Relations between subsurface damage depth and surface roughness using the Abbott Firestone curve

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Abstract:
Subsurface damages (SSD), which are introduce during grinding process of optical components for high power lasers applications, act as initiator for laser damage and are responsible of the low lifetime of these components. The knowledge of the SSD depth is essential to remove the damaged layer of the optical component during the last finishing step of grinding. However, existing methods to measure the SSD depth are either destructives or costly and complicated. Thus these methods are hardly useable industrially. That is why many studies have been made on the relation between the SSD and the surface roughness of grinded glasses. These studies founded several relations between the SSD depth and the peak to valley roughness (Rt), but the observed relations between these two parameters change with the grinding mode used and with the surface roughness measurement methods. In our study, the relations between SSD and surface roughness are widely explored to find a better and easier way to assess the SSD depth. For that purpose other surface roughness parameters are measured, especially the one from Abbott Firestone curve. Several grinding modes are tested, from rough grinding to finishing, with loose or bound abrasives. Finally, the accuracy of the relations between SSD and surface roughness is also studied. The results show that the $100f_{Mr}^2$ parameter from the Abbott Firestone curve is more accurate than Rt for an assessment of the SSD depth.

Keywords: subsurface damage, surface roughness, Abbott Firestone, fused silica glass

1 Introduction
Fused silica optical components are used in fusion class laser facilities as Laser Megajoule and the National Ignition Facility to transport and focus laser beams. Due to the high fluences, these laser beams can cause damages on the optical components surface, damages that grow with each laser shots and lead to unusable optics. In other hands, manufacturing steps of optics, from grinding to polishing, are known to introduce mechanical cracks in the subsurface of the glass, known as SSD (subsurface damage). Actually, during grinding step, the diamond abrasives act as indenters [1] that embrittle locally the material. Early works have shown that these damages can notably be precursors of laser damages and thus limit greatly the lifetime of optical components [2]. By consequence, the reduction of SSD during the manufacturing process is very important for the production of high fluence laser resistant optics.

The removal of SSD during each manufacturing steps of an optic need the knowledge of the SSD depth. That is why, the characterization of SSD is the subject of many studies and several methods have been developed to measure it. These methods can be classified in two parts: the destructive one and the non-destructive one. For the destructive methods, the principle consists generally in achieving either a local wear (ball dimpling [3] or MRF dimpling [4]) or a global wear (e.g. taper polishing or MRF taper [5]) on the piece to reveal the micro-cracks whose depth can then be measured by conventional microscopic observation. Another method consists of following, during successive etchings of the optic in a HF bath, either the evolution of peak to valley surface roughness or the decrease of contaminants [6]. For non-destructive methods, light microscopy can be used as whitelight tomography or confocal fluorescence microscopy [7] to characterize the SSD. However these methods are less accurate than the destructive one and limited to small areas of characterization. So, an easy method to assess the SSD depth would be very precious for the manufacturing process of the optics in order to define the depth of each grinding step. That is why many studies try to
define an empirical relationship between the surface roughness, which is easy to measure, and the depth of defects under surface.

First, Preston [8] reported that the depth of subsurface defects is three times higher than the Peak-to-Valley roughness. The scaling factor observed between SSD depth and Rt roughness are equal to 4 for Hed [9], 1.4 for Randi [10] and 9.1 for Miller [11]. The discrepancy in the proportional factor is mainly due to the various preparation methods and measuring principles used for both surface roughness and SSD [6]. In all of these studies only the peak to valley roughness was taken into account and no information is given on the accuracy of the relationship between the SSD depth and the surface roughness. In a previous study we investigate the Abbott-Firestone curve [12] or bearing area curve which describes the surface texture of an object. The curve allows assessing the average depth of valley of the roughness profile and the relative volume fraction of cracks existing in the surface. We demonstrated that the percentage of valley \((100-Mr)\) from the Abbott-Firestone curve can be correlated to the SSD depth [13].

In the following study, we investigate the relationships between several surface roughness parameters and the SSD depth (including the peak to valley surface roughness \(R_t\), the mean surface roughness \(R_a\), the root mean square surface roughness \(R_q\) and the Abbott-Firestone parameters). A lot of grinding experiments have been made where abrasive grain size and cutting parameters vary. Two modes of abrasion are also tested (bound abrasive or loose abrasive). We determine the best indicator of the SSD depth and calculate the accuracy of the relationships between the SSD depth and the surface roughness parameter. The best indicator found is also compared with the results of other authors.

In the first section, the sample preparation and associated characterization are briefly described. Then we explain the method for the comparison of the different relationships between the SSD depth and the different surface roughness parameters. Results are finally presented and discussed.

