Institution: Cranfield University		
Unit of Assessment: UoA12		
Title of case study: WAAM3D		
Period when the underpinning research was undertaken: 2006-2015		
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 Stewart Williams	Professor of Welding Science and Engineering	2005- present
Dr Filomeno Martina	Senior Lecturer Additive Manufacture	2014 – Jan 2021
Dr Jialuo Ding	Research Fellow Additive Manufacture	2012 – present
Dr Paul Colegrove	Senior Lecturer	2006 – 2018
Dr Helen Lockett	Senior Lecturer	1990 – 2017 (currently Casual Consultant)
Period when the claimed impact occurred: Aug 2013 – Dec 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Wire-based 3D metal printing technology, developed through Cranfield University research, has been successfully commercialised: **attracting external investment** of **GBP3,000,000**, generating **GBP3,000,000 sales within six months**, and **creating 15 jobs**.

Commercialisation has transformed the sustainability of the supply chain for manufacturing processes in aerospace and oil & gas industries : **reducing consumption of energy intensive materials** e.g. titanium up to 80%, and up to 70% manufacturing cost savings, compared with conventional methods.

Systems and components developed by spin-out company WAAM3D Limited have been used by Lockheed Martin, Thales, TechnipFMC, Relativity Space and Weir. Accuron Technologies Ltd (Singapore) have **invested GBP1,500,000** in WAAM3D with a **further GBP1,500,000 option.**

2. Underpinning research (indicative maximum 500 words)

Research began at Cranfield University in 2006 to address how manufacturing from large metal forgings could be replaced by a cheaper, faster, and more sustainable process in terms of use of materials. The focus was on titanium, a metal that is neither precious nor rare, and used extensively in aerospace and energy generation sectors as the strongest of lightweight metals. Titanium, however, requires 650 MJ of energy per kg to produce - making it very expensive (Ti ~$50/kg) - and significant amounts of the metal are wasted as part of traditional manufacturing methods. A typical airframe panel starts with ten+ times material than finally goes on the aircraft (the buy-to-fly (BTF) ratio).

In principle, 3D printing could potentially save huge amounts of material, costs, and energy. But existing 3D metal printing processes, or Additive Manufacture (AM), were mainly based on powders with low build rates (10-100g/hour), low build volumes (<300mm maximum dimension), with insufficient material properties and integrity, and still expensive.

A fundamental study pioneered the use of Wire + Arc Additive Manufacturing (WAAM) as a cheaper and faster alternative to the traditional 'subtractive' method of manufacture in aerospace applications. The basic concept of WAAM uses an electric arc attached to the end of a robot to melt a wire and deposit molten metal in layers in a predetermined pattern. (See Figure 1) In practice it is very complex to apply to the production of large-scale safety critical engineering components. Research challenges included managing high build rates with accurate geometrical control; obtaining equivalent or better properties with guaranteed structural integrity; and being sufficiently cost effective to ensure a robust business case.

Figure 1. WAAM system being used to manufacture titanium space component which is now qualified

Initial research concentrated on investigating different process options [R1]. Subsequently, the relationships between process parameters and factors such as deposition geometry, microstructure, and properties for a wide range of materials was established [R2]. This enabled full understanding of the process capabilities to support development of design tools and actual part manufacture [R3]. To achieve even higher levels of performance a new patented approach was invented, using in-process cold work between every deposited layer [R4], delivering properties in excess of previous production materials.

For manufacture of large structures, two critical problems were solved: management of distortion using various techniques including innovative tooling solutions [R1], supported by process modelling for prediction of stresses [R5]; and the development of a local shielding solution, for reactive metals e.g. titanium, to enable production of large parts without the use of a large and expensive chamber [R6].

