Institution: Liverpool John Moores University (LJMU)		
Unit of Assessment: Sub-panel 12: Engineering		
Title of case study: Innovation in Abrasive Machining Technologies		
Period when the underpinning research was undertaken: 2000 to 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
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Period when the claimed impact occurred: August 2013 to December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

This ICS builds on the world-class abrasives research within the Unit that has helped transform global industrial grinding practice. The research addresses ever-increasing demand for better quality and higher productivity, focusing on high efficiency deep grinding (HEGD) and mass finishing (MF). It has shaped government strategy in additive manufacturing and the development of innovative next-generation abrasive technologies. It has directly resulted in the realisation of a £2.5m factory, built in the UK (2017) for high volume production of an advanced abrasive tool possessing environmental credentials in a sector valued circa US$33.9 billion in 2020. The research has also directly led to the improvement of performance and productivity of a number of industrial companies including Landis-Lund, Jinan Kechuang, Saint-Gobain Abrasives Ltd., Jones & Shipman, British Glass, OTEC and Croft.

2. Underpinning research

The underpinning research in this ICS builds on 20 years of world-class abrasives research that has helped transform global industrial grinding practice. By addressing current challenges, the research broadens abrasive machining applications. The key research insights and findings include:

[a] Research in high efficiency deep grinding (HEDG), initially led by Prof. Brian Rowe [**RO1, RG1**], has resulted in a tenfold increase in material removal rate (up to 2000 mm^3/mm/s) and a fivefold reduction in specific energy (down to 6~7 J/mm^3). The models developed for grinding kinematics, mechanics and thermal heat transfer has provided the insights for optimising grinding performance [**RO2,3**].

[b] Fundamental research of abrasive machining, focused on the workpiece-to-tool interactions, has led to pioneering work in the material removal mechanics, high efficiency deep grinding processes, special fluid delivery systems, and minimum quantity lubrication (MQL) for grinding processes [**RO1,2,4, RG2,3,4**]. The outcomes of these research studies have been adopted in abrasive tools, machine tools, automotive and aerospace industry sectors [**RG5-9**]. A digital-based process optimisation tool (POSY) was developed [**RG5,6**] for production decision support and process cost estimation [**RO5**].

[c] Based on the research foundations established in [b] above, a new glass abrasive tool has been developed as the first innovation in this field for more than 50 years, for the mass finishing (MF) industry, with improved process insight and understanding [**RO5, RG4-6**]. This evolution of direction resulted in the funded collaborative research with industry [**RG5,6**] in the emerging area of metal additive manufacturing, a technology strongly reliant on the capability of surface finishing for its wider industry uptake, as well as in the fast-growing biomedical engineering sector. The research direction has been increasingly focused on the wider disciplines of digital engineering, robotics, and numerical modelling.

[d] Research into intelligent machine control systems has led to new adaptive controlled grinding process systems [**RO3, RG1**]. This resulted in the development of a servo-assisted manual

machine tool control system (SAMM) that was taken forward to production by an international machine tool manufacturer [**RO2, RG8**]. Artificial Intelligence-based methodologies coupled with the adaptive control strategies led to the development of the first fully-integrated intelligent grinding machine control [**RO6**] that is now a commonplace system integration. This system reduces operator management and intervention. With an optimised grinding cycle based on on-line monitoring, the grinding cycle time was reduced by up to 50%. This breakthrough attracted an international collaboration with the University of Shanghai for Science and Technology (USST) and Ningbo Great Group Co. Ltd. [**RO3**].

The research was carried out in collaboration with a wide range of manufacture-industry partners and supported through external funding of over £3m from sources including the EPSRC, Innovate UK, EU, and industry from 2000 to 2020 [**RGs 1-9**].

3. References to the research

Six underpinning research outputs are given below:

RO1 - Rowe W.B., Tan J. (2001), “Temperatures in High Efficiency Deep Grinding (HEDG)”, Annals of CIRP, Vol.50(1), pp. 205-208 (http://dx.doi.org/10.1016/S0007-8506(07)62105-2).

RO2 - Morgan M.N., Jackson A.R., Baines-Jones V., Batako A., Wu H., Rowe W.B. (2008), “Optimisation of fluid delivery in grinding”, Annals of the CIRP, Vol.57(1), pp. 363-366 (https://doi.org/10.1016/j.cirp.2008.03.090).

