# What Laser Users Should Know About Fabrication of High Damage Threshold Optics

A whitepaper from:

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## Executive Summary

High power lasers are enabling new product designs and new manufacturing processes across the globe. One reason is the ever-increasing average and peak power of continuous and pulsed lasers. Another is the greater number of wavelengths from deep ultraviolet through far infrared for which high power lasers are available.

Accompanying the growth of laser applications is the escalating demand for high-quality laser and laser system optics. There is a low tolerance for unreliable machines or for inconsistent production processes. All components of the laser system, including the laser optics, must be consistently reliable.

IRD Glass is supporting the laser industry's growth as a premier supplier of high damage threshold laser (HDTL) optics and valued manufacturing partner of laser and laser system OEMs.

This white paper summarizes approaches used by IRD Glass before, during, and after optical fabrication to ensure consistently high damage thresholds for custom reflective, transmissive, and absorbing laser optics.

## Higher Power Laser Sources

The demand for optical components capable of handling high power laser beams has grown by double digits in recent years. This growth has been largely a response to the steadily increasing power from both continuous wave (CW) and pulsed solid-state fiber and disk lasers.

The increasing average power of CW and pulsed lasers with millisecond to nanosecond pulse widths has helped to drive the growth of laser cutting, drilling, welding, marking, and 3D printing applications.

Meanwhile, high power ultrafast lasers have quickly moved from the laboratory into production. With picosecond and femtosecond pulse widths, these laser sources are the basis for new laser processing applications in semiconductor, electronics, and medical device production.

Another important trend is the growing number of wavelengths, particularly those in the deep UV and visible (e.g. blue, green) portions of the electromagnetic spectrum, for which high power lasers are enabling new applications.

### Demanding High Quality for Every Component

Users of laser optics are demanding ever-higher levels of quality for all applications. Variations between components and production batches that lead to unpredicted degradation or failure of the laser equipment or the laser process is 'a killer' for industrial users and suppliers.

The common approach to specifying quality of high power laser optics is to define a laser-induced damage threshold (LIDT). LIDT is the maximum value of laser radiation which an optical component will handle with a zero probability of damage. Refer to ISO 21254-1:2011 for information on laser-induced damage threshold testing.

Specifying and testing HDTL optics can be complicated. Many variables affect the damage threshold. Failure is statistical, depending on laser, environmental, and other variables unrelated to the optical component. Furthermore, the way test data is interpreted can also influence a component's perceived reliability.

Therefore, it is important to define up-front the requirements of the optical component and a plan for consistently achieving them. With clear requirements in hand, the manufacturing team can move forward with confidence to develop a production process that addresses the special demands of HDTL optics.

Some designers choose a tapered design in order to reduce the divergence (numerical aperture) of the light from the homogenizer. However, since the efficiency of tapered rods is influenced by dimensional precision, this higher quality output also comes at a cost.

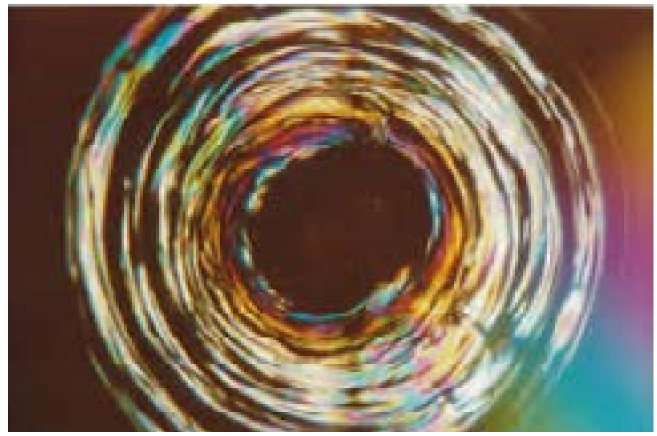

*Figure 1: Example of laser-induced damage of a high power laser optic. Source: Wikipedia.*

## What Fabrication Processes Must Control for High Damage Threshold Laser Optics

How and why an optic fails depends in part on the characteristics of the laser source. CW and long-pulse pulsed lasers produce thermal damage that begins at defects on or below the surface of the component. On the other hand, ultrafast pulsed lasers produce breakdown of an optic by plasma formation and ablation.

However, independent of the laser type, the following features of the substrate must be controlled during fabrication since they contribute to the damage threshold of a laser optic.

