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# FY07 LDRD Final Report A Fracture Mechanics and Tribology Approach to Understanding Subsurface Damage on Fused Silica during Grinding and Polishing

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## Disclaimer

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# FY07 LDRD FINAL REPORT
# A Fracture Mechanics and Tribology Approach to Understanding Subsurface Damage on Fused Silica during Grinding and Polishing
05-ERD-067

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The objective of this work is to develop a solid scientific understanding of the creation and characteristics of surface fractures formed during the grinding and polishing of brittle materials, specifically glass. In this study, we have experimentally characterized the morphology, number density, and depth distribution of various surface cracks as a function of various grinding and polishing processes (blanchard, fixed abrasive grinding, loose abrasive, pitch polishing and pad polishing). Also, the effects of load, abrasive particle (size, distribution, foreign particles, geometry, velocity), and lap material (pitch, pad) were examined. The resulting data were evaluated in terms of indentation fracture mechanics and tribological interactions (science of interacting surfaces) leading to several models to explain crack distribution behavior of ground surfaces and to explain the characteristics of scratches formed during polishing. This project has greatly advanced the scientific knowledge of microscopic mechanical damage occurring during grinding and polishing and has been of general interest. This knowledge-base has also enabled the design and optimization of surface finishing processes to create optical surfaces with far superior laser damage resistance.

There are five major areas of scientific progress as a result of this LDRD. They are listed in Figure 1 and described briefly in this summary below. The details of this work are summarized through a number of published manuscripts which are included this LDRD Final Report.

In the first area of grinding, we developed a technique to quantitatively and statistically measure the depth distribution of surface fractures (i.e., subsurface damage) in fused silica as function of various grinding processes using mixtures of various abrasive particles size distributions. The observed crack distributions were explained using a model that extended known, single brittle indentation models to an ensemble of loaded, sliding particles. The model illustrates the importance of the particle size distribution of the abrasive and its influence on the resulting crack distribution. The results of these studies are summarized in references 1-7.

In the second area of polishing, we conducted a series of experiments showing the influence of rogue particles (i.e., particles in the polishing slurry that are larger than base particles) on the creation of scratches on polished surfaces. Scratches can be thought of a as a specific type of sub-surface damage. The characteristics (width, length, type of fractures, concentration) were explained in terms of the rogue particle size, the rogue particle material, and the viscoelastic properties of the lap. The results of these studies are summarized in references 6-7.

In the third area of etching, we conducted experiments aimed at understanding the effect of HF:NH$_4$F acid etching on surface fractures on fused silica. Etching can be used as a method: a) to expose sub-surface mechanical damage, b) to study the morphology of specific mechanical damage occurring by indentation, and c) to convert a ground surface containing a high concentration of sub-surface mechanical damage into surface roughness. Supporting models have been developed to describe in detail the effect of etching on the morphology and evolution of surface cracks. The results of these studies are summarized in references 8-9.

In the fourth area of scratch forensics or scratch fractography, a set of new scratch forensic rule-of-thumbs were developed in order to aid the optical fabricator and process engineer to interpret the cause of scratches and digs on surfaces. The details of how these rules were developed are described in each of the references included in this summary (1-9). Figure 2 provides as a summary of some of the more commonly used rules-of-thumbs that have been developed in this study.

In the fifth and final area of laser damage, we demonstrated that the removal of such surface fractures from the surface during optical fabrication can dramatically improve the laser damage resistance of fused silica optics exposed to high-peak power laser light. This effort involved utilizing the techniques and scientific understanding developed in the four areas described above and implementing them to design, facilitize, and monitor optical fabrication processes to create surfaces that contain little or no sub-surface mechanical damage (See Fig. 3).

