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Sub-surface damage issues for effective fabrication of large optics

X. Tonnellier[a,b*], P.Shore[a,b], P.Morantz[a,b], A.Baldwin[b], D.Walker[c,d], G.Yu[c] and R.Evans[c]

[a]Ultra Precision and Structured Surfaces Centre, Optic Technium, LL17 OJD, UK
[b]Cranfield University Precision Engineering Centre, Cranfield University, MK43 0AL, UK
[c]National Facility for Ultra Precision Surfaces, Optic Technium, LL17 OJD, UK
[d]Zeeko Ltd, Coalville, Leicester, LE67 3FW, UK

ABSTRACT

A new ultra precision large optics grinding machine, BoX®, has been developed at Cranfield University. BoX®is located at the UK's Ultra Precision Surfaces laboratory at the OpTIC Technium. This machine offers a rapid and economic solution for grinding large off-axis aspherical and free-form optical components.

This paper presents an analysis of subsurface damage assessments of optical ground materials produced using diamond resin bonded grinding wheels. The specific materials used, Zerodur®and ULE®are currently under study for making extremely large telescope (ELT) segmented mirrors such as in the E-ELT project.

The grinding experiments have been conducted on the BoX®grinding machine using wheels with grits sizes of 76 μm, 46 μm and 25 μm. Grinding process data was collected using a Kistler dynamometer platform. The highest material removal rate (187.5 mm^3/s) used ensures that a 1 metre diameter optic can be ground in less than 10 hours. The surface roughness and surface profile were measured using a Form Talysurf. The subsurface damage was revealed using a sub aperture polishing process in combination with an etching technique.

These results are compared with the targeted form accuracy of 1 μm p-v over a 1 metre part, surface roughness of 50-150 nm RMS and subsurface damage in the range of 2-5 μm. This process stage was validated on a 400 mm ULE®blank and a 1 metre hexagonal Zerodur®part.

Keywords: Diamonds resin bond grinding wheel, Grinding, Subsurface damage, Zerodur, ULE, Machine dynamics

1. INTRODUCTION

1.1 Technologies challenges

A number of projects are studying the possibility of making a next generation of Extremely Large Telescopes (ELT).

At the end of 2006, two concepts, Euro50 and OWL,[1] were merged by the European community into a new project, the European Extremely Large Telescope[2] (E-ELT). This telescope will have a 42 m primary mirror made from 906 segments each of 1.45 m size with a hexagonal shape.

The potential materials for such segments are glass, glass ceramic or ceramic.[3] Low thermal expansion glass and glass ceramics, such as ULE®and Zerodur®respectively, have been employed for many years in the manufacturing of large optics.

Sagem and Kodak have reported manufacturing process concepts for making >1 metre hexagonal mirrors. The blank is progressively ground to reach the desired shape. Then, the mirror is lapped and polished to get the correct form geometry and to remove any subsurface damage induced by previous machining process.[4]

A possible production improvement is to achieve a grinding process that is capable of producing better shaped surfaces having less subsurface damage and at higher material removal rates. To achieve this production capability, a new ultra precision large optics grinder[5] - BoX®- has been developed at Cranfield University.

During this machine development, grinding processes were tested on a 5-axis Holroyd Edgetek grinding machine. A dedicated fixture was used in order to simulate the BoX®grinding mode.[6] The grinding forces and power,[7]

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[*] x.p.tonnellier@cranfield.ac.uk, Telephone: +44 (0)1745 535 143, www.cranfield.ac.uk/sas

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as well as the wheel wear[8] induced by this particular grinding mode have previously been reported.
The Box®grinding machine is part of an Ultra Precision and Structured Surfaces (UPS^2) facility, in Technium OpTIC, St Asaph, North Wales.[9]

1.2 Ultra Precision and Structured Surfaces (UPS^2) facility[9]

The £15 million Technium OpTIC, based in St Asaph, North Wales, is a significant initiative of the Welsh Optics Forum. This facility houses a temperature controlled Ultra Precision Surfaces (UPS) laboratory.[9] Containing UK world's most effective ultra precision machining systems for large optics fabrication.