RO3 - Chi Y., Li H., Chen X. (2017), “In-process monitoring and analysis of bearing outer race way grinding based on the power signal”, Proc IMechE Part B: J Engineering Manufacture, Vol.231(4), pp. 2622–2635 (https://doi.org/10.1177/0954405416635032).

RO4 - Batako A.D.L., Tsiakoumis V. (2015), “An experimental investigation into resonance dry grinding of hardened steel and nickel alloys with element of MQL”, International Journal of Advanced Manufacturing Technology, Vol.77(1-4), pp. 27-41 (https://doi.org/10.1007/s00170-014-6380-8).

RO5 - Jamal M., Morgan M.N., Peavoy D. (2017), “A digital process optimization, process design and process informatics system for high energy abrasive mass finishing”, International Journal of Advanced Manufacturing Technology, Vol.92, pp. 303-319 (https://doi.org/10.1007/s00170-017-0124-5).

RO6 - Morgan M.N., Cai R., Guidotti A., Allanson D.R., Moruzzi J.L., Rowe W.B. (2007), “Design and implementation of an Intelligent Grinding Assistant (IGA) system”, Invited paper – Inaugural Issue International, International Journal of Abrasives Technology, Vol.1(1), pp. 105-135, (https://doi.org/10.1504/IJAT.2007.013853).

Each cited research output underwent a rigorous peer-review process prior to publication.

Major research grants associated with this impact case study include:

RG1 - “Precision Grinding with Vitrified CBN”, EPSRC (GR/M35161/01), 1999- 2002, £348,636, PI: B.W. Rowe.

RG2 - EPSRC GR/R68795 (2002-2005), “A new grinding regime - Thermal limitations to material removal by grinding”, £239,934, in partnership with Castrol Int., De Beers Industrial Diamonds (UK), Renold Engineering, Weston Electrical Units Ltd, Unova UK Ltd, Saint-Gobain Abrasives and Metostress with £520k of additional industrial support, PI: B.W. Rowe.

RG3 - EPSRC GR/S82350 (2004-2007), “Optimisation of Fluid Application in Grinding”, £322,959, in partnership with Holroyd Machine Tools, Cinetic, Wendt Boart Ltd, Cosworth Racing Ltd, Dantec Dynamics and Castrol Int, PI: M. Morgan.

RG4 - EPSRC EP/N022998/1 (2016–2019), “Process design for next generation mass finishing technologies”, £329,978, in partnership with MTC, Fintek, Potters-Ballotini, GTS, Allens Cranshafts, Repclif and Sharmic, PI: M. Morgan.

RG5 - Innovate UK [TSB 101275] (2013–2016), "Thermally treated recycled glass as a vibratory finishing abrasive", £570,000, in partnership with MTC, Vibraglaz, Potters-Ballotini, Fintek, GTS and Rolls-Royce, PI: M. Morgan.

RG6 - Innovate UK [IUK - 132873] (2017–2018), "Metal AM process informatics for improved surface finish of complex parts", £165,000, in partnership with MTC, Croft Additive Manufacturing Ltd and Fintek, PI: M. Morgan.

RG7 - "Research into vibration assisted grinding of advanced materials", Rolls-Royce (R266030), 2012 -2015, £103,700, PI: A. Batako.

RG8 - "Vibration assisted high efficiency deep grinding - A strategy for eco-machining", TSB/InnovateUK (BD133H), 2009-2010, £218,550, PI: A. Batako.

RG9 - "Micron diamond processing of advanced ceramics", Element Six, 2013-2019, £88,000; PI: X. Chen.

4. Details of the impact

Sustainable development for a smart future requires novel manufacturing technologies capable of producing continually evolving precision components, for improved product performance with lower energy consumption and higher productivity. Underpinning research that has been conducted since 2000 has brought significant impacts over the assessment period.

A. High Efficiency Deep Grinding (HEDG)

The HEDG offers a fivefold reduction in energy consumption and material removal rates up to 10 times higher than prevailing common practice. The maximum material removal rate achieved by the most advanced commercial grinding machine is 200 $mm^3/mm/s$ compared to 1000-2000 $mm^3/mm/s$ achieved by HEDG. It cuts down the grinding specific energy from over 120 J/mm^3 (400 J/m^3 for nickel alloy) to an average of just 7-10J/mm^3 [**RO1, RG1,2**].

