Institution:
Glyndŵr University

Unit of Assessment:
13: Electrical and Electronic Engineering, Metallurgy and Materials

Title of case study:
Economic impacts of computer controlled polishing and metrology of ultra-precision surfaces
[13/1]

1. Summary of the impact (indicative maximum 100 words)

A unique UK national capability for large optics manufacture and associated technologies has been exploited. This case study describes the benefits realised from research into high precision surface-removal processes plus metrology, applied to large area functional surfaces producing precisions down to nanometres. Research into metrology for optical manufacturing, into increasing the dynamic range of a CNC polishing machine and into the issues associated with scaling up from prototype to commercial mass production of large off-axis aspheric mirror-segments for future extremely large telescopes has made a significant contribution to the progress of the ESO European Extremely Large Telescope project and has brought commercial benefits to Zeeko Ltd.

2. Underpinning research (indicative maximum 500 words)

The research focusses on state-of-the art high precision surface-removal processes (grolishing and corrective polishing) plus metrology applied to large area functional surfaces producing precisions down to nanometres. It has successfully responded to 'market pull':- ever-increasing technical demands from scientific, industrial, defence and consumer optics, healthcare, semiconductor fabrication and precision engineering. The research undertaken under the auspices of Glyndŵr University at Optic Glyndŵr [Optoelectronics Technology and Incubation Centre] builds on prior research undertaken under the auspices of UCL led by Walker (Professor of Optics), who since 2009 has been employed jointly by Glyndŵr and UCL (0.5fte each).

Research into metrology for optical manufacturing (references 1, 2)
A key insight was recognition of the requirements for dimensional precision (in X,Y, theta, magnification and geometric distortion) to assure correct mapping of coordinate frames between CNC machine, measurement-data and surface. Without this, the machine "polishes in the wrong place", and corrective polishing doesn't converge. This triggered development by Walker's team of a novel, holistic approach of "on-machine metrology" for large optics, where the part is left undisturbed without leading to vibration and thermal issues. The need for independent verification became paramount to avoid systematic errors. In response Prof. Rees led the team that developed a pentaprism profilometer; the first such instrument ever successfully deployed in-situ on a large CNC polishing machine. Its precision was demonstrated to meet project requirement, both experimentally and through a detailed uncertainty analysis.

Research underpinning the European Extremely Large Telescope (references 3, 4, 5)
Research at Optic into manufacturing large off-axis aspheric mirror-segments for future extremely large telescopes, led to a deeper understanding of the unprecedented issues scaling from prototype to commercial mass-production. A previously insurmountable challenge was to avoid rolling edges down (crucial as rolled edges on segments lead to stray light in the telescope, reducing contrast of key science objectives). The key insight (Walker) proved to be tuning variable spot-sizes always to give a *turned-up* edge, starting broad, then narrowed and finally removed at the very last step. The basic process was perfected on sub-scale parts by Yu over 2010-2012, using a combination of experimental work in Glyndwr's facility and numerical simulation in collaboration with UCL and Zeeko with further research into scale-up to full-size segments.

Research into increasing the dynamic range of a CNC polishing machine (reference 6)
Polishing is inherently a slow-removal process, and there has been a commercial drive to develop feeder-processes that can bridge the gap between hard-grinding and polishing. This led to a new

family of more aggressive “grolishing” processes, to smooth-out defects in pre-ground surfaces, and so accelerate subsequent polishing. Since 2009 these have been refined by Yu and PhD students in a programme of experimental trials at Optic. This work used Zeeko IRP600 and 1200 machines, with parts measured by stylus profilometry. This has led to a pallet of such processes, based on either loose abrasive methods, or bound diamond abrasives. A key discovery was that hard tools could be used on aspheric surfaces, providing that aspheric mis-fit is accommodated by abrasive grain-size. This has been extended to polishing, providing the key process-step for controlling mid-spatial-frequencies on E-ELT mirror segments.

Prof. David Walker – Professor of Optics (October 2009 – present)
Dr Guoyu Yu – Optical Scientist (December 2009 – June 2013); Senior Research Lecturer (June 2013 – present)
Prof Paul Rees - Professor Of Optics: Metrology & Technology (May 2010 – present)

3. References to the research (indicative maximum of six references)
These are available on request if required and not in the public domain.

1. Hongwei, J., King, C., Walker, D., (2010), ‘**Simulation and validation of a prototype swing arm profilometer for measuring extremely large telescope mirror-segments**’, Optics Express, Vol. 18 Issue 3, pp.2036-2048

Standard interferometric testing of aspheric optics is a classic “ill conditioned” problem – measuring the difference between an aspheric test-wavefront, and an aspheric reference-wavefront generated by null-lenses. Errors in these lenses imprint errors in the final mirror, as witnessed by Hubble Space Telescope. A separate test relying on geometric rather than interferometric principles is highly attractive in providing independent verification, and this paper describes such a method.