- BoX®ultra-precision large optics grinder (2 metres capacity) developed at Cranfield University
- Zeeko ultra-precision polishing machine, 1.2 metres capacity embodying classic, abrasive pad and fluid jet polishing technologies.
- Reactive Atom Plasma surface finishing facility developed by RAPT Industries in partnership with Cranfield University.

The laboratory also has a full suite of surface metrology equipment, including high measurement interferometers: stability for form measurement, miniature high accuracy interferometers, and white-light scanning interferometers. In addition, it houses a large optics swing arm profilometer developed by the UK's National Physical Laboratory.

1.3 Results discussed

The purpose of the work described in this paper has been to establish the level of subsurface damage (SSD) in ULE®and Zerodur®using different material removal rates. A comparison of surface roughness and SSD qualities is provided in relation to grinding parameters. This work was carried out on the BoX®grinding machine on 100 mm square specimens.
This process was repeated on a 400 mm square ULE®part and on a 1 m Zerodur®hexagonal part. A highest material removal rate (187.5 mm^3/s) was used to ensure that a 1 metre diameter optic can be ground in less than 10 hours. The results are compared with the targeted form accuracy of 1 μm p-v over a 1 metre part, surface roughness of 50-150 nm RMS and subsurface damage in the range of 2-5 μm.

2. SUBSURFACE DAMAGE EVALUATION OF BRITTLE MATERIALS

2.1 Subsurface damage mechanisms

Ductile or brittle fracture mode grinding[10] can be used to machine brittle materials such as Zerodur®and ULE®. Ductile mode grinding has been reported to give low subsurface damage[11] (SSD). However, achievable material removal rate is low, as for example the critical depth of cut is $\sim$50 nm[12] on Zerodur®.
Higher manufacturing rates are supported using micro brittle fracture grinding. However, the brittle mode leaves surface and subsurface damage on ground surfaces. An efficient grinding process requires optimisation of the grinding parameters to reduce the level of SSD.
Micro fracture mechanisms that lead to SSD in brittle materials have been extensively investigated by Lawn.[13] Median cracks commence and propagate with increase of indentation load. With indentation unloading, the median cracks close and lateral cracks grow towards the surface. These fracture mechanisms result in surface and subsurface defects.
Different models to predict SSD have been proposed using the maximum chip thickness and the material properties.[14] Other attempts to estimate the SSD have been proposed in order to correlate it with the abrasive grain size[15] or the surface roughness.[16] The importance of grinding machine performance[17,18] has also been identified. Most recently, some work carried out on Zerodur®using a 25 μm grit size grinding wheel introduced the separation of SSD into 'Process' related and 'Machine dynamics' related damage.[19]

2.2 Subsurface damage evaluation techniques

In order to measure the extent of subsurface cracks, different non-destructive and destructive measurement methods have been developed. Some non-destructive subsurface inspection techniques,[20] such as ultrasonic Rayleigh wave measurement, have proved successful for information and qualification of significant and deep cracks.

Destructive methods have proved to be more successful for detecting micron and sub-micron scale fractures. Cross-sectional transmission electron microscope (TEM) analysis has shown good results for detection of sub-micron scale defects in glasses and crystals.[21] This TEM process is however time consuming and less appropriate for large defects in multi-phase advanced ceramics. Repetitive polish, etch and optical microscopy have been widely employed to observe SSD in ground glasses.[22] A variant of this repetitive polish and etch method[23] is a 'wedge' polishing approach which simplifies assessment of how defect density relates to depth beneath the ground surface.[8]

Two terms were employed to describe the subsurface damage level. The majority of subsurface cracks cluster together near the surface and terminate at a characteristic 'cluster depth'. A small minority of cracks propagate deeper beneath the surface. The 'single last fracture depth'[15] is usually much deeper than the cluster.

3. BOX GRINDING MACHINE

The BoX®machine is a precision 3 axis grinding machine as shown in Figure 1.

