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Surface quality of a 1m Zerodur® part using an effective grinding mode

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ABSTRACT

A new ultra precision large optics grinding machine, BoX®, has been developed at Cranfield University. This machine is located at the UK's Ultra Precision Surfaces laboratory at the OpTIC Technium, North Wales. 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 surface and subsurface damage assessments of Zerodur® ground using diamond resin bonded grinding wheels. Zerodur® was tested as it is one of the materials 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 grit sizes of 76 µm, 46 µm and 25 µm. 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 on small parts.

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 1 metre hexagonal Zerodur® part.

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

1 INTRODUCTION

1.1 Technology challenges

A number of projects are studying the possibility of making a next generation of Extremely Large Telescopes (ELT). The European Extremely Large Telescope[1] (E-ELT) is a current project following the merger of two study concepts, Euro50 and OWL[2]. 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 ceramics, such as Zerodur®, are employed in the manufacturing of large optics.

Some manufacturing processes for making >1 metre hexagonal mirrors have been reported by Sagem and Kodak. First, the blank is ground to reach the desired shape. Then, the part is lapped and polished to get the correct form geometry. Any subsurface damage induced by previous machining process is removed[4].

A possible production improvement is to achieve a effective grinding process capable of producing better shaped surfaces with less subsurface damage and at higher material removal rates. The polishing process will therefore be shortened. To achieve this production capability, a new ultra precision large optics grinder[5] - BoX®- has been developed at Cranfield University (Figure 1). This grinding machine, BoX®, is part of an Ultra Precision and Structured Surfaces (UPS^2) facility, in Technium OpTIC, St Asaph, North Wales[6].

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1.2 Ultra Precision and Structured Surfaces (UPS^2) facility[6]

The £15 million Technium OpTIC, based in St Asaph, North Wales, is a significant initiative of the Welsh Optics Forum.

Fig 1. BoX® grinding machine

This facility houses a temperature controlled Ultra Precision Surfaces (UPS) laboratory[9], containing the 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 measurement interferometers: high 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 evaluate the output quality of the BoX® grinding process on a 1 m Zerodur® hexagonal part. A material removal rate up to 187.5 mm^3/s was used to ensure that this 1 metre optic can be ground in less than 10 hours.

Additional process evaluations were carried out, on the BoX® grinding machine, on 100 mm Zerodur® square specimens. The levels of surface profile, surface roughness and subsurface damage (SSD) using different material removal rates were assessed. A comparison of surface roughness and subsurface damage levels is provided in relation to grinding parameters. 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.

Grinding forces and grinding power[7], as well as wheel wear[8, 9] induced by this particular grinding mode, have previously been recorded and reported.

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2 BOX GRINDING MACHINE

The BoX® grinding machine is a precision 3 axis grinding machine (Figure 2). A vertically arranged Z linear axis sub-system carries a fixed inclination grinding spindle. The Z axis subsystem itself is mounted within a horizontal X linear axis carriage. A large rotary C axis table is employed to hold the workpiece.

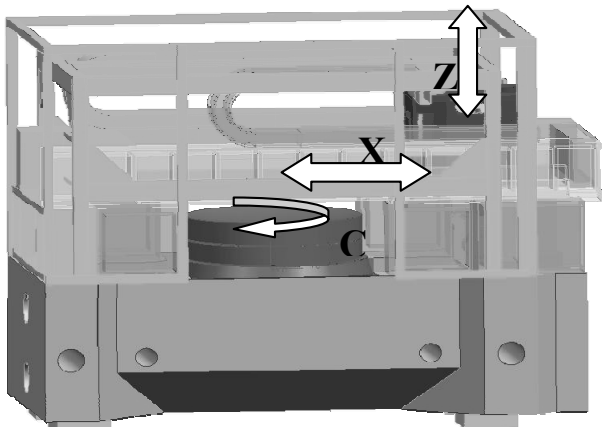

Fig. 2: 3 axis BoX® grinding machine

The grinding spindle is tilted at a fixed 20 degrees angle to enable machining of free-form optics[10] 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. This particular grinding mode is illustrated in Figure 3.

