Subsurface damage in precision ground ULE® and Zerodur® surfaces

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Abstract: The total process cycle time for large ULE® and Zerodur® optics can be improved using a precise and rapid grinding process, with low levels of surface waviness and subsurface damage. In this paper, the amounts of defects beneath ULE® and Zerodur® surfaces ground using a selected grinding mode were compared. The grinding response was characterised by measuring: surface roughness, surface profile and subsurface damage. The observed subsurface damage can be separated into two distinct depth zones, which are: 'process' and 'machine dynamics' related.

OCIS codes: (160.2750) Glass and other amorphous materials; (220.4610) Optical fabrication; (240.5770) Roughness; (350.1260) Astronomical optics; (350.1820) Damage; (350. 3850) Materials processing

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#85518 - $15.00 USD Received 23 Jul 2007; revised 7 Sep 2007; accepted 8 Sep 2007; published 11 Sep 2007

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1. Introduction

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. Currently, a number of projects are studying the possibility of making the next generation of European Extra Large Telescope. These generally follow the Keck hexagonal segmented mirror scheme. The segments are expected to be in the size range 1-2.5 metres in glass, glass ceramic, ceramic or Beryllium [1]. 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 [2].

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 [3] **-** BoX® **-** has been developed at Cranfield University. A 5-axis Holroyd Edgetek grinding machine with a dedicated fixture has been used in advance in order to validate the BoX® grinding mode. The grinding forces and power [4] as well as the wheel wear [5] induced by this particular grinding mode were previously 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, for ULE® and Zerodur®, is provided in association with grinding parameters.

2. Theoretical details

2.1 Brittle materials

Ductile or brittle fracture mode grinding [6] can be used to machine brittle materials such as Zerodur® and ULE®. Ductile mode grinding has been reported to give low SSD [7]. However, achievable material removal rate is low, as for example the critical depth of cut is ~50 nm on Zerodur® [8]. 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 [9]. 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.

2.2 Subsurface damage evaluation

Different models to predict SSD have been proposed using the maximum chip thickness and the material properties [10]. Other attempts to estimate the SSD have been proposed in order to correlate it with the abrasive grain size [11] or the surface roughness [12]. The importance of grinding machine performance has also been identified [13, 14]. Most recently, some work carried out on Zerodur® using a 25 µm grit size wheel showed that subsurface damage was believed to be separable into 'Process' related and 'Machine dynamics' related [15].

#85518 - $15.00 USD Received 23 Jul 2007; revised 7 Sep 2007; accepted 8 Sep 2007; published 11 Sep 2007

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 [16], 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 [17]. 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 [18]. A variant of this repetitive polish and etch method [19] is a “wedge” polishing approach which simplifies assessment of how defect density relates to depth beneath the ground surface [20].

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’ is usually much deeper than the cluster depth and corresponds to the deepest penetration of such cracks into the sample [12].

3. Experimental details

3.1 Specimens and grinding equipment

Zerodur® and ULE® specimens used in these tests were 100 mm x 100 mm x 20 mm.

Table 1. Material properties [21, 22]

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

Tests were carried out on a Holroyd Edgetek 5-axis superabrasive grinding machine. A fixture was added on the grinding table so that the material blank can be tilted at 70° to the horizontal (the grinding spindle axis is horizontal). The fixture recreates the 20° wheel tilt angle employed on the BoX® machine and employs a vacuum system to hold the test samples in place (Fig. 1).