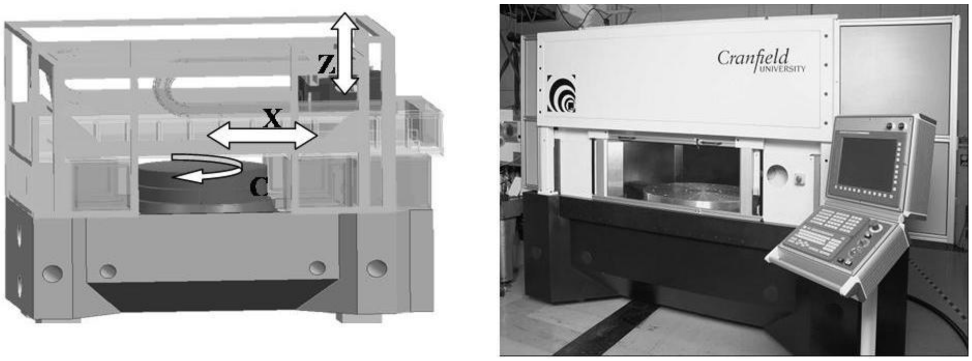


Figure 1. BoX®precision grinding machine

A vertically arranged Z linear axis sub-system carries a fixed inclination grinding spindle. The Z axis sub-system itself is mounted within a horizontal X linear axis carriage. A large rotary C axis table is employed to hold the workpiece. The grinding spindle is tilted at a fixed 20 degrees angle to enable machining of free-form optics[24] of slope up to 18 degrees. This maximum slope is considered suitable for the surfaces such as E-ELT segment and space telescope mirror geometries.

All bearings in the stressed loop of the BoX®machine are of a hydrostatic oil bearing type. The BoX®has been designed to have high static (> 100 N/μm) and high dynamic loop stiffness (low moving mass <750 kg with high 1st resonant frequencies > 100 Hz).

With these characteristics and an in situ measurement profilometer employing a 'non-stressed' metrology frame, a form accuracy of 1 μm peak to valley is targeted with minimal levels of induced subsurface damage. In addition, the hydrostatic oil bearing grinding spindle has a 10 kW power capacity permitting a high material removal rate of 200 mm^3/s to be achieved.

The machine is supported by temperature control systems with $+/- 0.1^o$C control for the oil bearings, water cooling systems and grinding fluid.[25] The grinding mode used does lead to a moving contact point that requires computation and compensation. This is achieved using an advanced control technique and system.[26]

4. EXPERIMENTAL DETAILS

4.1 Materials

Three materials have been studied in this project, Sintered Silicon Carbide (S/SiC), Zerodur®and ULE®. They were chosen due to their previously successful uses in the build of large optics. However, only two materials, ULE®and Zerodur®, have been studied for SSD in this work. The SSD investigation of (S/SiC) requires additional development.
The material parameters important in the creation of subsurface damage are shown in Table 1.

Material	Elastic Modulus E *GPa*	Hardness H *GPa*	Fracture toughness K_c $Mpa.m^{1/2}$	Brittleness H/K_c $m^{1/2}$
ULE®	70	4.6	1.8	2560
Zerodur®	91	6.2	0.9	6890

Table 1. Zerodur®and ULE®parameters

Both ULE®and Zerodur®have low thermal expansion coefficients. The difference of fracture toughness and hardness between those two materials means that Zerodur®has a brittleness three times higher than ULE®. ULE®(Ultra Low Expansion) is a glass material produced by Corning. Zerodur®is a glass ceramic material made by Schott.

4.2 Specimens' size

The specimens' size was 100 mm x 100 mm and 20 mm thick. The specimens were ground flat. The size was chosen to be small enough for SSD evaluation. The subsequent process validation was made on a 400 mm x 400 mm x 25 mm thick ULE®plate and on a 1 m across corners hexagonal Zerodur®part. Both specimens were ground spherical to a 3 m radius of curvature. This particular shape was chosen based on the available metrology.

4.3 Grinding wheels

Three 'toric' shaped resin bonded diamond cup grinding wheels have been evaluated. Each grinding wheel has a 325 mm outer diameter with an abrasive layer width of 60 mm. Three grit sizes were chosen for this grinding process, 76 μm, 46 μm and 25 μm.
The grinding wheels' cross sectional form was trued and shaped to a 300 mm radius using a nickel electroplated diamond roller. The grinding wheels were balanced in-situ with a Schenck dynamic balancing system. They were dressed using a green carborundum stick. A slot type coolant nozzle[27] was used. This provided consistent coolant laminar flow across the whole contact region between the specimen and the grinding wheel. The coolant used was Chemsearch Dowel diluted at 2% in water.