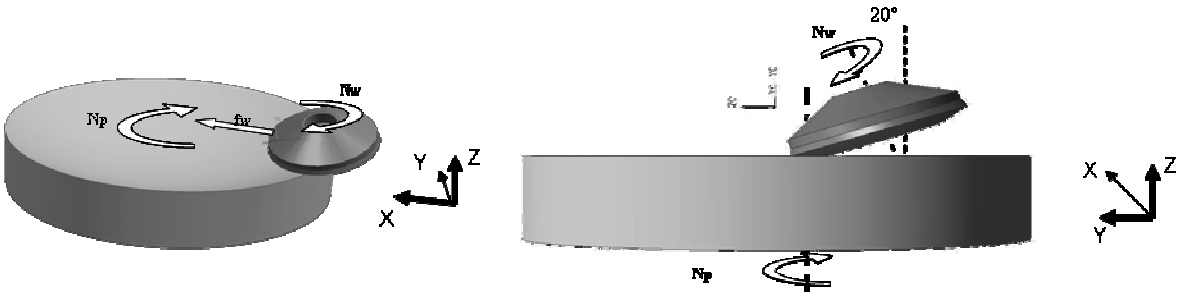

Fig. 3: BoX® grinding mode

All bearings in the stressed loop of the BoX® grinding 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°C control for the oil bearings, water cooling systems and grinding fluid[11]. 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[12].

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3 EXPERIMENTAL DETAILS

3.1 Materials

Zerodur® is a glass ceramic material made by Schott. It has a low thermal expansion coefficient. The material parameters are shown in Table 1.

Elastic modulus E *(GPa)*	Micro hardness H *(GPa)*	Fracture toughness T *($MPa.m^{1/2}$)*	Thermal Conductivity k *(W/(m.K))*	CTE *($10^{-6}/K$)*
91	6.2	0.9	1.63	0.05

Table 1: Zerodur® properties

3.2 Specimens' size

The specimens' size was 100 mm x 100 mm and 20 mm thick. The dimensions were chosen to be representative of the grinding process while suitable for subsurface damage evaluation.

The subsequent process validation was made on a 1 m across corners hexagonal Zerodur® part (Figure 4). The part was ground spherical to a 3 m radius of curvature. This particular radius of curvature was chosen based on the available metrology.

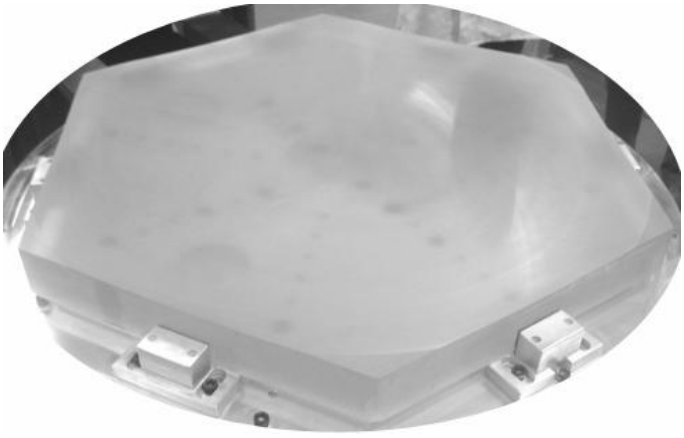

Fig. 4: 1 m across corners hexagonal Zerodur® part

3.3 Grinding parameters

The grinding parameters values employed are shown in Table 2.

Grinding Conditions	Depth of cut a_e *(μm)*	Feedrate f_r *(mm/step)*	Work speed v_w *(mm/s)*	Material removal rate Q_w *(mm^3/s)*	Grit size *(μm)*
Rough cut	500	15	25	187.5	76
Semi Finish cut	200	10	20	40	76, 46 & 25
Finish cut	50	1.5	25	1.9	76, 46 & 25

Table 2: Grinding parameters values

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For both finish and semi finish cuts, three 'toric' shaped resin bonded diamond cup grinding wheels have been evaluated. Three grit sizes were chosen for this grinding process, 76 µm, 46 µm and 25 µm. For the rough cut only the coarser wheel was tested. The grinding wheels' cross sectional form was trued and shaped to a 300 mm radius using a nickel electroplated diamond roller.

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. Those grinding parameters are shown in Figure 5.

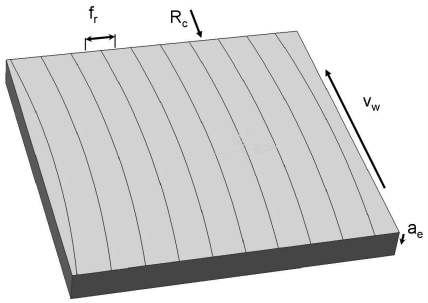

Fig. 5: Grinding parameters example

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.

