A statistical study of the relationship between surface quality and laser induced damage

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ABSTRACT

Laser induced damage of optical components is a concern in many applications in the commercial, scientific and military market sectors. Numerous component manufacturers supply "high laser damage threshold" (HLDT) optics to meet the needs of this market, and consumers pay a premium price for these products. While there's no question that HLDT optics are manufactured to more rigorous standards (and are therefore inherently more expensive) than conventional products, it is not clear how this added expense translates directly into better performance. This is because the standard methods for evaluating laser damage, and the underlying assumptions about the validity of traditional laser damage testing, are flawed. In particular, the surface and coating defects that generally lead to laser damage (in many laser-parameter regimes of interest) are widely distributed over the component surface with large spaces in between them. As a result, laser damage testing typically doesn't include enough of these defects to achieve the sample sizes necessary to make its results statistically meaningful. The result is a poor correlation between defect characteristics and damage events. This paper establishes specifically why this is the case, and provides some indication of what might be done to remedy the problem.

Keywords: Laser damage threshold, HLDT, damage testing, surface quality, SAD, inspection

1. INTRODUCTION

There's certainly no question that laser-induced damage of optical components is a very real problem which limits the performance of laser-based systems in a number of applications, resulting in costs to both users and manufacturers. Photonics product manufacturers have responded to the need for high laser damage threshold optics with a variety of specialized fabrication methods, products and services. In terms of component fabrication, these include surface cleaning and polishing techniques which are specifically intended to yield "low defect" surfaces. Just as important are coating deposition methods which minimize the presence of external contaminants, and which produce a particular thin film structure and stoichiometry thought to be less susceptible to laser damage. Additionally, there are various instruments for performing metrology related to laser damage threshold, as well as companies that provide third-party laser damage testing as a service. Needless to say, all this activity increases the price of high damage threshold optics relative to components that are not specifically qualified for this purpose. The problem, however, is that the exact mechanisms of laser damage have not been adequately characterized. Therefore, all the steps currently being taken to mitigate damage cannot be said to guarantee success.

Ideally, the specific physical characteristics of optical surfaces and coatings should be well correlated with laser damage events, and laser damage testing should provide meaningful predictions of optic performance with manageable test samples. While challenging to realize, this would enable manufacturers to consistently and deterministically produce optics which meet a given laser damage threshold, and would avoid building unnecessary costs into these products.

2. TRADITIONAL TESTING LIMITATIONS

The problem commonly encountered in defining a damage threshold specification for a given component is illustrated in Figure 1, which summarizes the results of laser damage testing on a single part. Specifically, this component was tested at numerous sites, at fluences ranging from 2 J/cm² to 55 J/cm² (at 1064 nm, 20 Hz repetition rate, 20 ns pulsewidth). Each time damage occurred at a particular site, the fluence level which caused damage was recorded. From this raw

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data, the probability of experiencing damage at each fluence level used in the testing was calculated, and these results are plotted as circles on the graph. Then, a calculation that attempts to utilize as much of the data as possible was used to fit the data and extract a “damage threshold” value for the part.

The final result of this calculation predicts that this component has a 0% chance of damage when exposed to fluences of 25 J/cm² or less, and a 100% probability of being damaged when irradiated at fluences of 86 J/cm² or higher. Yet, clearly, damage was recorded at a much lower fluence (5 J/cm²) than the 0% probability value. Additionally, the data demonstrate another common problem of testing: assuring that enough data is accumulated without unduly burdensome sample quantities.

