface quality measurement system to go from raw data to the defect only image.

First, both a raw image of scattered light (A) and a highly defocused image (B) of the same scene are acquired. Image processing software then divides the first by the latter in order to flat field (normalize) the raw data (C). This normalized image is then subjected to binary segmentation. Specifically, the software takes all pixels that are below a value determined in advance to be the noise floor of the imaging system and sets them to black, and all pixels above this are set to white (D). Finally, the normalized image is multiplied by this binary mask image to produce a final image (E) in which all the noise and background pixels are set to zero (black), and the defects show up in gray scale.

To derive the total integrated brightness of all defects, the software first identifies what it considers to be discrete defects by looking for collections of pixels that are connected. This allows individual non-zero pixels to be ignored if they are considered to be either spurious, or from features that are too small to matter. The total value of all the defect related pixels is summed to produce the total integrated brightness.

4.3 Dynamic range considerations

The brightness range of the scattered light from defects in a single image acquired by this system can be fairly large. Early testing quickly revealed that a 8 bit (256 gray levels) CCD camera did not possess the necessary dynamic range to simultaneously record both the brightest and dimmest features typically found in these images. Furthermore, 8 bit CCD cameras are typically constructed from commercial grade sensors with small pixels having a relatively high noise floor.

Currently, the system in use at REO is based on a 12 bit, scientific, cooled CCD camera (4096 gray levels). This delivers sufficient dynamic range for most uses of the system; multiple exposures to properly image both the brightest and dimmest features can be employed in very high dynamic range situations. Cooling of the CCD is essential to lower the noise floor to acceptable levels and deliver adequate sensitivity for the most demanding applications, as well as to maintain consistency of the imaging system over time.

A 16 bit (65536 gray levels) CCD camera would deliver superior dynamic range, but these cameras are prohibitively expensive for this application.

4.4 Calibration

Any system built for long term use in a production setting needs to maintain long term consistency and calibration. There are essentially three areas in the system where variations can occur over time. These are the CCD camera, the microscope optics and the illumination system. For example, microscope optics can get dirty, thus lowering their transmission, or the halogen bulb source can dim over time. All these factors can be calibrated out by putting a stable reference standard into the system and then measuring its scatter. At REO, we utilize NIST-calibrated, diffuse scatterers for this purpose.

5. RESULTS

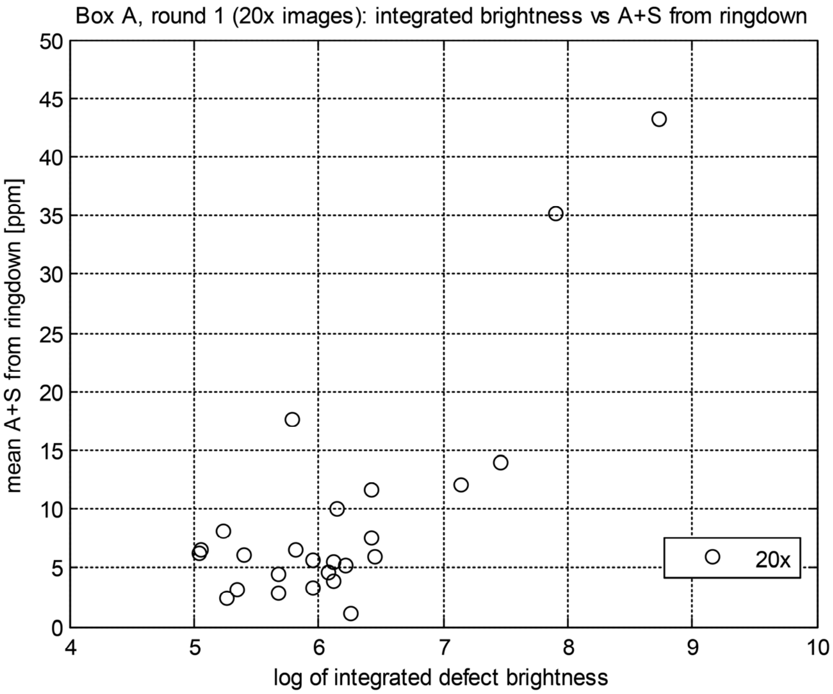

Figure 4. Spatially resolved ringdown data plotted versus log of integrated defect brightness for 25 HeNe laser mirrors.

