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Scratch Forensics

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Scratch Forensics

Tayyab Suratwala, Phil Miller, Mike Feit, and Joe Menapace

Scratches on optical components which are formed during fabrication, cleaning, handling and end-use, are widespread and almost always detrimental. The impact of scratches on the end-use of the optic includes increased optical scatter, reduced system performance, and reduced strength. In the case of optics used in high intensity laser applications, prevention of scratches is paramount because they are closely associated with laser damage.

Evaluation of the characteristics (dimensions, location on optic, shape, and orientation) of a scratch can serve a powerful tool to identify the cause of the scratch and lead to mitigations to prevent their reoccurrence. It is likely that opticians have used such techniques for hundreds of years. In recent years, by applying techniques of fracture mechanics and tribology, several new semi-quantitative rules-of-thumb have been developed allowing one to estimate the size and shape of the scratch inducing asperity or rogue particle, the load on the particle, the depth of the fractures in the scratch, and properties of material housing the rogue particle. The following discussion reviews some these techniques, which as a whole, we refer to as 'Scratch Forsenics'.

1) What Causes Scratches? Scratches are a line of localized fractures and/or plastic deformations that occur on surfaces as a result of an asperity or particle which mechanically loads the surface of an optic above some critical load as it slides relative to the optic surface.

To illustrate how scratches are formed below we describe the formation of a polishing scratch. However, these concepts are of a general nature and are equally applicable to scratches created during other fabrication steps, during handling and during end-use where a particle or asperity comes from different sources. Scratches caused during polishing can be particularly detrimental because material removal rates, during polishing, are typically very small relative to the depth of the scratch. Thus very long times are often needed if scratches are to be removed by polishing.. Hence, many times the optic must be returned to grinding, which is essentially starting the optical fabrication process over again. This can be very costly and time consuming in cases where scratches on the optical surface are unacceptable.

During polishing, small (less than a few microns) particles of polishing compound are suspended in an aqueous fluid to form a slurry which is loaded onto the optical surface by means of a polishing pad or pitch. The average load per particle in such cases is typically very low ($P \ll 10^{-6}$ N) and average stresses on the optical surface are many orders-of-magnitude lower than the fracture or yield stress of the material. Under such conditions no scratching occurs. However, in the presence of even a single isolated particle (i.e. a

rogue particle) which is large relative to the mean particle size of the slurry, the load can become high enough to cause stresses sufficient to initiate fracture or plastic deformation on the surface of the optic (see illustration). The stick-slip action of the rogue particle as it moves relative to the optic leads to a tensile stress on the trailing edge of the particle where it contacts the optic. Since brittle materials fracture orthogonal to the direction of maximum principle tension, the trajectory of the particle is recorded by a series of small fractures or chatter marks. Thus scratches can also be referred to as a series of 'trailing indentation' fractures.

It is important to recognize that it is the rogue particles that are ultimately the cause of all scratches. Such rogue particles may be foreign particles from the environment, contaminates from other operations such as grinding media, dried slurry agglomerates, dislodged pitch particles from the lap, loose glass particles, or asperities from pad or other optic contact. Regardless of their origin the most effective method of preventing scratches is to remove the sources of rogue particles or prevent rogue particles from coming into contact with the optic.
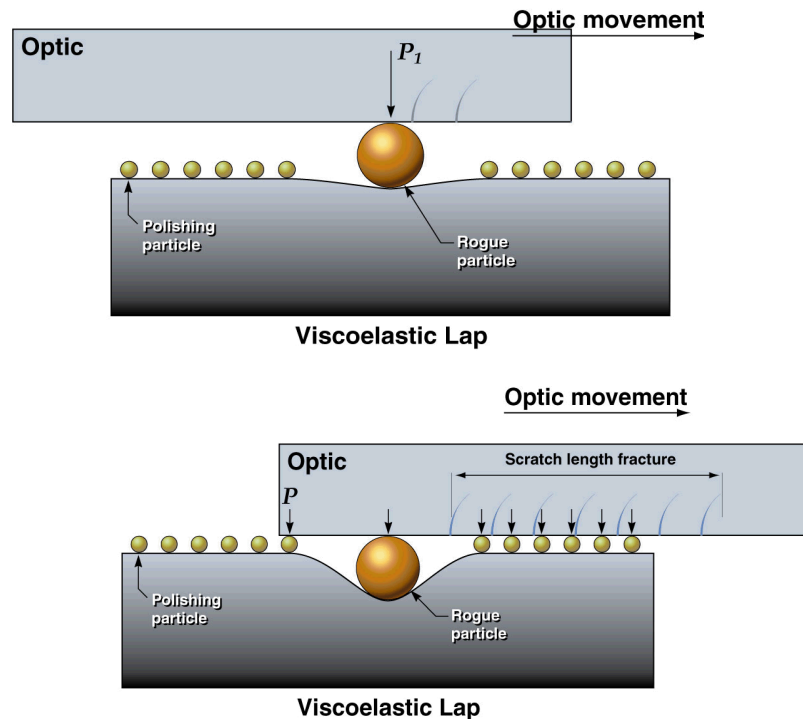
2) Types Of Scratches. Scratches can be caused by rogue particles or asperities which are either blunt or sharp. In general, scratches caused by blunt particles are typically a series of trailing fractures. In contrast scratches caused by sharp particles often leads to a combination of plastically deformed materials and trailing fractures. The types of fractures and their extent is also largely dependent on the load impressed on the optic by the rogue particle: 1) at low loads (P < 0.05 N), particularly in the presence of a sharp particle, a plastic trench is formed without fractures; 2) at intermediate loads (0.1 N < P < 5 N) well defined radial (or trailing indent) fractures along with lateral cracks are