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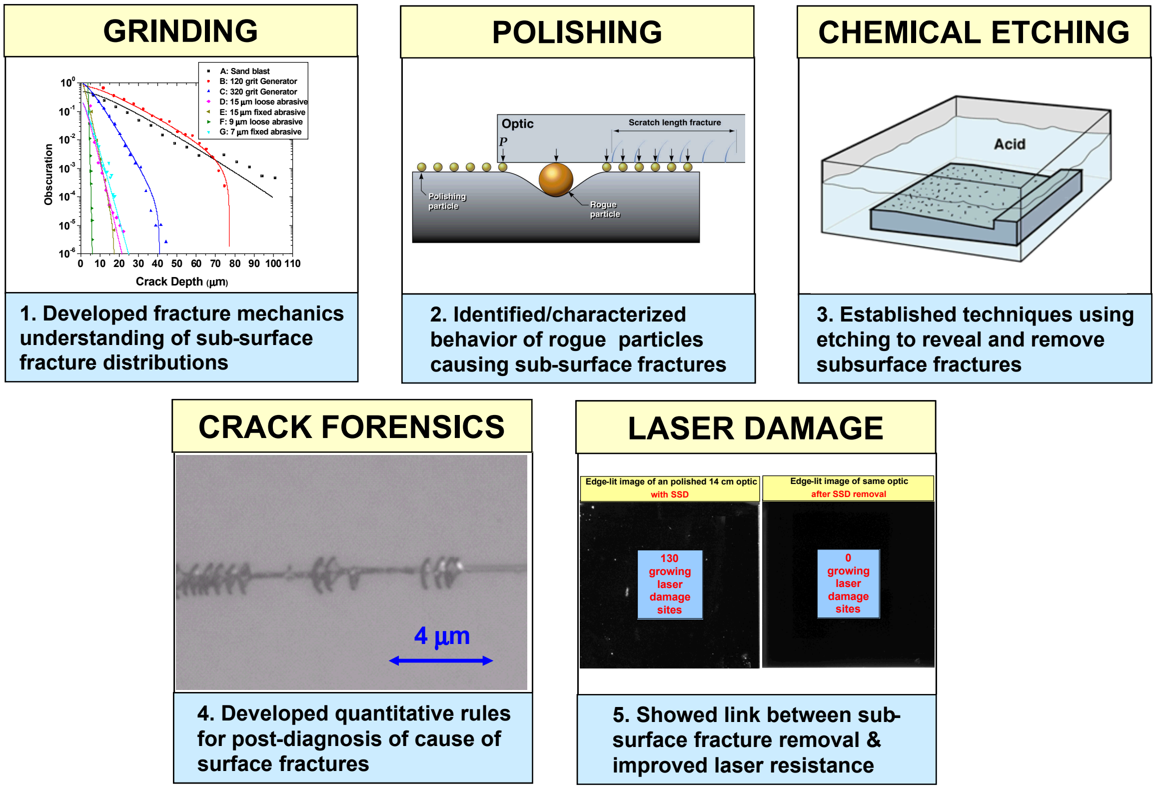


**GRINDING**

1. Developed fracture mechanics understanding of sub-surface fracture distributions

**POLISHING**

2. Identified/characterized behavior of rogue particles causing sub-surface fractures

**CHEMICAL ETCHING**

3. Established techniques using etching to reveal and remove subsurface fractures

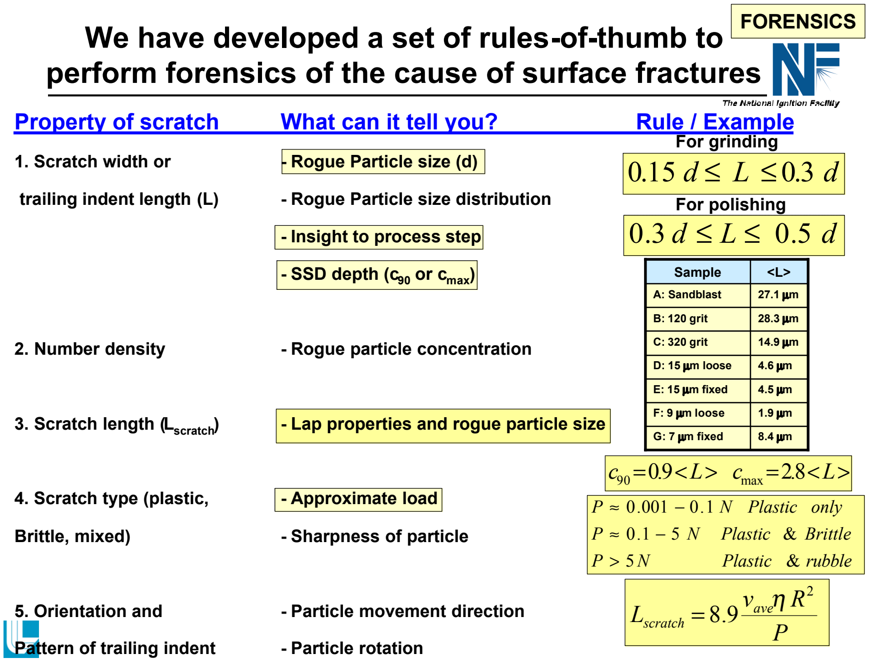
**CRACK FORENSICS**

4. Developed quantitative rules for post-diagnosis of cause of surface fractures

**LASER DAMAGE**

5. Showed link between sub-surface fracture removal & improved laser resistance

**Figure 1:** Five major areas of scientific progress that was achieved as result of the LDRD effort (05-ERD-067).



FORENSICS

## We have developed a set of rules-of-thumb to perform forensics of the cause of surface fractures

| Property of scratch | What can it tell you? |
|---|---|
| 1. Scratch width or trailing indent length (L) | - Rogue Particle size (d)<br>- Rogue Particle size distribution<br>- Insight to process step<br>- SSD depth ($c_{90}$ or $c_{max}$) |
| 2. Number density | - Rogue particle concentration |
| 3. Scratch length ($L_{scratch}$) | - Lap properties and rogue particle size |
| 4. Scratch type (plastic, Brittle, mixed) | - Approximate load<br>- Sharpness of particle |
| 5. Orientation and Pattern of trailing indent | - Particle movement direction<br>- Particle rotation |