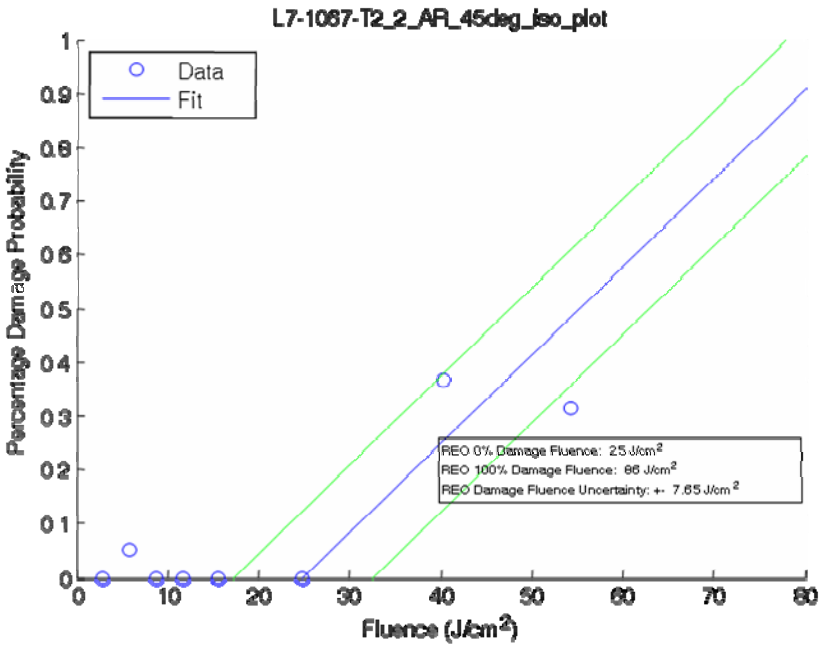

Figure 1. Laser damage threshold testing results for a single component exposed to fluences over the 2 J/cm² to 55 J/cm² range.

To a certain extent, this anomalous result occurred because the testing protocol used was not rigorously correct. This is because testing in strict accordance with ISO 11254 would typically only utilize fluences sufficiently high to ensure a reasonable probability of getting useful data. Lower fluences, where damage is not expected to occur, would simply be ignored. However, the fact that damage did occur at a low fluence highlights exactly how traditional testing protocols can yield results which are not entirely reliable. This should be no surprise to anyone who regularly works with laser induced damage. Nonetheless, LDT test results are rarely interpreted as the statistical statements that they are, but rather, are taken as absolute statements about a given optic.

We believe that the main reason that traditional testing routinely fails to accurately characterize and predict damage threshold (at least in the fluence/repetition-rate/pulsewidth regime considered here) is that the defects which give rise to damage are typically sparsely distributed over the aperture of an optic. This makes the probability of hitting one during laser damage testing extremely low, unless a very large number of test shots are used in the available test area (which is also problematic, since defects are then more likely to be irradiated multiple times resulting in “conditioning,” which can change the damage threshold). Also, not all defects are equal: defects consisting of certain contaminants may be more likely than others to cause damage. Testing is thus a relatively random process, which typically doesn’t utilize a large enough data set to be statistically valid. Furthermore, traditional damage testing fails to accurately record the correct fluence at which damage actually occurs. This is because it ignores the Gaussian intensity distribution of the incident laser beam and its location with respect to a damage-causing defect. Several other groups have made similar suggestions.[1,2,3]

The goal of the research presented here was to better characterize this situation. Specifically, we wanted to advance the state of knowledge regarding laser damage in a direction that might ultimately lead to a test that is truly predictive of the actual probability of damage at any fluence.

3. EXPERIMENT DESIGN

In order to achieve this goal, we combined traditional laser damage testing with automated surface quality inspection. A sufficiently large sample size (several thousand defects) was used to ensure the validity of subsequent statistical analysis. Our intent was twofold. First, we wanted to create a record of the overall surface quality of the parts under test and compare this to LDT testing. Second, we wished to establish a clear "before and after" picture of what types of defects caused damage, and to document the morphology of damage that resulted from them. Knowing the exact location of the defect which produced damage, together with the location of the input, also enabled us to determine the actual fluence (at the defect location) which caused damage. This corrected fluence was then correlated with defect size.

3.1 Devices under test

A total of 50 optical components were fabricated specifically for this testing. These were 1 inch diameter, flat, fused silica substrates, coated on one side for high reflection (nominally 99.9% at both 1064nm and 532 nm, at normal incidence). All of the parts were judged by trained inspectors to meet or exceed a 20-10 specification according to MIL-13830. Ten parts were coated at a time in five different coating runs. Ion beam sputtering (IBS) technology was utilized for thin film deposition.

3.2 Surface quality inspection

After coating, each part was measured to determine the distribution of defects across its entire clear aperture using our own automated surface quality inspection (AQSI) system.[4] This system is capable of identifying and imaging individual defects, and the size, brightness (under darkfield illumination) and location (xy coordinates) of each defect was recorded for each of the 50 parts. For this testing, we focused on defect count per area, and the ASQI was used only to provide an overview of the surface quality (SQ) of the parts. It may be expected that parts with poorer SQ (higher defect density) will have lower laser damage thresholds. Part of the aim of this study was to quantitatively test this expectation.