2 Experimental and methods

2.1 Samples surface preparation

Two types of materials were used for this study: square-shaped fused silica glass (HOQ from Heraeus) samples (100x100mm \(^2\) x 20mm thick) were used for bound abrasive grinding tests, and Round-shaped Corning 7980 fused silica samples (50 mm diameter and 10 mm thick) were used for loose abrasive grinding tests.

For bound abrasive grinding we used an OPTOTECH SMP500-2C grinder machine. In order to have a good repeatability of the surface roughness measured we control temperature of the spindle of the machine to have a stabilized process for each test. Additionally a well known - in terms of depth of SSD - roughing was first performed on each sample in order to have the same reference state that guarantees removal of residual SSD in the first grinding step of the study itself. Four bound abrasive wheels were used from rough grinding to finishing (D126, D91, D64 and D25 grit). Except for finishing (D25 wheel) the samples were ground by blocking the rotation axis of the workpiece table and by translating the grinding wheel horizontally in order to simplify the kinematic of the grinding process. 13 grinding tests were performed for the D126 wheel (respectively 5 for D91 wheel and 11 for D64 wheel), 5 of those tests are with the same cutting conditions to analyze the repeatability of the process (respectively 3 for D64 wheel). The range of grinding conditions used is the following: the wheel rotation speed varies between 1000 and 2000 rpm, the feed rate varies between 0.01 and 0.04 mm per revolution, and the depth of cut varies between 0.4 and 1 mm. 5 grinding tests were made with the D25 wheel, 3 of which are done with the same conditions. The samples were ground with a rotation of the workpiece table and by translating the inversely rotating grinding wheel vertically. The wheel rotation speed varies between 3000 and 4000 rpm, the workpiece table rotation speed varies between 12 and 16 rpm, the feed rate varies between 1.25 and 1.7 mm per revolution and the depth of cut is set to 0.1 mm.

For loose abrasive grinding a Logitech PM5 single side lapping and polishing machine was used. 9 samples was manufactured using varying processing conditions with varying rotation speed (5 to 70 rpm), load (0.8 to 2.8 kg), abrasive (Al\(_2\)O\(_3\) or SiC), abrasive size (9 to 30 \(\mu\)m) and slurry concentration (7 to 20 %). A full description of the manufacturing of these samples is available elsewhere [14].
2.2 Samples characterization

To characterize the precision grinding operation, the surface roughness for each of the grinded surfaces was measured using a MITUTOYO (SJ-201) contact stylus profilometer, equipped with an inductive probe with 2µm radius and 90° angle. Each profile is filtered with a Gaussian filter (and a double Gaussian filter for the calculation of Abbott-Firestone curve) according to the norm ISO 13565 [15]. The cut-off length for the filter is 0.8 mm. According to the normalized procedure [15], scans of 4mm length were performed, on 16 areas uniformly distributed on the surface of each sample [6]. For each sample, several parameters are calculated from the measured profile:

- the peak to valley surface roughness $R_t$,
- the mean surface roughness $R_a$,
- the RMS surface roughness $R_q$,
- the kurtosis surface roughness $R_{ku}$ characteristic of the narrowness of the height distribution,
- the surface roughness $\delta$ (moment of order 4) defined by Suratwala [6].

The Abbott-Firestone parameters are also calculated ($R_k$, $R_{pk}$, $R_{vk}$, $M_r1$, and $M_r2$). More information on Abbott-Firestone curve is presented in our previous work [13]. All these parameters are mean values obtained on all 16 scans. The peak to valley surface roughness $R_{tmax}$, corresponding to the maximum value obtained on all 16 scans, is also raised.

SSD depth was measured by means of acid etching (80% HF, 20% HNO3); it consists in following the evolution of surface roughness $R_t$ during successive acid etchings. $R_t$ is measured after each etching step and the maximal value of $R_{tmax}$ among the whole set of measurements is equal to the SSD depth as described by Neauport [6].

2.3 Method to search for the best indicator of the SSD depth

For every surface roughness parameters, one searches the best linear relationship between SSD depth and the parameter that fit the data of the whole batch of samples. With that best fitting relationship an estimated SSD ($SSD_{calc}$) depth is calculated from the roughness parameter for every test. Then, for every surface roughness parameter and for every test, the error (in percent) between the measured SSD ($SSD_{meas}$) and the estimated SSD depth is calculated with the following formula:

$$ error = \frac{SSD_{meas} - SSD_{calc}}{SSD_{meas}} $$

Finally for every surface roughness parameter the mean of the error is calculated from the whole set of experiments. The best indicator of the SSD depth is determinate by the surface roughness parameter that gives the minimal mean of the error. For comparison with previous studies, the results of Miller [11] are used. Miller studied relationship between SSD depth and $R_t$ for a wide variety of grinding parameter from sand blasting to 9µm abrasive with bound or loose abrasive mode. So his data are used to do the same error calculation and allows to compare the accuracy of our results.