**Rule / Example**

For grinding

$$0.15\,d \le L \le 0.3\,d$$

For polishing

$$0.3\,d \le L \le 0.5\,d$$

| Sample | <L> |
|---|---|
| A: Sandblast | 27.1 µm |
| B: 120 grit | 28.3 µm |
| C: 320 grit | 14.9 µm |
| D: 15 µm loose | 4.6 µm |
| E: 15 µm fixed | 4.5 µm |
| F: 9 µm loose | 1.9 µm |
| G: 7 µm fixed | 8.4 µm |

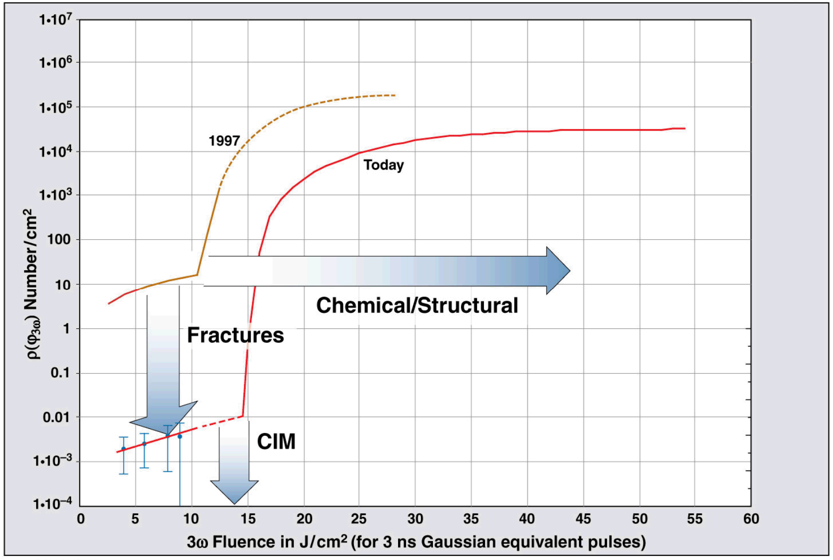
$$c_{90} = 0.9 <L> \quad c_{\max} = 2.8 <L>$$

$$\begin{array}{ll} P \approx 0.001 - 0.1\,N & \textit{Plastic only} \\ P \approx 0.1 - 5\,N & \textit{Plastic \& Brittle} \\ P > 5\,N & \textit{Plastic \& rubble} \end{array}$$

$$L_{scratch} = 8.9\frac{v_{ave}\eta R^2}{P}$$

**Figure 2**: A summary of some of the scratch forensic rules-of-thumb that have been developed.

## 3 ½ orders-of-magnitude improvement in laser damage resistance has been achieved as a result of finishing R&D



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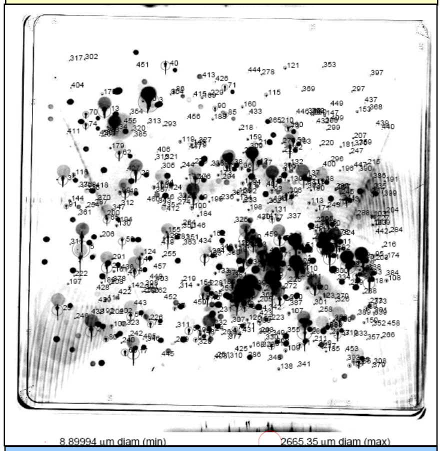
## Recent tests on PDS illustrate the increased laser damage resistance of new 3ω processes

*The National Ignition Facility*

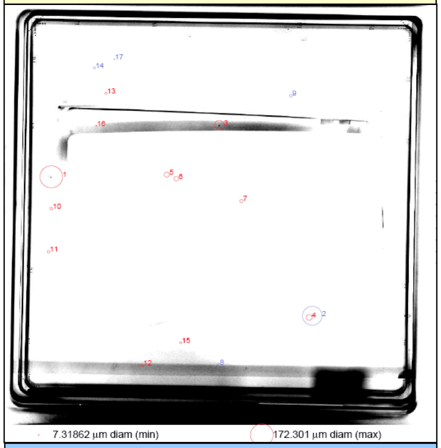
**FODI images of 1ω and 3ω surface finishes**

**1ω finish GDS 710203**



**37 shots; max 9.6 kJ 3ω;**
**448 sites; max size 2665 μm**

**3ω finish OWFL 272046**



**61 shots; max 9.6 kJ 3ω;**
**5 sites; max size 172 μm**

Figures 3: (a) Plot of the laser damage density as function of 3ω laser fluence illustrating the dramatic improvement in laser damage resistance of fused silica surfaces as result of removing surface fractures by improvements in optical fabrication. (b) FODI images from the NIF laser illustrating the improved laser performance which has been strongly influenced by the improvement in optical fabrication of the fused silica surfaces.