INTRODUCTION
A number of projects are studying the possibility of making next generation Extremely Large Telescopes (ELT). The European Extremely Large Telescope (E-ELT) is one such project. The E-ELT will have a 42 m primary mirror made from 906 hexagonal shape segments of 1.45 m size across corners. Two potential materials for these mirror segments are ULE® and Zerodur® [1].

Manufacturing processes examples for making >1 metre hexagonal mirrors have been reported by both Sagem and Kodak. First, the blank is ground to 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 [2].

A possible production improvement is to achieve an effective grinding process that can produce better shaped surfaces with less subsurface damage. This will reduced subsequent polishing operations. To achieve this effective grinding capability, a new ultra precision large optics grinder - BoX® - has been developed at Cranfield University (Figure 1). This grinding machine now forms part of an Ultra Precision and Structured Surfaces (UPS²) facility, at the Technium OpTIC, St Asaph, North Wales [3].

The purpose of the work described in this paper has been to establish the induced level of subsurface damage (SSD) in ULE® and Zerodur® when grinding at differing levels of material removal rate.

SUBSURFACE DAMAGE MECHANISMS OF BRITTLE MATERIALS
Ductile or brittle fracture mode grinding can be used to machine brittle materials [4] such as Zerodur® and ULE®. Ductile mode grinding has been reported to give low subsurface damage (SSD). However, achievable material removal rate is low, as for example the critical depth of cut is ~50 nm [5] on Zerodur®. Higher manufacturing rates are supported using micro brittle fracture grinding. However, the brittle mode leaves surface and subsurface damage.

Micro fracture mechanisms that lead to SSD in brittle materials have been extensively investigated by Lawn [6]. An efficient grinding process requires optimisation of the grinding parameters to reduce the penetration depths of the micro fractures.

In order to measure the extent of subsurface cracks, different non-destructive and destructive measurement methods have been developed. [7, 8] Destructive methods have proved, and remain, more successful for detecting micron and sub-micron scale fractures. Repetitive polish, etch and optical microscopy have been widely employed to observe SSD in ground glasses [9, 10].

Two terms have been employed to describe the subsurface damage observed. The majority of subsurface cracks cluster together near the surface and finish at a characteristic 'cluster depth'. A small minority of cracks propagate deeper beneath the surface the so-called 'single last fracture depth' which is often much deeper than the cluster [11-12].
FIGURE 1. BoX® precision grinding machine

EXPERIMENTAL DETAILS

Grinding parameters
The grinding parameters controlled are the depth of cut (a₀), the feed per revolution (fᵣ), the surface speed (vₑ). They are shown in Table 1. The grinding wheel cutting speed (vₑ) is kept constant at 30m/s.

<table>
<thead>
<tr>
<th>Grinding Conditions</th>
<th>Depth of cut a₀ (µm)</th>
<th>Feed Rate fᵣ (mm/rev)</th>
<th>Surface speed vₑ (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough cut</td>
<td>500</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Semi Finish cut</td>
<td>200</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Finish cut</td>
<td>50</td>
<td>1.5</td>
<td>25</td>
</tr>
</tbody>
</table>

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

Grinding wheels
'Toric' shaped resin bonded diamond cup grinding wheels have been employed. Three abrasive grit sizes were chosen for this grinding process, 76 µm, 46 µm and 25 µm.

Material
Two materials were tested (see Table 2). A glass material, ULE® (Ultra Low Expansion), produced by Corning and a glass ceramic material, Zerodur®, made by Schott.