observed; 3) at higher loads (P > 5 N), the plastically deformed track fractures into a rubble-like appearance, and lateral and trailing indent cracks are less pronounced [Swain; Lawn]. The identification of the types of fractures and the presence of plastic deformation provides clues to the shape of the rogue particle as well as the approximate load that was present during the formation of the scratch.
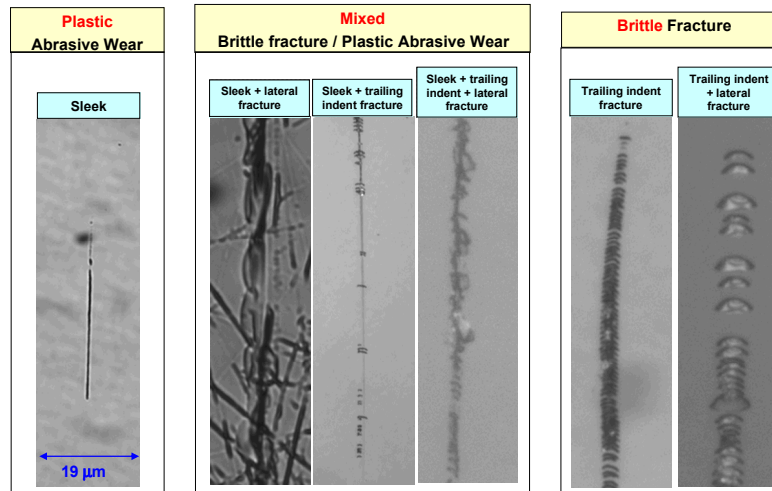
3) <u>Relationship Between Width and Rogue Particle Size</u> The width of a scratch provides insight about the size of the rogue particle. For a spherical particle, Hertzian fracture mechanics can be used to predict the size of the contact zone between the surface and the rogue particle. However, in practice rogue particles are usually not spherical, thus predictions regarding the size of the particle become less certain. However, in experiments using rogue particles of known size that were intentionally added to polishing slurries we correlated the width of scratches (w) with particle size (d) and find that found that:

$$0.3\,\boldsymbol{d} \leq \boldsymbol{w} \leq 0.5\,\boldsymbol{d}$$

In other words, the width of the scratch is roughly 30-50% of the apparent size of the rogue particle. For example, if one observes 100 μm wide scratches, it is likely that rogue particle responsible for their formation is approximately 200-300 μm. Given this one can rule out that the possibility that such a scratch was caused by say 15 μm particles of which may have been the size of the grinding media used in the previous steps in the process.

4) <u>Relationship Between Width And Depth</u> The width of the scratch has been found in our studies to be related to the depth of the fracture. Since ultimately the depth is determined by the load on the rogue particle and knowing that the load range is limited, we can use the following rule-of-thumb to probabilistically predict the depth of scratch:

$$c_{90} \cong 0.9\,w$$

In other words, if you have 30 μm wide scratch, you have a 90% probability of being able to remove it if you remove 0.9*30 or 27μm. This rule is particularly useful for assessing how much material must be removed in order to remove a scratch, which in turn answers

whether it is more economical to continue polishing or to return the workpiece to an earlier step in the process.

