SHAPING OUR NATIONAL COMPETENCY IN ADDITIVE MANUFACTURING

A TECHNOLOGY INNOVATION NEEDS ANALYSIS CONDUCTED BY THE ADDITIVE MANUFACTURING SPECIAL INTEREST GROUP FOR THE TECHNOLOGY STRATEGY BOARD

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Special Interest Group
Additive Manufacturing

ADDITIVE MANUFACTURING SPECIAL INTEREST GROUP (AM SIG)

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EXECUTIVE SUMMARY

Additive Manufacturing (AM) technologies have the potential to change the paradigm for manufacturing. As a high value manufacturing economy, the UK has a great deal to gain from increased AM penetration. There are opportunities for technology adoption in key sectors such as aerospace, medical devices and implants, power generation, automotive and the creative industries, with some companies already engaged in technology assessment and small scale use. There are also domestic and export opportunities for companies engaged in the AM machine tool, materials and enabling software markets.

The broader strategic role for AM in the future of the UK high value manufacturing economy was outlined in the recently published Technology Strategy Board study "A Landscape for the Future of High Value Manufacturing in the UK". In this document, AM has been identified as one of twenty-two priority technologies which should be developed as a UK national competency to meet future challenges, and enable business to respond to changing global trends and new market drivers. This positioning of Additive Manufacturing as a strategic manufacturing competency for the UK has been reinforced in the updated High Value Manufacturing Strategy published by the Technology Strategy Board in May 2012.

As a 'tool-less' and digital approach to manufacturing, AM presents companies and consumers with a wide and expanding range of technical, economic and social benefits. The AM 'industry,' which accounts for machine tool and materials sales and associated services, was valued at just $1.9billion in 2011 but with the sustained double digit growth in recent years, it is realistic to forecast the sector to be worth in excess of $7.5billion by 2020, based on organic growth and the continued deployment of today's technologies. However, if current technological and commercial barriers can be overcome, the future AM sector could be worth in excess of $100billion per annum by 2020.

Given the scale of the market opportunity, the strategic value of AM to the UK and the relative immaturity of the sector at this time, it is important for both public and private sector stakeholders in the UK to better understand the current position of AM, both globally and domestically, and to identify the barriers and therefore technology innovations needed to gain national leadership across the AM supply chain.

In response to this need, the UK Technology Strategy Board set up a Special Interest Group in Additive Manufacturing (AM SIG) to undertake a Technology Innovation Needs Analysis (TINA) to understand both the needs of industry to adopt AM and the UK's capacity to support and exploit innovation across the AM supply chain. The findings from this study and recommendations for the future are provided in this report.

The AM SIG, led by the Materials KTN and supported by Econolyst Limited, has identified a large range of current and potential AM applications and development within UK manufacturing. Research suggests that all sectors are interested in the use of AM for both "cloned" part manufacture and "freedom of design" part manufacture. Significant public and private sector investment (circa £90million) has been made or committed within the UK in recent years to drive up the Technology Readiness Level (TRL) of AM. This funding has established the UK as a leading location for AM R&D activity across the supply chain. The aerospace, healthcare, creative industries and motor sport sectors are most active in using AM technology within the UK today, with examples of products under development being tested in niche applications or being sold on a small scale. The energy generation sector and the remainder of the automotive sector are less proactive.

The UK has a well-established and equipped AM research community. 81 organisations have been involved in AM research within the UK since 2007, including 24 universities and 57 companies. The average engagement by the university and industrial sector is 11 years and 10 years respectively. The UK is one of the world's leading sources of AM related knowledge and research activity, along with Germany and the USA, when benchmarked through participation in collaborative pan-European research projects and through a comparison of papers presented at AM-focused research conferences. UK industry has also made a significant commitment to supporting AM research and technology transfer activities over these years. Despite this maturity, AM remains a research intensive technology area, with the largest percentage of employees in both academic and industrial establishments at post graduate or post-doctoral level, as opposed to technician level. This may be a barrier to wider adoption supporting the view that the technology is more focused on laboratory use than on the shop floor.

Although the UK is clearly engaged in the development of AM technologies and applications, it is far from leading in any one specific area. The UK is not yet considered a leading AM machine tool source, when compared to Germany with six vendors or the USA with ten. However, it has the building blocks to become one, with the potentially strong market position of UK's only vendor and a number of developmental technologies such as High Speed Sintering & Selective Laser Sintering.

The UK also has the potential to build a strong AM supply chain with the presence of enabling software companies, materials providers developing innovative product offerings and world class product designers with a strong interest in AM. When this is coupled with the strong multi-sector interest by world class OEMs and end-users, the UK is well positioned to realise the high value potentials of AM technologies. However, a great deal of technological, economic and educational barriers must be addressed if AM is to achieve wide scale adoption within the UK.

There are a number of actions recommended to drive forward UK AM research and commercialisation. These include investment in technologies to address barriers related to costs, quality, limited range of materials and size of components. However, it is important to consider these against the need to define a clear implementation strategy for the UK, led by industry.

The AM SIG would like the UK to consider the following strategic options available to the UK:

- Development of new machine platforms based on the UK's excellent research capability in photonics and other energy sources, process control, materials science, ink jet technologies and software developments.
- Consolidation of current UK research excellence and exploitation of current successful prototypes and demonstration projects.
- Stimulating development and exploitation of new business models, arising out of the increased design freedom and democratisation of AM.

The AM SIG recommends that, at this point, what the UK needs is a further structured engagement between the UK AM supply chain, end-users and the research base to consider these strategic options in detail and identify the most effective routes to implement AM.

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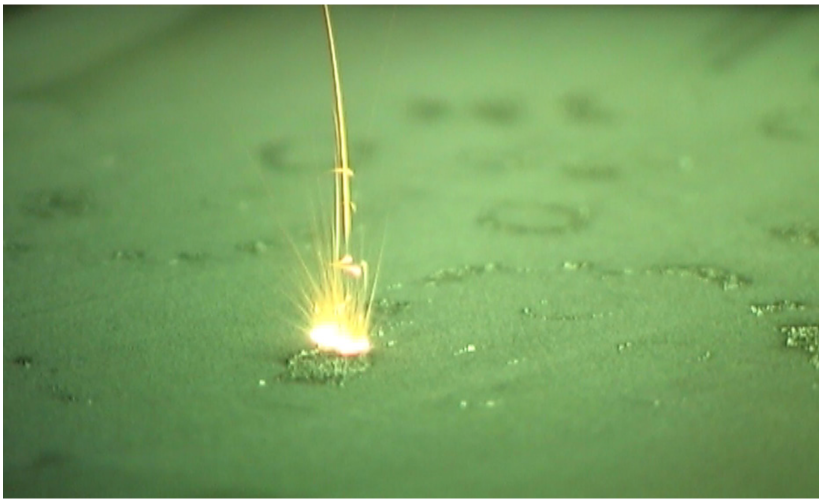
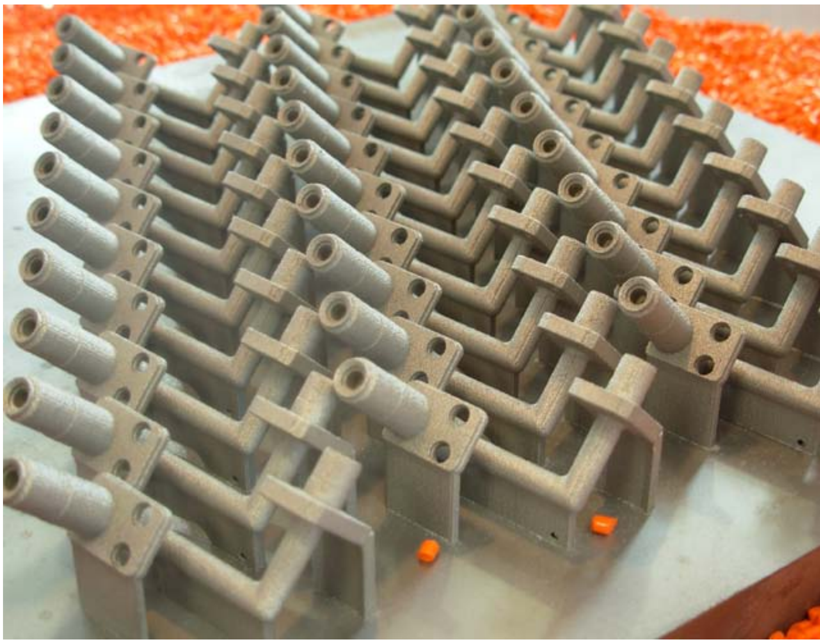
1. INTRODUCTION

WHAT IS ADDITIVE MANUFACTURING?

Additive Manufacturing (AM) is a term used to describe the production of tangible products made using a growing set of digitally controlled machine tools. Often referred to as 3D printing, the approach differs radically from more traditional manufacturing methods, in that products are produced through the selective addition of materials layer-upon-layer, rather than through machining from solid, moulding or casting.





WHY IS AM OF GROWING INTEREST TO DESIGNERS, MANUFACTURERS & CONSUMERS?

As a 'tool-less' and digital approach to manufacturing, AM presents companies and consumers with a wide and expanding range of technical, economic and social benefits. AM technologies have the potential to change the paradigm for manufacturing, away from mass production in large factories with dedicated tooling, with high costs, to a world of mass customisation and distributed manufacture. AM can be used anywhere in the product life cycle from pre-production prototypes to full scale production, as well as for tooling applications or post production repair. AM processes are stimulating innovation in component design, enabling the manufacture of parts that cannot be made by traditional methods and are stimulating alternative business models and supply chain approaches. For example, using AM it is possible to mitigate the need for expensive tooling, freeing up working capital within the supply chain and reducing business risk in new product innovation, with new products being brought to market in days rather than months.

The layer-wise nature of AM enables the manufacture of highly complex shapes with very few geometric limitations compared to traditional manufacturing processes. This freedom-of-design has led to the technology being used to manufacture topologically optimised shapes with improved strength to weight ratios for example, an important consideration in both aerospace and automotive design to reduce vehicle weight and fuel consumption.

By coupling geometric freedom with tool-less manufacture, AM also enables the production of economically viable personalised products, from medical implants manufactured using CT and MRI scan data to consumer goods such as shoes, jewellery and home ware.

The layer-wise manufacturing approach also reduces the amount of raw materials used, placing a lower burden on natural resources and the environment. Moreover, AM has the ability to greatly compress the supply chain and allows concurrent manufacture at multiple locations nearer to the point of consumption, which has obvious supply chain benefits to the consumer, the local economy and the environment.

As a digital technology, AM is progressively being integrated with the internet, enabling consumers to engage directly in the design process, and allowing true consumer personalisation. The recent introduction of home based 3D printing has now enabled consumers to also engage in the manufacture of products, using digital data bought or shared online, circumventing much of the traditional manufacturing and retail value chain.

However, it must be acknowledged that AM is not a panacea for all manufacturing problems and current media attention focused on AM has the potential to oversell the capabilities of the technology, whilst failing to address its limitations. In short, AM is currently being over-hyped, which has the potential to disenfranchise potential technology adopters.

WHY SHOULD ADDITIVE MANUFACTURING BE OF INTEREST TO THE UK?