Research was brought together and applied to manufacture full component demonstrators in a wide range of materials and on the multi-metre scale [R1]. Tailored cost and life cycle analysis tools were used to demonstrate benefits at an industrial scale. Extensive industrial case studies and technology transfer projects were undertaken - with EPSRC, Innovate UK and EU funding taking the technology to TRL 9. In order for industry to take advantage of the research, a spin-out company WAAM3D was set up to deliver the full supply chain - provision of technology, equipment, software, know-how training and support.

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

[R1]. Williams, S.W., Martina, F., Addison, A.C., Ding, J., Pardal, G., Colegrove, P., (2016) Wire+ arc additive manufacturing, *Materials Science and Technology* 32(7), 641-647,
https://doi.org/10.1179/1743284715Y.0000000073

[R2]. Wang, F., Williams, S., Colegrove P., & Antonysamy, A. A., (2013), "Microstructure and Mechanical Properties of Wire and Arc Additive Manufactured Ti-6Al-4V", *Metal and Mat Trans A*, 44(2), 968-977,
https://doi.org/10.1007/s11661-012-1444-6

[R3]. Kazanas, P., Deherkar, P., Almeida, P., Lockett H., & Williams, S., (2012), "Fabrication of geometrical features using wire and arc additive manufacture", *Proc IMechE Part B: J Engineering Manufacture*, 226(6), 1042-1051
https://doi.org/10.1177/0954405412437126

[R4]. Martina, F., Colegrove, P.A., Williams, S.W., & Meyer, J., Microstructure of interpass rolled wire+ arc additive manufacturing Ti-6Al-4V components, *Metallurgical and Materials Transactions A*, 46(12), 6103-6118
https://doi.org/10.1007/s11661-015-3172-1

[R5]. Ding, J., Colegrove, P., Mehnen, J., Ganguly, S., Sequeira Almeida, P.M., Wang, F., & Williams S., (2011), Thermo-mechanical analysis of Wire and Arc Additive Layer Manufacturing process on large multi-layer parts, *Computational Materials Science*, 50 3315–3322
https://doi.org/10.1016/j.commatsci.2011.06.023

[R6]. Ding, J., Colegrove, P., Martina, F., Williams, S., Wiktorowicz, R., & Paltc, M. R., (2015), Development of a laminar flow local shielding device for Wire + Arc Additive Manufacture, *Journal of Materials Processing Technology* 226, 99-105
https://doi.org/10.1016/j.jmatprotec.2015.07.005

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

WAAM3D Ltd
A spin-out company WAAM3D Limited (Reg no. 11435762) was incorporated in June 2018 to exploit WAAM technologies (with the three main academics involved, Professor Williams, Dr Ding and Dr Martina acting as company directors).

In December 2019, an equity investment of **GBP3,000,000** in two tranches of GBP1,500,000 was made by Accuron Technologies Ltd, the owner of several manufacturing companies in Singapore and Europe (Singapore Aerospace Manufacturing, Sitec Manufacturing, JW Kane, Esmo Group, Mechantronic GmbH, Zasche Handling) [S1]. Accuron is also establishing a joint venture company with WAAM3D in Singapore to set up a component manufacturing facility using WAAM3D equipment and services [S3].

WAAM3D provides a complete ecosystem for companies; turnkey systems with specialist hardware, bespoke software and full customer support including system training, part building and small batch manufacture. (See Figure 2) After receiving the initial investment the company has already made **significant sales of GBP3,000,000** and produced **a profit of GBP300,000 in six months of trading**. The company has >7000 sq. ft of commercial and workshop premises in Milton Keynes and created 15 new jobs (headcount: 15; FTE: 15). [S8] Strategic partnership agreements have been put in place with key supplier companies including Kuka Robots. [S7] The company has also already been **awarded approximately GBP500,000 grant research funding.**