5) Relationship Between Length And Lap Properties Our studies have also shown an interesting and useful relationship between the length of the scratch and the lap properties. The average length of scratch (L) has been found to increase with the size of the rogue particle which is approximated by:

$$L \cong 8.9 \frac{v_r \, \eta \, R^2}{P}$$

where v_r is the average relative velocity of the particle relative to the optic surface, η is the viscosity of the lap, P is the apparent load on the rogue particle and R is the rogue particle radius. This relationship stems from the fact that length of scratch during polishing is governed by the time it take for the rogue particle to penetrate into the lap; when the rogue particle has penetrated completely, the load on that particle is reduced to the point where it can not initiate mechanical damage and hence the scratch stops (second part of first figure).

The Figure below illustrates the general trends of measured scratch lengths as a function of rogue particle size, pad viscosity (due to temperature and material changes), and applied pressure. The trends in the plot are consistent with the above equation.
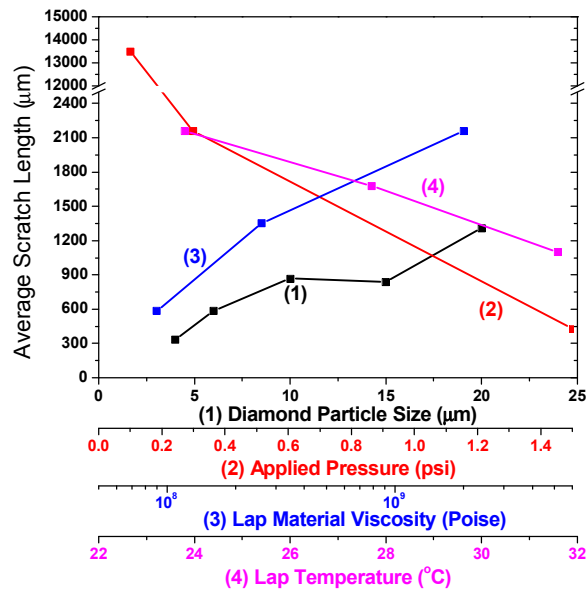
6) Scratch Forensics: A Case Study Consider, for example, a scratch found on an optic after intermediate polishing of fused silica glass using a polyurethane lap and 0.5 μm Ceria polishing compound (see micrograph below). The scratch is 1.9 μm wide and 130 μm long. From the microstructure, one concludes from the orientation of the trailing indent fractures, the rogue particle or asperity is traveling from left to right relative to the optic surface. Also, the rogue particle has both a blunt and a sharp character due to the presence of both trailing indent fractures and plastic deformation (sleek) observed in the

microscope image. Based on these types of features of the scratch, it can be concluded that the load causing the scratch is approximately 0.1 -1 N. Notice also that the width of the trailing indent fracture is different along the scratch suggesting the particle has a more complex shape and is possibly rotating or twisting at various asperities on the particle. The largest width of the scratch is 1.9 μm, hence the size of the rogue particle is likely 3.8-5.7 μm. Finally from the known scratch length on can estimate the time of contact knowing some of the viscoelastic properties of the lap. If various types of laps are being used in the process one may be able to determine which one using the equation for scratch length above.
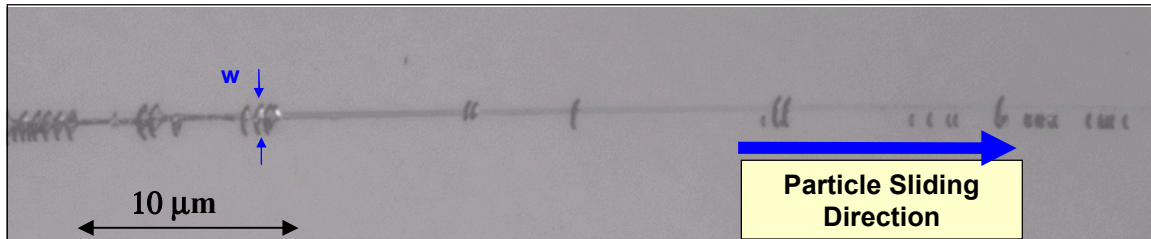
You may now see and appreciate scratches in a new light whether you are an optician who makes optics for a living or an end user who may just be frustrated from a CD/DVD that is scratched and skips. The next time you see a scratch you may be tempted to look at is more carefully with a Loop or a microscope to try out some of the scratch forensics techniques described above.

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