AM is not only a disruptive technology that has the potential to replace many conventional manufacturing processes, but also an enabling technology allowing new business models, new products and new supply chains to flourish. However, it is also a nascent technology exploited today by only a small number of early global adopters.

The AM 'industry,' which accounts for machine tool and materials sales and associated services, was valued at just $1.9billion in 2011 (Wohlers Report 2012). The AM sector has however enjoyed sustained double digit growth in recent years, with the sector seeing almost 30% compound annual growth in 2011 alone, and it is realistic to forecast the sector to be worth in excess of $7.5billion by 2020, based on organic growth and the continued deployment of today's technologies.

Analysis of potential applications by current AM users and industry analysts, however, suggests that the technology has less than 8% market penetration. This

AM IS A NEW TOOL IN THE TOOLBOX. IT IS NOT A UNIVERSAL PANACEA TO REPLACE ALL OF TODAY'S MANUFACTURING METHODS

limited penetration is largely attributed to a lack of visibility within the global manufacturing community, but more significantly the current shortcomings of today's technology, resulting in a number of barriers to wider scale technology adoption have not helped. It is suggested that if these barriers can be overcome, and penetration can be increased into the potential 92% of applications identified, the future AM sector could be worth in-excess of $100billion per annum by 2020 (extrapolated from Wohlers Report 2012). Put into context, the current global aerospace sector is worth some $330billion per annum today.

As a high value manufacturing economy, the UK has a great deal to gain from increased AM penetration. There are clearly opportunities for technology adoption in key sectors such as aerospace, medical devices and implants, power generation, automotive and the creative industries, with some companies already engaged in technology assessment and small scale use. However, there are also domestic and export opportunities for companies engaged in the AM machine tool, materials and enabling software markets.

THE STRATEGIC IMPORTANCE OF AM AS A NATIONAL COMPETENCE

AM has a broader strategic role to play in the future of the UK high value manufacturing economy, as outlined in the recently published Technology Strategy Board study "A Landscape for the Future of High Value Manufacturing in the UK". In this document, AM has been identified as one of twenty-two priority technologies which should be developed as a UK national competency to meet future challenges, and enable business to respond to changing global trends and new market drivers. The Technology Strategy Board has identified AM as one of the four competencies contributing to the development of new,

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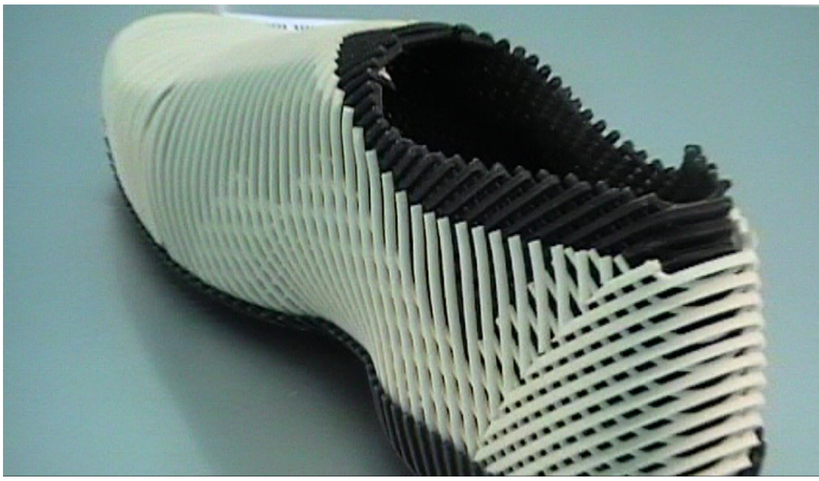
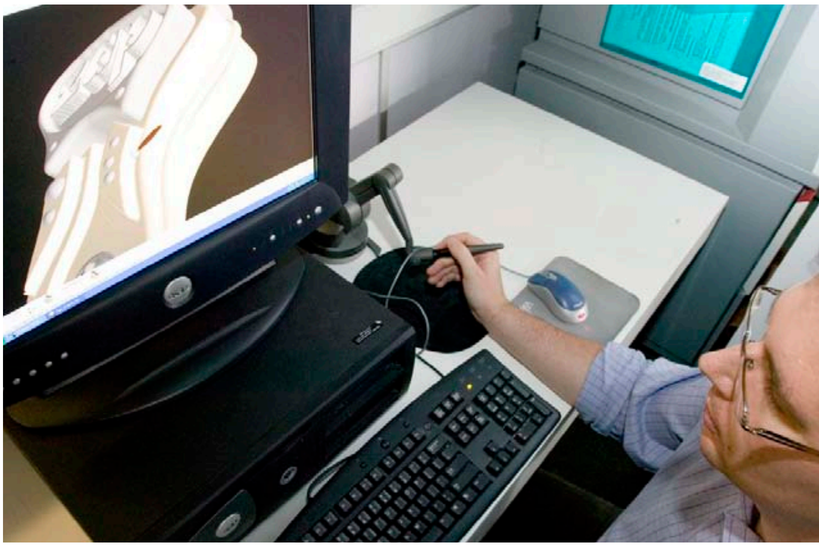
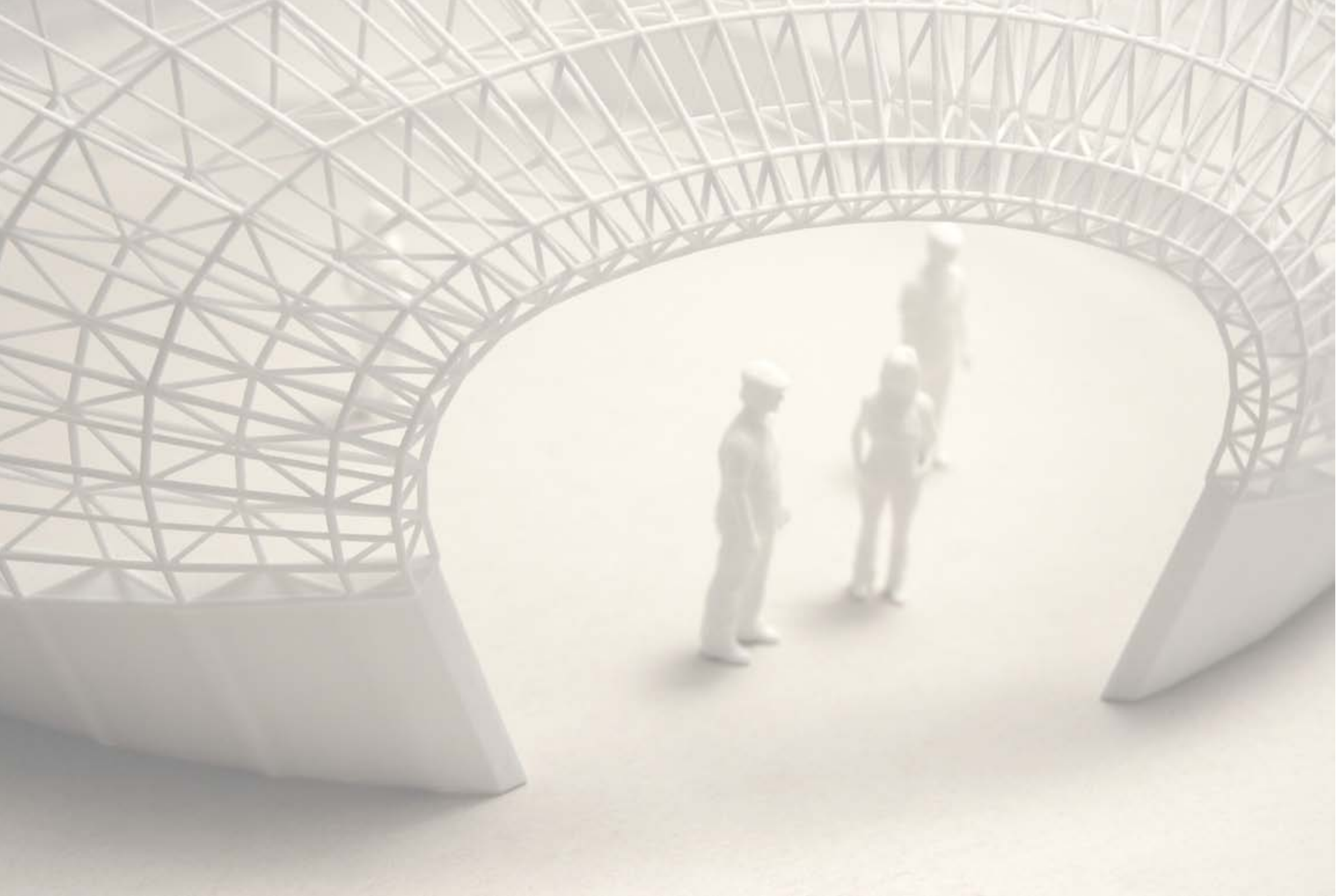






agile, more cost-effective manufacturing processes. This positioning of Additive Manufacturing as a strategic manufacturing competency for the UK has been reinforced in the updated High Value Manufacturing Strategy published by the Technology Strategy Board in May 2012.

The technology, while a national competency in its own right, also helps to address all five of the high-level manufacturing themes around which the strategy is centred. As such Additive Manufacturing has the potential to meet the future needs for:

i. **Resource efficiency** - helping to secure UK manufacturing technologies against scarcity of raw materials, energy and other resources;

ii. **Efficient manufacturing systems** - increasing the global competitiveness of UK manufacturing technologies by creating more efficient and effective manufacturing systems;

iii. **Materials integration** - enabling the creation of innovative products, through the design and integration of new materials and embedded electronics to create new functionally driven parts;

iv. **New manufacturing processes** - providing world beating platforms for new, agile, more cost-effective manufacturing processes; and

v. **New business models** – enabling new and sometimes disruptive business models to realise superior value systems.

AM is clearly positioned to play an important role in the future of the UK's high value manufacturing economy, and a number of industry bodies have already been established to champion the capabilities and opportunities presented by AM, including the Additive Manufacturing Association (AMA) and AM-NET, the UK networking forum for AM applications, research and the supply chain. AM is also being championed by bodies such as the GTMA, the Motor Sport Industry Association and the Association of Industrial Laser Users (AILU). However, to-date there is no one singular working group focused on driving forward the UK AM innovation agenda, largely through lack of a clear industrial strategy and a lack of central coordination.

WHY DO WE NEED A TECHNOLOGY INNOVATION NEEDS ANALYSIS FOR AM?

Given the scale of the market opportunity, the strategic value of AM to the UK and the relative immaturity of the sector at this time, it is important for both public and private sector stakeholders in the UK to better understand the current position of AM, both globally and domestically, and to identify the barriers and therefore technology innovations needed to gain national leadership across the AM supply chain. Only then will it be possible to establish a 'national vision' for AM and establish a mechanism to drive forward change.

Prior to further Technology Strategy Board investment in AM, a decision was taken to commission a Technology Innovation Needs Analysis (TINA), to understand

THINK OF AM CURRENTLY EVOLVING IN THE WAY CAD-CAM DID IN THE 1980'S

both the needs of industry to adopt AM and the UK's capacity to support and exploit innovation across the AM supply chain.

WHY IS THE TINA NEEDED NOW?