Figure 4 shows a plot of values obtained using the automated surface quality measurement instrument against spatially resolved ringdown data for the same parts. Specifically, 25 helium neon laser high reflectors (7.75 mm diameter, 5 mm clear aperture diameter) were measured using both techniques. The microscope system for measuring total integrated scatter was operated at a 20X magnification.

The ringdown data is for the total absorption and scatter (A+S) of the part under test; the effects of transmission losses and all losses from the reference optic have been eliminated. The cavity ringdown setup uses a ~500 µm diameter beam that samples the optic under test at five separate locations that were roughly centered on the same field of view as the microscope measurement. The multiple samples help to ensure that the ringdown measures everything in a microscope field of view (~700 µm x 500 µm at 20X). However, issues of proper coverage and registration can have an impact on the comparison of the ringdown and the microscope, because each could see a different set of defects.

This data shows a limited correlation between the two measurement techniques. It will probably be necessary to sample a larger group of parts, covering a broader range of defect densities, in order to establish a clear correlation between ringdown and total integrated scatter data.

The total integrated scatter does, however, show a good correlation with visual inspection, as shown in Figure 5. Specifically, this presents the results for inspection of several batches of various HeNe laser components (e.g. high reflectors and output couplers for several different output wavelengths); each batch contained about 100 parts, and was inspected to a “0-0” nominal callout for surface quality. The reject fraction (1= all parts in job were rejected; 0 = all parts were accepted) is plotted versus the average log integrated defect brightness for each entire batch. This data was obtained with the microscope system operating at a 20X magnification.

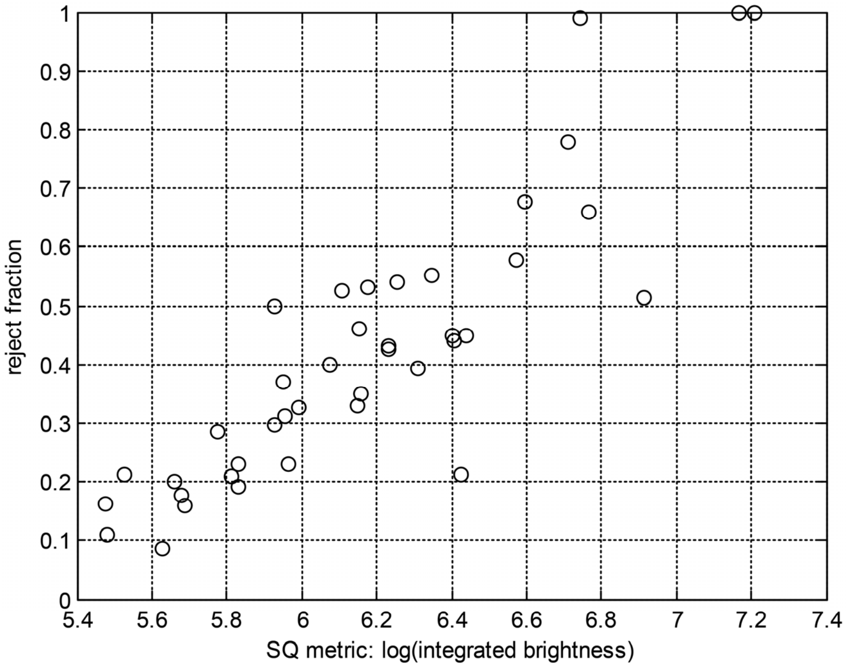

Figure 5. Comparison of the results of visual inspection (shown as the fraction of parts rejected per lot) versus the average of the log of integrated defect brightness for each lot.