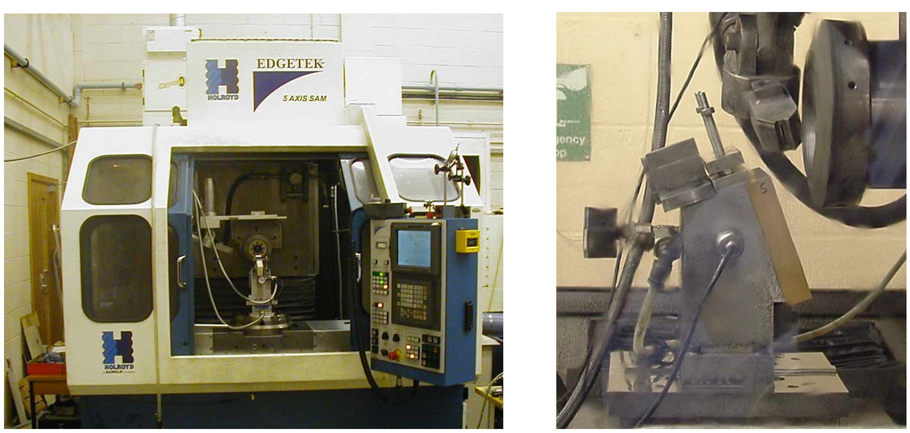

Fig. 1. (a). Holroyd Edgetek 5 axis machine and b) grinding set-up used

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Three diamond abrasive resin bonded cup grinding wheels, FEPA 6V5, were used to perform ‘rough’, ‘semi finish’ and ‘finish’ cuts. Wheel details are given in Table 2. A nickel electroplated wheel with 181µm diamond grit size was employed to true and form the grinding wheels’ cross sections to a 300mm radius.

Table 2. Grinding wheels specifications

Manufacturer		Wendt Boart	Wendt Boart	Cranden
Grit size	(µm)	76	46	25
Grit Concentration	(%)	75	50	50
Wheel diameter	(mm)	200	150	150
Abrasive layer width	(mm)	35	25	25
Cutting radius Rc	(mm)	242	183	183

The wheels were balanced in-situ using a Schenk dynamic balancing system. Before each cut, the wheel was ‘dressed’ by plunging into a dressing stick. The coolant employed throughout was a water based fluid with 2% Dowel. To achieve a relatively laminar flow, the pressure was set to 2 Bar. A slot nozzle design was chosen to provide ‘laminar like’ flow over the large engagement zone. All tests used a 30m/s grinding speed (v_s). The surface roughness and surface waviness of specimens were assessed using a Form Talysurf profilometer. The stylus used was a 2µm radius conisphere diamond. The values of surface roughness (Ra) and surface profile (Pt) parameters were used to characterise the surface quality.

3.2 Grinding mode and grinding parameters

The grinding mode used in these tests (Fig. 2) corresponds to the BoX® grinding mode [3]. This type of grinding mode has previously been described in the use of the Large Optical Generator [23] as well as the grinding of aspherical optical components [24].

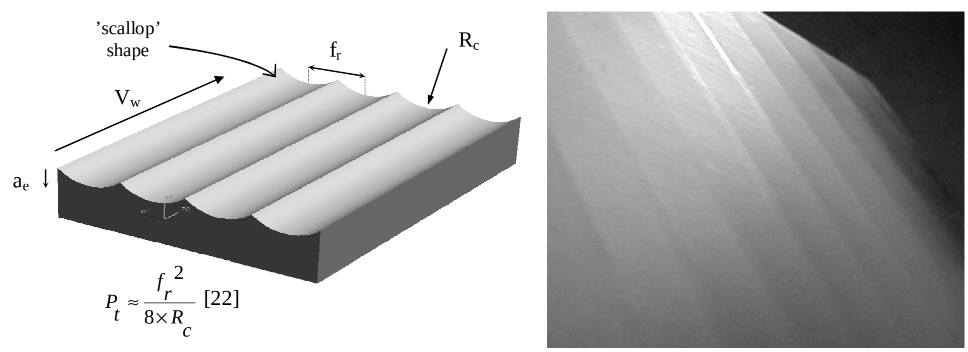

Fig. 2. (a). Grinding mode, b) Semi finish surface (Zerodur®)

In that particular grinding mode, the surface profile corresponds to the ‘scallop height’. The profile is associated with wheel cutting radius (R_c) and the feed per step (f_r). Table 3 shows the grinding parameters employed for the tests carried out.