Significant public and private sector investment (circa £90million) has been made or committed within the UK in recent years to drive up the Technology Readiness Level (TRL) of AM. This funding has established the UK as a leading location for AM R&D activity across the supply chain. However, the impact and outcomes of this funding have yet to be mapped out and the strategic direction of AM research activity within the UK remains unclear. Moreover, our competitive strengths and relative weakness remain largely unknown, hence the need for a detailed analysis of the UK's capacity and capability to drive forward AM, in response to the needs of industry.

ESTABLISHING THE MANUFACTURING TECHNOLOGIES OF INTEREST

Additive Manufacturing (AM) processes join materials layer upon layer, to make objects. Synonyms include 3D printing, Generative Manufacture, e-Manufacture, Additive Layer Manufacturing, Freeform Fabrications, Solid Freeform Fabrication and Layer Manufacturing.

However, many other manufacturing approaches can also claim to be additive, such as carbon composite lay-up production, the production of plastic electronics by ink-jet printing or photo-voltaic cell manufacture using direct-write deposition.

Within the context of the TINA, a definition was agreed by the AM SIG based on the American Society for Testing Materials (ASTM) standard 2792-12 - "A standard terminology for Additive Manufacturing". The technology classification agreed by the SIG can be seen detailed in Table 1, which shows seven top level classifications for Additive Manufacturing technologies, below which there are a range of different material classifications, and discrete manufacturing technologies produced by a range of global companies. Within the TINA we have considered the current state of the art of these seven top level classifications, and examined these in the context of both the UK end-user community and the enabling AM supply chain.

The TINA methodology

In October 2011, the High Value Manufacturing Team at the Technology Strategy Board established an Additive Manufacturing Special Interest Group (AM SIG) to conduct a Technology Innovation Needs Analysis (TINA) on AM. The Materials KTN leads this group with input from AAD KTN, ESP KTN and Econolyst Limited. Within the 6-month duration of this study, the group captured the current status of AM technology development in the UK and identified the sources of key investments to date. The group has also characterised the UK industry need for AM technology and the drivers and barriers affecting its adoption, and has assessed the UK's capability and capacity to engage in future AM research, technology transfer and commercial exploitation. The study provided the opportunity to benchmark UK research activities against other global players. This is important in order to determine whether the UK has a position of leadership that needs protecting or could be further developed to provide a sustainable competitive advantage for the nation.

The TINA presents the analysis of views expressed by key AM supply chain players and leading academics through structured consultation and face-to-face interviews, backed by a review of industry roadmaps, research reports, international conferences and funding data covering the period 2007 to 2016.

It should be noted that, during the research phase of the TINA, no access was granted to privileged or confidential information, and only public domain documentation and opinion were used. As such, the AM SIG accepts that certain information relating to the commercial readiness of AM process by early adopters and high value sector champions may have been omitted to protect competitive advantage.

Table 1

Classification of additive manufacturing processes defined by the AM SIG – adapted from ASTM classifications

* Technology typically associated with turbine blade repair, but also used for AM applications

Classification	Material	Process description	Commercial systems (country)	Developmental system (country)
Powder Bed Fusion	**Metal**	Direct metal laser sintering Selective laser melting Selective laser melting Selective laser melting Selective laser melting Selective laser melting Selective laser melting Electron beam melting	EOS (Germany) Concept Laser (Germany) Renishaw (UK) Realizer (Germany) Phenix (France) SLM Solutions (Germany) Matsuura (Japan) ARCAM (Sweden)	
	Polymer	Selective Laser Sintering Selective Laser Sintering Selective Heat Sintering Selective Mask Sintering High speed sintering Selective Laser Printing	EOS (Germany) 3D Systems (USA)	Blue Printer (Denmark) FIT (Germany) Sheffield Uni (UK) Renishaw / DMU (UK)
	Ceramic	Selective Laser Sintering Selective Laser Sintering	Phenix (France) EOS (Germany)	
Directed Energy Deposition	**Metal (powder feed)**	Direct Metal Deposition Laser Engineer Net shaping Laser Consolidation Laser Deposition Laser Deposition* Laser Deposition* Ion Fusion Formation	POM (USA) Optomec (USA) Accufusion (Canada) Irepa Laser (France) Trumpf (Germany) Huffman (USA)	Honeywell (USA)
	Metal (wire feed)	Electron Beam Direct Melting Wire & arc deposition (WAAM) Shape Metal Deposition (SMD)	Sciaky (USA)	Cranfield Uni (UK) Nuclear AMRC / RR (UK)
Material Jetting	**Photopolymer**	Polyjet Projet Ink-jetting	Objet (Israel) 3D Systems (USA) LUXeXcel (Netherlands)	
	Wax	Thermojet / Projet T-Benchtop	3D Systems (USA) Solidscape-Stratasys (USA)	
Binder Jetting	**Metal**	M-Print / M-Lab	ExOne (USA)	
	Polymer	3DP	Voxel Jet (Germany)	
	Ceramic	3DP (models & parts) 3DP (medical implant) S-Print (sand cores)	3D Systems (Z-Corp) Therics (USA) ExOne (USA)	
Material extrusion	**Polymer**	FDM (Dimension & Fortus) FDM (Replicator) FDM (UP) FDM (Cube & BFB)	Stratasys (USA) MakerBot (USA) Delta Microfactory (China) 3D Systems (USA)	
VAT photopolymerisation	**Photopolymer**	Stereolithography Digital Light processing Digital Light processing SLA / DLP	3D Systems (USA) Envisiontec (Germany) Asiga (USA) DWS (Italy)	
	Photopolymer (ceramic)	CeraFab CeramPilot	Lithoz (Austria) 3DCeram (France)	
Sheet lamination	**Hybrids**	Ultrasonic Consolidation	Fabrisonic / Solidica (USA)	
	Metallic	Ultrasonic Consolidation	Fabrisonic / Solidica (USA)	
	Ceramic	Laminated Objet Manufacture	CAMLEM (USA)	

TECHNOLOGY INNOVATION NEEDS ANALYSIS

WHAT IS THE CURRENT STATE OF THE ART IN AM APPLICATIONS?

The current AM sector is built on technology originally intended to make prototypes and models used during the product development cycle. Over the past decade, early adopters have taken these technologies and applied them to some limited manufacturing applications. In parallel some technology platforms have developed to support these 'production part' applications. However, the current AM sector is largely built on legacy prototyping systems.

Table 2 shows current and emerging applications of AM compared to each of the technology classifications defined by the AM SIG. As it can be seen, very few technologies have generic applications. For example metal powder and wire feed systems, which have a high material deposition rate, but relatively low resolution, are being trialled for applications in aerospace airframe production and some limited aerospace power applications. However, due to their relatively poor resolution, they are not currently suited to medical applications, or applications in the creative industries. This differs greatly from binder jetting systems, which produce higher fidelity components but with lesser mechanical properties, which have found applications

KEY

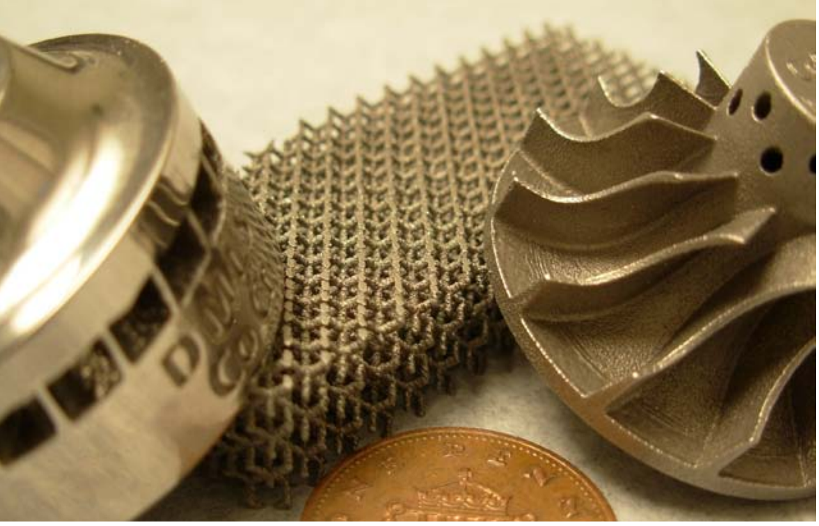
Y = Applied

N = Not Applied

Table 2

Current commercial or near to market application of AM relative to sector

classification	Material	Aerospace (airframe)	Aerospace (power)	Aerospace (Cabin)	Auto (road)	Auto (sport)	Medical (orthopaedic)	Medical (prosthetic / orthotic)	Medical (Dental implants)	Medical (surgical guides)	Medical (hearing aids)	Energy (generation)	Energy (storage)	Creative industries (artefacts)	Consumer goods (Jewellery)	Consumer goods (Toys & games)	Consumer goods (Home / fashion)	Defence (Weapons)	Defence (PPE & armour)	Defence (logistics & support)	Electronics (packaging)	Electronics (sensing)	Prototyping	Tooling & Casting
Powder Bed Fusion	Metal	Y	Y	Y	Y	Y	Y	N	Y	N	N	Y	Y	Y	Y	N	N	Y	Y	Y	N	Y	Y	Y
	Polymer	N	N	Y	Y	Y	Y	Y	N	Y	Y	N	Y	Y	Y	Y	Y	N	y	Y	Y	Y	Y	Y
	Ceramic	N	Y	N	N	N	Y	N	Y	N	N	N	Y	Y	N	N	N	N	Y	N	N	Y	Y	Y
Directed Energy Deposition	Metal (powder feed)	Y	Y	N	Y	Y	N	N	N	N	N	Y	N	N	N	N	N	N	Y	Y	N	N	Y	Y
	Metal (wire feed)	Y	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	Y	Y	N	N	Y	Y
Material Jetting	Photopolymer	N	N	N	N	Y	N	Y	N	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	Y	Y	Y
	Wax	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y
Binder Jetting	Metal	N	N	N	Y	Y	N	N	Y	N	N	N	Y	Y	Y	N	N	N	N	N	N	Y	Y	Y
	Polymer	N	N	Y	Y	N	Y	Y	N	Y	N	N	Y	Y	N	N	N	N	N	N	Y	N	Y	N
	Ceramic	N	Y	N	N	Y	Y	N	Y	N	N	N	Y	Y	N	Y	N	N	N	N	N	Y	Y	Y
Material extrusion	Polymer	N	N	Y	Y	N	Y	Y	N	Y	N	N	N	Y	N	N	N	N	N	Y	Y	Y	Y	Y
VAT Photopolymerisation	Photopolymer	N	N	N	N	N	N	Y	N	Y	Y	N	N	Y	Y	N	Y	N	N	N	Y	Y	Y	Y
Sheet lamination	Hybrids	Y	Y	Y	N	Y	N	Y	N	N	Y	N	Y	N	N	N	N	N	Y	N	Y	Y	Y	N
	Metallic	Y	Y	Y	N	Y	N	N	N	N	N	Y	Y	N	N	N	N	Y	N	N	Y	N	Y	Y
	Ceramic	N	Y	N	N	N	Y	N	Y	N	N	N	Y	N	N	N	N	N	N	N	N	N	Y	N
Other AM processes (emerging)		Applications Unknown																						



in the creative industries, but not within aerospace. As singular technologies, powder bed metals and powder bed polymer systems are the most generic, with applications spanning the aerospace, automotive, medical, energy, creative industries, defence and electronics sectors.

SO HOW IS THE UK ADOPTING AM?