6. CONCLUSIONS

The agreement between the automated surface quality inspection system and human operators clearly shows that this technique gauges essentially the same parameter as traditional surface quality inspection. But, the advantage of the instrument is that it accomplishes this measurement in a way that is quantitative, repeatable, and can be calibrated.

Furthermore, the authors do believe that the correlation between the automated surface quality inspection system and ringdown testing will be established with more extensive testing, and that there is a solid theoretical basis for linking the two. Specifically, both techniques are dependent upon the amount of light scattered by defects. In ringdown, light is scattered out of the system, creating a loss which reduces the decay time of the cavity. In the microscope, scattered light is captured and imaged by the system. To quantify this, consider that in a ringdown setup, the loss from each individual scattering center is simply described by:

$$\mathrm{Loss} = \frac{P_s}{P_{in}} \tag{1}$$

Where: P_s is the light scattered from a single defect
P_{in} is the light power incident on optic

The total cavity loss due to scattering is just the sum of the losses from each individual scattering defect.

In the surface quality inspection microscope system, which utilizes dark field illumination, only the non-specular scatter from a defect is collected and imaged (rather than rejected). In this case, the fraction of the incident light that is scattered is:

$$S_f = \frac{I \times \sigma}{I \times f_{ov}} \tag{2}$$

Where: S_f is the fractional scatter
I is the intensity of illumination in the field of view
σ is the defect scattering cross section
f_{ov} is the field of view (and also the illumination area)

This microscope itself has some internal transfer function (due to its own optical efficiency), the microscope objective has a limited numerical aperture, and the camera system has some photoelectric conversion factor that is less than unity. All this reduces the amount of scattered light that is measured by the sensor. This "total measured brightness" of a defect can be written as:

$$B_t = \varepsilon \times C \times t_{exp} \times \Omega \times I \times \sigma \tag{3}$$

Where: B_t is the total measured brightness by the microscope/CCD system
ε is transfer efficiency of the microscope
C is the conversion efficiency of the CCD sensor
t_{exp} is the exposure time
Ω is the solid angle of light collection of the objective
I is the intensity of illumination in the field of view
σ is the defect scattering cross section

Some substitution leads to:

$$B_t = (\varepsilon \times C \times t_{exp} \times \Omega \times I \times f_{ov}) \times S_f \tag{4}$$

Thus, the automated surface quality inspection microscope measurement depends linearly on the fraction of scattered light, just as does ringdown (although, in practice, it may be difficult to establish the precise value of the proportionality constant). Needless to say, several other factors, such as illumination wavelength, would have to be taken into account to directly relate ringdown and scattered light microscope measurements, but there doesn't appear to be any reason why these can't be calculated or measured empirically.

In practice, the maximum allowable S_f (scatter) can be specified for a laser optic over a user-selected field of analysis, f_{oa}, which is chosen to match the incident beam size. This S_f/f_{oa} specification, called the scatter density, can be applied across the usable clear aperture of a laser optic to directly specify the maximum allowable scatter loss *per beam diameter*. Since the technique presented here allows for the easy adjustment of f_{oa} (by simply making the area considered in the integration calculation the appropriate sub- or super-set of f_{ov}), it provides a straightforward and production-suitable method to measure this quantity.

In conclusion, it's widely understood that traditional inspection techniques for surface quality have practical limitations, and don't yield results that are repeatable or that correlate well with how a component performs in actual use. Various scatter and loss measurement techniques are available that more directly measure parameters of interest to the laser builder. However, conventional techniques such as cavity ringdown or scatterometry, while quantitative, are not practical for implementation as high-volume quality control tools. Also, they don't allow for easy alteration of the aperture under consideration. We propose that a useful metric for the optics buyer would be a specification that quantifies their acceptable level of scatter loss density, that is, the loss per unit area (for example in units of ppm/mm^2), since the typical application only uses a portion of a component's clear aperture in actual operation. Then, a technique, such as the total integrated scatter measurement method described here, could be used to ensure that scatter loss in any subaperture of an optic under test does not exceed that limit.

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