A slot type coolant nozzle[13] was used. This provided consistent coolant laminar flow across the whole contact region between the specimen and the grinding wheel. The water based coolant was used.

3.4 Grinding mode

The normal BoX® grinding mode generates a spiral curve as illustrated in Figure 6. This type of grinding mode has previously been described in the use of the Large Optical Generator[10] as well as the grinding of aspherical optical components[14].

Fig. 6: Semi finish grinding mode example

Due to the spiral curve generated, the 100 mm samples were set on an outer diameter at 450mm radius. This simplified the roughness measurement along the grinding direction. It also made possible to use a constant surface speed over the whole sample surface. The 100 mm parts were waxed on a plate. This plate was bolted on a stiff fixture allowing quick turnover between tests.

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4 EXPERIMENTS RESULTS

4.1 Surface profile and surface roughness

The surface profile and surface roughness values obtained, for each grinding condition tested, are shown in Figure 7.

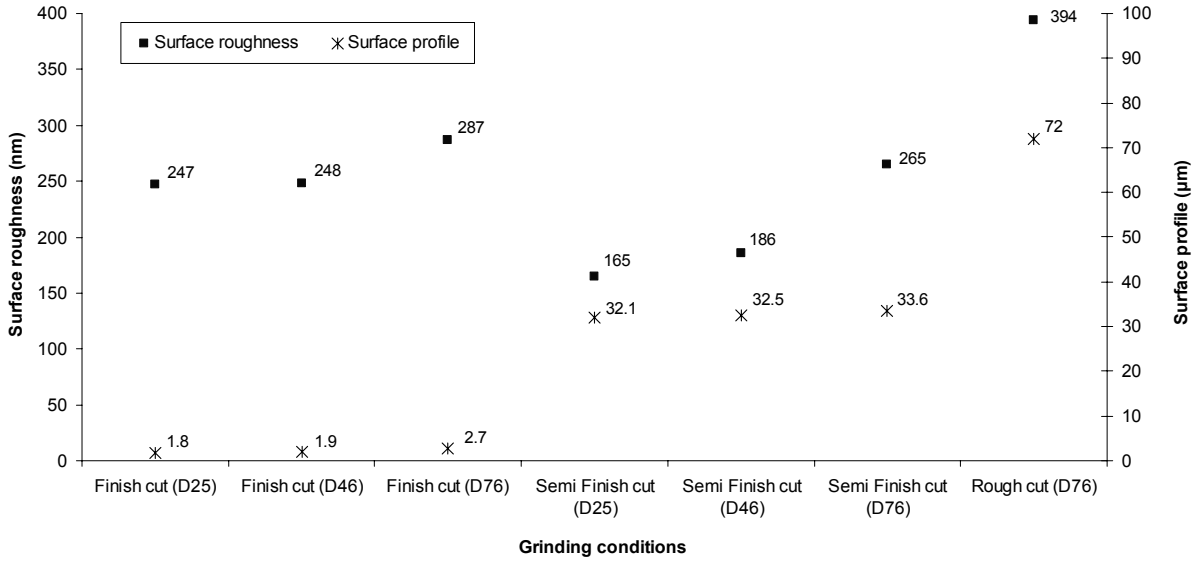

Fig. 7. Surface profile (Pt) and surface roughness (Ra) results

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, influence more the surface profile results than the grit size. However, the surface profile increases slightly when increasing the grinding wheel grit size.

The surface profile obtained during a finish cut is $P_t < 2$ µm. The surface profile results highlighted that the three step grinding process is adequate. As previously mentioned, the rough cut removes the bulk material. Therefore, the coarser wheel, D76, was used. The surface profile (Pt) obtained of 72 µm validates the 200 µm depth of cut for the semi finish cut. The amount of surface error generated by the semi finish cut can also be removed during the finish cut. By using a smaller grit size, the surface profile did not decrease significantly. The final finish cut creates the final form accuracy (P_t), surface roughness (R_a) and level of subsurface damage (SSD). Therefore, for similar finish cuts, the three different grinding wheels were used to measure those three output qualities.

The surface roughness obtained during a finish cut is $R_a < 250$ nm. 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. Interestedly, the semi finish cuts result in better surface roughness. This can be explained due to a lower surface speed while the cutting speed remains constant.