Partner Landis-Lund, a branch of an industrial engineering group, Fives, has used the HEDG in its twin crankshaft grinders worldwide since 2013 [**SC1**]. The results show the grinding cycle time was reduced by 50% thus doubling the production. Specific grinding energy has reduced from 43 J/mm^3 to 7 J/mm^3 with an associated specific grinding material removal rate of 2000 $mm^3/mm/s$. With annual production of around 120 machines and a grinding capacity of some 1,000,000 parts per year, the impact on the bottom line has been significant. *"… A mechanism for predicting an acceptable rough grinding regime has been built into the decision process for production engineering in our cylindrical component manufacturing. Landis-Lund have been able to add a reliable tool backed by solid research evidence that allows competitive tendering for work which would otherwise have been seen as beyond the capacity of present machine configuration"* [**SC1**].

Saint-Gobain Abrasives Ltd has also benefited from the HEDG. *"In this particular case the research shows us a way to extend the area of application for grinding wheels into areas formally held by milling. This has helped Saint-Gobain move outside traditional areas of grinding with HEDG"* [**SC2**].

International engagement led to the development of novel Lithia-glass-ceramic bonded wheels that have very high wear resistance and 2-3 times longer life than their counterparts. *"…The joint work with LJMU has helped us position the developed bond on the market and secure over $0.5m financial support from the Chinese government and other private equities to set up our own new factory of grinding wheel production in the High and New Technology Development Zone, in Jinan of Shandong Province, as 'Jinan Kechuang Super Hard Material Products Co. Ltd'..."* (Director X.F. Zhang) [**SC3**].

B. Vibration Assisted High Efficiency Deep Grinding (Vibro-HEDG)

Innovation in low frequency vibration assisted HEDG, "Vibro-HEDG", attracted six industrial collaborators from the grinding process supply chain - Jones & Shipman (machine tool manufacturer), Tyrolit (grinding wheel manufacturer), Fuchs (cutting fluid manufacturer), Bosch Rexroth (drives and controls manufacturer), Joloda International Ltd (heavy lifting gear manufacturer), and Winbro Group Technologies (aerospace parts manufacturer) [**RG8**]. As a result of the collaboration, a theory was developed [**RO4**] and an oscillatory motion was experimentally added to the process. Subsequently, Jones and Shipman designed and manufactured the world's first commercial prototype of this machine in 2014. This concept has also been adopted by Blohm in Germany to develop a highly efficient ('Prokos') grinding technology, which is a direct industrial application of the Unit's work in low frequency oscillation/vibration of the workpiece.

Technical Services Coordinator of Jones & Shipman stated *"…As a grinding machine manufacturer with an international market presence … experience with … HEDG shows that there is a large market available, especially in the aerospace industry. Currently available machine tools have … reached their limit of machining speeds. A step change in speed and efficiency… Vibro-HEDG gives increased machining rates and at the same time reduces energy requirements by 30%. With the introduction of this new product, our market share has been growing in Europe and more significantly in emerging markets such as China, India and Brazil…."* [**SC4**].

C. The Mass Finishing (MF) Abrasive Product

Fundamental research of MF with glass abrasives has led to a new abrasive tool based wholly on thermally treated recycled glass that was conceived and developed for the mass finishing industry [**RG4-6**]. The tool has a proven capability and strong environmental credentials. The research initiated collaboration between LJMU and the UK HVM Catapult, which was the catalyst for the formation of regional Manufacturing Technology Centre (MTC) located at LJMU, the MTC@LJMU, rebranded (2019) as MTC@Liverpool to better reflect its wider regional remit.

The MF research has directly led to Potters-Vibraglaz building a new £2.5m factory in the UK (Barnsley) for high volume production of the abrasive product [**RO5**] within a sector valued circa £1B/annum, immediately creating 8 new jobs. Sales revenue reached £1.2m in the first two years of production (2017 -2019) [**SC5**]. The Technical Director (Potters-Ballotini/Vibraglaz), Mr S. Vaughan, stated: *"…The cooperation over the past decade with Professor Morgan and his team has been invaluable in supporting and contributing to the development of this product. This has widened our product range in both the general purpose and niche markets for finishing products, and has added opportunity to extend our customer base and approach to sales and marketing. …"* [**SC5**].

The product uses only recycled/recyclable glass and offers a method of finishing that is more environmentally beneficial than any other process technology. It also offers a cost saving of 40% per tonne of media due to legislative compliance, waste management, and tool economies [**SC6**]. The Principal Technologist of GTS, Mr. M. Marshall states: *"... this has added to our baseline understanding ...and also aided our understanding of how thermal processing and physical forming in the laboratory needs to be developed when the technique comes to scale up and exploitation…the team at LJMU brought their experience and abilities to bear to make progress and deliver results"* [**SC6**].