The aerospace, healthcare, creative industries and motor sport sectors are most active in using AM technology within the UK today, with examples of products under development being tested in niche applications or being sold on a small scale. The energy generation sector and the remainder of the automotive sector are less proactive. For example in power generation, gas turbine manufacturers are happy to follow the lead of aerospace gas turbine technology research in the field of AM.

Research suggests that all sectors are interested in the use of AM for both "cloned" part manufacture i.e. the replacement of existing manufacturing technology in an established application, and "freedom of design" part manufacture i.e. the use of AM to build shapes that cannot be produced using other methods.

Parts and components requiring short production runs are being targeted to avoid the high penalty cost of tooling amortisation; for example, short production runs of automobile parts, and limited aerospace components used within low stress applications in cabins. The potential to make legacy products, such as discontinued spare parts for cars and museum replicas, is also being evaluated in some instances. However, within the UK there are currently no publicly available examples of large scale, routine production using AM technologies.

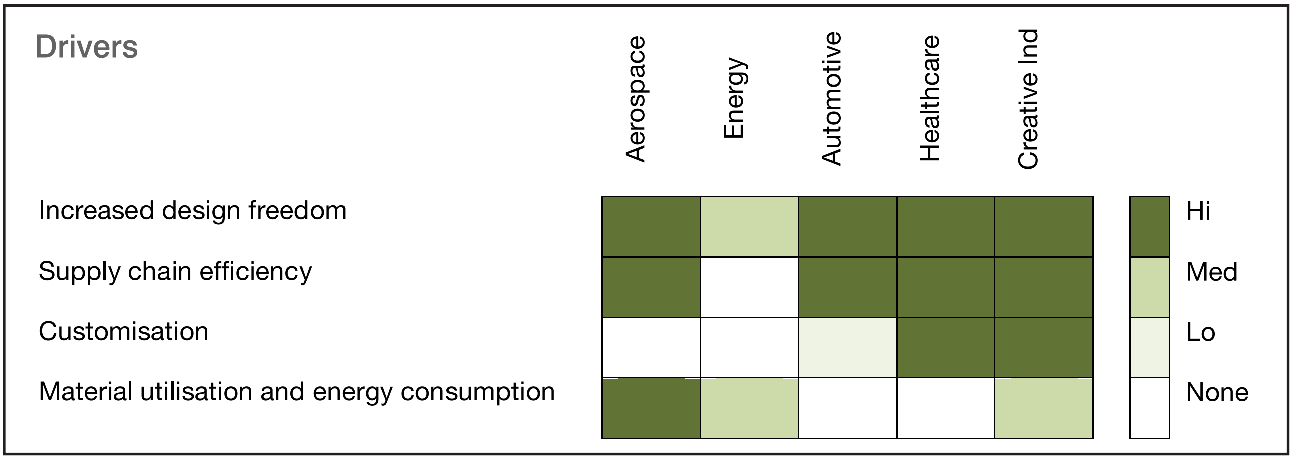
AM within the UK is also being used to customise products. In the medical field, companies are making orthopaedic implants and dental crowns adapted to individual patients. The creative industries are designing and producing items such as jewellery and furniture tailored to customers' requirements in addition to toys produced by companies such as Makielabs (see case study)

In some sectors, niche applications such as highly functional prototyping are being used to gain experience of manufacturing with AM technologies and to prove the metallurgical and mechanical properties of components produced. Aerospace companies have also made components for satellite applications and Formula 1 is using AM for both polymer and metal parts in a small way.

The AM SIG has identified a large range of potential and current AM applications and developments within UK manufacturing. It has also confirmed that there are four generic drivers for AM technology adoption. The relative importance of these drivers largely depends on the application sector, as shown in Figure 1.

Figure 1

Generic drivers for AM technology adoption



Case Study – Makielabs London (creative industries)

Makielabs was founded in 2011 with a simple vision to use AM to produce bespoke toys (dolls) using design data from the consumer. The start-up was match-funded by £100K of Technology Strategy Board funding secured through the Tech City Launchpad competition. With this funding Makielabs were able to develop a dedicated computer interface for both PCs and iPad through which consumer of all ages are able to model their own Makieworld characters. Using back-end software tools, Makielabs are then able to send AM 'print' data to a number of UK AM service companies for production. The 3D printed characters are then assembled in London prior to shipping. Makielabs has recently launched its first commercial offering, which has been highly successful, resulting in the company securing over £1million of private sector venture capital investment (5th June 2012) to increase production capacity and to take the product offering to the next level.

In summary it has been established that the primary drivers within the UK for AM technology adoption are:

- Increased design freedom enabling greater functionality of products, reducing part counts and saving weight;
- Supply chain efficiencies to improve cost competeviness in both manufacturing and transactions, accelerate product development and manufacture and establish new business models;
- Personalisation and customisation of products, tooling and fixtures;
- Material utilisation improvement and reduced energy consumption, particularly where subtractive processes lead to the waste of expensive starting materials. These issues have implications both in terms of sustainability and cost effectiveness.

HOW DOES THE UK AM SUPPLY CHAIN COMPARE TO THE REST OF THE WORLD?

Many of the AM process technologies shown earlier in Table 1 are available as commercial technology platforms. Most of these platforms originate from the USA and Germany, with the only UK technology vendor being Renishaw plc. The company develops, manufactures and sells metallic selective laser melting systems for a range of applications, including medical implants and devices, dental crown production and metallic part prototyping. Renishaw operates in a competitive sub-sector of AM, namely metallic powder bed systems, where it competes against seven other companies making similar technology platforms. Although the company has Intellectual Property (IP) in this domain (patents) it finds itself having to license external IP to vend its products. Renishaw has entered the AM market as an established machine tool and technology company. However, their current AM product portfolio is limited to just two generic metal AM machines, focused on the functional prototyping and low-volume production markets.

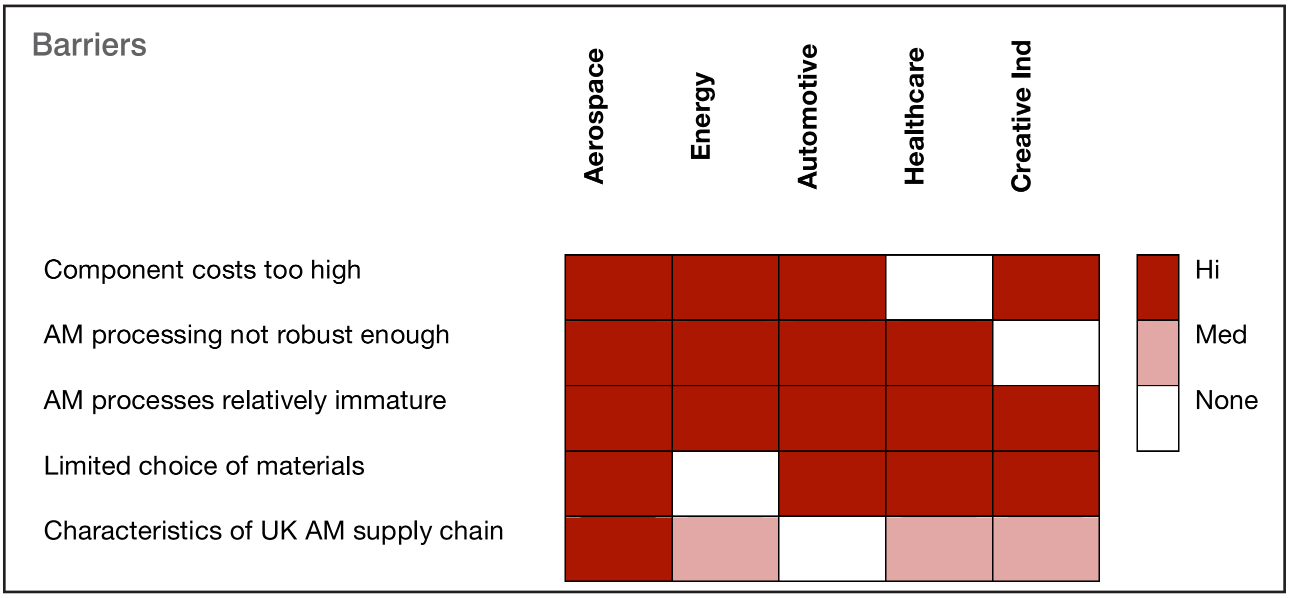
The UK is, therefore, not yet considered a leading AM machine tool source, when compared to Germany with six vendors or the USA with ten. However, the UK does have a number of developmental technologies such as High Speed Sintering & Selective Laser Sintering and a number of enabling software companies and materials vendors developing product offerings within the AM supply chain.

Analysis by the AM SIG suggests little evidence of sector 'clustering' within the AM supply chain. What exists may be a function of loosely affiliated bonds resulting from funded projects rather than developed business strategy. However, like the CNC machine tools sector, carbon composites sector or ICT sector, the enabling AM supply chain within the UK needs to come together to function as a sector. Without co-ordinated integration between machine vendors, materials companies and software developers, there will be little if any innovation or business growth. Functioning as a sector, the companies will share common customers and sell their products through common channels. More importantly, they will be able to differentiate between their needs and those of the technology users.

Looking towards the top of the AM supply chain, it is also concerning to see little commercial exploitation by the UK industry leaders in terms of applications. Within the aerospace sector, companies including Boeing, Northrup Grumman, GE and Honeywell all have highly developed large internal AM research groups, as have companies such as EADS and Avio. Within the automotive sector, BMW is driving forward innovation in the use of both polymeric and metallic AM systems in collaboration with supply chain companies such as FESTO. In the medical sector, Italian company Alder Ortho is already using AM for the mass production of orthopaedic implants, with mature research in this field also being undertaken by USA based Stryker Orthopaedic and Johnson & Johnson's DePuy. This could be attributed to a more conservative approach to technology adoption within the UK, when compared to a more high risk taking attitude within the USA. However, this is a purely anecdotal perspective. Within the healthcare sector, there are also national market drivers to consider, such as the implications of maximising profits within the US insurance funded private healthcare market, or the cost implications of offering affordable healthcare under the Medicare program. In each case, it could be that AM is being used to address a financial driver, which may not be seen as a priority within the UK NHS. The UK does have one company using AM to make forming tools for dental aligners (Clear Step), but this business model is based on the much larger and

Figure 2

Generic barriers for the key sectors



well established activities of USA based company Align Technologies. The UK has, however, been an early adopter along with Italy of precious metal sintering, with UK Gold dealers Cookson's Precious Metals being one of only three facilities in the world offering noble metal sintering of gold for jewellery, electronics and high value engineering applications such as satellites.