4.2 Subsurface damage depth

A 'wedge polished' technique with additional etching was used to assess subsurface damage depths. It has been explained in detail in previous publications[9, 15, 16].

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'. Additional cracks propagate deeper beneath the surface to a 'single last fracture depth'[17]. Both levels were measured for each grinding condition. The 'cluster' and 'single last fracture' depths results are shown in Figure 8.

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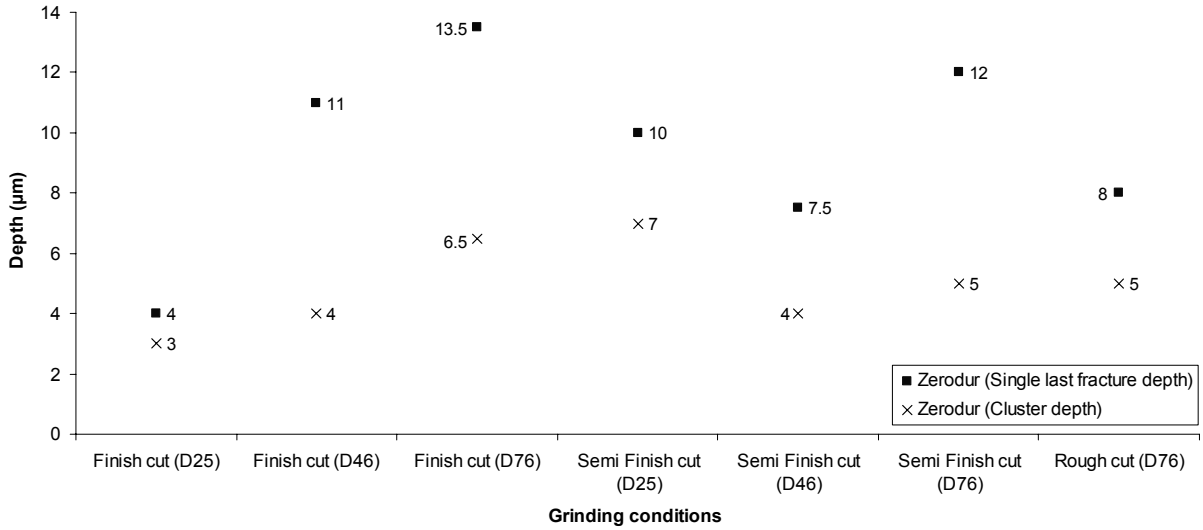

Fig. 8: Single last fracture depth and cluster depth results

The single last fracture depth obtained during a finish cut is 4 µm with a D25 grinding wheel.

For each grinding condition, the cluster depth results show the same trend as for the single last fracture depth. During a finish cut, results highlight that reducing the grinding wheel grit size reduces the subsurface damage level. This tendency remains correct for semi finish cuts using 25 µm and 76 µm grit sizes. However, the D46 grinding wheel leaves less subsurface damage. Using the same grit size, 76 µm, the rough cut leaves less damage than the semi finish and finish cuts. Similarly, the D46 grinding wheel induced shallower damage during a semi finish cut than a finish cut.

The results obtained on 100 mm test samples, Figure 7 & 8, demonstrate the grinding process output quality. The final accuracy achieved was Pt <2 µm and Ra <250 nm. The final subsurface damage depth was < 5 µm. The grinding process target was achieved on 100 mm² samples.

4.3 Process performance on large parts

Following the results obtained on small 100 mm flat samples, the grinding process was subsequently replicated on larger parts. First, a ULE® part, 400 mm x 400 mm x 25 mm, was successfully machined from a flat to a 3 m radius of curvature sphere. Thereafter, a 1 metre across corner hexagonal Zerodur® part was ground. A 3 m radius of curvature was ground as well. This 1 metre hexagonal Zerodur® part was ground from a flat to a 3 m radius of curvature sphere. A 32 mm saggitta was removed.

The final 0.5 mm was removed in less than 10 hours. This proves the efficiency of the grinding process developed.

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 better final ground surface form accuracy.

A second measurement was done with an interferometer to measure the final surface form obtained. However, the surface roughness had to be improved to obtain an interferogram. This was achieved by a 'flash' polishing using a Zeeko IRP1200 polishing machine. The interferogram obtained is shown in Figure 9.

The interferogram gives a form accuracy of PV = 3.71 µm (PV_q(99%)= 2.62 µm) and a surface roughness of 632 nm RMS. As expected, the interferogram and CMM data are slightly different as one is based on a full aperture measurement while the other is a cloud of points.