3 Results and discussions

First we check the repeatability of our grinding experiments and measures. The figure 1 present for each set of tests using the same operating conditions (same wheel speed, feed rate and depth of cut) for D126, D64 and D25 wheel the dispersion of the measure of SSD depth and surface roughness parameters (5 tests D126, 3 for D64 and D25). This dispersion is expressed by the standard deviation of the set of measures divided by the mean value of the set and given in percent.

For D126 and D64 wheels, which correspond respectively to rough and intermediate grinding tests, the SSD depth measurements present less than three percent of dispersion. The surface roughness parameters present a spread comprise between five and ten percent, which correspond to the precision of the profilometer used in the study. Therefore the grinding experiments prove to be highly repeatable. For the finish grinding (D25) we observe a much larger spread of SSD depths (up to 35%) and surface roughness measurements. The repeatability of finish grinding is not quite as good. It can be explained because of the thermal expansion of the spindle and grinding wheel during the processing. In fact, due to very low feed rate during finishing (5 µm/min), the grinding test time approaches half an hour and so the thermal expansion during the grinding is
not negligible. The expansion causes increasing load on the spindle during the grinding which is responsible for the spread of SSD depths measured. So our grinding process is not well fitted for the finishing step and a much better control of the thermal expansion, or a thermal compensation system are needed to improve the repeatability of the grinding experiments.

The figure 2 presents the best indicator of SSD depth found for all the grinding tests presented in §2.1. It plots, for each surface roughness parameter, the mean error between the measured SSD and the estimated SSD as presented in §2.3. The graph shows that the parameter Mr2 minimizes the mean error for the estimation of SSD depth. As an affine function of Mr2, the same mean error is observed for 100-Mr2, which represents the fraction of valley of the roughness profile. The figure 3 presents the evolution of SSD depth as a function of 100-Mr2 for all the tests (rough grinding to finishing) and a linear regression of the data. Despite a relatively high mean error on the estimated SSD depth (30%) with the Mr2 (or 100-Mr2) indicator (figure 2), the figure clearly shows a relationship between SSD depth and the fraction of valley. Such error can be explained by the spread of the experimental data, which is expected because of brittle fracture mechanisms than form the SSD. The figure 2 shows also that using Mr2 (or 100-Mr2) for the estimation of SSD depth conduct to less error in mean than using \( R_{\text{tmax}} \) (30% for Mr2 against 40% for \( R_{\text{tmax}} \)).
We also compare our results to the one of Miller [11]. Miller studies the relationships between $R_{t\text{max}}$ and SSD depth in grinding for a wide range of abrasive grain size (9µm to sand blast) and different grinding configurations (bound or loose abrasive grinding). We used his results to find the best fitting linear relationship between $R_{t\text{max}}$ and SSD depth and plot the error of the estimated SSD in figure 2. The result shows a mean error of 54% for Miller data. With our data the error using $R_{t\text{max}}$ as indicator is inferior (40%) but in the same range. This validate that the variety of grinding test realized in this study is comparable to the one found in other studies.

All these results clearly demonstrate that the $100f_{Mr^2}$ (or $Mr^2$) roughness parameter is a better indicator of the SSD depth than $R_{t\text{max}}$ which was used in past studies. The following relationship between SSD depth and $100-Mr^2$ is found to best fit the experimental data for a wide range of grinding conditions:

$$SSD\ depth = 4 \times (100 - Mr^2) - 30$$

(2)

Considering the wide variety of grinding conditions tested (rough grinding to finishing, loose and bound abrasive), $100-Mr^2$ can be used to assess the SSD depth for a wide range of applications with a safety factor applied to the relationship.

4 Conclusion

Characterization of the SSD is a crucial step to determine the optimum process parameters. We prove that the fraction of valley of the roughness profile ($100f_{Mr^2}$), calculated with the Abbott-Firestone curve, present a linear relationship with the SSD depth, and is a more accurate indicator of the SSD depth than the maximum peak to valley roughness ($R_{t\text{max}}$) used in past studies. It is a non destructive characterization method that can be used, with a fairly large safety factor, for quickly estimate the depth of SSD in fused silica, regardless of grinding conditions.

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References