Institution: 10007822

Unit of Assessment: 12

Title of case study:

Ultra-precision machining: improved competitiveness of UK manufacturing

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

Cranfield's research into ultra-precision machining and production science has led to new production machines, and to commercial availability of advanced optical surfaces, at a level of accuracy previously impossible. Cranfield's industrial clients have won contracts for advanced surface production worth >£5 million in under five years. Cranfield made:

- more mirror surfaces of NASA's James Webb Space Telescope than any other organisation;
- the exceptionally accurate surfaces that are redefining the value of the kelvin through determination of the Boltzmann constant for the National Physical Laboratory.

2. Underpinning research (indicative maximum 500 words)

Ultra-precision manufacturing of surfaces at the highest levels of achievable accuracy is a long-term focus of the Precision Engineering Institute at Cranfield. Research in several areas of the multi-disciplinary field of ultra-precision technology underpins this. These include all areas of machine design and control, tool path generation, material removal process and specialist dimensional metrology.

In 2003, the Large Optics Manufacturing Study (LOMS) was conducted for the DTI [G1]. This research identified the market and potential UK manufacturing capability for ultra-precise and large optics for astronomy, lithography and power generation [P1]. LOMS led to an EPSRC grant for research into manufacturing of ultra-precision surfaces with a novel manufacturing process chain [G2]. The idea was that the exceptional productivity from our new approach for figure accuracy at high production rate would revolutionise the market for large optics [P2]. The Cranfield Box machine, designed and built as the first element of this chain, has achieved the fastest and most accurate grinding of large optics reported [P3] at sub-micron RMS figure error for 1.5 metre freeform optics, with the lowest sub-surface damage depth [P4].

Parallel research into the production of freeform optics by diamond turning [G3] led to a capability to manufacture surfaces which are not rotationally symmetric whilst possessing exceptionally good figure accuracy and smooth surface texture [P5].

Key infrastructure funded through SRIF was pivotal in developing new surface metrology techniques, without which the advancements in surface manufacture could not have been achieved. These metrology techniques included surface conformal interferometric co-ordinate metrology in support of multi-mirror array measurement [P6], low-uncertainty high density scanned surface mapping for error compensated diamond turning [P5] and thermally compensated surface mapping for freeform ground surfaces [P3].

The integration of these research strands into a more powerful combination led to a proposal for an

EPSRC Integrated Knowledge Centre (IKC) in Ultra Precision and Structured Surfaces (UPS^2) [G4,G5]. This centre, funded from 2007 until late 2012, performed nearer market research at relatively high technology readiness level in optical and related surface production technology with a focus on IP generation, spin-out potential and business engagement, moving toward commercial impact in the manufacture of high-value products. One significant programmed activity of the UPS^2 IKC was to perform industrial research into the manufacture of ultra-precise surface structuring master roll mould tools. The need for these tools reflects a shift in mass production of precise high-value products away from the step-and-repeat process currently used to make microelectronic, display and area-optical products towards a continuous reel-to-reel approach.

Key Researchers	Post details and dates involved	Research
Prof P Shore	Professor (2003-present)	Machine design, material removal process
P Morantz	Senior Research Fellow (1999-2007); Principal Research Fellow (2007-present)	Machine design, control, tool-path generation, material removal process, dimensional metrology
J Allsop	Senior Research Fellow/UPS^2 Manager (2008-present)	Tool path generation, material removal process
Dr X Tonnellier	Research Assistant (2005-2009); Research Officer (2009-present)	Material removal process
Dr P Comley	Senior Research Fellow (2008-present)	Material removal process

3. References to the research (indicative maximum of six references)

Evidence of quality - Peer reviewed papers

P1 Shore P, Morantz P, Ultra-precision: enabling our future. *Philosophical Transactions of the Royal Society A - Mathematical Physical and Engineering Sciences*, **370**(1973), pp. 3993-4014, 2012.
doi: 10.1098/rsta.2011.0638

P2 Shore P, Cunningham C[a], DeBra D[c], Evans C[d], Hough J[e], Gilmozzi R[f], Kunzmann H[g], Morantz P[a], Tonnellier X[a], Precision engineering for astronomy and gravity science. *CIRP Annals - Manufacturing Technology*, **59**(2), pp. 694–716, 2010.
doi: 10.1016/j.cirp.2010.05.003

P3***** Comley P, Morantz P, Shore P, Tonnellier X, Grinding metre scale mirror segments for the E-ELT ground based telescope. *CIRP Annals - Manufacturing Technology*, **60**(1), pp. 379-382, 2011.
doi: 10.1016/j.cirp.2011.03.120

P4 Tonnellier X, Morantz P, Shore P, Baldwin A, Evans R[h], Walker D[h], Subsurface damage in precision ground ULE® and Zerodur® surfaces. *Optics Express*, **15**(19), pp. 12197-12205, 2007.
doi: 10.1364/OE.15.012197

P5* de Podesta M[b], Underwood R[b], Sutton G[b], Morantz P, Harris P[b], et al. A low-uncertainty measurement of the Boltzmann constant. *Metrologia*, **50**(4), pp. 354-376, 2013.
doi: 10.1088/0026-1394/50/4/354

P6* Shore P, Morantz P, Lee D[a], Manufacturing and Measurement of the MIRI Spectrometer Optics for the James Webb Space Telescope, *CIRP Annals - Manufacturing Technology*, **55**(1), pp. 543-546, 2006.
doi: 10.1016/S0007-8506(07)60478-8

* 3 identified references that best indicate the quality of the research

Key to papers:

a - UK Astronomy Technology Centre, STFC, Edinburgh; b - National Physical Laboratory, Teddington; c - Stanford University, California; d - University of North Carolina, Charlotte; e - University of Glasgow; f - European Southern Observatory; g - Physikalisch-Technische Bundesanstalt (PTB), Germany; h – University College London.

