Institution: University of Wolverhampton (UoW)

Unit of Assessment: UOA12: Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: Direct Metal Laser Sintering and Melting (DMLS/M) for producing complex geometrical parts in advanced materials.

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

The University was the first adopter of the Direct Metal Laser Sintering/Melting (DMLS/M) technology in the UK resulting in significant research and knowledge transfer activities in the UK and globally. The University has and continues to be a catalyst in technology introduction for 5 out of the 10 UK companies that use this technology. This accounts for £2.5M of capital investment within the UK and is currently the largest concentration of this technology worldwide. Research has involved process optimisation, analytical simulation, materials development (including MMCs) with UK and international partners. Application research engagement has been in Automotive (including F1), Aerospace, Medical and Jewellery sectors.

2. Underpinning research (indicative maximum 500 words)

DMLS/M involves sintering/melting powder into solid geometries that cannot be achieved by conventional processes. Research has resulted in the development of new techniques and parameters for the processing of existing and new alloy powders. Key researchers associated with this case study are Professors Stanford and Kibble. Examples of international collaborations are:

(i) Maxillofacial implants in Ti-6Al-4V, in collaboration with Professor Brian Gabbitas (Waikato University, New Zealand); Waikato University funded a researcher on a 6 months placement at The University. The University provided the research input to produce the complex implant and optimisation of material properties. The approach is unique linking design of a mandible with a porous structure to reduce weight and stimulate better bio-factor attachment. [1] Subsequently, Stanford was invited to (and funded by) Waikato University (June 2012), to disseminate his research at Waikato University, University of Auckland and the National Titanium Development Agency. Research collaboration continues including work on DMLS/M of titanium aluminides.

(ii) Pioneering work on the superplastic behaviour of DMLS/M Ti-6Al-4V. A key insight was the realisation that the fine microstructure obtained by the DMLS/M process could be exploited for superplastic forming of DMLS/M pre-forms. Professor Ji Sik Kim (Kyungpook University S.Korea), on a 1 year sabbatical to the University, was invited to collaborate on this work as he had research experience in SPF. The University supervised the project built the high temperature mechanical test equipment and optimised the DMLS/M process and relevant metallurgy to deliver a successful conclusion and published output. [2] Subsequently, Kibble and Stanford were invited and funded by Kyungpook University to present and disseminate research on DMLS/M technology to research centres in South Korea (September 2010). The research collaboration is continuing, including exploring other alloy systems.

(iii) Collaboration with the University of Warwick and Red Bull F1, on Ti-6Al-4V, has led to published work, e.g. [3]. The University provided the DMLS/M process development and optimisation necessary to produce thin wall sections. The work has enabled the design and manufacture of key valve blocks that give accurate and predictable fluid dynamics with minimal system losses.

A major issue with DMLS/M is residual stresses in 'built' parts. 3-dimensional finite element modelling and validation has been undertaken of the DMLS/M process to enable the prediction of residual stresses. This work has provided a key insight on how to minimise residual stresses through the manipulation of laser scanning strategies [4]. This work has produced a PhD completion, at the University (2012-13) and because of the analytical skills developed further employment of the graduate, in a KTP (and post KTP) with Bronx Engineering Ltd

Bio engineering research is also being undertaken on modelling and building hip implants with functionally graded structures that approximate the modulus of elasticity of bone [5]. The aim is to eliminate 'bone stress shielding' and implant failure. A range of cellular geometries is being evaluated to optimise implant properties.

Knowledge gained on mechanical alloying (MA), e.g. [6] is enabling us to carry out pioneering research on using MA techniques to produce suitable powders to make MMCs by DMLS/M. Conventional MA does not produce spheroidal alloyed powder particulate and hence this material cannot be used for DMLS/M. However, a breakthrough at The University has led to a MA methodology whereby spheroidal shape (+reinforcement) is retained in powders that include Al-SiC, Ti-TiB2/TiN/TiC, Cu-W.

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

1. Izhar A. Aziz, Brian Gabbitas, Mark Stanford (2012), Direct Metal Laser Sintering of a Ti6Al4V Mandible Implant, Key Engineering Materials, 2012 (520) pp.220-225. ***(in REF2 output 4 for Stanford)***

2. Ji Sik Kim, Kevin Kibble**,** Mark Stanford (2012), Quantitative analysis on the anisotropic behaviour of superplastic deformation in laser melted (LM) Ti–6Al–4V alloy, Materials Science and Engineering A, 532 (2012), pp.236-244. ***(in REF2 output 1 for Kibble)***

3. David E. Cooper, Mark Stanford, Kevin A. Kibble, Gregory G. Gibbons (2012), Additive Manufacturing for product improvement at Red Bull Technology, Materials and Design, 41(2012), pp. 226-230.