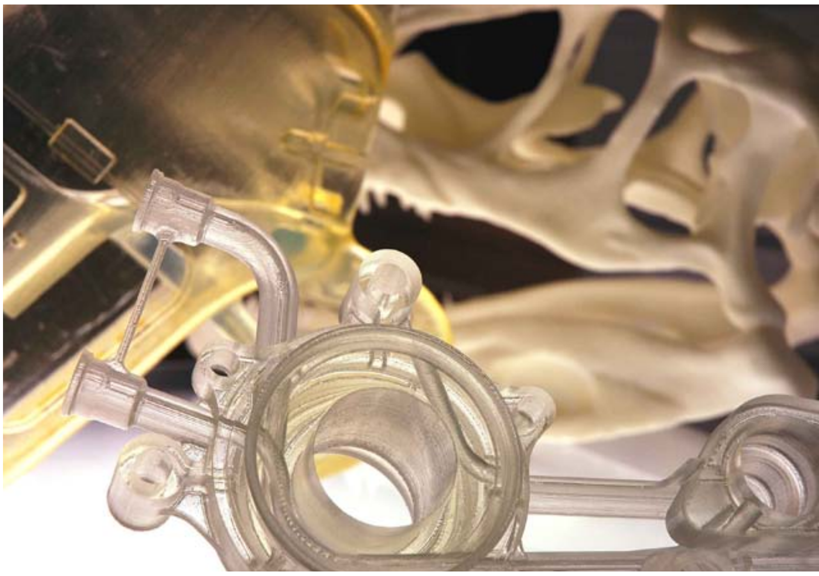
Overseas investment in AM is also driving both machine tool development and applications elsewhere. The EU has committed over €100million to AM projects focused on both new technology development and existing technology improvement, in addition to applications spanning all major sectors. The US government has recently announced a $45million competition to establish the first in a series of new national centres for advanced manufacturing, the first of which will be focused wholly on AM. The Australian and South African government have both developed strategies to look at the potential of developing materials capacity for the AM supply chain, largely focused around titanium.

In summary, although the UK is clearly engaged in the development of AM technologies and applications, it is far from leading in any one specific area, hence the importance of developing a clear forward strategy.

WHAT ARE THE BARRIERS TO TECHNOLOGY ADOPTION?

Whilst this TINA has identified examples of the use of AM technologies to produce components in each of the key sectors and shown that the UK AM community is developing, the study has also uncovered a number of technology and business barriers, which are suppressing wider scale technology adoption.

Many barriers were common to at least three of the key sectors known to be engaged in AM implementation within the UK. However, the barriers were sometimes caused by industry or application specific factors and may require different approaches or levels of intervention to resolve. For example, within the aerospace sector, the barriers for introducing components made by AM into engines are different from those for introducing components into the cabin, as the operating environment, product specifications and materials involved are quite different. As a further example, component surface finish concerns both the aerospace and creative industries sectors. However, in specifying



the process, the aerospace sector needs to confirm the effect on component in-service performance, which requires extensive long term testing and accreditation, whilst the creative industries are aiming to achieve an aesthetic finish that is acceptable to their customers.

The common barriers experienced by each sector are ranked in Figure 2, in terms of relevance.

The key issues resulting in these barriers are summarised below.

1. Component costs are too high when compared with established manufacturing technology:

- Deposition rates of processes are too slow. For example, for most applications powder bed metal based processes need to be between four and ten times faster than the current rate. At the current rate of build, machine depreciation results in parts of too high cost except for some very small complex geometries, such as dental implants;
- Powders and resins are too expensive for part mass production and in the case of metals not tailored to AM. This impacts significantly on overall part cost, as for higher deposition rate process, the material cost becomes the major factor in final part cost;
- Current AM machines have size constraints, particularly for powder bed processing; limiting the

scale of parts or production volumes than can be economically processed in one batch;

- Current AM machines are not cost effective for production in terms of their sales price compared to their production output capabilities unless the final product can demand an extremely high price per unit volume of material;
- Highly regulated sectors, such as the aerospace and medical devices sectors, require that new products and processes must meet exacting industry standards before they can be introduced. This qualification necessarily involves longer and more rigorous development and implementation cycles, which add to the costs. This barrier particularly affects the ability of SMEs to introduce new products to the healthcare market.

2. AM processes are not robust enough:

- Process consistency between batches and machines is lacking, largely as a result of uncontrolled process variables, variations within the enabling machine supply chain, specifically with machine optical trains, and material batch differences;
- Few in-line process control and monitoring methods are available to give manufacturers greater confidence that specifications are being met or that closed loop process rectification is taking place;
- Limited data is available to develop sufficiently accurate and detailed mathematical models to simulate AM processes, limiting the amount of pre-production simulation and planning and often resulting in failed component builds and expensive errors;
- Post processing operations are often needed to meet product specification, for example surface finishing to achieve a specific roughness, machining to meet a dimensional tolerance, residual stress relieving and heat treatment to promote specific metallurgical conditions, removal of build support structures and disposal of waste materials. These steps introduce extra cost, extend the manufacturing cycle and increase the possibility of process variance.

3. AM processes and enabling design data methodologies are relatively immature in comparison to traditional manufacturing processes, which is limiting the ability to implement the technology in certain applications and impeding the stimulation of potential customers to consider the adoption of AM:

- Many applications are at relatively low Technology Readiness Levels (TRL), for example, many metallic powder bed and blown powder applications are perceived to have a TRL between 3 and 5; TRL 9 is typically associated with a technology that is 'ready' for wide scale production application;
- The AM supply chain is not mature and often fragmented as a result of this low TRL; necessitating extensive supplier searching and discussion between supply chain partners to agree technical specifications and requirements;
- Low awareness of AM technologies means that they are failing sometimes to make full market impact even where they offer clear benefits, for example some companies making dental crowns in the medical devices sector remain unaware of AM, although it is being used by their competitors;
- Designers are not trained in AM application and do not achieve the maximum benefit from the design freedom offered by AM. The result being that the potential geometric possibilities which can drive business benefit are not fully realised;
- Design tools, such as 3D CAD, are not written to exploit the geometric flexibility and benefits of AM. For example, they are largely unable to process complex lattice structures, honeycombs, topologically optimised structures or organic geometries;
- Some in industry are sceptical that AM will meet their production requirements. For example, whilst parts of the automotive sector are embracing AM technologies through component production and research activity, other organisations view AM technology as "too high tech" to be of use in routine manufacture;
- Property data for AM components is sparse and there is little accessible performance data, for example mechanical and fatigue data for the aerospace sector; mechanical and biological response data for the healthcare sector;
- There is an absence of standards for qualifying AM approaches, which hinders adoption and makes comparison of final part properties difficult.

4. There is a limited choice of materials available for AM, which is slowing the wider adoption of the technology:

- Materials are often not optimised for AM processes. The goal of faster deposition rates is likely to lead to rougher surface finish, which may reduce fatigue resistance even with post processing. Alloys developed specifically for rapid deposition may alleviate this problem;

- Polymers processed by 3D printing (photo-polymer & binders) are not sufficiently strong or durable; an unacceptable situation in the creative industries if several thousand pounds are being charged for an arts or craft based item. Parts have a limited shelf-life due to hydroscopic and UV instability;

- Colour choices from polymers are limited. In many cases, AM development has been driven by engineering sensibilities, which means a vast market of the creative industry sector, where colour detail is sought, is not being served. Where colour is available, such as ceramic 3D Printing, it is in materials that are not suited to AM applications due to limited mechanical properties.

5. The UK AM supply chain is fragmented and weak in places, which means that the UK is poorly placed to drive the next generation of process technology developments:

- There are few UK manufacturers of AM systems and only one manufacturer of industrial systems;

- Much of the Intellectual Property Rights to AM technology is owned by companies outside the UK, which hinders the sector's ability to exploit the technology, particularly in manufacturing machine platforms;

- Despite good linkages between organisations active in AM they are often linked with funded projects of finite length. As a consequence the networks formed may not be sustainable nor produce synergistic benefits as the members often do not share learning;

- The business models for the effective supply of components made using AM technology are not fully developed and may involve additional business risks; for example, in supplying consumers with products that they had designed themselves, it is not clear who has the responsibility for ensuring that the product is safe and who would have the liability in the case of product malfunction;

- Although the UK has well established competency in software development, simulation and modelling, equipment design, laser manufacturing systems and materials, these organisations are often not engaged with the AM supply chain and their expertise is not fully exploited.

Table 3

Technology innovation approaches needed to jump the barriers to AM adoption

Barrier	Contributing Factors	Possible Approaches to the issues
Component costs are too high for wide scale technology adoption	Deposition rates of powder bed processes are too slow	Increasing deposition rate using new scanning methodologies or energy sources
	Powders are expensive	Identify new powder production sources or supply methodologies
	AM machines have size constraints limiting productivity	Increase envelope of existing AM machines or identify alternative machine configuration suited to production manufacture
	AM machines have a high capital investment cost	Identify new supply chain opportunities to reduce Bill-of-Materials (BOM), or identify alternative financing methods such as shared ownership or group procurement
	New business models are needed drive down the cost of supply	Developing new business models based on increased access to machine underutilisation such as online brokerage systems or automated capacity mapping and load balancing between suppliers
AM processes are not robust enough to support high volume production	Need consistency between batches and machines	Methodologies to ensure consistent materials supply, new batch sampling standards and measurement techniques specifically for AM products
	Few in-line process control and monitoring methods	Development of in-process monitoring and control methodologies and systems including optical, thermal, acoustic, physical and chemical analysis
	Post processing operations are often needed to meet product specification	In process thermal control to reduce post process requirements or hybrid systems combining additive processes with thermal and stress releasing post processing or in-line machining to meet dimension or surface finish specifications
AM processes and product data are relatively immature	Many applications have a perceived low TRL within specific sectors	Develop a database of applications case studies showing detailed examples of AM being used in different sectors, highlighting the TRL and the known barriers to adoption. Maintain focus on sector specific AM research
	Limited accessible performance data for AM components	Developing a shared database of performance data for selected materials by studying the effect of process parameters on properties
	Limited accessible performance data on available materials and processing parameters	Develop an open-source or 'club' for materials information sharing and data pooling
	Absence of standards for qualifying AM materials and processes	Promote industry engagement in the ASTM F42, BSI and ISO working groups on standards development
	Designers are not trained to exploit the full geometric capabilities of AM	Identify best practice globally in design for AM and develop a series of training modules for specific AM processes, materials and application sectors
	Supply chains are not mature and often fragmented	Develop a formal UK industry sector network focused on developing an end-to-end AM supply chain within the UK, linking to known sectors of competence including optics, photonics, sensors, materials, inkjet printing and powder metallurgy
	Low awareness of AM technology in some sectors, with scepticism of technology in others	National programme of AM awareness events based on industry specific case studies, technology transfer support information and supply chain assistance
Limited choice of materials available	Materials are often not optimised for AM processes	Fundamental analysis of factors and process attributes affecting the material properties of different materials using different AM mechanism, leading to a materials modelling tool to identify suitable future materials of interest. Followed by validation of new materials with known market demand
	Polymers processed by 3D printing are not sufficiently strong or durable	Identification of new semi-crystalline and amorphous polymers suited to different AM mechanisms (sintered & extruded) followed by material preparation's and extensive process parameterisation
	Choice of polymers is limited	Identification of AM mechanisms capable of processing and depositing selective colour material, followed by development of materials and processing parameters
UK AM supply chain is fragmented and weak in places	Few UK manufacturers of AM systems	Promotion of AM market opportunities based on current growth and projected future scale to engage new companies in supply chain development
	Inter-organisational linkages in the UK AM community are artificially supported by funded projects of finite length	Develop a national industry body with a clear mandate based on developing both the UK AM applications base, but also the UK AM supply chain

WHAT ARE THE TECHNOLOGY INNOVATIONS NEEDED TO JUMP THE BARRIERS?

Cleary there are a great deal of technological, economic and educational barriers that must be addressed if AM is to achieve wide scale adoption within the UK. Table 3 opposite details a number of approaches to how these barriers could be addressed.