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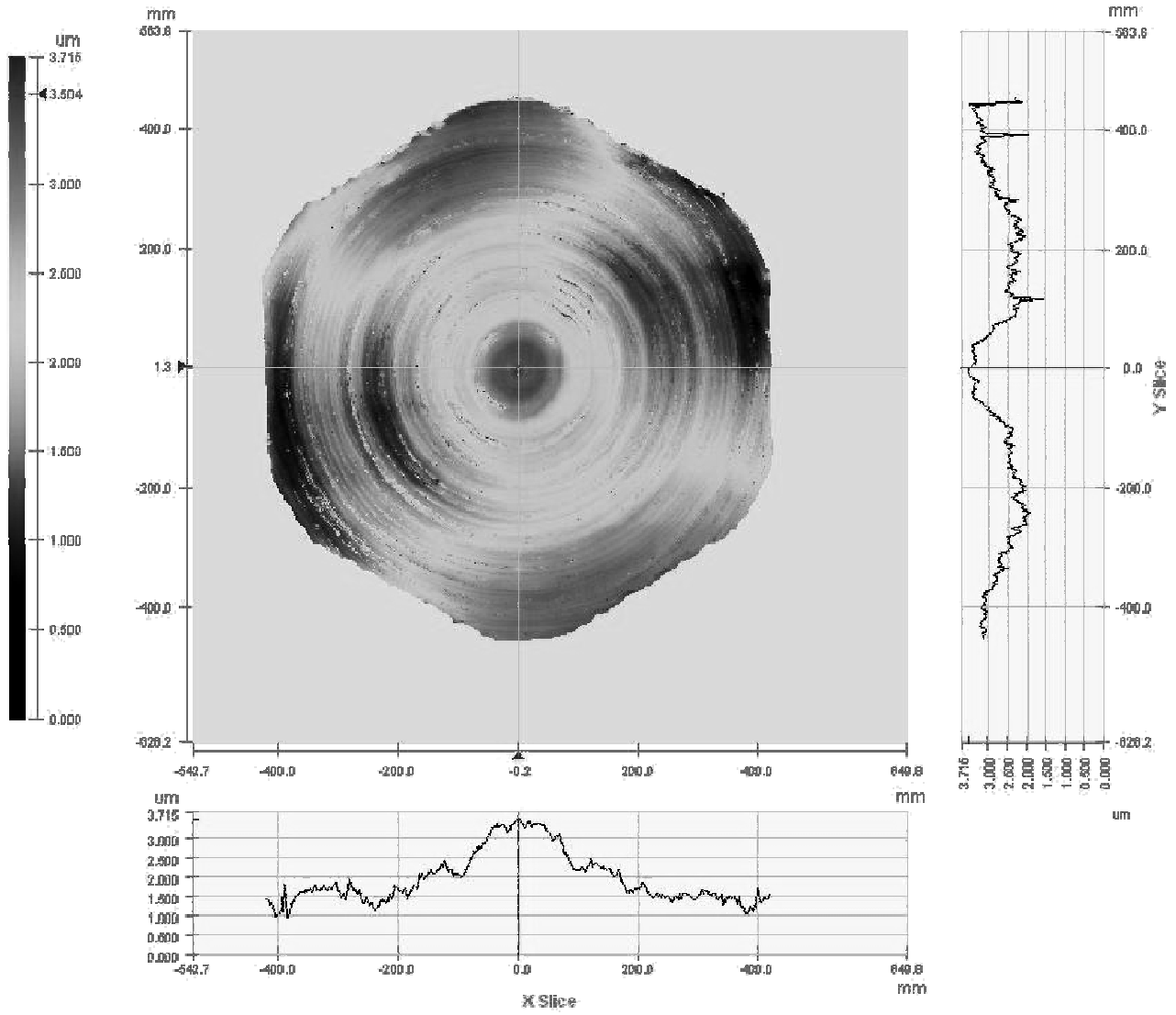

Fig. 9: 1 metre Zerodur® part ground surfaces

5 CONCLUSIONS

This paper shows the results obtained on Zerodur® 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. The total grinding process time achievable to remove 0.5 mm from a pre-shaped optical blank is 10 hours.

Further work will be to optimise similar effective grinding processes on different optical materials with low subsurface damage and good form accuracy.

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