4. C J Wang I A Roberts R Esterlein M Stanford D J Mynors (2009), A three-dimensional finite element analysis of temperature field during laser melting of metal powders in additive layer manufacturing, International Journal of Machine Tools and Manufacture, 2009 (49), pp. 916-923. ***(in REF2 output 2 for M Stanford)***

5. Kevin Hazlehurst, Chang Jiang Wang, Mark Stanford, (2013), Evaluation of the stiffness characteristics of square pore CoCrMo cellular structures manufactured using laser melting technology for potential orthopaedic applications, Materials and Design 51 (2013), pp. 949–955, (10.1016/j.matdes.2013.05.009). ***(in REF2 output 3 for Stanford)***

6. K A Kibble S A Hewitt (2009), Effects of ball milling time on the synthesis and consolidation of nanostructured WC-Co composites, International Journal of Refractory Metals and Hard Materials, 2009 (27), pp.937-948. ***(in REF2 output 2 for Kibble)***

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

The University was the first university to adopt DMLS/M in the UK with the purchase of a DTM2500+ Sinterstation (year 2000) and then an EOS M250Ext machine (year 2004). This equipment was central to application-led research [1]. Funding for the equipment came from ERDF grants. The impact has been significant for the UK economy and the University, offering recognition nationally and internationally [2]. The University also co-ordinated a DTI application for £2M led by Rolls-Royce PLC made under a Direct Write call [3]. The submission attracted an 18 member industrial consortium and the University's collaboration with the consortium (post 01/01/2008) has had profound impact throughout the Additive Layer Manufacturing (ALM) sector, e.g. Williams F1 were the first F1 team to adopt metal based ALM parts developed and produced by the University. [4]; a KTP with Powell and Harber Limited [5] achieved production time savings of up to 40% for products produced using DMLS tooling with conformal channels and the tooling lead times reduced by up to 50% [5]. The results from this project have been disseminated [6,7].

The University won £1M of funding from Advantage West Midlands (AWM) for the project "Process Innovation For Rapid Product Development". The programme ran from June 2007 to September 2010 and the work undertaken assisted 47 companies, ensured 125 jobs safeguarded, created 18 new jobs. [8] The grant funded the acquisition of an EOS M270Ext DMLS/M platform. This machine was released to the University under a unique research agreement and was the first EOS GmbH machine installation globally to process 'reactive' titanium and aluminium alloys and leading to the production readiness for reactive materials of the M270Ext. [1] EOS UK Ltd has for the last 5 years supported and promoted the University with £100k of 'in-kind' powders and £300k for operational software. The University is the only educational user of this technology nationally therefore the University research activities have impacted on the introduction of the technology throughout the EOS(UK) customer base. In 2013 there are now 32 EOS M270 laser melting systems in 10 UK companies. The University has been a catalyst in DMLS/M technology introduction for 5 of these companies, accounting for £2.5M of capital investment. The UK industrial market has the largest concentration of this technology worldwide and the University has played a significant role in this concentration activity. [4] Sector impacts follow:

Net Shape Tooling; Tooling materials, applications and techniques have been refined in order to realise steel and cupro-nickel tooling in industry [9-10], Technology transfer programs were used to attract companies in to a cluster of net shape process users and then disseminate the use and application of DMLS/M. to the companies. In this instance 50% of the companies in PIRPD [8] adopted this type of tooling.