DOES THE UK HAVE A SUITABLE RESEARCH BASE TO ADDRESS THESE BARRIERS?

The UK has a well-established and equipped AM research community. 81 organisations have been involved in AM research within the UK since 2007, including 24 universities and 57 companies. The average engagement by the university and industrial sector is 11 years and 10 years respectively. Although AM technology has been used commercially for 25 years, direct AM part production only gained traction within the last 10 years, positioning the UK as an early proponent of AM research.

Despite this maturity, AM remains a research intensive technology area, with the largest percentage of employees in both academic and industrial establishments at post graduate or post-doctoral level, as opposed to technician level. This may be a further barrier to wider adoption, supporting the view that the technology maturity is more laboratory-focused than shop floor focused.

The organisations involved in UK AM research are well equipped with 151 AM machine platforms at their disposal. The most common of the 109 machines procured from commercial vendors are metal and polymer powder bed systems and extrusion based polymeric systems, whilst the most common of the 46 machines, which are modified commercial machines or self-assembled machines, are metal powder feed systems, which blow powder into a laser beam.

How is the UK AM research community constituted?

A network of organisations working together on AM research has largely been established in the UK through participation in funded projects with the majority of AM research expenditure, and therefore arguably the majority of AM research activity, focused on less than 20 of the 81 organisations across the supply chain.

The projects funded by the Technology Strategy Board since 2007 have created a loose network of over 50 UK based organisations. Although there is a nascent network here, the TSB has no formal requirement for the separate projects to share good practice or learning between the different project groupings. EU FP7 projects have established a similar informal network, albeit with different linkages, and again there is no formal requirement to share knowledge between project groups.

What is the scale of public and private sector investment in AM R&D?

£95.6million has been invested in collaborative or university AM R&D projects and Technology Transfer activities within the UK between 2007 and 2016. Of this, £80million has been committed to research, with £15.6million for technology transfer and business support.

Industry has made a significant commitment to supporting AM research and technology transfer activities with £25million invested, whilst public funding bodies contributed the majority of the balance with the Technology Strategy Board, the EU Framework Programmes (FP6 & FP7), and the European Regional Development Fund (ERDF) being the most significant supporters at approximately £13million each.

AM funding from both national government and EU sources increased steadily between 2007 and 2012, increasing year on year in the period. However, the bulk of projects were initiated in either 2007 or 2011. Technology Strategy Board commitment to supporting new AM

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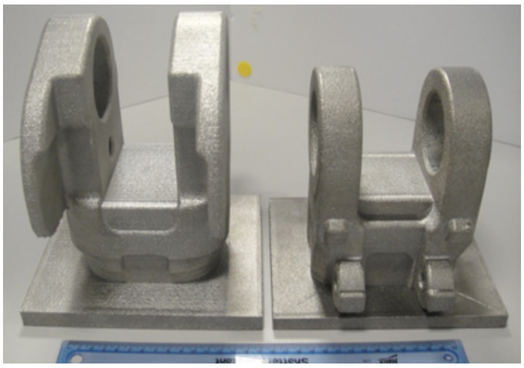
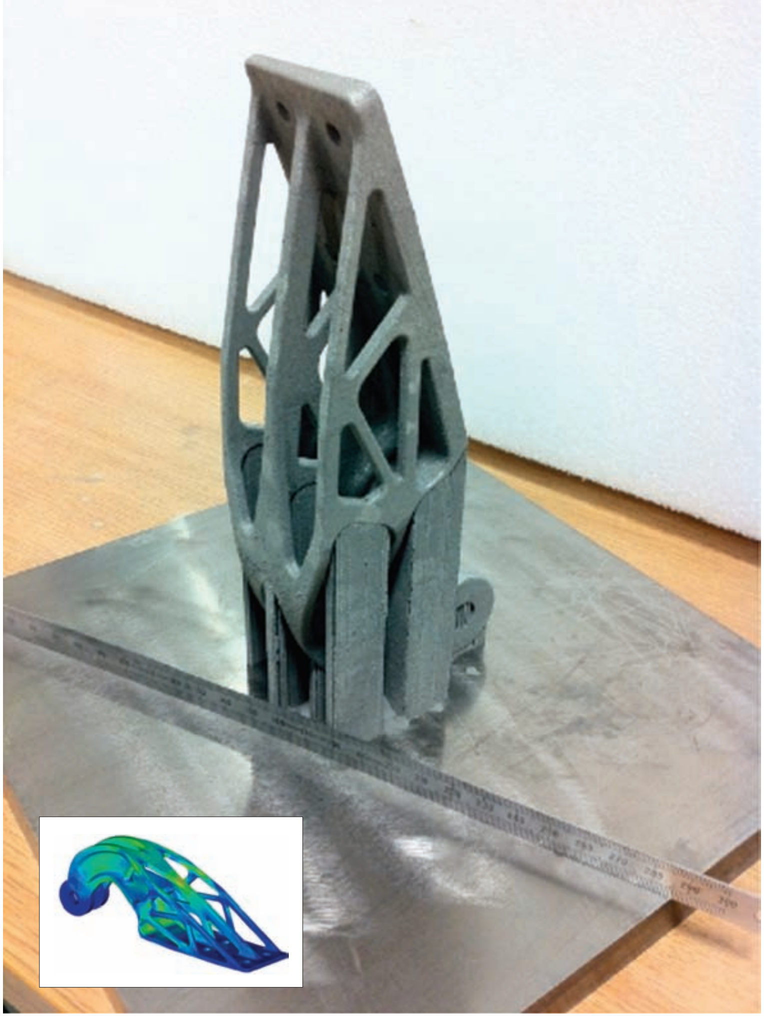




projects peaked in 2009 at £12million (project value including funding). By 2011, the level of TSB support for new AM projects was just £1million, suggesting the need for a strategic pathway to enable increased support for AM research and exploitation within the UK. The pipeline of investment beyond 2011 currently declines as supported projects come to completion.

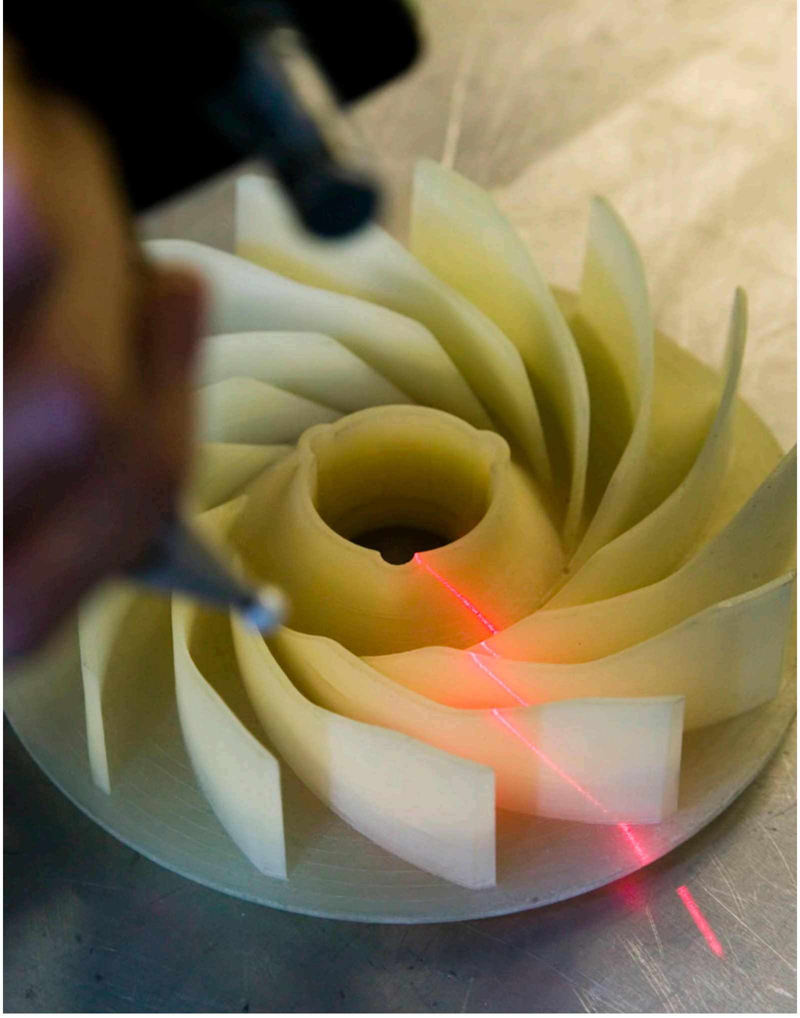
Based on current funding commitments, the UK AM research community will become largely supported by non-TSB funding sources, such as the EU's Framework Programme by the end 2012. At this time, only EPSRC platform funding remains stable through the support of the Centre for Innovative Manufacturing in Additive Manufacturing, which is led by Nottingham University, with Loughborough University as a partner.

Given the significant investment already made in AM research within the UK, it could be assumed that many of the barriers to technology adoption should have already been addressed. However, it is important to put this monetary investment into some context. The UK has benefited from £80million of public and private sector investment in AM R&D since 2007 (including current commitments through to 2016). However, if we consider the three publicly traded AM technology vendors, they have an annual R&D expenditure of $45million (3D Systems $20-million, Stratasys $10million, Objet $15million) or £28.6million collectively. This compares to a UK pro-rata value of around £8million of AM R&D expenditure, this being significantly less that any of the three large publicly traded vendors, as individual companies.

In summary, after a period of significant financial support, the UK AM research community may be at a fiscal peak, with a potential short-fall of future funding to sustain the current level of research activity. To assist developers and stabilise funding, a long-term market driven AM technology strategy is required, which would enable greater collaboration and focus on areas where the rate of return on research investment is greatest.

Where are the centres of critical mass in AM research & technology transfer?

Almost £67million of the total public funding has been invested in UK universities, RTOs and research centres to support AM developments for work between 2007 and 2016. £51.4million of this has been invested in R&D activity centered at Nottingham University, Loughborough University, Materials Solutions Ltd, TWI and the Universities of Liverpool, Exeter and Birmingham. £16.2million has been invested in technology transfer largely at Sheffield, Exeter, Lancaster, Wolverhampton and London Metropolitan Universities.



Which industries are committed to driving AM forward in the UK?

By sector, aerospace is by far the largest supporter of AM technology development. The industry invested £13million between 2007 and 2016, which in turn has levered £20.5million of public funds for research work within academia and industry, about a third of the budget of all R&D activity. The automotive and medical sectors are the next largest supporters of research funding, contributing £3.5million and £3million to lever AM research activities of £6.5million and £11.5million, respectively. If the creative industries, consumer products and fashion/home categories are considered as one generic sector, then the combined creative industries sector has accessed £2.5million of industry contribution to lever around £7.5million support for the sector.

Industrial research spending in AM is highly concentrated with half of the total spend by just six companies; representing two software companies, one AM machine tool vendor and three technology end users in the aerospace and defence sectors.

The UK's AM research capabilities in comparison with other countries

The UK is one of the world's leading sources of AM related knowledge and research activity, along with Germany and the USA, when benchmarked through participation in collaborative pan-European research projects and through a comparison of papers presented at AM-focused research conferences.

