**Institution: University of Wolverhampton**

**Unit of Assessment: 12 Engineering**

**Title of case study: Advanced functional materials for the next generation of powder-bed fusion additive manufacturing**

**Period when the underpinning research was undertaken: 2004 – 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:** |
|---|---|---|
| Professor Mark Stanford | Professor of Advanced Manufacture | 1992 – 2019 |
| Professor Kevin Kibble | Professor of Materials Engineering | 1990 – 2018 |
| Dr Arun Arjunan | Reader in Additive Manufacturing of Functional Materials | 2013 – Present |
| Dr Ahmad Baroutaji | Senior Lecturer in Engineering | 2017 – Present |
| Iain Lyall | Senior Technician in Additive Manufacturing | 2007 – Present |

**Period when the claimed impact occurred: August 2013 – December 2020**

**Is this case study continued from a case study submitted in 2014? N**

## 1. Summary of the impact

Innovations in digital fabrication such as additive layer manufacturing and novel functional materials are a key enabler for industry 4.0 and the digital supply chain revolution. Research into additive layer manufacturing at the University of Wolverhampton was conducted in collaboration with industrial end-users including the [text removed for publication], [text removed for publication], Andel Plastics and Cookson Gold. This led to new product developments which enhanced the competitiveness of these collaborating companies. Further, our research on personalised infection resistant tissue engineering scaffolds for improved patient recovery informed the UK Parliamentary POSTnote on bioprinting, creating policy impact.

## 2. Underpinning research

The University of Wolverhampton was the first adopter of metal additive manufacturing in the UK acquiring DTM2500+ Sinterstation in the year 2000 and then an EOS M250Ext machine in 2004. Since then, our research in the field continues to be a catalyst for both industry competitiveness and policy development. The research underpinning the impacts relates to the development of functional materials that can be 3D printed for on-demand problem-solving. The group specialises in the development of additive manufacturing processes and materials with unprecedented mechanical, acoustic, and biological properties. The research led to the following important findings [F]:

<u>F1. Additive manufacturing functional microporous metal alloys</u>
Rationally designing material at the microscale has been a long-standing challenge in the field of materials. Our research found that through controlling pore shape, distribution, and arrangement, microporous titanium and aluminium alloys can deliver targeted functionality such as stiffness, specific flow permeability, negative Poisson's ratio and osseointegration. A novel architecture for both thin- and thick-walled structure with low variation in relative density while delivering negative Poisson's ratio was demonstrated. Using the novel architecture, the elastic modulus can be controlled by changing the re-entrant angle without affecting relative density [R1] leading to stable auxetic lattice materials [R1] and multiscale permeability [R2]. Overall, our research in this field enabled a new understanding regarding the fabrication and performance of additively manufactured microporous mechanical metamaterials.

F2. Additive manufacturing titanium pre-forms for superplastic forming
The increase in grain aspect ratio within the microstructure leads to poor superplasticity. Various titanium alloys with elongated α grains exhibit good superplasticity because of the constituent phases in each alloy system. In two-phase titanium alloys featuring hard (α) and soft (β) phases, the β accommodates phase/grain boundary sliding (P/GBS) even if the aspect ratio is high. In comparison, our research on additive manufacturing titanium alloys revealed ultrafine microstructures as a result of algorithmic optimisation of selective laser melting [R3]. The superplastic forming (SPF) process is used in a wide range of high-value-added manufacturing sectors to make lightweight, complex-shaped components for high-performance applications. Currently, it is a high-cost process, for example, the superplastic forming of titanium alloys involves a high-temperature furnace, costly tooling, and has high utilisation of resources such as argon gas and energy. Our research developed the next generation of functional materials by combining additive manufacturing with super plastic forming to demonstrate the widespread application of the process to manufacture lower-cost products [R4].

F3. Additive manufacturing of highly reflective silver and copper-silver alloys
Conventional manufacture of highly reflective metals such as silver relies on forging, lost-wax casting, rolling, hand fabrication, or machining. Pure silver is highly reflective, thermally, and electrically conductive making it a challenge to be laser processed for additive manufacturing. The reflective and conductive properties are problematic resulting in poor energy absorption during the additive manufacturing process. Before our research it was considered that additive manufacturing of pure silver is unfeasible without using high power laser systems. Our research combined unique powder characteristics along with process parameters such as laser power, scan speed, hatch distance and layer thickness to additively manufacture pure silver and its alloys. The research developed a novel process interaction and chamber bed optimisation resulting in controlled track enabling complex structures [R5] suitable for both the jewellery industry and biomedical implants. Additive manufacturing of pure silver was considered unfeasible before our research.

