Sub-surface mechanical damage of fused silica glass during grinding by various sub-aperture tools with and without ultrasonics

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During optical fabrication, the grinding process removes material via surface microfractures generation at relatively fast volumetric removal rates compared to polishing. However, this inherently comes at a penalty of leaving behind subsurface mechanical damage (SSD), which needs to be removed during subsequent process steps. Removing SSD from the final optic is critical to reduce surface scatter, increase material strength, and/or enhance laser-induced damage resistance (1).

In this study, the SSD depth after grinding fused silica glass with a comprehensive set of sub-aperture fixed abrasive grinding tools (cup, wheel, belt, pad, and rotary face mill (with and without ultrasonics)) and process parameters have been statistically measured using the taper wedge technique (2, 3) and evaluated. More specifically, various grinding processes were conducted on polished, round, flat fused silica glass samples with a diameter of 10 cm. The diamond-based grinding tools evaluated included: cup (D7 resin, D15 metal, D46 metal) from Satisloh; wheel (D15 metal, D46 metal) from Satisloh; belt-on-wheel (9 µm and 45 µm diamond in resin belt) from OptiPro; multilayer fixed diamond pad/foam (6 µm Trizact™ from 3M on blue foam from Satisloh); and rotary ultrasonic face milling (35 µm, 90 µm, and 125 µm abrasive sizes in metal host) (OptiSonic™ from OptiPro).

The SSD depth distribution measured using the MRF or Taper wedge polishing technique are shown in **Figure 1** as obscuration (which is proportional to crack area) as a function of depth in the workpiece. The dominant factor controlling SSD depth was found to be the abrasive size regardless of the tool type and process conditions (**Figure 1a**). In addition to abrasive size, significant reduction in SSD depth was achieved by: 1) reducing the load distribution on the abrasive particles via increase in tool contact area and/or decrease in mechanical loading; 2) using a more compliant host tool medium; and 3) in a more novel way, using ultrasonics. Combining low abrasive size, larger contact area, and a compliant host, the 6 µm diamond in a resin matrix (Trizact™) on a foam pad led to very low SSD depth (~4.6 µm).

With the rotary face mill tool, the use of ultrasonics consistently led to a SSD depth reduction (ranging from 17-34%) (**Figure 1b**). A fracture mechanics-based model (schematically shown in **Figure 2**), where the relevant normal load is parallel to the feed direction, has been developed to explain how ultrasonics leads to lower SSD depth. The key factors, supported by finite element stress analysis and load measurements (not shown), are: 1) the initiation of fractures at higher **z** heights during the tool's ultrasonic vertical oscillations, thus propagating less deep into workpiece; 2) reduction in load (and hence reduction in fracture propagation distance) due to smaller tool-workpiece feed direction contact area (again caused by higher **z** heights relative to depth of cut); 3) upward movement of the tool during oscillation leads to fracturing toward the surface instead into the depth; and finally 4) at tool's lowest point of oscillation cycle, there may not be enough time for the fracture to propagate to its full length.

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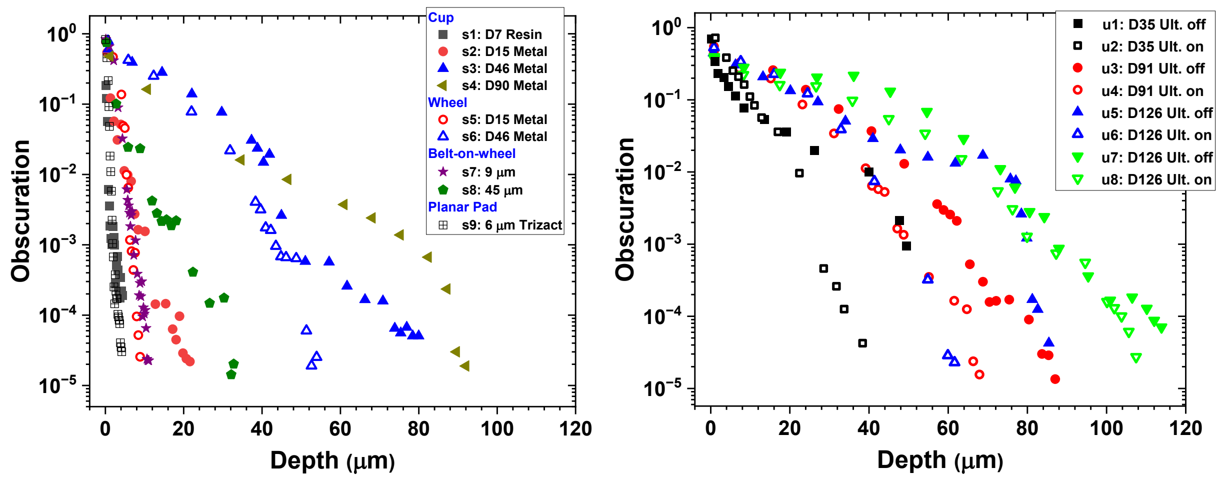

(a) **(b)**

Figure 1. Measured SSD depth distributions for various sub-aperture grinding tools.

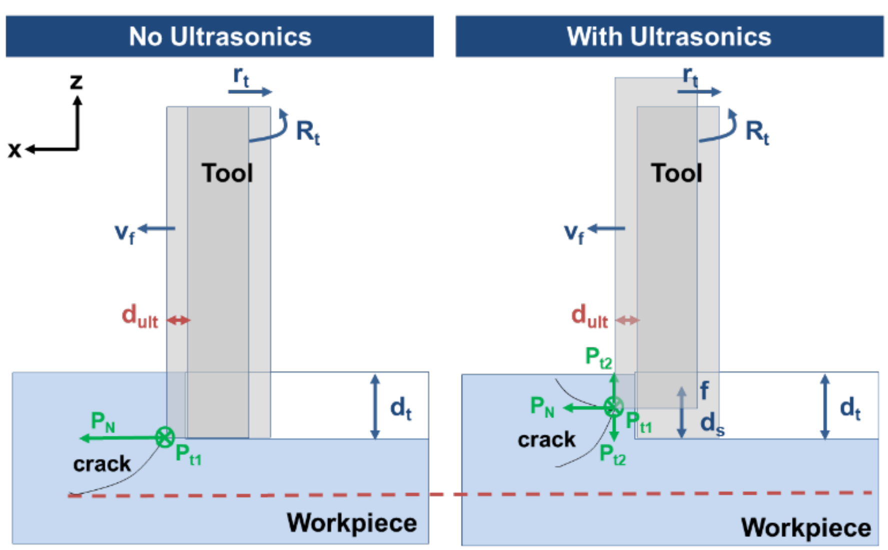

Figure 2. Comparison of proposed mechanical loading and fracture propagation using a rotary face mill grinding tool without ultrasonics (left) and with ultrasonics midway through upward or downward motion (right). r_t=tool radius, R_t=tool rotation rate, v_f=feed velocity, d_t=depth of cut, d_s=ultrasonic vertical oscillation, f ultratsonic frequency, d_{ult}= feed motion during one ultrasonic oscillation, P_i are various mechanical load (i=N for normal load, $t1$ & $t2$ for tangential loads)