<table>
<thead>
<tr>
<th>Grinding Conditions</th>
<th>Wheel type</th>
<th>Surface roughness Ra (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough cut</td>
<td>D76</td>
<td>303</td>
</tr>
<tr>
<td></td>
<td>D76</td>
<td>266</td>
</tr>
<tr>
<td>Semi Finish cut</td>
<td>D46</td>
<td>186</td>
</tr>
<tr>
<td></td>
<td>D25</td>
<td>165</td>
</tr>
<tr>
<td>Finish cut</td>
<td>D76</td>
<td>231</td>
</tr>
<tr>
<td></td>
<td>D46</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td>D25</td>
<td>191</td>
</tr>
</tbody>
</table>

TABLE 2. Zerodur® and ULE® parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ULE</th>
<th>Zerodur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus E (GPa)</td>
<td>70</td>
<td>91</td>
</tr>
<tr>
<td>Hardness H (GPa)</td>
<td>4.6</td>
<td>6.2</td>
</tr>
<tr>
<td>Fracture toughness Kₑ (MPa.m⁰.⁵)</td>
<td>1.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Brittleness H/Kₑ (m⁻⁰.⁵)</td>
<td>2560</td>
<td>6890</td>
</tr>
</tbody>
</table>

Both ULE® and Zerodur® have low thermal expansion coefficients.

The difference of fracture toughness and hardness between those two materials means that Zerodur® has brittleness three times higher than ULE®.

Test specimen size was 100 mm x 100 mm and 20 mm thick.

Sub-surface damage evaluation
Using a 'wedge' polishing and surface etching approach, the SSD was evaluated using an optical microscope.

Grooves were polished using a Zeeko IRP polishing machine. They were placed in line with the grinding direction and at bottom of the ‘cusping’. The wedge depth was measured using a profilometer.

The number of defects per mm² relative to the depth below the ground surface has been analysed using optical microscopy. Identification of defects for counting was based on judgment.

EXPERIMENTS RESULTS

Surface roughness
The surface roughness along the grinding direction, (Rₐ), changes with the grinding wheel grit size. Typically larger grit size results in an increase of the surface roughness for ULE® and Zerodur®.
Overall, Zerodur® has higher roughness than ULE® for equivalent grinding conditions. Interestingly, during a finish cut on ULE®, the D46 grinding wheel gives better results than the D25 grinding wheel. On Zerodur®, under those same grinding conditions, the two grinding wheels leave equivalent surface roughness.

Subsurface damage
Figure 2 and 3 show different microscope pictures taken of Zerodur® and ULE® cracks for each grinding conditions employed.

For each material, the shape of the cracks is similar for each grinding conditions. However, larger grit size tents to induce longer cracks. The Zerodur® cracks are small and slightly curved in comparison to ULE® where observed cracks are 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®.

‘cluster’ and ‘single last fracture’ depth results were measured and are shown in Figure 4.

The cluster depth results in ULE® are larger than in Zerodur®. However, this depth difference is typically within 1-2 μm. Interestingly, the semi finish cut (D25) leaves deeper cluster damages in Zerodur® than ULE®.

Overall, the single last fracture depths follow the same trend as cluster depths. The subsurface damage depths in ULE® are larger than in Zerodur®. During the rough cut (D76), the single last fracture depth is more than twice the depth in ULE® compared to Zerodur®. This can be explained by a lower brittleness value for ULE® leading to larger cracks using higher grinding forces. However, the finish cut (D46) and semi finish cut (D76) give more damage in Zerodur®.

Those results are in accordance with the consideration that the single last fracture depth is highly associated with machine dynamics whilst the cluster depth is related to material mechanics. [10] A previously reported correlation between surface roughness and subsurface damage is not observed in these results.

The important subsurface damage values are those created during the finish cuts. Importantly, the finish cut using a D25 grinding wheel leaves 8 μm in ULE® and 4 μm in Zerodur®. Using the same grinding parameters, the subsurface damage depth increases with the grit sizes. The finish cuts using 25 μm grit size reach the target value for Zerodur® (<5μm) but not for ULE®.
CONCLUSIONS
This paper shows results obtained when grinding optical materials using the BoX® grinding system. An efficient process has been developed for precision grinding large optics. Total grinding process time to remove 0.5 mm from a pre-shaped 1 metre optical blank is 10 hours.

On Zerodur®, 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 difference of subsurface damage can be related to relative material brittleness. No significant connection was seen between surface roughness and subsurface damage using the BoX® grinding mode. Further work will be carried out regarding the influence of grinding machine dynamics and induced subsurface damage levels in optical surfaces.

ACKNOWLEDGMENTS
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REFERENCES