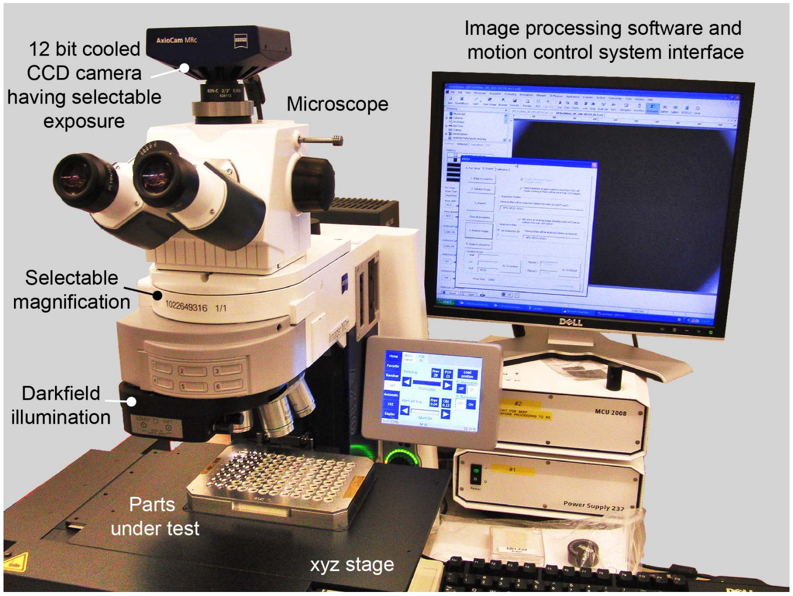

Figure 2. An automated surface quality inspection (AQSI) system which utilizes a microscope optical system and CCD camera to measure the brightness of light scattered from defects under darkfield illumination conditions.

3.3 Damage testing

All 50 parts were then subjected to laser damage testing. We used a modified version of an automated laser damage testing (LDT) apparatus.[5] Each part was divided into a hexagonal grid, and a single site at the center of each grid was irradiated. Testing was performed at approximately 10 different fluence levels, at about 10 sites for each fluence (for a total of 100 tests on each component, and about 5000 sites total). A Nd:YAG laser operating at the fundamental (1064 nm) wavelength was used. The laser pulsewidth was 20 ns, and the laser was operated at a 20 Hz repetition rate. Each site was exposed to 240 pulses (regardless of whether the site damaged or not), and testing was performed in general accordance with suggestions from ISO 11254, which specifies that a variety of beam parameters (e.g. beam diameter, fluence, etc.) and testing conditions be recorded. This system also incorporated an automated damage detection technique. Specifically, it acquired an image of each test location before laser irradiation. Then, another image was taken after laser exposure at the same location, and under the same illumination conditions (magnification, etc) to determine if damage occurred. The inspection of test sites is done using dark field, as opposed to differential interference contrast (DIC) microscopy.

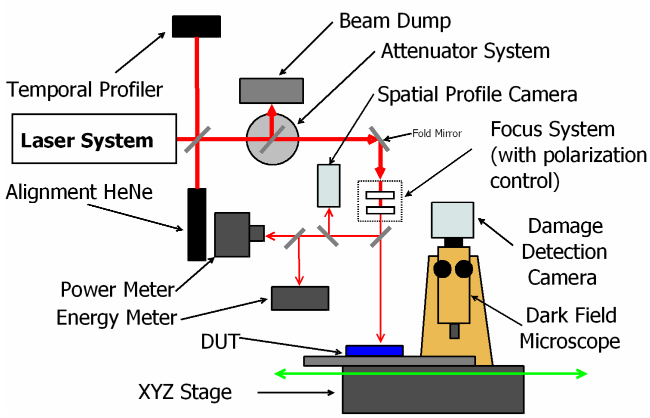

Figure 3. Schematic of the experimental setup used for laser damage threshold testing.

4. RESULTS

4.1 AQSI Testing

The combined results from the AQSI inspection of all 50 components is summarized in the histogram in figure 4. In this plot, defect size is defined as the square root of the total measured defect area; this metric is used since defects are not always round. As expected for “laser grade” (20-10 or better) optics, the defects identified are relatively small (mostly under 8 µm in size) and sparsely distributed (less than one defect per square millimeter).