4.4 Grinding parameters

The grinding parameters controlled are the depth of cut (a_e), the feed per revolution (f_r), the surface speed (v_w) and the cutting speed (v_c). The material removal rate (Q_w) was also calculated.
The grinding parameters employed for the tests carried out are shown in Table 2.

Grinding Conditions	Grit size μm	Depth of cut a_e μm	Feedrate f_r mm/rev	Work speed v_w mm/s	Cutting speed v_c m/s	MRR Q_w mm^3/s
Rough cut	76	500	15	25	30	187.5
Semi Finish cut	46	200	10	20	30	40
Finish cut	25	50	1.5	25	30	1.87

Table 2. Grinding parameters

The rough cut removes the bulk material. A semi finish cut eliminates the amount of damage induced by the rough grinding. The first finish cut takes out the previous grinding damage. Finally, the second finish cut creates the final form accuracy, surface roughness and level of subsurface damage.

4.5 Grinding mode

The normal BoX®grinding mode generates a spiral curve. This type of grinding mode has previously been described in the use of the Large Optical Generator[24] as well as the grinding of aspherical optical components.[28] To simplify the roughness measurement along the grinding direction, the samples were set on the rotary table at a radius of 450mm.
This particular grinding mode is illustrated in Figure 2.

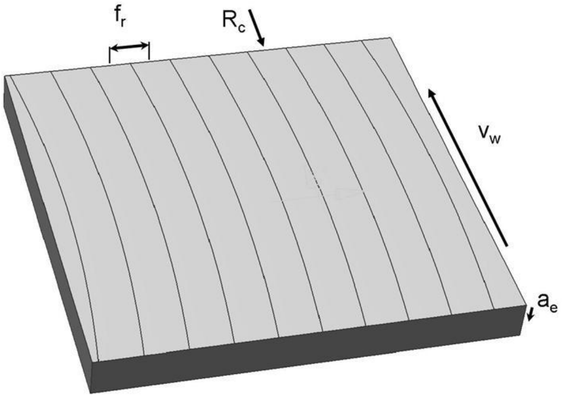


Figure 2. Semi finish grinding mode example

The fixture used was designed to be stiff and elevated the samples within reach of the Z axis stroke. This was necessary due to the samples' thickness compared to the large blanks typically used in BoX®. The samples were held in position on a steel plate with 'wax'. This plate was bolted on a Kistler force dynamometer. For each experiment, the grinding forces were recorded in three orthogonal directions.

5. EXPERIMENTS RESULTS

5.1 Grinding performance

As previously mentioned, the finish cut creates the final form accuracy (P_t), surface roughness (R_a) and level of subsurface damage (SSD). Therefore, the three different grinding wheels were used to measure the output qualities for similar finish cuts.
The surface profile and surface roughness values obtained using the finish grinding condition, are shown in Figure 3.

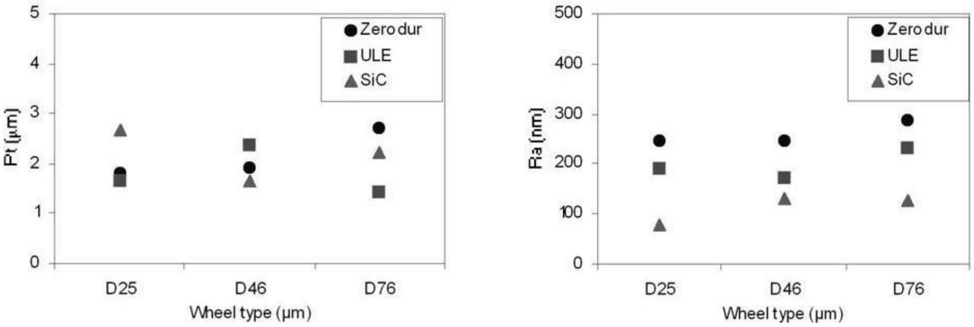


Figure 3. Surface profile (P_t) and surface roughness (R_a) results - Finish cut

For the surface profile, the Zerodur®tests show an increase when increasing the grinding wheel grit size. However, the rest of the tests do not show a specific trend across materials with different grinding wheels. The P_t theoretical value can be calculated using the feed rate per revolution and the abrasive layer radius of curvature. Therefore, the machine dynamics as repositioning errors, are influencing more the surface profile results than the grit size.