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Table 3. Grinding parameters

	a_e (μm)	f_r (mm/step)	v_w (mm/s)	Q_w (mm^3/s)	Grit size (μm)
Finish cut	50	1.5	25	1.9	25 & 46
Semi finish cut	200	10	20	40	46
Rough cut	500	15	25	187.5	76

4. Results

4.1 Surface geometry results

The surface profile (P_t) was measured perpendicular to the grinding direction. The results are reported in Table 4.

Table 4. Surface Responses

	P_t (actual) (μm)		Ra 'along v_w' (nm)		P_t (theory) (μm)
	ULE®	Zerodur®	ULE®	Zerodur®	
Finish cut (D25)	1.98	1.91	124	137	1.54
Finish cut (D46)	3.22	3.56	368	646	1.54
Semi finish cut (D46)	66.51	64.15	462	707	68.31
Rough cut (D76)	115.03	114.72	335	487	116.22

The values show good correlation with equations developed for other processes of surface generation [25]. For the finish cut, the profile value is noticeably influenced by the errors, particularly in respect of scallop to scallop height consistency. Examination of a Form Talysurf profile [5] shows that the bottoms of each ground cusp are distributed around the average surface line by approximately 2 μm p-v. This is as a result of error motion of the grinding machine's axes at these high force levels; this effect is at least partially a function of static and dynamic stiffness of the machine. The difference between ULE® and Zerodur® is important when considering surface roughness 'along v_w' but less significant for the surface profile.

4.2 Subsurface damage assessment

4.2.1 Surface preparation

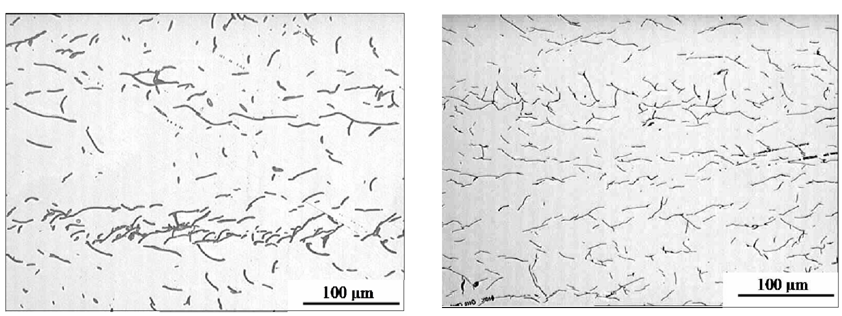

Fig. 3. Finish cut using D46 a) Zerodur® b) ULE®

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 in line with the grinding direction and corresponding to the bottom of the scallop where the ground

#85518 - $15.00 USD Received 23 Jul 2007; revised 7 Sep 2007; accepted 8 Sep 2007; published 11 Sep 2007

surface is at its lowest point. The depth of the wedge was obtained using a profilometer. Etching of the polished ‘wedge’ was made using a HF/HCl solution on Zerodur® and a HF solution on ULE®. Etching rate on ground surfaces was established to choose an adequate and safe etching time. The etching times were set to 10 and 30 seconds which removes approximately 1µm and 0.5µm depth on Zerodur® and on ULE® respectively.

Figure 4 shows an example of the SSD in a Zerodur® and ULE® sample after etching. Labels on zones in Fig. 4 indicate distance along the wedge in mm, then depth in µm. This technique permits examination of numerous depth zones in one operation. Examination of different depths in a single location would require a protracted iterative polish-etch cycle.