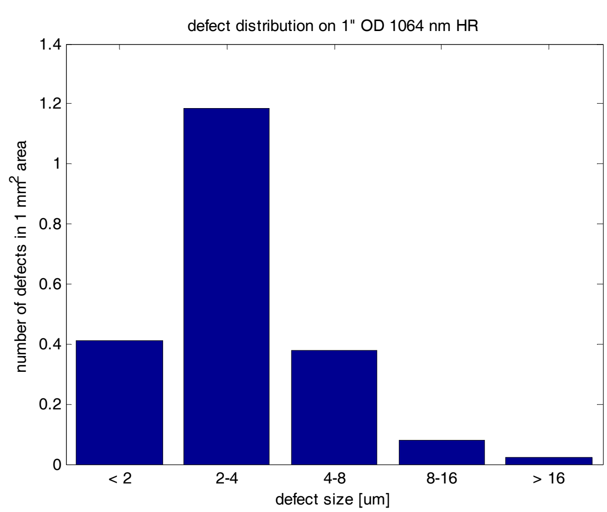

Figure 4. Histogram showing the size distribution of over 4000 defects identified by the AQSI on the 50 components under test.

4.2 Damage Testing

Figure 5 is a histogram of the results of laser damage testing for the 50 optics. More specifically, it plots the fluence at which the "first damage event" occurred for each of the 50 components.

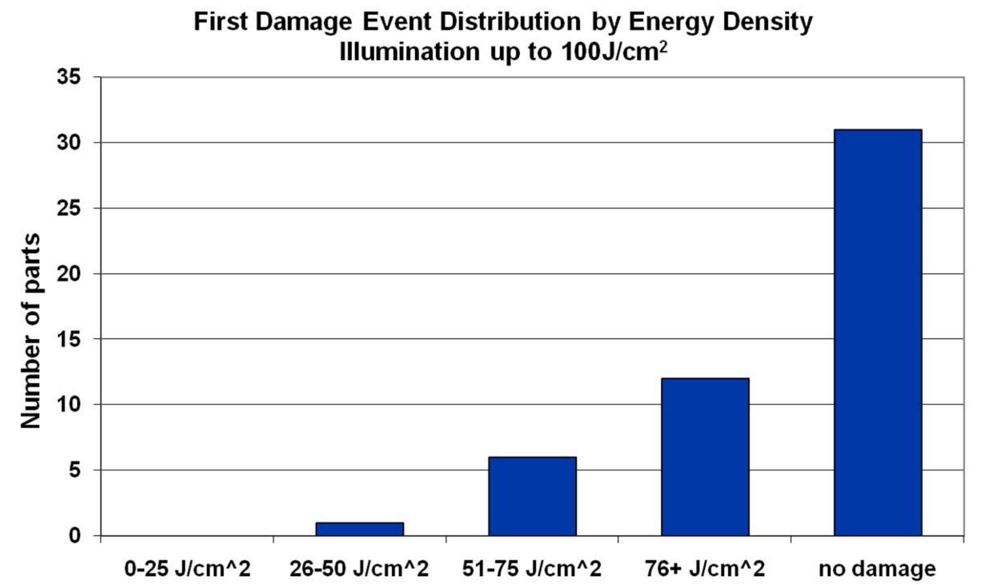

Figure 5. Histogram showing the "first damage event" results for the 50 components under test.

4.3 Comparison of ASQI and traditional LDT testing

The next figure combines the results of the previous two. Each circle represents the first damage event fluence for a single component. The laser fluence at which that component first damaged is plotted as a function of the defect density, as measured using the AQSI. This plot shows no correlation.

