Productive Modes for Ultra-Precision Grinding of Freeform Optics

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INTRODUCTION

There are numerous applications demanding the use of medium to large freeform surfaces and optics. These include short wavelength microlithography, segmented ground based telescopes, compact space based observers, high power laser systems, IR defence systems and even international temperature definition apparatus. The authors have been engaged in developing effective fabrication of freeform surfaces demanded for all of the above mentioned applications [1,2,3,4].

This paper introduces developments carried out that have significantly improved the production method for grinding freeform shape optics. Much of the work carried out has been reported in detail elsewhere, the developments are broadly introduced here and clearly referenced.

BACKGROUND

Numerous optical systems can benefit from application of freeform surfaces. Available performance benefits can include: compact system design, reduced number of optical elements, reduced mass, shorter optical paths and reduced angle of incidence/absorption, naming but a few. These benefits are not unlike those seen in earlier decades when rotationally symmetric aspheric surfaces started to be adopted replacing optical systems formed by spherical shape optics.

Ultra precision generation of freeform optics has been well demonstrated for a number of years using the diamond turning process in a mode called slow slide servo technique [5]. However, limitations of diamond turning restrict its application to a narrow range of metals and crystals. Its application for producing optics made in glass and ceramics has not yet proved to be effective. Consequently, the generation of optical surfaces in glass and ceramics has been predominantly performed using fixed abrasive grinding prior to subsequent polishing and figuring processes. Ultra precision machines employing purely positional controlled surface generation techniques typically can achieve form accuracy to size in the range of 1 part in 10^6. Meaning a 1 metre surface can be machined to a form accuracy of 0.001mm (1 micrometre RMS). Achieving beyond this relative level of size to form accuracy has not yet been reported at any notable level of production output.

BOX MACHINE

In 2004, the authors embarked on designing and building a large scale freeform optics grinding machine, see Figure 1. The BoX® machine was conceived to be able to grind freeform optical surfaces of up to 2 metres in diameter, achieve 1 part in 10^6 form accuracy / size ration and have a production rate of 1 metre^2 per 10 hours removing a minimum depth of 1 mm. Achievement of the above goal has been reported in detail [6].

FIGURE 1. BoX® Freeform grinding machine

Significant data regarding the associated levels of induced sub-surface damage has also been presented in scientific and academic journals [2,3]. This sub-surface analysis linked the machine dynamic performance to the induced level of sub-surface damage at given rates of material removal.

The BoX® machine design is based on a simple 3 axes cylindrical co-ordinate motion system employing a toric shaped grinding wheel and specially defined optical tool path software. The tool path software adjusts the motional path of the machine linear axes to enable accurate freeform surfaces to be effectively produced. This motional tool path adjusts the contact point of the wheel with respect to the freeform surfaces moving the work to wheel contact point in 2 directions around the toric shape wheel, see Figure 2.

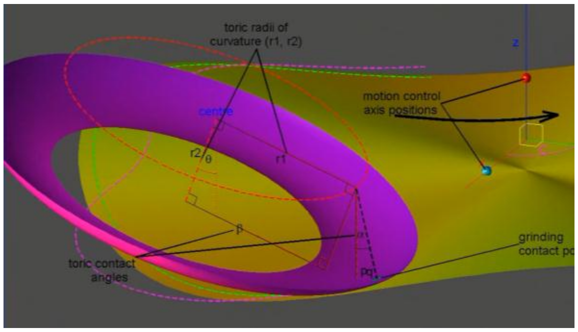

FIGURE 2. BoX® Tool path control method

The key benefits of this simple 3 axes cylindrical co-ordinate machine design can be summarised as:

- Low number of machine interfaces (bearings) offering achievement of high static loop stiffness
- Limited level of moving mass maximising dynamic stiffness
- Eased application of large area hydrostatic bearings maximising smoothness, load capacity whilst minimising vibration levels at high load levels
- Simple 2 plane symmetric machine design that minimises tilts errors caused by any thermal distortion from high power sub-systems