F4. Additive manufacturing of patient specific tissue engineering scaffolds
Our work on additive manufacturing of tissue engineering biomaterials has developed functional materials for reducing stress shielding, maladapted stress concentration, and implant site infection [R6]. Our research demonstrated that additive manufacturing can reconstruct the host bone based on X-ray nano-computed tomography (X-ray nCT) using morphology matched titanium alloy. The novel microporous architecture developed matched the stiffness, strength, and porosity of the host bone in addition to the bone morphology. Our approach reduces complications such as stress shielding, maladapted stress concentration and the risks of infection in load-bearing critical length defect reunion [R6]. Our approach of infection resistant materials also offer alternative approaches to solving the challenges associated antimicrobial resistant.

**3. References to the research**

All the underpinning papers have gone through a stringent peer review process. As evidence of the research quality, our research informed the 'AMT/8 Additive Manufacturing' BSI standards development committee responsible for standards to support innovative advancements within additive manufacturing processes relevant to the UK industry; thus, inputting into the international additive manufacturing standards committee ISO/TC 261 and the European additive manufacturing standards committee CEN/TC 438.

R1. A. Arjunan, M. Singh, A. Baroutaji, C. Wang. (2020). Additively manufactured AlSi10Mg inherently stable thin and thick-walled lattice with negative Poisson's ratio. *Composite Structures*, 247, 112469. https://doi.org/10.1016/j.compstruct.2020.112469. (REF 2 Output).

R2. A. Arjunan, M. Demetriou, A. Baroutaji, C. Wang. (2020). Mechanical performance of highly permeable laser melted Ti6Al4V bone scaffolds. *Journal of the Mechanical Behavior of Biomedical Materials*, 102, 103517. https://doi.org/10.1016/j.jmbbm.2019.103517. (REF 2 Output).

R3. J.S. Kim, K. Kibble, M. Stanford. (2012). Quantitative analysis on the anisotropic behaviour of superplastic deformation in laser melted (LM) Ti-6Al-4V alloy. *Materials Science & Engineering: A*, 532, 236-244. https://doi.org/10.1016/j.msea.2011.10.085.

R4. M. Mis, R. Hall, J. Spence, N. Emekwuru, K. Kibble, M. Stanford, F. Banakhr. (2019). Construction of next-generation superplastic forming using additive manufacturing and numerical techniques. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 233(1), 154-165. https://doi.org/10.1177/0954405417716493.

R5. J. Robinson, A. Arjunan, M. Stanford, I. Lyall, C. Williams. (2020). Effect of silver addition in copper-silver alloys fabricated by laser powder bed fusion in situ alloying. *Journal of Alloys and Compounds*. 857, 157561. https://doi.org/10.1016/j.jallcom.2020.157561.

R6. K. Bari, A. Arjunan. (2019). Extra low interstitial titanium based fully porous morphological bone scaffolds manufactured using selective laser melting. *Journal of the Mechanical Behavior of Biomedical Materials*, 95, 1-12. https://doi.org/10.1016/j.jmbbm.2019.03.025. (REF 2 Output).

Underpinning Grants
G1. Pollard, A. Composite & Additive Layer Materials Engineering Research & Innovation Centre (CALMERIC). ERDF. Value GBP1,112,399. 2019 – 2022. Underpins R1 and R5.

**4. Details of the impact**

Additively manufactured functional materials can redistribute manufacturing, away from mass production in centralised factories to a world of mass personalisation. This will lead to equitable and personalised manufacturing driven by demographic demand contributing to a sustainable and zero carbon economy. In this regard, our research demonstrates custom materials, parametric process optimisation, microporous structures, and multifunctional biomedical devices. Over the REF period, our research has delivered a portfolio or significant impacts from improving industrial competitiveness, developing a new company (6DME Ltd), to contributing to a bioprinting POSTnote amongst many others. As such the impacts [I] are:

I1. Developing state-of-the-art porous architecture for vehicle performance testing

[text removed for publication]

I2. Improving competitiveness of industrial partners

[text removed for publication]