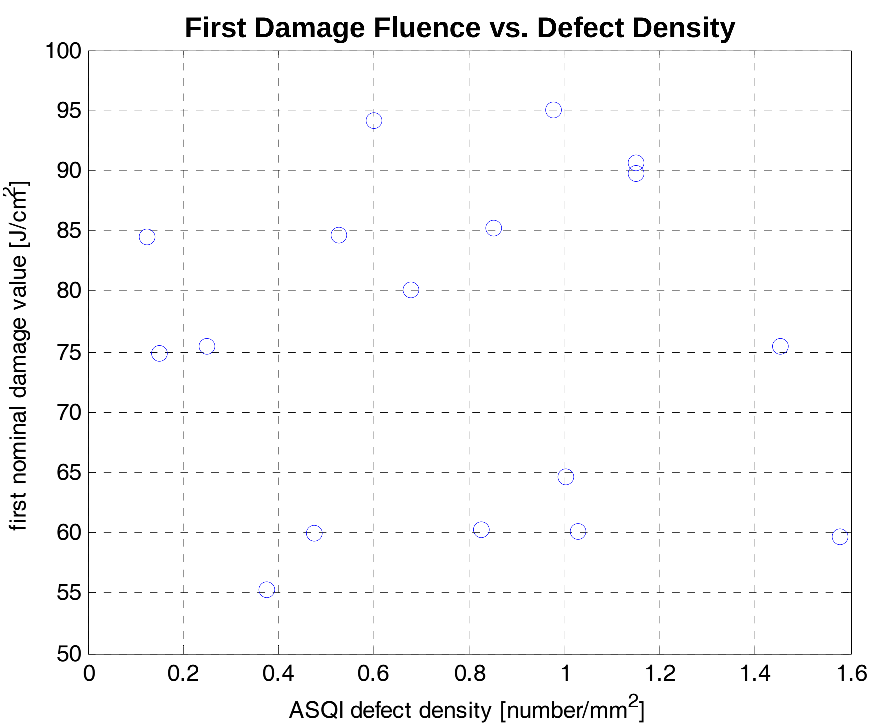

Figure 6. A plot of first damage fluence vs. defect density shows no correlation.

In order to understand this lack of correlation, we looked at the pairs of “before” and “after” images from the LDT system. Recall that the ASQI system provided a numerical summary (over many defects) of the SQ of any given part. The LDT system showed us the exact details of the SQ at the points on the part that were exposed to the laser test pulses.

Figure 7 shows five pairs of photos taken with the automated LDT test system. Each pair of pictures captures the same field of view on various optics both before and after laser damage testing. Each photo pair is reproduced at the same scale and under the same illumination and acquisition conditions (though image contrast may be enhanced for reproduction purposes). In each instance, the incident laser pulse was centered in the field of view, and the peak fluence is noted; the beam diameter is indicated in the first image pair. If a defect was present in the field of view, its size and position are also shown. From these image pairs, we can make several observations. First, in cases were damage occurred, a defect was usually present in the “before” image, but not always. Next, in cases of damage where a defect is identifiable, its size seems to play no role in the extent of the subsequent damage. Defects of a size that lead to damage in one case may not have caused damage in another. Thus, these results by themselves do not indicate any clear underlying behavior.