E-ELT PRIMARY MIRROR SEGMENT

The capability of the BoX® freeform grinding approach was clearly demonstrated in producing 1.46 metre sized freeform mirror segments for the ESO E-ELT see Figure 3. These freeform shaped primary mirror segments, made in both Corning ULE® and Schott Zerodur®, were ground using the BoX® machine
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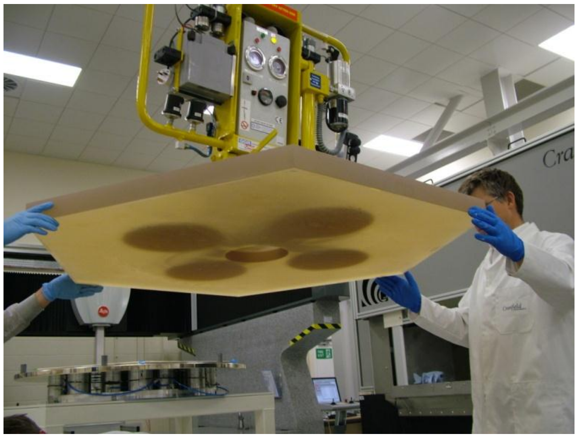

FIGURE 3. E-ELT primary mirror segment

The achieved level of form accuracy was better than 1 micrometre RMS, see Figure 4. The processing duration was below 20 hours (equivalent to 10 hours per m^2).

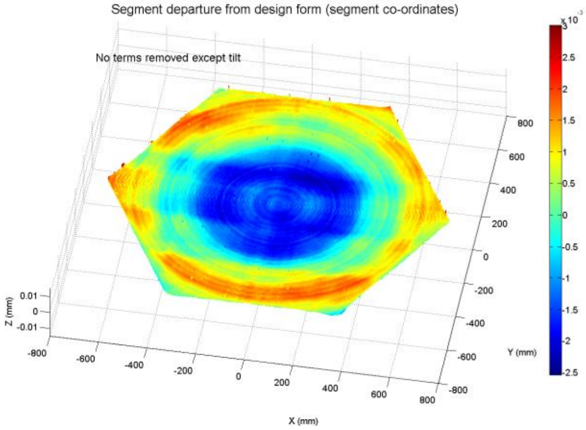

FIGURE 4. Form accuracy E-ELT primary mirror segment: 0.6 um RMS from Leitz pmmf 30.20.10

Whilst the E-ELT mirrors represent freeform surfaces their departure from being rotationally symmetric is only 0.15mm. Nevertheless the achievement of 0.6 micrometre RMS (4.8 micrometres P-V) measured with 580,00 data points represents a significant achievement given the rapid processing rate.

DECENTRED SPHERE GENERATION

Proving the performance of a diamond turning machine for producing freeform surfaces has been demonstrated by machine suppliers through the generation of a so-called decentred sphere. The consideration being that the spherical surface is easy to measure yet the machine motion demands to produce a decentred spherical surface significant but also easily understood.

Consequently, the BoX® machine performed the same decentred spheric generation task to prove its functionality. A 1 metre radius of curvature spherical surface is rapidly ground in a decentred mode. The offset distance of 13mm yields a maximum acceleration/deceleration of the linear axes of 20mm/second^2 at a processing rate of 1 metre^2 per 10 hours.

Critically, in this dynamic grinding mode, is the level of induced sub-surface damage. Investigation of ground decentred spherical surfaces was undertaken. Ground surfaces of this type were robotically polished in the regions that equated to the surface areas of minor and major acceleration/deceleration, See Figure 5.