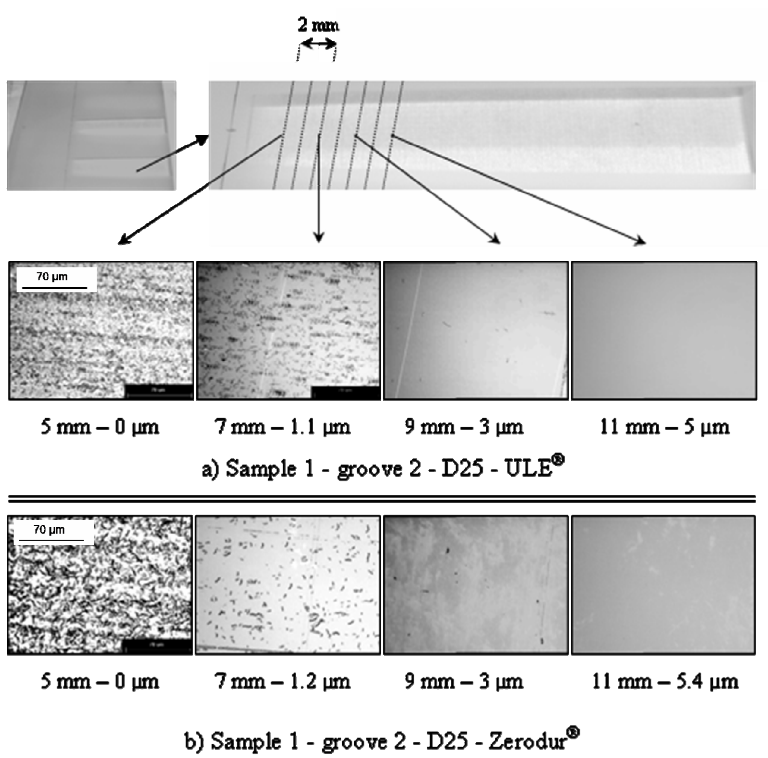

Fig. 4. Subsurface damage after etching – a) ULE® b) Zerodur®

The number of defects per mm^2 relative to the depth below the ground surface has been analysed by visual microscopy. Identification of defects for counting was based on judgment. Where the degree of interconnect rendered counting difficult, the results have been omitted from the analysis – such results represent very shallow damage depths.

4.2.1 Measurement results

Figures 5(a)-5(b) and Figs. 6(a)-6(b) show the amount of SSD for two finish cuts on ULE® and Zerodur® using 25 µm and 46 µm grit wheels respectively. A similar graphing procedure was used for each SSD observation.

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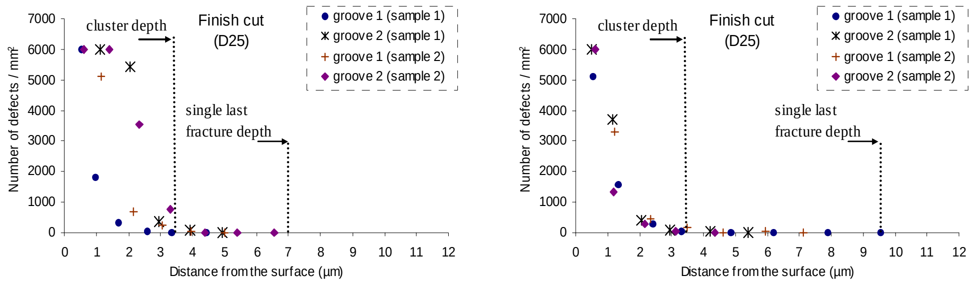

Fig. 5. Number of cracks per mm^2 for different depths beneath ground surfaces - D25 wheel - a) ULE® b) Zerodur®

For both materials, the amount of defects decreases more rapidly using the finer grit size wheel, 25 µm. For example, in Fig. 5(a), the last crack in ULE® is observed at a depth of 6.5 µm using a D25 wheel, whereas in Fig. 6(a), the last crack appears at a depth of 14.5 µm.