- Glass composition and homogeneity

Achieving a consistently high damage threshold begins with selecting the substrate material. Optical properties critical to damage threshold, namely absorption and scattering, vary with composition and details of the glass manufacturing process. For example, low absorption of fused silica correlates to a low -OH content. Striae (local variations in the index of refraction), impurities, and inclusions introduced in glass processing affect the damage threshold through optical interference and absorption effects.

- Surface finish

Surface defects, such as cracks, scratches, digs, and voids, reduce the threshold for laser damage. They do this mainly by producing localized laser interference, heating, and reductions of the mechanical strength of the glass.

- Subsurface damage

Cracks beneath the surface produced in machining brittle materials such as glasses and ceramics reduce the damage threshold as they propagate from thermal stresses generated by laser irradiation.

- Residual stress

Stresses locked into the surface and subsurface regions during fabrication can contribute to premature failure of the optic surface through fatigue or aging mechanisms.

- Contamination by residual grinding and polishing compounds

Grinding and polishing compounds from optical fabrication processes may become trapped within small cracks or pits. These can reduce the damage threshold of polished surfaces by reacting with the glass and locally changing its mechanical properties. Residues may also react with the energy source (e.g. electron beam or ion beam) during subsequent coating of optical surfaces. The reaction products may change the composition of the surface or redeposit onto the optical surface as debris that affects coating adhesion.

- Dust, dirt, and other unwanted material

Impurities on the surface may preferentially absorb the laser beam, adding to heating of the surface.

- Coatings

Many laser optics include complex metal or dielectric coatings comprising tens of layers for enhanced reflection (mirror) or transmission (window). Coatings are often designed to reflect or transmit the laser wavelength and others in the visible portion of the spectrum associated with cameras and process sensors.

Damage thresholds depend on the materials of both the substrate and coatings and the optical fabrication processes. Coatings may amplify defects in the substrate so that the damage threshold of a coated optic can be significantly less than that of the improperly fabricated, uncoated optic.

## How IRD Glass Ensures Consistent Quality of High Damage Threshold Laser Optics

IRD Glass has produced high power laser components for over 20 years. From this experience, the team has learned how to control the quality parameters for coated and uncoated high damage threshold optics.

### Substrate material selection

As stated earlier, the substrate material is one key to determining the damage threshold. The material also affects the cost of the components. Higher purity glasses are generally more expensive. Furthermore, glasses vary in machining and polishing rates and, therefore, processing times because of differences in mechanical properties and chemical compositions.

While fabricating millions of optical components from many materials, IRD Glass has learned a lot about the products from major suppliers of optical materials, including the strengths and limitations of the suppliers' manufacturing processes.

IRD Glass brings to a manufacturing partnership expertise to advise the customer's optical design team on the type and manufacturer of glass that will yield the most consistent performance and an optimum tradeoff between cost and quality. from ordering the raw material to shipping and everything in between, including coating.

Their experience takes you well beyond the spec sheets. IRD's manufacturing team can assist with specifying the material based on subtle differences in homogeneity of the material and its properties. Some of these differences are not even detectable using classical inspection methods yet they can affect processing behavior and laser-induced damage threshold.

## Optical surface fabrication

Preparing the optical surfaces is the most critical step in fabricating HDTL optics.

Fabricating precision optics involves complex processes requiring control of mechanical and hydrodynamic forces, chemical reactions, and structural effects on glass surfaces and sub-surfaces. Defects (scratches, digs, voids, cracks, sleeks) and residual stresses on the optical surfaces will affect the finished component's robustness. These defects will also affect any coatings applied to the surfaces.

The following sections provide a glimpse at how IRD approaches the production of high damage threshold optics considering their cost and quality goals.

- Grinding & Lapping

Fabrication of laser optics begins with multiple steps of each of two processes: (1) fixed abrasive grinding and (2) loose abrasive grinding, also known as lapping. Each step gets the optic closer to its finished shape and size.

In addition, each of the steps in grinding and lapping removes open and closed subsurface micro-cracks, referred to as subsurface damage (SSD), produced in the previous step. A 'rule of thumb' in optical fabrication is that the SSD is approximately 0.3 times the mean diameter of the abrasive grit or particle. Therefore, each successive step in grinding and lapping uses a smaller grit size to reduce the SSD.

Process parameters, including pressure, velocity, temperature, and type and size of the abrasive particles, are selected for the specific optical material being fabricated. The material removal rate and roughness produced in grinding and lapping vary with the fracture toughness properties of the glass or ceramic. There are also differences in the reaction of optical materials to water and other chemicals used in these processes.