Further evidence of quality – underpinning research grants (total £9.6M 2003-2007)

G1 DTI/Thales Optics/WAG. Large Optics Manufacturing Study, £60k 2003 PI: P Shore

G2 EPSRC GR/S85337/01. Basic Technology: Ultra Precision Surfaces: A new paradigm (accuracy capability of 1 part in 10^8), £2.2M; 2004-2008 PI: P Shore

G3 EPSRC GR/R68139/01. Cranfield Innovative Manufacturing Research Centre, sub-project: Freeform manufacture of next-generation infrared optics, £464k, 2004-2007 PIs: P Shore, P Morantz

G4 EPSRC EP/E023711/1. *Integrated Knowledge Centre in Ultra Precision and Structured Surfaces*, £5,544k; 2007-2012 PI: P Shore, CI: P Morantz

G5 EPSRC EP/H003258/1. *Integrated Knowledge Centre in Ultra Precision and Structured Surfaces, Tranche 2*, £1.3M; 2007-2012 PI: P Shore, CI: P Morantz

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

Cranfield's research in manufacturing and measuring has led to production techniques and machines that have transformed the manufacture of ultra-precision surfaces such as the mirrors used in space telescopes. A spinout company has taken Cranfield's research and created a multimillion pound business. The research has also laid the foundations for a new definition of the kelvin in a radical revision of the SI unit system.

Major elements of impact include:

- UPS^2-IKC [G4, G5] designed and built a large-scale diamond-turning and structuring facility, implementing the production research it had funded. Cranfield staff operate this commercially on a site now managed by Glyndŵr University. Trading as UPS^2, it is recognised by its customers as the world's leading commercial facility [C1, C2, C3] for the supply of ultra-precision large-scale structured drums for making structures such as lenses. UPS^2 has sold in excess of £2 million of product in three years to more than 30 customers, several of which are global industrial companies with household names, such as 3M, Samsung, Microsoft, and Amazon.

- Optropreneurs Ltd was industrial co-creator of the UPS^2-IKC proposal to EPSRC [G4, G5]. In 2008, with assistance of UPS^2-IKC and based on production technology developed through the UPS project [G2] reported in [P2], Optropreneurs secured a €5 million contract from ESO to manufacture prototype primary mirror segments for the world's largest telescope [C4]. ESO's European Extremely Large Telescope (E-ELT) Construction Proposal [C5] identified the Cranfield Box grinding machine for its production planning for the primary mirrors [P3,P4]. Contracts for their manufacture will be valued at > £100 million to the selected contractor.

- The James Webb Space Telescope (JWST), NASA's replacement for the Hubble Space Telescope, is due to be deployed in or after 2018. A principal aim is to find life-supporting earth-like planets. Cranfield made more mirror surfaces for JWST than any other organisation. The mirror surfaces (accurate to < 10nm RMS) were made on machines designed and built at Cranfield using novel machining and metrology techniques, since copied elsewhere. The Mid InfraRed Instrument (MIRI) made in the UK containing the Cranfield mirrors has been delivered to NASA [C6]. This impact has been publicly recognised by NASA [C7].

- A radical revision of the SI unit system is underway, involving the redefinition of its seven base units in terms of fundamental constants. This achievement of unprecedented low uncertainty of measurement would have been impossible without Cranfield's research in manufacturing and measuring [C9]. The kelvin will be defined within two years in terms of the Boltzmann constant. A UK team, including scientists from Cranfield, has completed the lowest uncertainty temperature measurement ever performed, establishing a new estimate of the value of the Boltzmann constant, which for the first time is accurate enough to meet the kelvin's redefinition criteria. The measurement has been founded on the accuracy of manufacturing of a new configuration of acoustic resonator made at Cranfield, based on world-leading research in surface generation through freeform diamond turning and freeform surface metrology. This means the value of the kelvin *and all temperature measurements worldwide* – or more explicitly the traceability of the kelvin's universal definition from the Boltzmann constant – will be secured by the accuracy of machining and measurement of the Cranfield apparatus [C8].

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

C1 Senior Science Specialist, formerly 3M – says "*The best commercial diamond turning facility in the world*"

C2 Research manager at Microsoft – says "*We cannot get this quality anywhere else*"

C3 Development Manager at SKC Haas – says: "*The only diamond turning centre globally that does process development at this level*"

C4 Contact: Former Managing Director of Optropreneurs.

C5 Source: The ESO E-ELT Construction Proposal http://www.eso.org/public/archives/books/pdf/book_0046.pdf (accessed November 2013)

C6 Contact: MIRI Project Manager, UK Astronomy Technology Centre

C7 Source: NASA & ESA "Extraordinary Contribution" & "Significant Achievement" Awards given to P Shore and A Heaume.

C8 Source: de Podesta M. Redefining temperature. Cover article. Physics World. 2013 August: p. 28-32. http://physicsworld.implere.com/Content/Article/physicsworld/b2fbcc85-cf93-439e-87d4-9bb3c42b0cf0 (accessed November 2013)

C9 NPL Project Leader and Science Ambassador said about Cranfield's contribution "*The perfection of the inner surface was without a doubt the key to the low uncertainty. Nothing else would have worked without your magic.*"