Jewellery: The University was the first worldwide to develop the melting of silver alloys for bespoke jewellery applications. Research assistance by The University with process parameter definition and machine platform development has led to Cookson Gold Ltd, investing in EOS M280 technology and subsequently assisting in EOS M080 platform development, a bespoke machine developed for precious metals DMLS/M. [4]

Motorsport: Research with part and material manufacture for Formula 1 teams, including Williams, Mclaren, Mercedes and Red Bull has been undertaken. Formative work has led to Mclaren adopting the DMLS/M technology. [4] Collaborative work with the University of Warwick validated the use of thin walled titanium Ti-6Al-4V tubes. The work led to co-authored papers published in race magazines, TCT conferences and journals, e.g. [11]. Co-author David Cooper now works for the DMLS/M bureau Innovate to Make I2M Ltd. Former DMLS/M technician at the University, M.Lindop, now manages the rapid prototyping at Red Bull Racing. Recent and on-going confidential work with Mercedes F1 has produced pioneering work regarding Ti-6Al-4V components. Large aero parts have been developed that have allowed testing and monitoring improvement whilst extending the capabilities of the DMLS/M technology. The impact here is still being realised and being applied not only throughout the F1 sector but also through aerospace and medical sectors. [4]

Aerospace: The DMLS/M platform at the University has been used to support a Rolls-Royce PLC led programme, namely, “Strategic Affordable Manufacturing in the UK through Leading Environmental Technologies” (SAMULET) programme, this is a Variance-Interbuild project for DMLS/M platforms. Contribution to the programme was to ascertain the repeatability for DMLS/M manufacture across multiple platforms, first round of results have been done carried out regionally next round will be conducted nationally. [12] Recent work with UTC Aerospace, Wolverhampton involves the optimisation of gear and epicyclic gearbox manufacture for flap actuation systems. Work here is two-fold, “very near” finished shape gears have been developed using DMLS/M, also a research collaboration with Birmingham University to hard face wear surfaces is being developed. [4]

Medical: Impact for DMLS/M products and research at The University is being promoted by conference activity, e.g. [13] and work in this sector is expected to grow.

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

1. EOS e-manufacturing forum and user meetings (Munich): 2004-2008, e.g. 2008 EOS e-Manufacturing summit “Ti64 and issues for part manufacture”.
2. ERDF Final Reports for the Advanced Engineering Cluster (AEC), West Midlands Technology Network (WMTN), and the Polymer Cluster (PC), 2004-2009.
3. DTI Technology Strategy Board Direct Write call, TP/4/AMD/6/S/22266), “Shifting the paradigm in tool and part manufacture through exploiting DMLS technology”, 2007.
4. Private communications (plus letters of support) from Williams F1, EOS UK Ltd, Mercedes F1, UTC Aerospace and Cookson Gold Ltd.
5. Powell & Harber (Precision Engineers) Limited KTP: *To introduce Direct Metal Laser Sintered tooling for injection mould products enabling faster prototype design to manufacture*. 2nd February 2006 to 13th August 2008. Partnership number: 1272.
6. M.Stanford, K.A.Kibble, M.Lindop, P.Boden and S Rodrigues, “Cost effective manufacture of injection mould tools using direct metal laser sintered (DMLS) tooling - an integrated

approach", RPD 2008, Rapid Product Development: "Designing the Industry of the Future", Oliveira de Azeméis, Portugal, October 29th to 30th 2008.
7. M.Stanford, M.Lindop, D.J.Mynors and S Rodrigues, "The production of fully dense conformal cooling channels in a cupro-nickel alloy using direct metal laser sintering (DMLS)", RPD 2008, Rapid Product Development: "Designing the Industry of the Future", Oliveira de Azeméis, Portugal, October 29th to 30th 2008.
8. PIRPD project (Process Innovation For Rapid Product Development, project code CRWT 7003; £1M AWM funded, 2007 - 2010.
9. An investigation into fully melting a maraging steel using Direct Metal Laser Sintering (DMLS) M Stanford K A Kibble M Lindop D J Mynors Steel Research International 2008 79(1) 847-852.
10. The use of Direct Metal Laser Sintered (DMLS) Tooling for the manufacture of zinc diecast components. M.Stanford, P. Holden, K.A.Kibble, M. Lindop, S.Tansell and C. Percival, Focus - zinc die-cast IZA Diecasting Focus 2008 Conference, Barcelona, 11-13 June 2008.
11. Gibbons G., Cooper D.E., Stanford M., Kibble K.A. "E-Manufacturing for Product Improvement at Red Bull Technology". Proceedings of the 7th International Conference on Manufacturing Research. September 2009
12. SAMULET Project 5: Processing Advanced Materials - Confidential information.
13. Hazlehurst, C J Wang and M Stanford, "A numerical investigation into the application of an orthotropic porous structure for a femoral stem manufactured using laser melting technology", 19th Congress of the European Society of Biomechanics, Patras, Greece, 25th-28th August 2013.