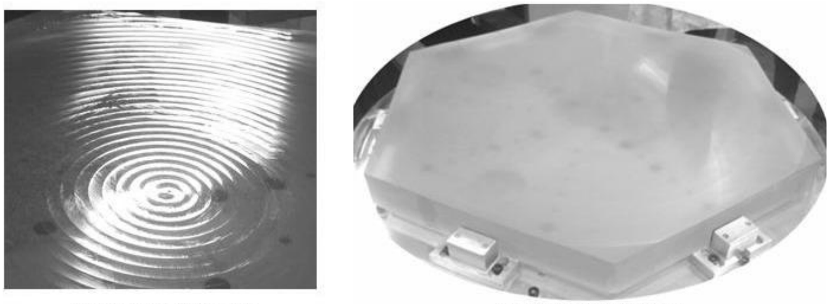
The surface roughness along the grinding direction, (R_a), changes with the grinding wheel grit size. Larger grit size results in an increase of the surface roughness for ULE®and S/SiC. Interestedly, for Zerodur®, the D46 grinding wheel gives better results than the D25 grinding wheel.

5.2 Process performance on large parts

The results obtained on small test samples (Figure 3) demonstrate the grinding process output quality. The final accuracy achieved was P_t <2 μm and R_a <250 nm for ULE®and Zerodur®. Meanwhile, for S/SiC, the results are P_t <3 μm and R_a <100 nm.

This process was subsequently replicated on larger parts.

First, a 400 mm x 400 mm x 25 mm ULE®part was successfully machined from a flat to a 3 m radius of curvature sphere. Thereafter, a 3 m radius of curvature was ground into a 1 metre across corner hexagonal Zerodur®part. An intermediate rough grinding surface and the final ground surface are shown in Figure 4a and 4b respectively.



a) Rough grinding cut *b) Finish grinding cut*

Figure 4. 1 metre Zerodur®part ground surfaces

The 1 metre Zerodur®part was ground from a flat to a 3 m radius of curvature sphere removing a 32mm saggitta. The final ground surface was measured using a Leitz PMM-F co-ordinate measuring machine. This CMM is located in the Hexagon Loxham Precision Laboratory at Cranfield University.

The target form accuracy of ± 1μm was achieved.

An error compensation approach can be implemented to achieve a better final ground surface form accuracy.

The final 0.5 mm was removed in less than 10 hours proving the efficiency of the grinding process developed.
'Flash' polishing using a Zeeko IRP1200 polishing machine was subsequently carried out to improve roughness thereby allowing an interferometer to be employed.
The interferogram obtained is shown in Figure 5.

