Experimental Ductile Grinding of Glass Specimens on the Cranfield Tetraform C Machine

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Introduction: Preceding Work

In the 1980s, Dr A Franks at the UK National Physical Laboratory (NPL) led a programme of research into the machining of brittle glass materials. Parallel collaborative studies at the University of Surrey, Guildford, UK by Prof K Puttick and colleagues modelled machining type material deformation to show that crack-formation was scalar-dependent. Using pyramidal diamond indenter tools, they demonstrated that single point incursions to depths to some critical value of the order of 1µm in both glasses and crystalline semiconductors could be made with crack formation controlled in apparently ductile plastic mode as shown in Fig.1 (Puttick et al 1989). This was extended to include dead-load ruling (Chao & Gee 1989, Gee et al 1992) and to semiconductors (Puttick et al 1994).

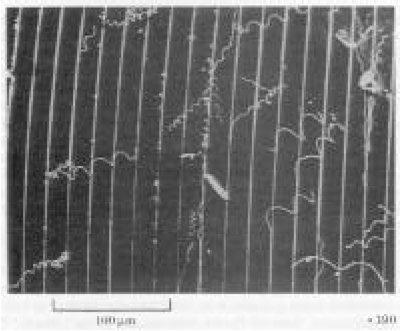

Figure 1 Single Point Ductile Machining of Glass (Puttick et al 1989)

Blackley and Scattergood (1991) provided an additional model for a curved tool producing an extended 'D' cut section profile, showing critical 'depth' could be more fully defined as a critical incursion dimension.

At NPL a stiff radical concept machine-tool was designed and built on which to extend studies aimed at producing optical surfaces approaching polished standards of surface finish. The 'Tetraform' machine tool (Lindsey 1992) employed a stiff tetrahedral structure comprised of substantive cylindrical members with internal damping, a vertical spindle carrying a cup-grinding wheel and two translation axes: a leadscrew horizontal traverse of 150mm and a high pressure hydraulic vertical in-feed of 100µm. On it Lindsey (1992) reported grinding Spectrasil B silica glass flats using a 104mm diameter 15-30µm diamond cup-wheel at feed-rates of 30mm/min (500µm/s) with surface roughness of 5nm R_a and sub-surface damage of 0.25-0.95µm for cut-depths of 0.5-10µm.

Design studies of the Tetraform concept continued at Cranfield University resulting in Tetraform C, an extended design based on the high stiffness obtainable with such a structure but employing two horizontal traverse axes (220mm x 120mm) and a 25mm vertical axis to permit form generation. The resulting structural design, coupled with the use of hydrostatic leadscrews and guideways for each axis, provides very high static and dynamic stiffnesses. The machine is shown in Fig 2 and details have been given by Corbett *et al* (1999).

Figure 2 Tetraform 'C'

Experimental Work

To classify glass specimens indentation and ruling were employed, depth-controlled by applied dead-load, indentation being a standard materials test procedure. Ruling is a specialised process performed on a machine originally developed for generating diffraction-gratings (Horsfield 1965) and suitably modified (Chao & Gee 1989, Gee *et al*. 1992).

Grinding on the Tetraform C machine was performed with samples initially set inclined so as to machine a wedge leaving recognisable regimes on the sample: (1) unground reference surface, (2) ductile ground surface, (3) transitional region (of increasingly frequent brittle damage) and (4) brittle ground region. Angles of surfaces generated were checked interferometrically and samples were examined using by Wyko optical interferometer and atomic force microscope. Examination of the areal extent of brittle fracture was by optical microscopy. From the results, constant depth machining parameters were selected and employed on further samples.

Materials employed were commercial float glass and Spectrosil B. The first was chosen for reasons of its production process: melt-formed on liquid tin, few surface structure defects were to be expected. This and its surface roughness formed a datum base from which to study the effects of subsequent mechanical incursion processes.

Results - Indentation

Averages of four readings of Vickers indenter load, indentation diagonal and lateral crack length were as follows:

Float Glass			Spectrosil B	
Load (g)	Diagonal (µm)	Crack Length (µm)	Diagonal (µm)	Crack Length (µm)
25	9.7		8.1	
50	13.7		10.4	
100	19.2		15.8	
200	26.7	13.5	23.1	
300	32.2	21.0	27.2	11.5
500	41.7	28.3	35.8	17.5

Results - Ruling

On float glass, loads of between 10 and 150g produced ductile material removal. Loads of above 180g produced brittle fracture and were tested to 350g.

On Spectrasil B, the ductile range was 10 to 250g with brittle damage observed above 250g and tested to 350g.

Results - Grinding

Float glass (initial R_a = 0.42nm):
For various feed-rates, the ductile ranges of depths and achieved roughnesses were as follows:

Feed-rate (mm/min)	Transitional depths (µm)	Roughness R_a (nm) Wyko
3	1-10	2.1 - 5.2
6	1-9	1.2 - 2.5
12	1-6.6	1.6 - 6.7

At 2µm constant depth, 3 and 6mm/min feed-rates yielded a surface free of damage with R_a between 3 and 6nm.

At 1µm constant depth and12mm/min feed-rate a damage-free surface was observed throughout but with some observed blemishes and R_a increased to between 13 and 22nm.

Spectrasil B (polished R_a = 0.62nm):
At feed-rates of 3 and 6 mm/min, wedge-depths to 4.5µm only were investigated due to set-up problems. These showed no brittle fracture. R_a was between 3 and 7nm with one sample achieving 1.04nm (see Fig 3).

2µm constant depth and 6mm/min feed-rate yielded a surface free of damage with R_a of 3.5 - 8.8nm.

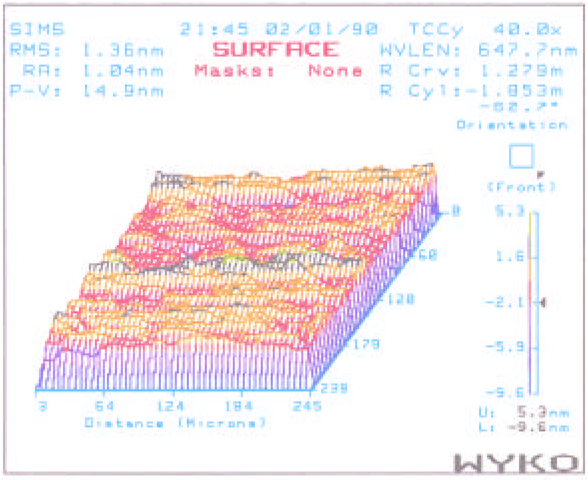

Figure 3 Wyko Interferometer plot showing surface finish obtained on Spectrosil diamond ground surface (1.04 nm Ra)

Discussion

The surface finish of the float glass samples (R_a ~0.4nm) was comparable with conventional polishes. Spectrasil B samples were polished to R_a ~0.6nm. 1nm R_a is typical of a quality optical glass surface produced by traditional free-abrasive polishing. Since that process also exploits ductile mode material removal, it is to be expected that an alternate machining process will either show results approaching this or manifest brittle damage (Gee 1996).

The work showed that on the Tetraform C machine, Spectrasil B could be readily ground with 2µm cut-depth at a cross-feed rate of 3-6mm/min to a finish of R_a~3nm, overlapping well with the earlier results of Lindsey (1992) on the original Tetraform at NPL. Underlying this, it should be pointed out that the Tetraform C machine has an extended (25mm) vertical axis to enable it to be employed for form generation. The current work indicates that these additional capabilities have not compromised target surface finish and damage performance.

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