D. Process Optimisation Methodology

The POSY system [**RO5**] offers cost savings (2019) associated with pre-production evaluation of new components in the order £2000<Costs<£5000 per part, with new parts commonly arriving at weekly intervals [**SC7**]. Technical Director of Fintek states: *"…The finishing results were outstanding and demonstrated the benefit of this POSY approach. I commend Professor Morgan and his research team on the quality and usefulness of this research work. Working with LJMU has increased our industry standing and we are now regarded as Surface Finishing Specialists throughout many fields - particularly additive manufacturing"* [**SC7**].

The system delivers optimised processes for many other applications including pharmaceutical, food processing, agriculture and automotive. This system's flexibility has directly led to its adoption by the MTC to support a number of high value projects, for example, *the* £14.3m DRAMA project over 3 years [**SC7**]. *"…The Process Optimisation system ……is unique and transformative as it now allows a process, which is dependent on the control of numerous parameters each having variable effect, to be designed to perform at an optimal set of conditions without extensive and expensive prior testing. A real benefit of the approach is the genericity and ease of application"* [**SC7**].

The world-leading research on 3-D discrete element modelling (DEM) for simulation of granular fluidised flows within MF processes [**RG4, RO5**] provided a new capability for realistic low cost exploration of the processes responsible for surface evolution within MF processes. This simulator improves the understanding of process physics and impacts machine tool design through optimised process economics and performance. Through collaboration with LJMU, OTEC GmbH, Germany, the European leader in advanced mass finishing technologies, has exploited this advance in the design of their most advanced machines to assist with wear avoidance. *"The effect of the increased knowledge has led to selling one additional finishing machine per year of approx. 80.000-100.000 €" for OTEC"* [**SC8**].

The work on grinding cycle optimisation strategies [**RO3**] has been used by Ningbo Great Group Co. Ltd. in China, securing more than 30% improvement of productivity in the production line of bearings. From 2016 to 2020, the implementation of these strategies directly resulted in financial benefit averaging ¥7m (£790k) per year, giving the company a competitive edge in the roller bearing market, which was valued at $21.3 billion in 2018. *"The application of your cycle optimisation strategies and grinding process parameter optimisation has positively impacted on our company performance in terms of the production time saving, the improvement of bearing grinding efficiency, and greatly improved our company's product quality. Sustained application of your technology secured an increasing improvement by more than 30% in the production efficiency of relevant products amounting to a total of ¥21m (£2.37m) gain from March 2016 to the end of 2019"* [**SC9**].

E. Metal Additive Manufacturing (AM) Research

The research in this area categorically demonstrated that MF processes can be designed to deliver high-quality surface finishes on AM parts possessing a complex geometry [**RO5**]. The research [**RG4**] demonstrated the benefit of two-stage finishing systems, which has important implications for the design of the finishing cell and has resulted in the development of a new finishing capability within the MTC [**SC7**].

A further key outcome from the partnership with Croft was the enhancement to the POSY (a single objective system) that elevated it to a multi-response optimisation system [**RO5**]. The advanced POSY system was successfully applied to their AM production of bespoke and advanced filter and filtration assembly components. The Technical Director of Croft AM, Dr L. Geekie states: *"This challenging project has delivered an in-process control for the production of AM components to target surface finish requirements and has proven the benefit of high energy mass finishing processes for high specification external finishing…"* [**SC10**].

5. Sources to corroborate the impact

SC1: R&D Director, Landis-Lund (Cinetic Landis Grinding Ltd), UK.

SC2: R&D Manager, Vitreous Bond Super-Abrasive, Saint-Gobain Abrasives Ltd., UK.

SC3: Director, Jinan Kechuang Super Hard Material Products Co. Ltd., China.

SC4: Technical Services Coordinator, Jones & Shipman, UK

SC5: Tech Manager, Potters Ballotini / Vibraglaz, UK.

SC6: Principal Technologist, British Glass (GTS), UK.

SC7: Technical Director, Fintek, UK; Principal Research Engineer, MTC, UK.

SC8: Managing Director, Company OTEC GmbH, Germany.

SC9: Manager of Equipment, Ningbo Great Group Co. Ltd, Zhejiang, China.

SC10: Technical Director, Croft AM.