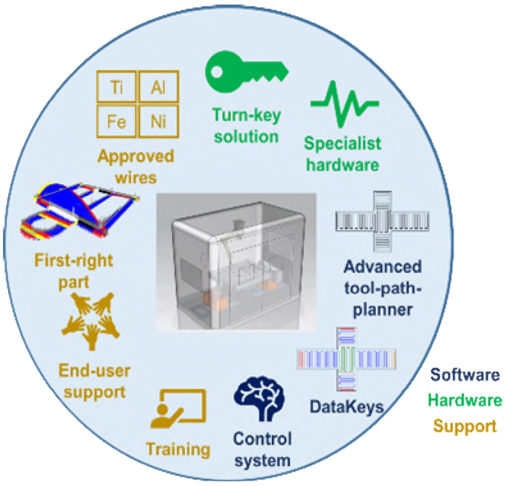


Figure 2 the full ecosystem for WAAM technology provided by WAAM3D

An ongoing pipeline of technology has been formally established for exploitation of continuing major research activity into wire-based 3D printing technology at Cranfield University. This has been done through the establishment of an integrated technology programme (ITP). (See Figure 3 below). Projects at low TRL level commence through joint project with WAAM3D followed by full commercialisation projects, entirely within WAAM3D. WAAM3D provides customer needs to inform the University and ensure a full impact route all the way from TRL1 to TRL9. The company has been provided with exclusive rights to a bundle of Intellectual Property to enable the industrial adoption of WAAM and has optional access to future IP. **Two patents were granted** in 2018-19 (GB2491472B 06-06-2018, GB2569673B 25-11-2019) and a further new patent application has been filed.

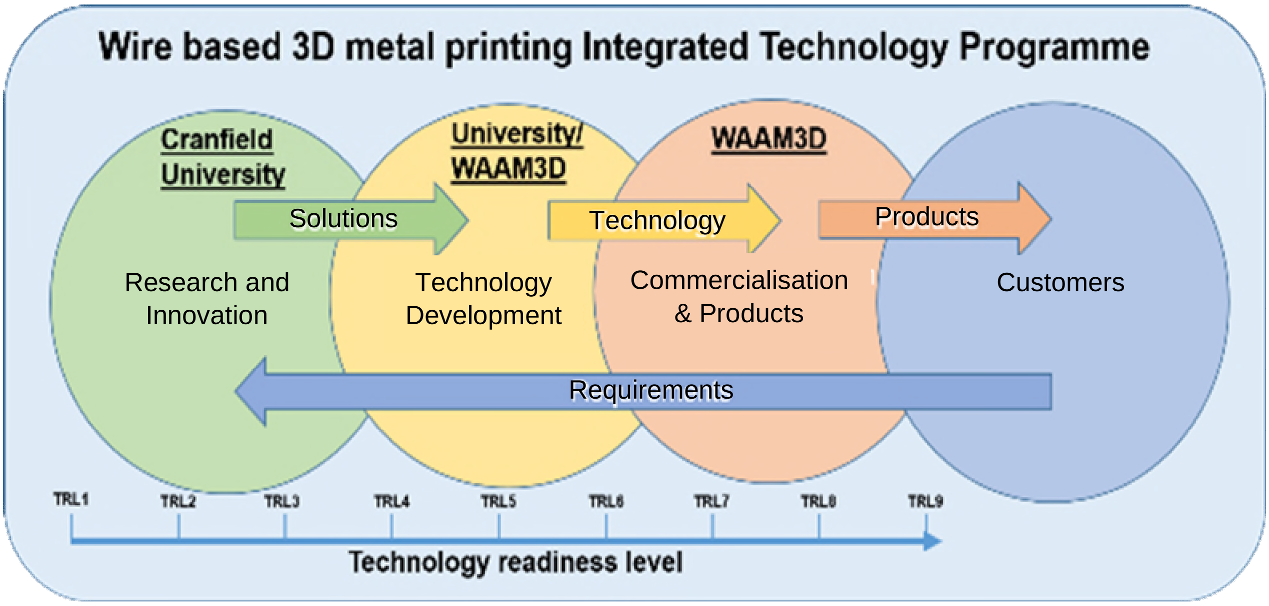


Figure 3 Integrated technology programme

End user technology adoption

Companies in various industry sectors have been assessing and qualifying WAAM technology for industrial engineering structural applications, including BAE Systems, Weir [S5], Airbus Commercial and Airbus Space.