2. Hongwei, J., King, C., Walker, D., (2010), ‘**Measurement of influence function using swing arm profilometer and laser tracker**’, Optics Express, Vol. 18 Issue 5, pp.5271-5281

The *influence function* is the imprint of the tool used in CNC corrective-polishing, and its characterisation, by polishing and measuring reference ‘spots’, is fundamental to numerical optimisation of the corrective process. However, the surface-slopes in these spots are usually too steep to measure interferometrically, and profilometry using industry-standard profilometers e.g. Form Talysurf is impractical for larger spot-sizes. This paper resolves the problem by a novel profilometric technique, contributing an important part of the polish/metrology process-chain.

3. Song, C., David Walker, D., Guoyu Yu, G., (2011), ‘**Misfit of rigid tools and interferometer subapertures on off-axis aspheric mirror segments**’, Opt. Eng. 50, 073401 (2011); doi:10.1117/1.3597328

This paper explores the mis-fit of a hard, small tool with an off-axis aspheric surface, as the tool traverses the surface. Managing mis-fit is critical in computer-controlled controlled polishing of mirror segments etc, and this work led to the ‘boundary conditions’ where such a technique could be applied in practice without introducing its own, new, mid-spatial defects. The paper also considers the analogous case of wave-front distortion in sub-aperture interferometry.

4. Walker, D., Yu, G., Li, H., Messelink, W., Evans, R., Beaucamp, A. (2012), ‘**Edges in CNC polishing: from mirror-segments towards semiconductors, Paper 1: edges on processing the global surface**’, Optics Express, Vol. 20, Issue 18, pp. 19787-19798

This paper documents, for the first time worldwide, a CNC process capable of polishing right to the edge of a surface, with no “waster” sacrificial glass attached, and without significant edge-misfigure. The success of the work has major ramifications on serial-manufacture of segments for extremely large telescopes, where edge-misfigure reduces signal-to-noise ratio on key science projects such as exo-planets. Other applications demand edge-definition, including image and pupil slicers and dice-level semiconductor polishing.

5. **,** Li, H., Walker, D., Yu, G., Sayle, A., Messelink, W., Evans, R., Beaucamp, A. (2013), ‘**Edge control in CNC polishing, Paper 2: simulation and validation of tool influence functions**

on edges', Optics Express, Vol. 21, Issue 1, pp. 370-381
This paper builds on Paper 3 above and explores changes in the detailed morphology of a polishing spot from an inflated membrane tool, as it overhangs an edge. This has never been explored before, and is fundamental to a quantitative understanding of the physics of edge-control.

6. Yu, G., Walker, D., Li, H. (2012), '**Implementing Grolishing Process in Zeeko IRP Machines**', Applied Optics, Vol. 51, Issue 27, pp. 6637-6640
Walker coined the expression 'grolishing', as a family of novel intermediate processes between grinding and polishing. paper describes experimental research which has resulted in a complementary range of grolishing processes, using bound or loose abrasives.

4. Details of the impact (indicative maximum 750 words)

European Extremely Large Telescope (E-ELT)

The European Southern Observatory's planned European Extremely Large Telescope (E-ELT) to be sited in Chile will have a 39m primary mirror with 798 hexagonal 1.4 m mirror segments and will be the largest optical/near-infrared telescope in the world. At its meeting on 11th June 2012, the ESO Council gave its approval for the construction programme to proceed **[reference a]** following review of preparatory work.

Two 5 M€ contracts were placed in 2008 with Sagem (France) and OpTIC Technium (acquired by Glyndŵr University in 2009 and renamed Optic Glyndŵr) for the provision of seven aspheric prototype segments for the primary mirror as part of the detailed design phase (phase B) during which critical components have been prototyped. These contracts include test setups and the necessary tooling and process development for the polishing. The research enabling the avoidance of rolling edges down has underpinned the implementation of Glyndwr's contract. The requirements were so demanding that this required the development of a unique polishing process and measurement system. In the UK, the E-ELT project is supported by the Science and Technology Facilities Council. According to the STFC, *'the team at Glyndŵr University St Asaph working with Leicestershire-based technology company Zeeko have become the first collaboration in the world to polish right to the edge of hexagonal-shaped mirror using direct mechanical polishing methods and at a scale of ten thousand times smaller than the diameter of a human hair'*. The STFC predicts that the project will generate contracts for UK industry worth some £90 million. **[reference e]**