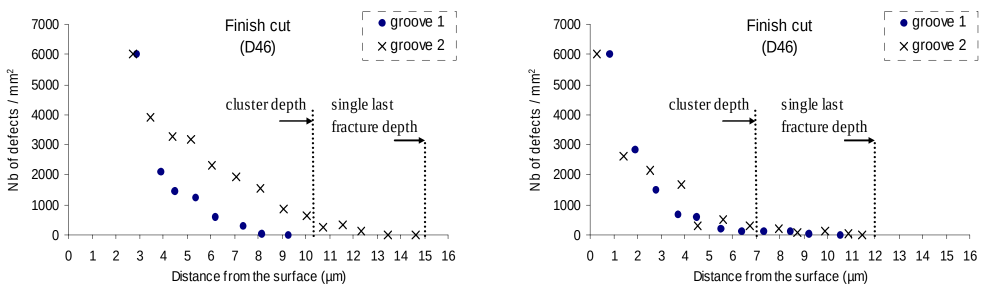

Fig. 6. Number of cracks per mm^2 for different depths beneath ground surfaces - D46 wheel - a) ULE® b) Zerodur®

As the last crack observation is difficult to make, the SSD level differs slightly between each groove and ground surface. It is interesting to note that the amount of defects per mm^2 reduces dramatically before this last crack. The 'cluster depth' is significantly influenced by reducing the abrasive size. However, an influence of abrasive size on SSD in respect of the 'single last fracture depth' is not clearly apparent. By contrast, a relationship between 'single last fracture depth' and material type is indicated.

A small number of samples were investigated due to the time consuming process of analysis. For the finish cut using the D25 wheel, the process was repeated once for each material; with the D46 and D76 wheels, one sample was used for each. To improve these initial findings, further work will be carried out in order to obtain statistical data.

Table 5 shows the SSD measured relative to the grinding parameters used for ULE® and Zerodur®.

Table 5. Subsurface damage data results

	Cluster depth (µm)		Single last fracture depth (µm)	
	ULE®	Zerodur®	ULE®	Zerodur®
Finish cut (D25)	3.5	3.5	6.6	9.5
Finish cut (D46)	10.5	8	14.6	11.5
Semi finish cut (D46)	11	8.5	17.4	15.6
Rough cut (D76)	12	11	14.7	12.2

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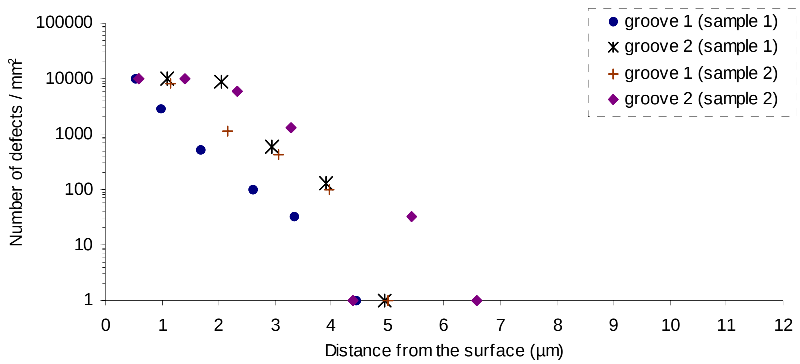
5 Discussion

The results show that the 'single last fracture depth' is deeper for Zerodur® than for ULE® when grinding with a D25 wheel, using the finish cut parameters. However, for all other conditions the subsurface damage found in ULE® is higher than in Zerodur®. This can be explained by relating the level of subsurface damage to the brittleness of the material. A crack is less likely to be created in ULE® but it is more easily propagated once the load becomes significant.

As Zhang [14] showed in ceramics, a lower brittleness value and higher grit size lead to higher SSD. However, the lower SSD level obtained for the rough cut using the 76 µm grit size wheel shows that there are other important parameters to look at when assessing SSD. The degree to which densification of ULE® influences both its brittleness value and its response to the finishing operation is not known at this stage.