"WAAM technology shows major business benefits compared to the existing manufacturing routes such as reduced inventory, short lead times from months to days and even production of spare parts in remote areas like mining sites." [S5] Head of Additive Manufacturing, The Weir Group

Additionally, some companies have moved through to full exploitation through the manufacture of parts for use.

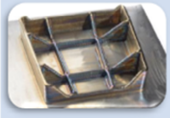
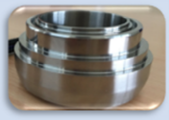
In the defense sector in 2012 Lockheed Martin UK (LMUK) installed a WAAM facility, with the assistance of the University. They have subsequently used this for a number of projects in space, military vehicles, and other domains. LMUK have qualified parts and materials for spaceflight and have used WAAM to build spacecraft fuel tanks, rocket motor combustion chambers, thick section armoured steel components (for ballistic protection of armoured vehicles), and other primary structures. These projects have demonstrated the capability for WAAM to build parts that would have been conventionally made using forgings and other processes, with equivalent quality and material performance. WAAM enables LMUK to greatly reduce the manufacturing costs of these parts and gives them the flexibility to readily change the component design with minimal cost. WAAM also greatly reduces by months, lead times for parts originally made from forgings. Several of LMUK's customers have contracted the organisation to build parts and components for them using their WAAM cell. [S4]

In the energy sector, TechnipFMC (TFMC) has installed several systems at their site in Dunfermline. These have been used for manufacture of specific parts saving significant time and therefore costs. For example, an energy project in Mozambique (Africa) was in difficulty when a business-critical test stage for components failed, putting the project delivery in jeopardy. Using WAAM, TFMC printed critical parts within four-and-a-half days, compared with the two-month lead time expected using traditional forging routes. Significant liquidated damages for the company were avoided. [S2]

A new manufacturing company, Guaranteed, has been set up by ArcelorMittal specifically to manufacture parts by WAAM technology for their own steel production plants that have long downtime due to failed parts and a strategic diversification into parts and component manufacture for e.g. train and rolling stock manufacturers. [S3]

All these systems utilise designs and processes supplied by the University and latterly utilise commercial grade equipment or software provided by WAAM3D.

Initial work on technology transfer with industry partners validated the following benefits from WAAM over the use of conventional manufacturing technology:

Component	Rear frame	Gear rib	Tank	Valve seat	Antenna tower	Cantilever beam
Industry	Military aircraft	Civil aircraft	Space	Energy	Space	Construction
Material saving	Confidential	70% = 194kg Ti64	25% ~100 kg Ti64	~20% IN718	96% = 575kg Al	-
Cost saving	Confidential	70%	~25%	-	Confidential	-
Lead time reduction	Years to few weeks	-	Months to weeks	2 months to < 1 week	-	-
Design change	-	-	-	-	Yes – 50% mass saving	Lattice structure
Company	BAES	Bombardier	ThalesAleniaSpace	GlenAlmond Technologies	Airbus Space and Defence	
						

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

[S1] President CEO Accuron Technologies £3m investor in WAAM3D

[S2] Principal Technology Expert, Director Core Technologies, TechnipFMC demonstrating of the impact of the technology in an applied setting

[S3] General Manager, Guaranteed a company set up to manufacture parts using WAAM technology

[S4] Head of Research and Technology, Lockheed Martin UK Ampthill Ltd

[S5] Head of Additive Manufacturing, The Weir Group PLC email explaining the benefits of WAAM manufacturing to Weir

[S6a&b] [a] ThalesAleniaSpace email with attachment
[b] ThalesAleniaSpace attachment explaining the benefits of WAAM technology to the Company

[S7] CEO KUKA

[S8] CEO WAAM3D