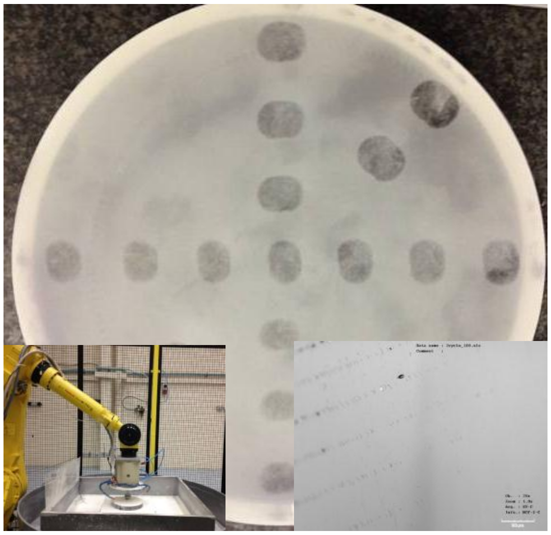

FIGURE 5. SSD evaluation of decentred sphere

The insets of Figure 5 show: (left) Cranfield's robot polishing system, (right) an optical micrograph showing worst case sub surface damage disappears at 14 micrometres below the surface of this decentred ground substrate..

NIF WEDGE LENS

An interesting lens demanded within the LLNL National Ignition Facility is a so-called wedge focussing lens. This lens has a freeform surface notably tilted with respect its second surface. Typically its freeform surface would be generated using a raster grinding process offered by a 3 linear axes Cartesian frame grinding machine. In the case of the BoX® machine, 4 of these 400mm square shape NiF lenses can be ground in a single set up as depicted in Figure 6. A 3.5 hour production grinding time can be achieved for the freeform surface of these high value lenses.

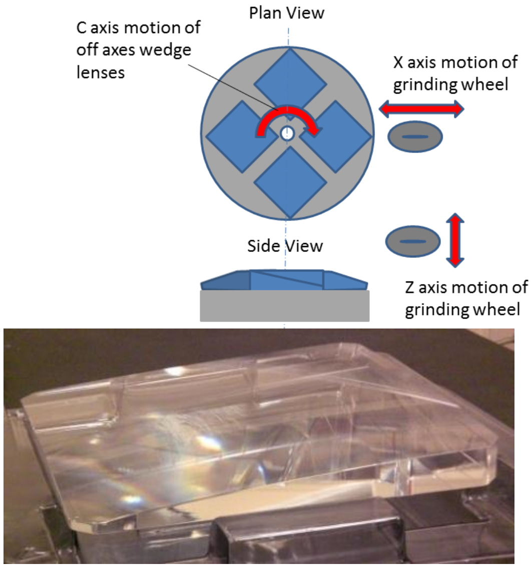

FIGURE 6. (above) Multiple mode grinding for NiF wedge lenses, (below) NiF wedge focus lens

LIGHTWEIGHT SPACE MIRRORS

The demand for lightweight space optics is increasing with greater complexity of the shape and substrate format. Reduced mass for a given level of substrate rigidity is a continuous development activity. This trend has brought about a shift to advanced ceramic substrates made for example, variants of silicon carbide.

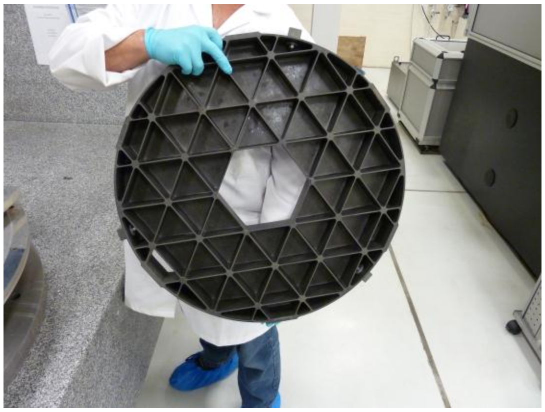

FIGURE 7. Light weight silicon carbide mirror substrate produced by Boostec of France

The trend to a reduced mass leads to thinner and thinner shell and support substrate structures. A consequence is that mirror grinding hugely benefits from a high responsiveness of the tool point. This high dynamic control of the tool point enables grinding passes to be made with correction for the differing deflection seen within each substrate shell structure. Figure 7 shows an advanced silicon carbide space optic substrate produced by the Boostec company of France.

By applying the BoX® grinding process, with tool path error correction for regional substrate deflection, higher quality form accuracy can be achieved with minimised processing times. Figure 8 illustrates the form accuracy and surface structure after BoX® grinding of the Boostec 600mm diameter very thin and highly light weighted silicon carbide substrate.