The E-ELT News & Events newsletter for November 2013 includes the statement, '*5. UK collaboration successfully polishes a prototype E-ELT mirror segment to ESO specifications A collaboration between Glyndwr University St Asaph, Zeeko, and others have met the <15 nanometer compliance surface accuracy over the entire optical aperture, and out to the edges, of a prototype 1.4m hexagonal mirror segment using direct mechanical polishing methods. Achieving this milestone demonstrates potential for manufacturing E-ELT mirror segments as well as other uses for large high-precision mirrors in ground and space applications*'. **[reference h]**

The E-ELT Construction Proposal: Executive Summary & Proposal Digest **[reference b]** states that '*The work carried out to date, primarily with industry, has reduced the risk for both the technical demands and the management of the programme. Following successful technical and financial reviews, the programme is in an excellent position to move into construction.* This position is underpinned by ESO's recent acceptance of the first prototype segment manufactured by Glyndwr **[reference d]**. This provides an additional process-chain and manufacturing capability which results in de-risking for the E-ELT project.

At the outset, ESO warned us that we could anticipate numerous technical challenges, and that proved the case. Under Glyndŵr, the project has made consistent progress. In certain respects results have exceeded ESO expectations, and in several key areas process capability is comparable with or exceeds that of global competitors:

- Glyndŵr's interferomtric test is the only test system in the world able to meet ESO specification and provides accuracy over 2x better than that of the main competitor
- Glyndŵr has polished surfaces having 5x worse input quality than envisaged by ESO, thus providing an effective de-risking of the prior grinding processes
- Glyndwr's prototype project has provided a positive influence on the UK's decision to subscribe £88m to the E-ELT construction-phase. This is reinforced by a recent unsolicited request by STFC to visit OpTIC-Glyndwr and Zeeko Ltd to discuss the UK's potential involvement in segment fabrication **[reference f]**.

Commercial impact on Zeeko Ltd

Zeeko Ltd (Company No. 03990080, www.zeeko.co.uk) was established in 2000 to commercialize Walker's research into advanced surface-removal processes and measurement techniques. The company manufacturers CNC polishing machines (50mm to 2m capacity) and metrology instrumentation. It exports almost all its products, to 15 countries spanning Europe, North America and Asia, mostly for the astronomy, defence, automotive, consumer, aerospace, remote-sensing, semiconductor-photolithography markets.

The ESO research enabling the avoidance of rolling edges down led directly to Zeeko's design and manufacture of the first 1.6m CNC polishing machine, thereby extending the company's product-range and ability to meet more demanding customer requirements **[reference g]**. Edge-control has also recently enabled Zeeko to make its first sale into the emerging EUV photolithography photomask market (Japan). The customer was previously unable to meet the flatness specification over a sufficient large area on these rectangular fused silica parts, using conventional CMP processes. **[reference g]**

The ESO mirror segments were pre-ground aspheric on the BoX Ultra-precision grinder (built by Cinetic Landis) at Cranfield University. The Zeeko staff participating in the ESO project were thereby exposed to the performance of an ultra-precision grinding machine. A key insight was the impact that the input-quality to polishing has on the polishing process-chain, in regard to total process time and control of mid spatial frequency defects. Following on from this experience, Cinetic Landis and Zeeko have agreed an exclusive agreement to sell a jointly developed Optical Grinding Machine in the Optics Market. This has brought to market a "total process solution" for medium-large optics, which can be traced to the segment project. **[reference g]**

Zeeko's operation and growth between 2009 and 2013 is directly underpinned by the past and current research of Walker's group. The number of employees almost doubled from around 28 in 2009 to around 50 in 2012, whilst turnover has increased from £3.5 million in 2009 to £4 million in 2012 (excluding the 1.6 metre £1.5m machine built for Glyndwr's ESO segment project). Zeeko Innovations Ltd was formed in 2012 based at Optic as a direct result of Glyndŵr research programme and has created three jobs. **[reference g]**

5. Sources to corroborate the impact (indicative maximum of 10 references)

Reference a: http://www.eso.org/public/news/eso1225
Reference b: http://www.eso.org/public/archives/brochures/pdfsm/e-elt-executivesummary.pdf
Reference c: http://www.eso.org/public/archives/books/pdf/e-elt_constrproposal.pdf
Reference d: ESO Certificate of Technical Acceptance – Technical acceptance of Segment SPN04 15/10/2013 – available on request
Reference e: http://www.stfc.ac.uk/2917.aspx
Reference f: Correspondence from STFC available on request.
Reference g: MD of Zeeko Ltd, Richard.freeman@zeeko.co.uk
Reference h: Project Manager - E-ELT Optomechanics at European Southern Observatory; mcayrel@eso.org