The UK is the leading European country in terms of engagement in EU FP7 AM research activity, with EU project participation and leadership exceeding all other countries, including Germany, which has the second largest percentage of AM machine tool vendors in the world after the USA. The UK leads 45% of the current 20 FP7 projects with work packages focused on Additive Manufacturing. Moreover, UK-based organisations constitute the largest proportion of participants of any eligible state with 23% of the 240 participants. The AM SIG does acknowledge that significant investment has been levered in both Germany and the USA (specifically a recent call for a $45million US AM research centre), and that these funds have come from both national funding bodies and the private sector. However, due to a lack of public domain information from these national funding bodies and of confidential privately funded activity, benchmarking could only be undertaken using EU FP7 project information, freely available within the public domain though the Cordis database.

The UK also holds a prominent global position in the AM research community, being the second largest source of conference papers. At an individual country level, the USA accounts for the largest number of papers (129), followed by the UK (75) and then Germany (71).

In summary it can concluded that the UK has a research extensive and experienced AM research community that is well respected internationally.

Table 4

AM application against UK technology competence

KEY
- H = High level research and innovation activity
- M = Medium level research and innovation activity
- L = Low level research and innovation activity
- N = No fit
- No UK capacity

Process	Material	Aerospace (airframe)	Aerospace (power)	Aerospace (Cabin)	Auto (road)	Auto (sport)	Medical (orthopaedic)	Medical (prosthetic / orthotic)	Medical (Dental implants)	Medical (surgical guides)	Medical (hearing aids)	Energy (generation)	Energy (storage)	Creative industries (artefacts)	Consumer goods (Jewellery)	Consumer goods (Toys & games)	Consumer goods (Home / fashion)	Defence (Weapons)	Defence (PPE & armour)	Defence (logistics & support)	Electronics (packaging)	Electronics (sensing)	Prototyping	Tooling & Casting
Powder Bed Fusion	Metal	H	H	M	M	M	L		H			L	N	L	L	N	N	N	M	N		N	H	H
	Polymer			L	L	L	N	H	N	L	N		N	H	M	M	M		M	N	L	M	H	M
	Ceramic																							
Directed Energy Deposition	Metal (powder feed)	H	H		N	M						H							M	N				
	Metal (Wire feed)	H	H									N						N		N				
Material Jetting	Multi-material					N		N			N		N		N	N	N		L		L	L	H	N
	Photopolymer																							
Binder Jetting	Metal																							
	Polymer																							
	Ceramic		N			N	M		N				N	H	N	N	M					N	H	N
Material extrusion	Polymer			L	N		N	L		N				N	N	N	N			N	N	N	H	L
VAT photopolymerisation	Photopolymer							N		L	N			M	L	L	L				M	M	H	M
Sheet lamination	Hybrids	L	N	N		L		N			N		N		N	N	N		L		L	N	L	N
	Metallic	L	N	N		L						N	N					N			N			
	Ceramic																							
Other AM processes (emerging)		**Applications Unknown**																						

UK RESEARCH CAPACITY TO ADDRESS AM BARRIERS & CHALLENGES

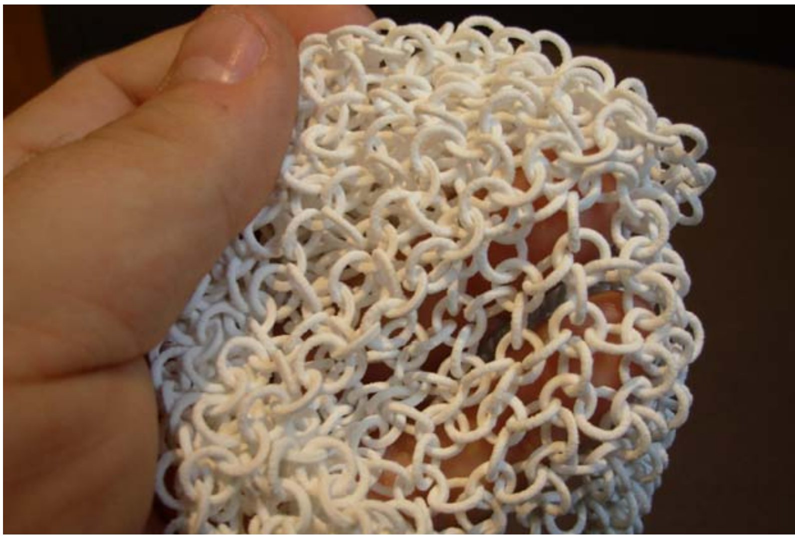
As we have seen, AM is both a cross sectoral technology and a multiplatform manufacturing approach. However, not all of the processes are suited to all applications and by correlating the potential and viable applications of AM against the UK research capacity and competence clear areas of strengths and weaknesses are revealed (Table 4).

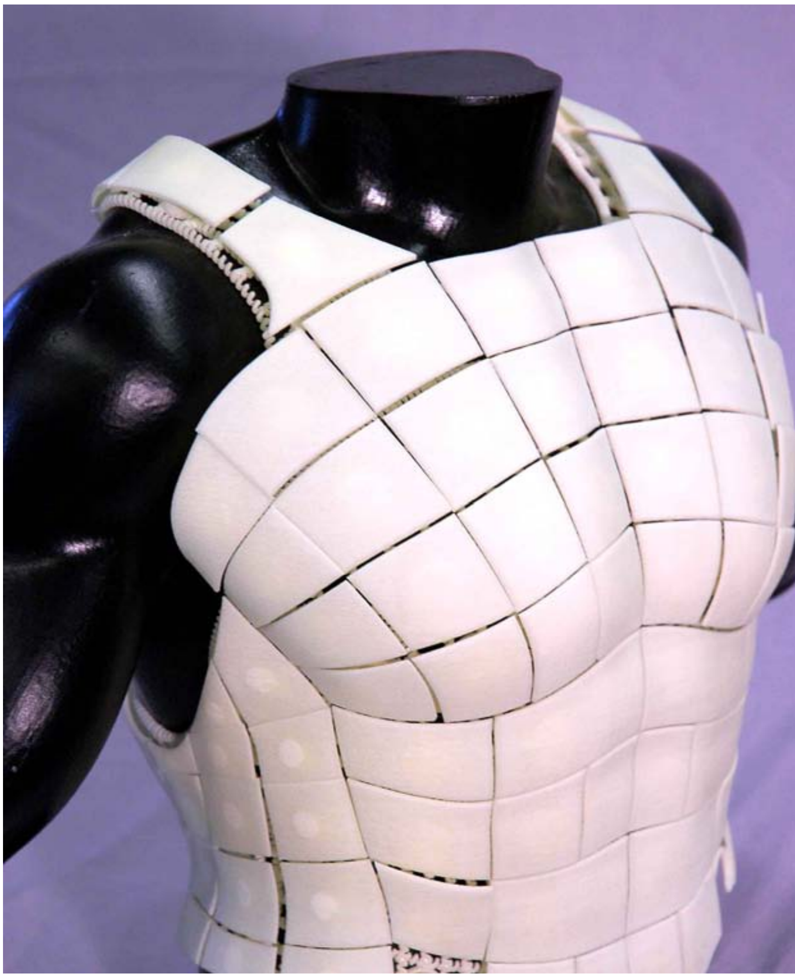
The UK has a strong research base focused on the following technologies and applications:

- Metal powder bed – aerospace airframe, aerospace power and medical applications, with some defence applications
- Polymer powder bed – medical (orthotics), consumer and creative industries, with some electronic packaging applications
- Metal powder feed – aerospace airframe, aerospace power and power generation (repair) with some defence applications
- Binder jetting into ceramics – some limited medical applications
- Metal filament (wire) feed – aerospace airframe and aerospace power
- Photopolymer (resin) VAT systems – creative industries, electronics and electronics packaging

Unlike other countries, detailed investigation of the UK AM research base suggests that there is a broad range of skills and experiences spanning the entire AM supply chain, rather than a singular focus on one aspect. AM research funding in the UK has to date been distributed evenly across the AM supply chain with between £14million and £18million of activity being undertaken in the fields of:

- process innovation; the development of new technology platforms
- process development; advancing the use of existing commercial platforms
- enabling technologies; the development of materials, software & energy sources
- process validation; relating to the commercial acceptance of existing platforms
- product validation, relating to the validation of discrete products made using AM technologies for specific applications





In summary, the UK holds a leading position in AM research, but activity is largely dominated by research capacity based on metallic powder bed and powder feed systems and to a lesser degree polymeric powder feed systems and photopolymer processes. The UK also has experience and capacity to both develop new AM processes and apply existing processes. However, the UK AM research community is highly fragmented with formal linkage and networks resulting solely from finite length funded projects. Many current projects will conclude in the next 12-months, resulting in the possible breakup of a leading global research community.

WHAT HAS BEEN DONE IN THE PAST TO ADDRESS THE TECHNOLOGY READINESS OF AM?

Additive manufacture with metallic powders has been the main focus of TSB supported projects with almost 80% (19 out of 24) of projects focused on this topic. These projects in turn concentrated on discrete applications with two processes; existing powder bed processing (68%; 13 out of 19) and blown powder processing (26%; 5 out of 19). This focus reflects the predominant interest in metallic powder applications, and powder bed and blown powder processing found by the industry needs analysis.

Of the other five projects, three projects focused on developing software tools and business methodologies, whilst one developed a new polymeric platform and one a new ceramic AM technology platform. A typical AM R&D project supported by the TSB advances the Technology Readiness Level by 2 points in 3 years. For example, completed metal powder projects have advanced the average TRL from 2 to 4, whilst those that are on-going (in mid-2012) are expected to advance from TRL 3 to TRL 5. This will be achieved at an average project cost of £1.1million.

A similar level of TRL progression is seen if the projects are divided between application sectors. Projects within the medical and aerospace sectors, which are both highly regulated, rank AM to be at the lowest TRL in terms of meeting their stringent needs, whereas projects in the niche automotive and creative industries suggest the technology is nearer to meeting their commercial needs. Interestingly, where a project has a mix of partners, for example including aerospace with other sectors, the overall perception of TRL is higher. It should also be noted that there is clear evidence of knowledge 'overspill' when sectors work closely together, such as the creative industries sector working in consort with the aerospace community.

Given that the AM SIG was not able to access commercially sensitive data, it must be acknowledged that there will be a certain element of TRL progression taking place 'behind closed doors' that have not been

Definition of the TSB accepted Technology Readiness Level scale

Technology Readiness Level (TRL)	1	2	3	4	5	6	7	8	9
Activity	Discovery & Research		Innovation					Commercialisation	
TRL Description	Basic principles observed and reported	Concept of application formulated	Experimental proof of concept	Concept or process validated in laboratory	System or component validated in relevant environment	System model or demonstrator in relevant environment	System prototyping demonstrator in an operational environment	Actual system completed and qualified test & demo operational environment	Actual system mission-proven in successful mission operation

taken into account during this assessment. It is also recognised by the SIG that, as technology matures through the TRL scale, so its commercial potential becomes clearer to the end user and the propensity to both disseminate knowledge and enter into collaborations decreases. It is widely felt that such a position exists within both the medical and aerospace user community, in effect distorting the true TRL and masking any approaching tipping point.

WHAT HAS BEEN THE FOCUS OF PAST ACTIVITY ?

Analysis of current and completed TSB funded AM research projects highlights resource efficient manufacturing, improving process throughput and part economics and improving manufacturing consistency leading to confidence in the design process as the primary focuses. Less emphasis has been placed on product customisation and supply chain efficiencies.