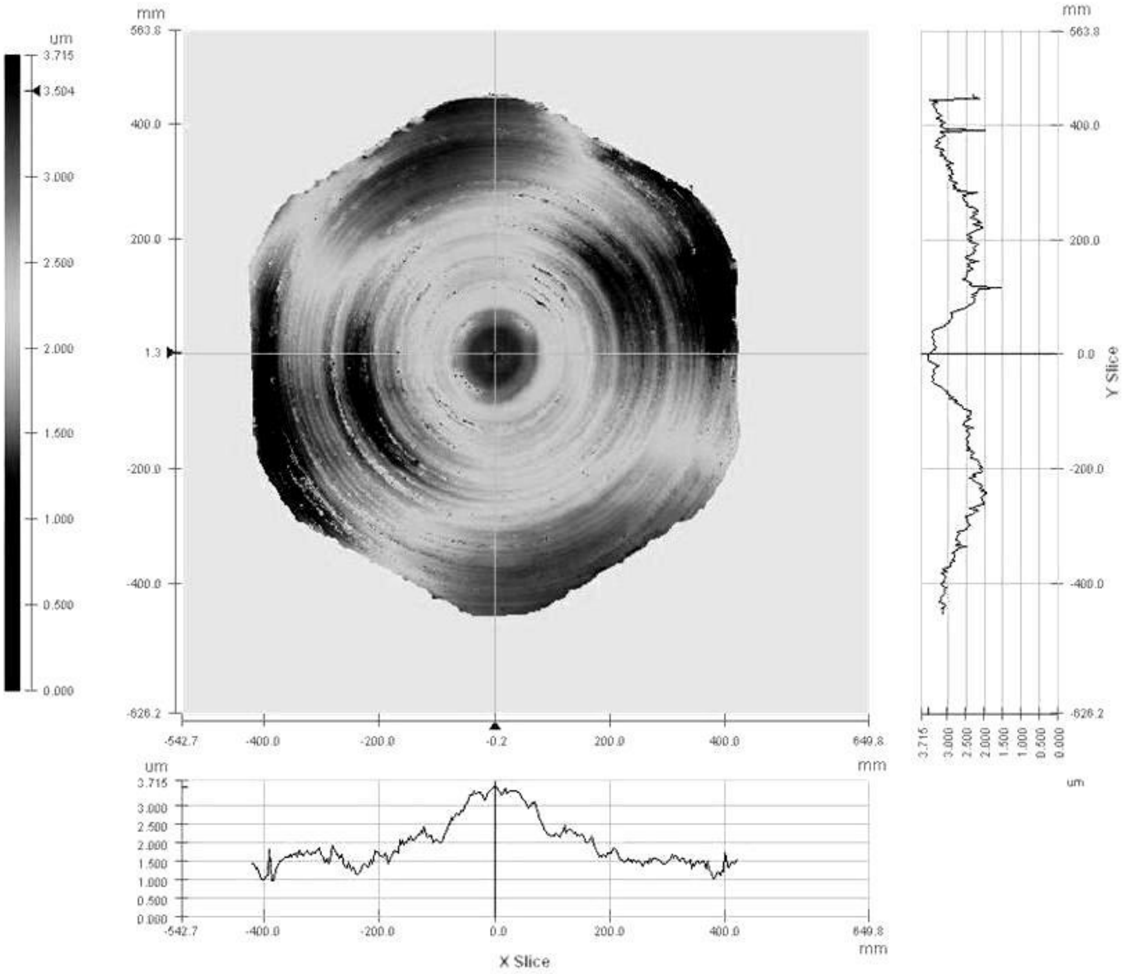


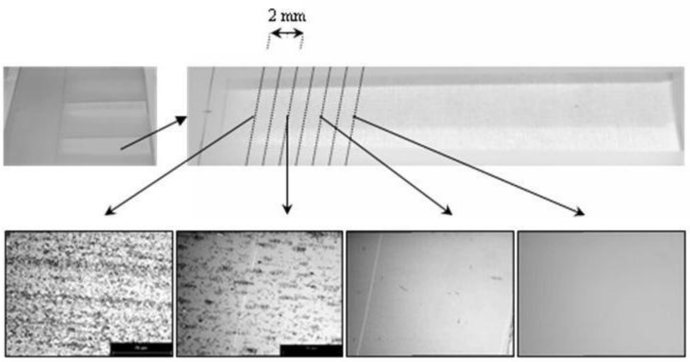
Figure 5. Ground part after interferogram 'Flash' polishing

The interferogram gives a form accuracy of PV = 3.715 μm ($PV_{q(99\%)}$= 2.62 μm) and a surface roughness of 632 nm RMS.