By plotting the number of defects per mm² against the distance from the surface using a logarithmic scale, two zones can be identified, see Fig. 7(b).

a)



b)

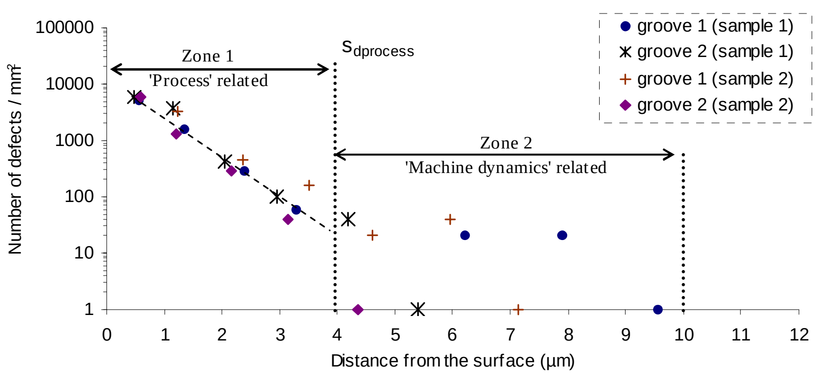


Fig. 7. 'Process' related and 'Machine dynamics' related zones (finish cut - D25) – a) ULE® b) Zerodur®

In Fig. 7(b) for Zerodur®, first the number of defects decreases rapidly (Zone 1) then it follows another distinct trend (Zone 2). Zone 1 is believed to be 'process' related and Zone 2 to be 'machine dynamics' related. The transition point between these two zones has been defined as $s_{dprocess}$. This is also the "cluster" depth in this case, which the authors believe is an artefact of process conditions only and not machine related. For Zerodur®, the value of $s_{dprocess}$ using the D25 wheel under "finish cut" conditions is 4 µm. The machine dynamics performance is therefore considered to be of significant importance. For the particular case of a finer grit size, 25 µm, ULE® seems to be less responsive to the machine dynamics. This is believed to be due to longer cracks, resulting from easier propagation in ULE® as observed in

Figures 3-4. The transition between Zone 1 and Zone 2 is unclear and further work will be needed to identify this value. The unclustered cracks, assumed to be ‘machine dynamics’ related, occur deeper beneath the surface in Zerodur®. Further results obtained using a dynamically stiff grinding machine, having smoother motion control, e.g. the BoX® machine, should clearly test this hypothesis.

6 Conclusions

The purpose of this research is to reduce to a minimum the required time for any subsequent polishing process. A high material removal rate at 187.5mm^3/s has been demonstrated using resin bonded diamond wheels on Zerodur® and ULE®.

Achieved surface roughness and subsurface damage levels using the finer grit wheel (D25) during finish cuts were 124 nm (Ra) and 6.6 μm respectively for ULE®. For Zerodur®, these results were 137 nm (Ra) and 9.5 μm respectively.

Our work shows the value of the “wedge” polishing technique to assess the amount of damage under a ground ULE® or Zerodur® surface. As previously discussed for Zerodur® [20], these results show that for ULE® the number of defects apparent at different depths beneath the surface is a combined function of ‘process’ related and ‘machine dynamics’ related damage. However, the material brittleness is believed to give further understanding of the distribution of the numbers of defects beneath the surface. A low brittleness value will give longer cracks that combine with ‘machine dynamics’ related cracks. More aggressive grinding parameters, in particular coarser grit sizes, can leave more and deeper cracks which reduce the importance of the ‘machine dynamics’ related damage in preliminary or rough grinding. Additional work will be carried out in order to develop a model relating subsurface damage to both ‘process’ related and ‘machine dynamics’ related issues. This model will be developed by performing the same grinding tests using the stiffer, hydrostatic bearing based grinding machine in order to prove the extent of machine dynamics effects in regard to the subsurface damage defects profile.

Acknowledgments

The authors would like to acknowledge project funding through the UK’s Joint Research Councils’ Basic Technologies programme and funding support from the McKeown Precision Engineering and Nanotechnology Foundation at Cranfield.

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