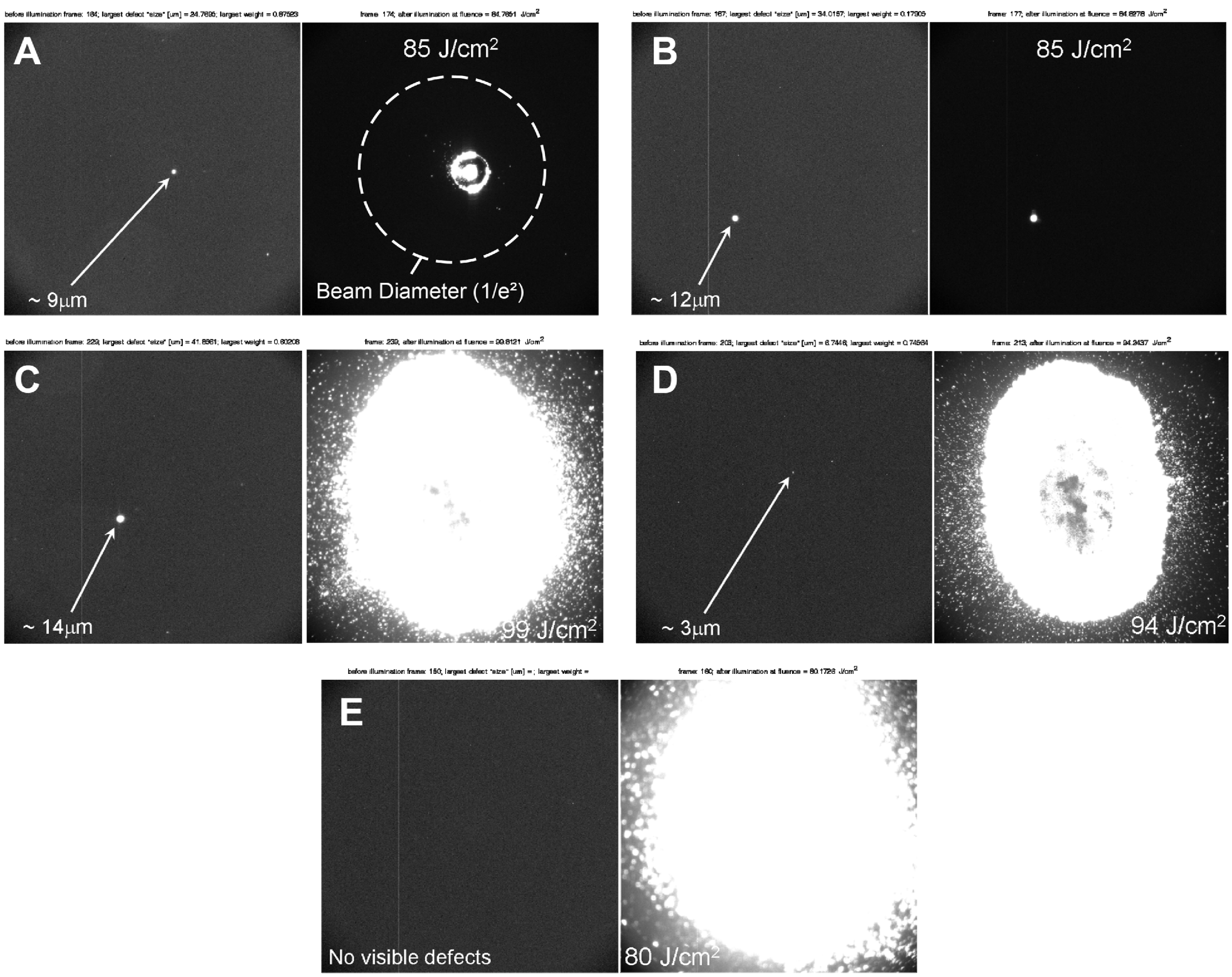

Figure 7. Photos of five regions on various components before and after laser damage testing (all at the same scale). The incident fluence at the center of each region pictured is noted, and the input beam diameter is indicated in photo pair A.

5. DISCUSSION

5.1 Considering actual laser fluence

Why is there no clear causal relationship between defect size and subsequent laser damage? We posit that it is because the defects are very small compared to the incident laser beam used for damage testing, and because the defects are sparsely and randomly distributed with respect to the Gaussian laser beam fluence profile (Figure 8). Because of this, a defect rarely experiences the peak beam fluence. As a result, traditional laser damage testing, which assumes that each defect is exposed to the peak fluence, typically yields erroneous results which demonstrate the same poor correlation found in this testing. In order to validate this theory, we used the position data for defects, collected using the automated LDT imaging system, to calculate the fluence that each actually experienced during laser damage testing.

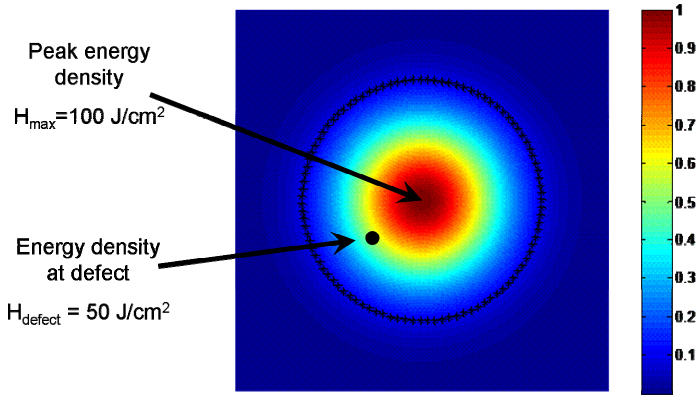

Figure 8. Knowing the precise location of the defect relative to the beam center, together with a calculated spatial profile of the beam (using measured beam parameters), allow the actual fluence at the defect to be calculated.

There were a total of 30 actual damage sites, found on 19 of the 50 components under test. Figure 9 is a histogram showing the number of damage events at each fluence level (now the actual fluence at the defect, not simply the peak fluence at center of the incident beam). In this chart, there appears to be at least some trend in the data, with higher fluences generally leading to more damage events. Moreover, there are relatively few “anomalous” results of damage occurring where no defects were imaged. We consider this an encouraging result in two ways. First, our LDT testing imaging system was adequate to detect a damage-causing defect in over 85% of cases and, second, there are relatively few “mystery” damage events that cannot be simply explained by the presence of a defect. While it may have been true that damage-causing defects are invisible to our dark-field visible-light inspection, this could only have occurred in a few cases.

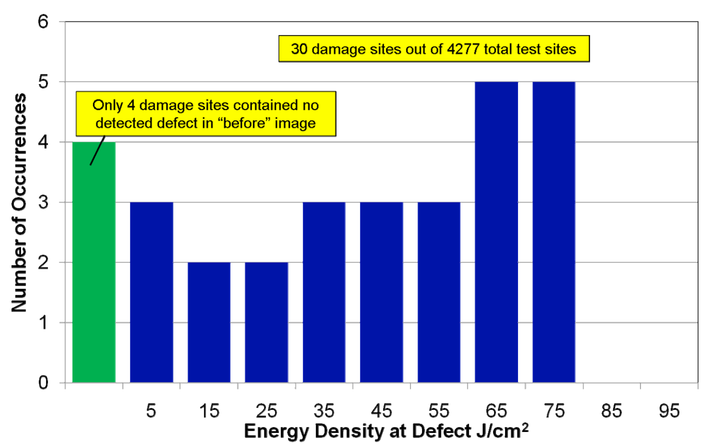

Figure 9. Histogram of the number of damage events for each fluence level at the defect.