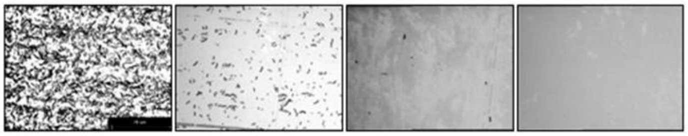
6. SUBSURFACE DAMAGE RESULTS

6.1 Subsurface evaluation technique

The subsurface damage was observed using a polishing process. A tapered groove was made parallel to the grinding direction using a Zeeko IRP polishing machine.[29]
The evaluation technique is illustrated in Figure 6.



a) Sample 1 - groove 2 - D25 - ULE®



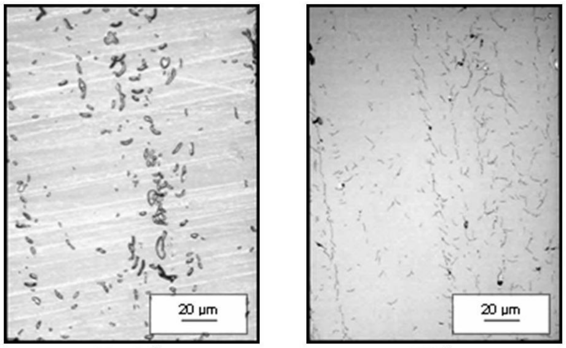
b) Sample 1 - groove 2 - D25 - Zerodur®

Figure 6. Subsurface damage evaluation technique

The grooves were polished along the grinding direction. Two grooves were made to average the subsurface damage values obtained. The polished tapered grooves were etched using HF and HCl acids for 10 seconds duration. The etching period was set to remove less than 1 μm from the ground and polished surface. A Form Talysurf profilometer was used to measure the depth of the groove at each measurement position. The surfaces were observed and the number of cracks counted using an optical microscope. The number of cracks per mm^2 against the depth under the ground surface were plotted. Those were used to investigate the possible separation of SSD into Process related and Machine dynamics related.[19]

6.2 Subsurface damage measurements

The subsurface damage cracks have different shapes and sizes in ULE®and in Zerodur®.
An example of SSD cracks created with a D25 grinding wheel are shown in Figure 7.



Zerodur® ULE®

Figure 7. Subsurface damage cracks using a D25 grinding wheel

The Zerodur®cracks are small and slightly curved. However, the ULE®cracks are much longer. They also overlap each other and have a more 'fork type' shape. The cracks length to thickness ratio is also larger for ULE®than Zerodur®.
The 'cluster' and 'single last fracture' depths results are shown in Table 3.

Grinding Conditions	Cluster depth		Single last fracture depth	
	ULE® μm	Zerodur® μm	ULE® μm	Zerodur® μm
Rough cut (D76)	8.5	5	18.5	8
Semi Finish cut (D76)	6	5	11	12
Semi Finish cut (D46)	4.5	4	9	7.5
Semi Finish cut (D25)	5	7	11.5	10
Finish cut (D76)	7	6.5	14	13.5
Finish cut (D46)	6	4	10	11
Finish cut (D25)	4	3	8	4

Table 3. Grinding parameters

Importantly, the finish cut using a D25 grinding wheel leaves 8 μm in ULE®and 4 μm in Zerodur®. During the rough cut (D76), the single last fracture depth is more than twice the depth in ULE®than Zerodur®. However, the finish cut (D46) and semi finish cut (D76) give more damage in Zerodur®. Overall, subsurface damage depths in ULE®are larger than in Zerodur®.
The cluster depth results show the same trend between both materials as for the single last fracture depth. This depth difference is typically within 1-2 μm. Those results are in accordance with the consideration that the single last fracture depth is machine dynamics related while the cluster depth is process related.
The important subsurface damage values are those created during the finish cuts. Results highlight that reducing the grinding wheel grit size reduces the subsurface damage level. The finish cuts using 25μm grit size reach the target value for Zerodur®($< 5\mu$m) but not for ULE®.

7. CONCLUSIONS

This paper shows the results obtained on optical materials using the BoX®grinding mode. An efficient grinding process has been developed for precision grinding of large optics.
On Zerodur®, the final profile accuracy (P_t) obtained is ± 1 μm over a metre. The surface roughness (R_a) and subsurface damage level obtained are 247 nm and 4 μm respectively. On ULE®, R_a and SSD level obtained are 191 nm and 8 μm respectively.
The total grinding process time achievable to remove 0.5 mm from a pre-shaped optical blank is 10 hours.
Further work will be carried out on the influence of grinding machines dynamics on induced subsurface damage levels in optical surfaces.

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