Since polishing, the next process, is time-consuming and not as cost-effective as grinding, a major goal of grinding and lapping is to minimize the SSD that must be removed in polishing.

- Polishing

Many of the considerations for material removal and control of surface finish in Grinding and Lapping also apply to mechanical and chemical polishing processes.

In polishing HDTL optics, the main goals are to eliminate subsurface cracks and to produce a surface having a finish better than 10 Å rms.

To accomplish these goals, IRD applies results of internal and external research. This research

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documents the relationships between process parameters used in fabricating HDTL optics and quality of the polished surfaces. See Figure 2 for an example.

- Cleaning

Cleaning throughout substrate fabrication removes lubricants, wear debris, and abrasive agents from rough and fine grinding, lapping, and polishing. Residual debris can interfere with coatings. It can also react with the glass to create local changes in optical and mechanical properties.

IRD uses several cleaning methods throughout fabrication, including:

- Hand cleaning with isopropyl alcohol.
- Cascaded baths with multiple detergents to remove organic compounds.
- Rinsing in deionized (DI) water.
- Oven baking to dry components.
- Spin drying.
- Washing with proprietary solvents to remove organic and inorganic materials.
- Hydrofluoric (HF) acid etching for stress relief.

The ideal cleaning method depends on the material being fabricated and the component's finish. Scratches are key to determining the laser damage threshold of an optic. Therefore, it is necessary to protect the optic from being scratched during cleaning. It is also necessary

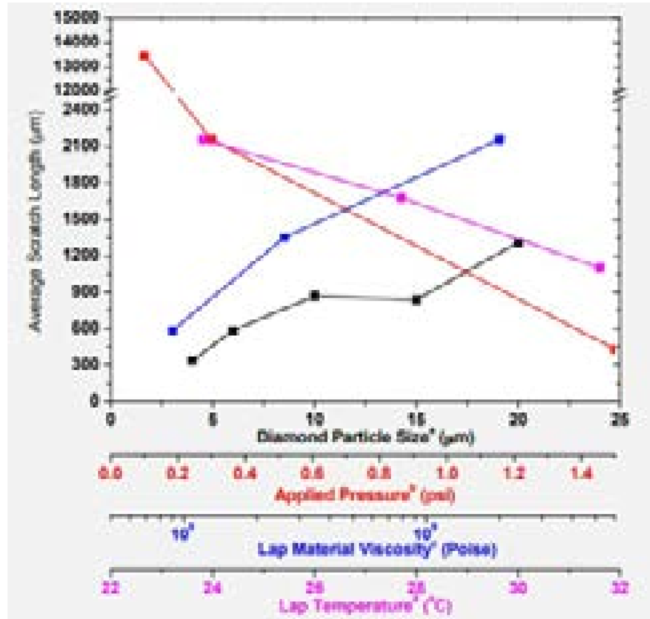


*Figure 2: Relationship between average scratch length and several process parameters in polishing. Reference: Suratwala, T., 2015, "Lecture 13: Glass Finishing (Grinding & Polishing)", presentation slides, Glass Processing Course (Lehigh University; Spring 2015), International Materials Institute for New Functionality in Glass (IMI-NFG), LLNL, delivered March 5, 2015.*

to prevent debris (e.g. fibers from polishing) from being added to the surface during cleaning (see Case Study below).

In most cases, HDTL optics require a customized cleaning process instead of a general optics cleaning process.

## Inspection

Since HDTL optics require exceptional and consistent quality, inspection during process development and for quality assurance in volume production is critical.

During process R&D, destructive tests are used to document relationships between process parameters and quality metrics. For example, HF acid etching is used to determine the depth of subsurface damage (SSD) in relation to abrasive size and other grinding, lapping, and polishing parameters.

Meanwhile, in production, optical inspection tools, including those listed below, are used for non-destructive evaluation:

- Stereo microscope for low to medium magnification inspection.
- High-intensity lights against a dark background for identifying surface defects—refer to MIL-PRF-13830B.
- Interferometer for measuring roughness and for characterizing debris, pits, and scratches.
- Interferometer for measuring flatness.
- Differential interference contrast (DIC) microscope for defect analysis.
- High magnification microscope with polarized and unpolarized lighting and stitching capability for large area inspection.

## Packaging

Proper packaging preserves the optical surfaces during shipment. In most cases, custom packaging supports the component on its edges or on non-critical surfaces outside the clear aperture. The packaging also prevents the component from shifting during shipment.