*Andel Plastics Ltd*
Our findings [F2] resulted in the development of high-performance conformal cooling injection moulding tools for Andel Plastics Ltd. The collaborative research started in 2015, investigating complex conformal cooling architecture for a new range of products. Our research was successful in developing high efficiency conformally cooled architecture for high efficiency superplastic forming. Using the additively manufactured novel tooling, we successfully fabricated a lens that had a helical water circuit in the main core that was otherwise unfeasible [C4]. The tool is currently being used by Andel Plastics and has produced 20,000 new parts up to 2019 for their customer [C4]. The Managing Director indicated that their customer "can confidently design new products knowing that we can safely create the necessary conformal cooling, as well as the Fresnel texturing they require" [C4].

*CooksonGold & 6DME Ltd*
The research on the additive manufacturing of silver [F6] developed a novel workflow and build chamber for Cookson Precious Metal Ltd (aka CooksonGold). Our research [F3] using a novel combination of process parameters was the first study to demonstrate additive manufacturing of pure silver and copper-silver alloys using SLM. Silver alloy based industrial projects completed at

CooksonGold were feasible due to the initial work completed at the University of Wolverhampton [C5]. As a result, CooksonGold was able to commercially manufacture silver alloys for the jewellery industry, created by the additive approach. The research on pure silver has continued and has led to a new company 6DME Ltd [C6] to commercialise novel additive manufactured materials for numerous applications including biomedical ones [F4]. Between 2017 and 2020, 6DME Ltd generated 8 collaborative publications, and 2 grant applications with the University of Wolverhampton and Cranfield University [C6].

I3. Informing POSTnote on bioprinting
Our research on the development of tissue engineering scaffolds [F4] informed the POSTnote on bioprinting [C7]. The POSTnote highlighted bioprinting in medicine and the associated biological, manufacturing, regulatory and ethical implications. The POSTnote informs regulatory issues, biological challenges, and ethical and legal issues concerning additive manufactured implants and scaffolds.

I4. Addressing the additive manufacturing skills gap
As a result of our continued research in the field, we developed the Additive Process Technology Integration with Management and Entrepreneurship: APTIME EUR408,820 [G2, C8], and ERASMUS+ funded project. This was the continuation of the “Additive Minds” training programme developed by University of Wolverhampton in collaboration with SRH Berlin and EOS GmbH [C9]. The programme was developed in 2016 to establish a global training programme for the additive manufacturing industry. The course featured a 7-week structure featuring hands on training, functional materials, and process parameter development. The final week focused on project management held at SRH in Berlin Germany. The fees were EUR57,000, and in total the course has completed training for 20 delegates who are leading additive manufacturing operations around the globe. Our research group is now leading the associated APTIME [C8] project developing the most comprehensive additive manufacturing course for entrepreneurs and industries.

As summarised from I1 to I4, our research on additive manufacturing of functional materials has established significant body of knowledge that is impacting industry, society, healthcare, and the environment. From advanced additive manufacturing to metamaterials, tissue engineering biomaterials and next-generation materials, our research is pushing the boundaries of functional materials through interdisciplinary enquiry.

**5. Sources to corroborate the impact**

C1. [text removed for publication]

C2a [text removed for publication]

C2b [text removed for publication]

C3. [text removed for publication]

C4. Testimonial from Andel Plastics Ltd

C5. Contact details of Director of 6DME Ltd (former Additive Manufacturing Development Manager at CooksonGold)

C6. 6DME business case and other information

C7. A. Arjunan, C. Burnham-Stevens, C. Connon, K. Dalgarno, J, Ding, M. Domingos, J. Dudman, A. El-Haj, A. Faulkner, L. Grover, D. Hay, YYS. Huang, D. Kalaskar, R. Lévy, P. Li, P. Murray, A. Smith, F. Spagnoli, E. Stead, and A. Stratton-Powell. 3D bioprinting in medicine. Bridging research and policy, The Parliamentary Office of Science and Technology. UK Parliament POST collated by Melissa Jackson and Peter Border, published on March 13, 2020. Full report: https://post.parliament.uk/research-briefings/post-pn-0620/

C8. APTIME project breakdown - https://ec.europa.eu/programmes/erasmus-plus/projects/eplus-project-details/#project/2019-1-UK01-KA203-062066

C9. Additive Minds business case and other information