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Optical component reliability in high-energy laser systems: challenges and insights

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Abstract. The laser-induced damage resistance of large optical components remains an important limitation for the maintenance costs, reliability, and further development of high energy/high-power (HEL/HPL) laser systems. With numerous manufacturers providing different laser-induced damage threshold (LIDT) values in the nanosecond regime, a simple ranking based on numbers alone may not provide a clear picture of the best choice. Variations in testing procedures, albeit following the ISO 21254 standard, further complicate the selection process. By employing a comprehensive 1-on-1 test procedure, it becomes possible to observe various parameters that influence LIDT values. An overview on how the laser beam size, the spectral characteristics of the tested optic and possible contamination of the surface are influencing the LIDT values will be presented.

1 Introduction

High-energy/high power lasers (HEL/HPL) systems have become essential for numerous applications, including laser fusion research, industrial processing, space to Earth power transmission and directed energy weapons [1-5]. However, the reliability of large optical components within these systems remains a significant concern. In particular, the LIDT—the maximum fluence a component can withstand without sustaining damage—plays a pivotal role in system performance.

One significant factor affecting LIDT is surface quality, both of the substrate and the coatings. The presence of imperfections, scratches, and contaminants on optical surfaces can significantly reduce the LIDT, especially if we think about the nanosecond laser regime and it usually decreases with the wavelength [6-8]. Even minute defects can act as stress concentrators, leading to localized damage when exposed to intense laser pulses. Therefore, it is essential to understand the relationship between surface quality and LIDT in order to select robust optical components.

The standard procedure for testing the LIDT of various optics is described in the ISO 21254:2011 [9]. Some laser optics producers are performing the LIDT tests in-house, but these tends be doubtable. They provide convenience and control, but external validation by independent labs or third parties can help alleviate doubts and ensure the accuracy of the measurements

In this paper, we examine the challenges posed when testing optical components for HEL/HPL (operating in nanosecond pulse duration regime) systems, where probably the major parameter influencing the LIDT is surface quality and contamination. By examining real-world scenarios and employing a comprehensive 1-on-1 test procedure, the aim is to shed light on how different testing conditions influences LIDT. Lessons learned will facilitate the provision of information to manufacturers, engineers, and system designers, thereby contributing to enhanced reliability and reduced maintenance costs.

2 Experimental

Crystalline silicon (cSi) was selected as a bulk or substrate material for its availability, quality, surface uniformity and crystalline nature, which provides more consistent and predictable optical behaviour. Details regarding the LIDT damage mechanism of the cSi is shown in Table 1.

Table 1. Damage mechanism in cSi as a substrate/bulk material as compared to standard optical glasses.

Absorptive laser-induced damage	
Material matrices absorbs laser radiation homogeneously	✓
Low heat conduction in optical materials	✗
Heated and melted coating	✓
Absorption at local defect-driven damage:	
Local heating of inclusions, void	✗
Extreme temperature gradient	✗
Plasma generation	✓
Breakdown of material matrix	✗

Distinct features of defect-driven laser damage are the laser beam size and the test surface coverage. When investigating LIDT influence of the laser beam size, it is worth consider the following factors:

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– Small beam sizes might not cover a significant amount of defects
– Gaussian beam profile minimizes the area of peak intensity
– ISO 21254 requires a beam larger than 200 µm for Gaussian beams and at least 10 sites at identical fluence.
For the test surface coverage it is important to keep in mind the real application – enlarge dimension optics which are intended to withstand high-energy/high-power laser beams. Therefore, the test should be concluded on a optics with similar dimensions, while the test area should be significant for the intended application.

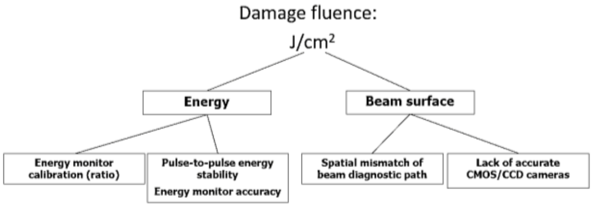

Fig. 1. Major LIDT measurement errors

If we try focusing to the beam surface errors, the LIDT measurement errors, which are related to the laser system used or with the energy/power measurement, could be fixed.
The LIDT test setup was previously described in [10]. A 1064 nm was selected for the test since it is probably the most used wavelength in the commercial LIDT testing, while the Si is almost transparent in this region.
A series of lenses were used in order to modify the laser beam dimension (from 44 to 484 µm) on the sample image plane.

3 Results and discussion

When employing a very small laser beam diameter for LIDT testing, substantial measurement errors can arise, leading to artificially inflated LIDT values for the tested sample. Moreover, just a fraction of the total sample clear aperture is actually irradiated by the laser beam.
The results in Fig. 2 show a rapid decrease in the LIDT value with the increase of the laser beam size, with almost one order of magnitude difference.

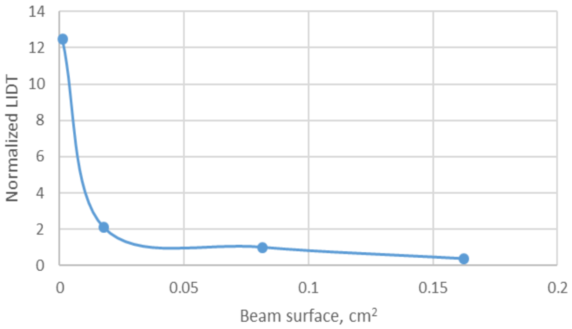

Fig. 2. The effect of laser beam size on the LIDT of the cSi sample.

As described in the ISO 21254 standard, the minimal recommended laser beam size of 200 µm should be followed up. The second point in the graph, related to a beam dimension of 161 µm is eloquent for this fact. Above this, one can observe a plateau region, with a slight decreasing trend with the increase of the beam size. This is directly related to the probability of irradiation of low-density surface defects by the increasing beam size.

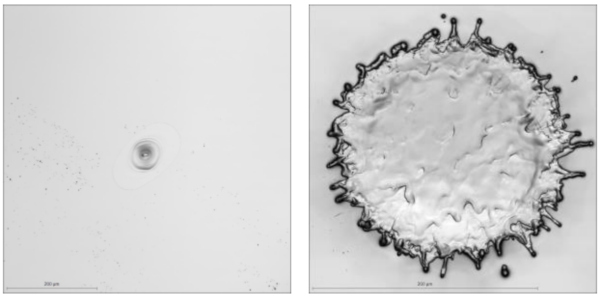

Fig. 3. Damage micrographs of the cSi using a 484 µm laser beam size for the minimum (lest) and high (right) fluence.

Given the above example, the general recommendation for those, which are measuring the LIDT, is to carefully design the LIDT setup, to measure correctly the beam diameter and to use >200 µm beam diameters. For those who are purchasing high-LIDT optics, they should have in mind the followings: ask for a test protocol, find similar test condition as in the intended employment and in case of batch purchase to ask for a LIDT test reference.

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