5.2 Normalizing testing conditions

These results can be even better understood when the statistics of the testing conditions are examined in more detail. In particular, most of the defects were not centered with respect to the laser beam, and therefore experienced relatively low fluences. This is quantified in figure 10, which shows the frequency of actual fluence encountered at the defect for several different fluence levels. Here it is seen that a much larger number of defects were irradiated at fluences below 10 J/cm², leading to the comparatively large number of damage events at these lower fluences.

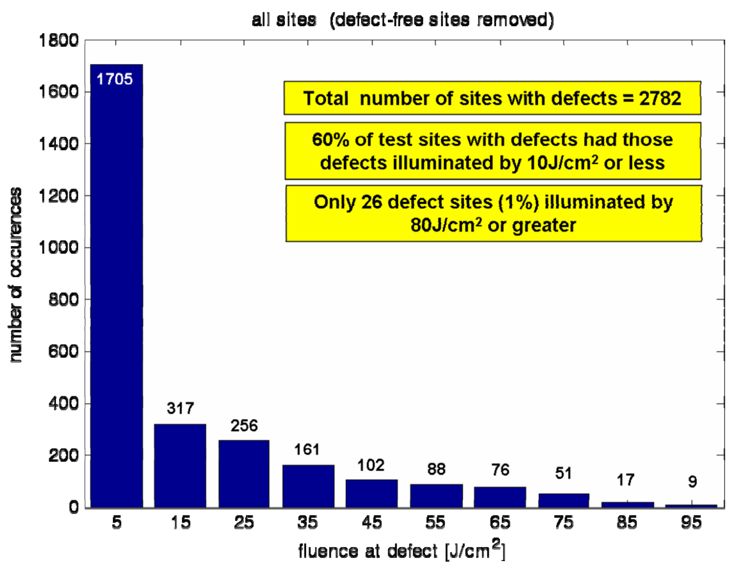

Figure 10. Histogram of the actual fluences at the defect sites.

Figure 11 plots the normalized probability of damage for the sample parts tested. Specifically, the number of damage events at each fluence level has been divided by the number of defect sites at which that fluence level occurred. Here, a clear correlation between higher fluences and increasing probability of damage is established. The top two fluence bins in the histogram (85 J/cm² and 95 J/cm²) are empty because of the low number of defects exposed to these levels (17 and 9 sites respectively). It is expected that a larger sampling size at these higher fluences would continue the trend of the chart.

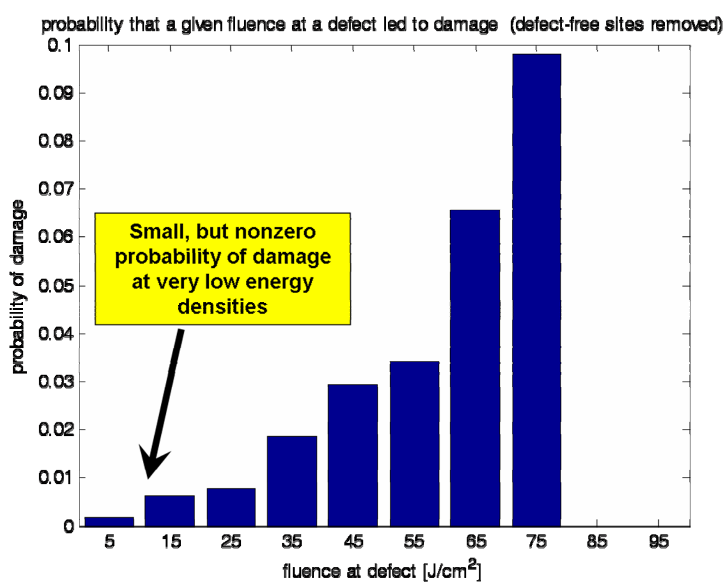

Figure 11. A normalized histogram of damage probability vs. fluence.

It should be noted that the chart shows that there is still a finite probability of damage at very low fluences. This is important, because traditional laser damage testing protocols would rate this sampling of optics with a relatively high damage threshold (specifically, above 55 J/cm² – see Figure 6). Yet, the probability for damage at low fluences, while small, is not zero.