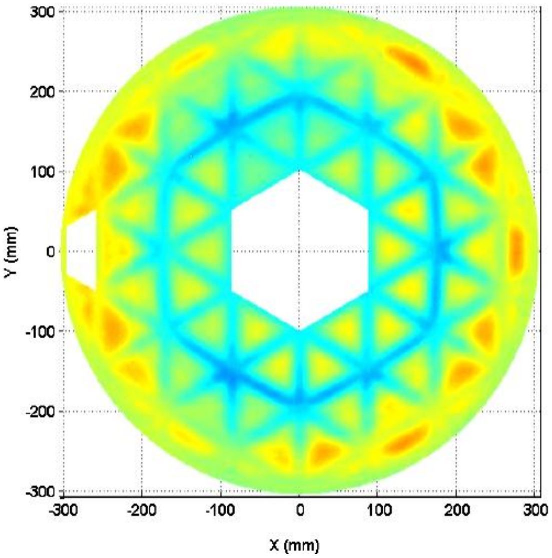

FIGURE 8. Minimising "print through" of space optics by dynamic tool path control

The achievement of improved form accuracy significantly alleviates time spent during subsequent polishing and reactive plasma figure corrections. These finishing process steps typically represent the major bottleneck processing operations, reducing their duration by advanced grinding represents a significant production cost saving opportunity. Figure 9 shows the finish ground thin shell silicon carbide mirror.

CONCLUSIONS

This paper has introduced the development of a number of freeform grinding modes. These modes are shown to be effective through high power and high dynamic machine motional performance. High dynamic response is gained by the BoX® grinding machines simple, low moving mass, 3 axes cylindrical co-ordinate basis. The slow slide servo technique previously applied to diamond turning machines is proved to be highly functional in a high power grinding machine. Low levels of sub-surface damage have been linked to machine tool dynamic loop stiffness. Multi component processing is shown to reduce grinding times. High quality form accuracy, even for thin section substrates, has been demonstrated by application of error correction techniques.

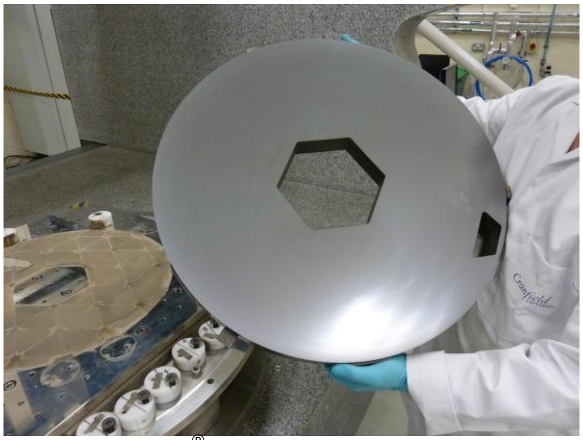

FIGURE 9. BoX® ground Boostec light weighted silicon carbide space mirror

REFERENCES

[1] Shore P, Morantz P. Ultra Precision – "enabling our future", Trans Royal Society, Phil. Trans. R. Soc. A. 2012 370 3993-4014

[2] Tonnellier X, Shore P, Morantz P. Sub-surface damage evaluation in grinding of large optics, ASPE, Portland, USA, Oct. 2008, 84-86

[3] Tonnellier T, Howard K, Morantz P, Shore P. Surface integrity of precision ground fused silica for high power laser applications, Procedia. 1st CIRP Conference of Surface Integrity, V19, 2011, 357-362

[4] de Podesta M, Sutton G, Underwood R, Perkin M, Davidson S, MorantzP. Assessment of Uncertainty in the Determination of the Boltzmann Constant by an Acoustic Technique, Int. J. Thermophysics, 2011, 32, 413-426

[5] Tohme Y, Lowe J. Machining of Freeform Optical Surfaces by Slow Slide Servo Method, ASPE, Portland, USA, Oct 2003

[6] Comley P, Morantz P, Shore P. Grinding metre scale mirror segments for the E-ELT ground based telescope, Annals CIRP, 01/2011 60(1) 379-382