## Case Study: Large Surface Area Precision Mirror for a High Power Laser Cutting System

IRD has demonstrated proficiency in producing high damage threshold laser optics, including a large area rectangular slotted mirror pictured below (Figure 3).

The customer, a leading global manufacturer of laser-based machine tools, originally approached IRD after struggling to find an optics supplier capable of meeting cost and quality requirements for the mirror.

During the Design for Manufacturability (DFM) review, the IRD team suggested that a bevel be added to the edges of each slot at the mirror surface. The bevel would replace a sharp edge that would generate fibers on the slot edge during cleaning. If not removed, the fibers would contribute to coating defects that would reduce the damage threshold.

The customer changed the design, adding a small (50 µm or 0.002 inch) bevel, the maximum allowable given the required clear aperture.

Even with this small bevel, IRD implemented a special cleaning process, one that would avoid creating fibers along the beveled-edges of the slots. The small bevel and custom cleaning process have contributed to mirrors that consistently achieve the laser damage threshold specification.

To achieve the cost and volume goals, IRD invested in process development and in a custom production cell. Through these efforts, the cycle time was reduced from over 8 hours per piece initially to less than 1 hour per piece in volume production.

Today, IRD Glass is one of only a few qualified suppliers in the world. They are also the preferred supplier for this component of a high power laser cutting system.

## Fabricating Consistent Quality, High Damage Threshold Laser Optics

IRD Glass has maintained a 98%+ on-time delivery rate for more than a decade.

How have they accomplished this while maintaining competitive lead times?

In part, by having robust, well understood, and documented manufacturing processes that ensure consistent yields and production times.

There is also IRD's commitment to delivery. Reports from customers in industries as diverse as aerospace, medical devices, telecommunications, and semiconductor equipment testify to IRD's position as a leader in precision custom optics manufacturing.

Contact IRD if you are designing a new high power laser optic or have an existing design for which you are looking to develop a second source.

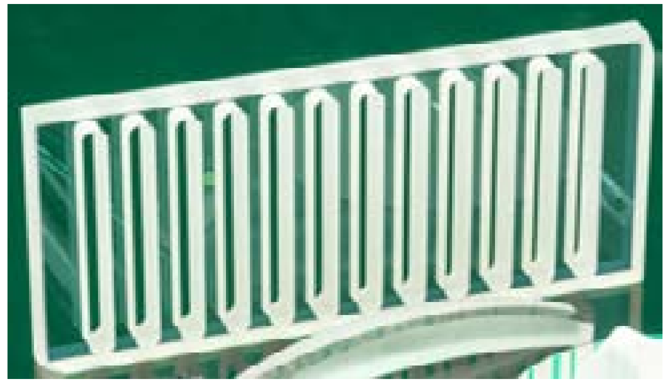

*Figure 3: Slotted high power laser mirror. Maintaining the specified clear aperture while ensuring a clean surface for coating requires close control of the bevel on the slot edges at the mirror surface.*

For your new design, IRD will provide a no-cost Design for Manufacturability Review. The technical team will review the design, making sure it can be produced with optimum cost, quality, and consistency.

If you wish, IRD will provide a cost estimate for prototype and production volumes. For designs currently in production, IRD engineers will show you the benefits of their consistent, industry-leading quality and on-time delivery for your components.

"Your biggest challenges are our biggest successes!"

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## About IRD

Minnesota-based IRD has been manufacturing precision glass and ceramic components since 1982. The company has two sites:

- IRD Glass in Litchfield, Minnesota—30,000 square feet (3,000 square meters), including a 10,000 square feet (1,000 square meters) addition completed in 2019.

- IRD Ceramics in Alexandria, Minnesota—10,000 square feet (1,000 square meters)

The company's 75+ employees proudly serve some of the most demanding global customers including Honeywell, TDK, Collins Aerospace, 3M, CyberOptics, Trumpf, Alcon, L3, and Agilent. Steady growth of 10% year-over-year for the last 5 years has come from long-term partnerships and strategic manufacturing agreements in which IRD has manufactured custom designs of precision optical components.

While the company does not design optical components, it works closely with its customer's designers and engineers to create designs that most cost-effectively and reliably provide the required performance.

Recently, IRD has expanded its manufacturing capabilities, including investments for sapphire windows, high power light homogenizers, and laser reflector cavities.

IRD is veteran-owned, ITAR registered, and holds several certifications, including ISO 9001:2015.