The final figure, which shows the damage probability for various sized defects at three different fluence ranges, exhibits a further correlation that we might expect. Namely, that physically larger defects more readily damage than smaller defects. One result which we might not expect, however, is that even the largest surface defects (12 µm - 25 µm), illuminated with the highest fluences (>54 J/cm^2), still have less than a 35% probability of damage.

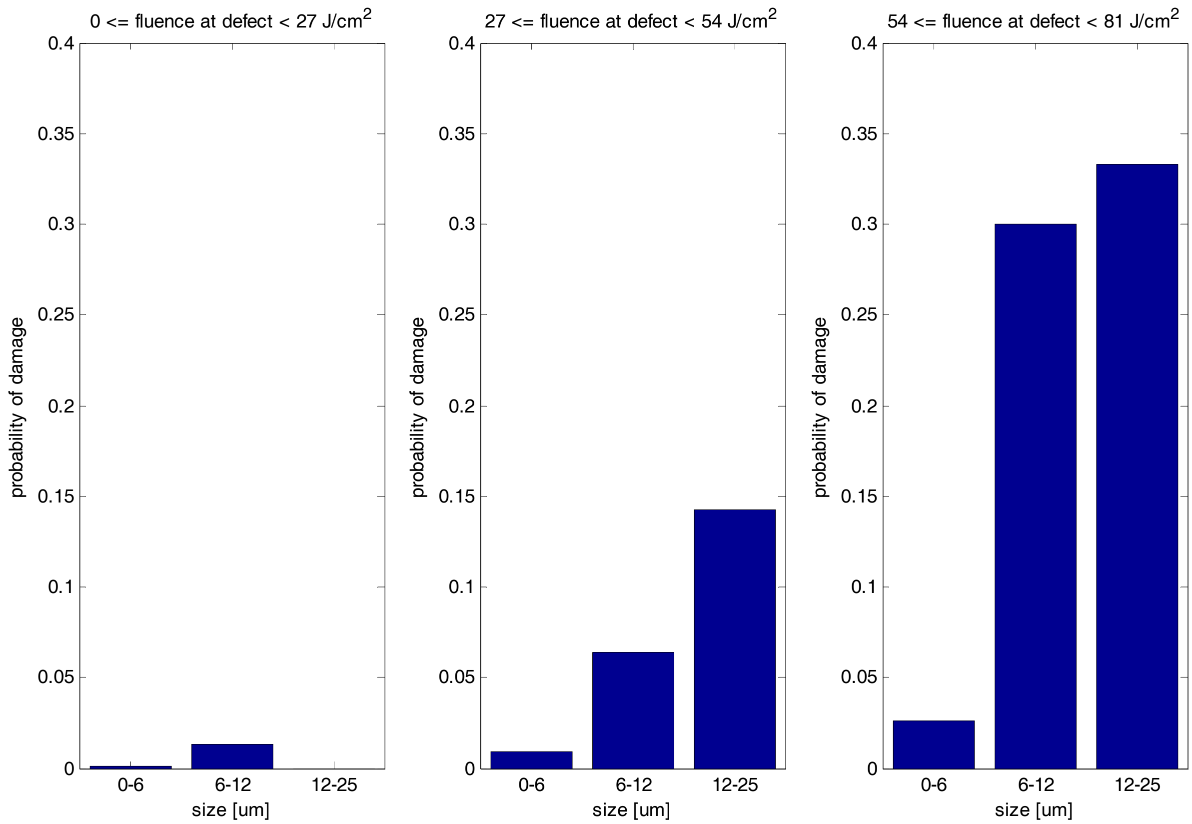

Figure 12. Damage probability vs. defect size, binned by energy density range.

6. CONCLUSIONS

Conventional laser damage testing protocols often fail to adequately characterize damage threshold principally because of simplifying assumptions about the test fluences. As a result, component sometimes suffer damage at much lower fluence levels than predicted by these statistically sparse tests. The long term result of this is that consumers of optical components often overspecify damage threshold on optics in order to ensure proper performance. However, this drives up the cost of optics unnecessarily (and still doesn't completely avoid damage events).

We believe that the approach presented here delivers realistic projections about the probability of laser damage at a given fluence. A key component of this method is the use of an automated LDT system with highly capable SQ inspection built-in to identify defects and note their position prior to damage testing, thus enabling the actual laser fluence at the point of any subsequent damage to be accurately calculated.

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