From the analysis of TSB funded innovation, it is clear that development activity is focused in the areas where barriers are perceived, namely process control and improving throughput, whilst using the technology for resource efficiency. However, it is also clear that significantly more innovation is needed to drive the technology readiness level up for specific high value applications, in the aerospace, medical and power sectors. Although much work has already been undertaken, much more is needed if the sector is to experience growth from a $1.9billion sector to a $100billion sector.

Table 5

Analysis of current and completed TSB funded AM innovation projects

	Drivers					Needs				
	Increased design freedom	Supply chain efficiency	Customisation	Resource efficiency	Reduced distortion	Economic processing	Consistent processing	Confident design and manf	Connected supply chains	
Projects	10	3	2	11	1	11	9	11	3	*Project Focus*
ALAMOS				■		■	■			50% cost reduction save £750k pa + environmental saving
DAMASCUS	■						■			Large structural parts
DIGITAL FORMING		■	■						■	3D software to allow consumers to decide on their products
DSOCAM		■		■				■		Using layout optimisation techniques
DWB								■		Bio ceramic implants
FFC -KTP				■		■		■		FCC processing of Ti
INTEGRATED WING							■	■		Landing gear using metallic powder
LASMI							■	■		Medical implants by metallic powder bed
LPE	■									Laser printing to deposit conductive or dielectric powders
PRISM	■									Integrated RFID
SLAMFUNC	■							■		Functionally graded parts using AM
SPACEPIPES							■	■		Al processing to make microfluidic structures
AIRSTREAM	■							■		Composite to metal joining with AM
ALSAM	■			■		■	■			Lightweight aluminium parts
ATKINS				■				■	■	Lifecycle analysis
AVLAM	■					■		■		Near term applications for ALM using Metallic Powder Bed
MAKIEWORLD		■	■						■	On line business to make dolls
RAPIDPART						■				Increasing the speed of powder bed process by 500%
RECLAIM				■	■	■	■			Laser cladding of turbine blades
SAMULET bae	■			■		■	■			EB metal powder processing for aerospace applications
SAVING	■			■		■		■		Lightweight and sustainable products
SCAMPER				■		■				Scaling of Laser metal deposition
SPRINT				■		■				Compact, faster and energy efficient lasering of polymers

CONCLUSIONS

The AM SIG findings have identified some clear strengths for the UK in the development and adoption of AM but there are several weaknesses that must be overcome, if the UK is to become a serious global player in AM. The opportunities for AM are large both for meeting UK internal needs and for exporting globally.

The potential disruptive nature of Additive Manufacturing is not in doubt, but the body of evidence gathered shows many strengths as well as weaknesses for the UK position in this area. The fact that other technologically advanced nations, such the USA and Germany, are investing heavily in developments and succeeding in commercial exploitation would suggest that the UK risks losing the advantages it has gained in some areas of research excellence.

The following summarises the Strengths, Weaknesses, Opportunities and Threats of the UK position and outline the next stages of the SIG's development.

AM HAS A BIG AND BRIGHT FUTURE, BUT IT'S STILL EARLY DAYS. WE NEED TO UNDERSTAND ITS CURRENT STATE OF MATURITY AND THE ASSOCIATED CONSTRAINTS/LIMITATIONS IN PRACTICAL USE

S.W.O.T ANALYSIS OF UK POSITION TO DRIVE FORWARD AM

STRENGTHS

- AM is seen as a strategic competence by the TSB, EU, ESPRC & DSTL, encouraging and supporting development from low TRL fundamental research leading to future innovations and potential exploitation;
- The UK has a broad and well established AM user community;
- The UK has a broad and well established AM research community;
- Elements of a potential supply chain do exist within the UK, even if they are not engaged today e.g. software, photonics, inkjet heads, optics etc;
- The UK has a world class design capability, which with the right education should be able to exploit the geometric benefits of AM for commercial leadership;
- The UK HVM report by TSB recognises AM as a competence for flexible manufacturing;
- The UK has strengths in process innovation for new AM technology and process validation;
- The UK is good at high value, low volume manufacturing;
- The UK has a broad science base able to develop new systems.

WEAKNESSES

- Limited (albeit inquisitive) number of industrial supporters;
- Lack of appreciation and understanding of benefits within generic businesses or sectors;
- The current supply chain is not fully engaged (missing links in optics, software, jetting etc);
- Limited machine tool building capability in the UK for high value machine tools;
- Cost of AM remains poor compared with other processes providing a disincentive to engage;
- No strategic direction to the commercialisation of AM in the UK;

- The supply chain is largely public sector funding dependent (with exceptions);
- Inability to turn process innovation into equipment offering;
- UK end-users are largely dependent on overseas technology;
- No open innovation culture in the sector;
- Conflicting end goals of the sectors and supply chain members.

OPPORTUNITIES

- Global marketplace for AM machines, software & material;
- Multi-sector applications leading to global leadership of UK AM manufactured products
- Multiple business drivers to technology adoption, based on potential production economics, geometric complexity, added functionality materials, resource efficiency and supply chain reconfigurations;
- Extensive eco-system for innovation including software tools, materials, machines, post processing and applications;
- Technology suited to flexible manufacturing and internet integration;
- Technology is of interest to private sector investors due to its current media coverage;
- Ability to influence inward investment with design freedom parts;
- Commoditising of manufacturing on a global basis.

THREATS

- Overseas ownership of core AM intellectual property may stifle the UK's ability to innovate and commercialise new processes;
- Significant levels of current applications research are centred on overseas technology, resulting in research knowledge being quickly exported to other global users;
- Other manufacturing processes such as powder metallurgy, nano technology and carbon composite manufacture may diminish the apparent benefits of AM over time;
- The lack of clear strategic vision may result in the AM community disbanding before any real commercial benefit can be achieved;
- Entry into the R&D market by other high technology countries such as Russia and South Korea may result in overseas technologies being more competitive and being commercially adopted before UK technology;
- Destabilisation of the Eurozone could make the UK an expensive location for R&D activity or an expensive source for machine tools.

DOES THE UK HAVE CLEAR LEADERSHIP IN ADDRESSING TECHNOLOGY INNOVATION NEEDS IN AM?

The UK has a world class AM research community, but it is not doing enough to either engage with the broader user community, or to drive innovation through to commercial exploitation within the UK technology supply chain.

The UK has the right end user companies to exploit AM, as it is a high value, high technology manufacturing economy. It is also a global leader in design thinking and applications, which are critical in driving the commercial success of AM.

The UK also has the fundamental building blocks to develop a robust AM supply chain from machine and materials manufacture through to design, simulation and modelling software tools.

However, with the exception of informal linkages resulting from funded projects, the sector is highly fragmented with no clear strategic direction or vision.

WHAT IS NEEDED TO FURTHER THE STATE-OF-THE-ART IN AM APPLICATIONS?

To help UK consolidate its current position in AM, open new markets and build a competitive advantage for the future, a number of strategic goals must be addressed, these include (in no particular order):

- Economic processing, without which mass market penetration is unlikely, no matter what downstream benefits AM can offer;
- Deposition rates between four and ten times faster than the current rate;
- Lower cost raw materials in a larger number of different varieties;
- Larger more flexible machine configurations, particularly for powder bed processing;
- In process closed loop control systems reducing process variance;
- Automated, lower cost, controlled post processing methodologies;
- Increase process and materials data to support designers & engineers;
- Training for designers in AM to maximise the benefit from the design freedom offered;
- Standards for qualifying AM approaches;
- Materials that are optimised for AM processes;
- Stronger and more durable AM polymers;
- More options to process in colour;
- Connected and synergistic supply chains to develop processes and applications for AM

WHAT ARE THE IMPLICATIONS OF DOING NOTHING?

It could be suggested that the UK AM research community and supply chain has received a significant investment in recent years, with little commercial exploitation to show. However, this would be a somewhat short sighted analysis. The UK has developed an internationally leading AM research community that has constantly driven up the Technology Readiness Level of machine tools not intended to be used for production applications. Through industry collaboration the TRL for some sectors has achieved the point of commercialisation, but for other sectors the known barriers still prevent wide scale adoption. The UK has seen a modest investment in AM, which has resulted in the UK being positioned as one of the world centres for AM research.

At this point if we were to do nothing further to support AM we would risk losing an enviable research base, with linkages to both an enabling supply chain and a credible applications market. It could be argued that it is not the UK's place to invest in developing applications using overseas technologies, as this will only give a short term commercial gain before technology development cascades overseas. However, if the UK were to learn from this knowledge and feed this back into its own indigenous supply chain, the UK could develop a competitive market position in the enabling AM supply chain of machines, materials and software tools.

CONSIDERATION FOR FUTURE ACTION

There are a number of actions that could be recommended to drive forward the UK AM research and commercialisation agenda. These will, of course, include investment in technologies to address the barriers related to costs, quality, limited range of materials and size of components. However, it is important to consider these against the need to define a clear implementation strategy for the UK, led by industry. The findings in this TINA show the UK has a world class research base but lacks that killer application that would lead to commercial exploitation on a global scale. Nevertheless, there are a number of strategic options available to the UK:

1. **Develop** new machine platforms based on the UK's excellent research capability in photonics and other energy sources, process control, materials science, ink jet technologies and software developments. This is a feasible option as the market for new platforms has already been created and the entry barriers are surmountable, owing to the current deficiencies in the capabilities of existing machine platforms. However, this option will require effective co-ordination of the supply chain and underpinning analytical, characterisation and modelling infrastructure. This is only viable if there is a clear pathway to commercial exploitation; a pull, rather than a push, strategy. This should target both export opportunities and UK-based applications.

2. **Consolidate** current UK research excellence and incentivise commercial exploitation of current successful prototypes and demonstration projects. This option will require an acceleration of development programmes along the TRL range beyond 6 for most sector applications, particularly the aerospace and medical sectors where stringent product qualifications are demanded. This is a viable option for small to medium sized components, particularly those demanding complex designs and/or are functionally driven. This option would benefit from the support of networking activities and public procurement programmes such as SBRI.

3. **Stimulate** the development and exploitation of new business models, arising out of the increased design freedom and democratisation of AM. This option will enable players such as the jewellery, games, toys and other creative industry sectors to actively exploit the opportunities provided by AM's ability to realise complex design freedoms and to manufacture locally or at home using 3D printers. The UK already has a range of developments that are fit to meet the requirements of the creative industries. This is a viable option requiring some degree of supply chain co-ordination between product designers, software developers and materials scientists to grow a sustainable competitive advantage for the UK.

Although these strategic options have been identified, the AM SIG recommends that, at this point, what the UK needs is a further structured engagement between the UK AM supply chain, end-users and the research base. It is necessary to engage with potential markets for products manufactured using AM. To help stimulate future dialogue we would suggest the following points be considered:

- Formalise industry networking by bringing together a recognised forum of AM developers and users to create and establish a network with a common voice and a common vision
- Promote learning between TSB supported projects to identify future quick win projects that solve real business problems
- Develop a UK implementation strategy for the AM technologies based on knowledge of current TRL's and commercial benefits
- Implement industrial policies to encourage and strengthen the growth of the AM supply chain companies
- An assessment led by industry of the potential UK and global market scales and opportunities for different AM technology platforms and materials across different sectors and applications.

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