Additive Manufacturing Aiming Towards Zero Waste & Efficient Production of High-Tech Metal Products

Reporting

Project Information

AMAZE

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Executive Summary:
The AMAZE Project, which stands for Additive Manufacturing Aiming Towards Zero Waste and Efficient Production of High-Tech Metal Parts was the largest and most ambitious metal additive manufacturing research project in Europe. Funded under FP7 with 26 partners in the field of Additive Manufacturing (AM), the project has the ambition to make the best quality metallurgical products ever made by using layer-upon-layer melt deposition of advanced alloys for the Aerospace, Space, Energy and Automotive sectors. The AM technology has great promise as a future production technique but at the project start this technology sector was not mature enough to be used broadly by industry.

There are a number of critical barriers which are hampering the adoption of additive manufacturing technology. These include:
- Limited range of proven materials and the associated mechanical property data.
- Lack of understanding of the opportunities and requirements of design for AM.
- Limited knowledge of the fundamental principles which underpin the AM process.
- Lack of industrial case studies which demonstrate the benefits and limitations of the process.
- Low productivity of AM metal processes and poor part quality.

The AMAZE project has addressed these and many other barriers to enable series production of high performance metallic parts to be undertaken.

AMAZE had the overriding key goal of “Building Confidence in Additive Manufacturing” for end user decision makers, both within the project consortium and wider EU industry.

The overall objectives of the AMAZE project were to:
- Rapidly produce large defect-free additively-manufactured metallic components up to two metres in size, ideally with close to zero waste.
- Achieve a tenfold increase in process productivity.
- Enable a 50% cost reduction for finished parts, compared to traditional processing.
- Improve dimensional accuracy by 25%.
- Reduce scrap rates to less than 5%.

Throughout the project 19 demonstrator components were selected and developed by the consortium through the various stages of the project to provide practical demonstrator parts against which the objectives could be quantified. Each of the objectives have been achieved with some variation for the four end user sectors and the five AM processes investigated.

The main achievements of AMAZE are numerous and could only be highlighted by the successful open forum event held at the end of the project, the presentations from which are available on the www.amazeproject.eu website.
Key results highlighted are: AM powder characterisation protocol, new software tools for adaptive machining and simulation of AM components, next generation AM machinery development, Norsk Titanium delivering the world’s first FAA-Approved, 3D-Printed Structural Titanium components to Boeing, Establishing the world’s first comprehensive design, process and material database for high quality AM production. The publication of over 51 papers and conference proceedings and a further 15 in preparation.

Project Context and Objectives:
The overarching goal of the AMAZE project is to Build Confidence in Additive Manufacturing.

Additive manufacturing (often referred to as 3D printing) was first introduced for the production of rapid prototypes almost 30 years ago. Unlike subtractive processes such as machining, where material is removed from a block to produce the required shape, or forming, where material is shaped in a mould, in additive manufacture parts are formed by the precise sequential deposition of layers of material.

This approach offers significant benefits over conventional manufacturing methods:
• Complex parts can be formed with relative ease, including high performance parts incorporating fine lattice structures.
• Highly efficient use of material compared to producing complex parts using conventional manufacturing processes, such as machining, which can waste more than 80% of the material.
• Parts can printed-on-demand without the need for tooling, giving unrivalled flexibility and allowing cost effective, low volume production, including one-off customised parts.
• Novel combinations of materials can be used which would be difficult, if not impossible, to process using conventional manufacturing methods.

Over the last 30 years numerous AM systems, all based on the fundamental principle of layer manufacturing, have been developed enabling a wide range of metallic, polymeric and even ceramic material to be processed.

AM has the potential to revolutionise the design and manufacturing of complex parts. However, despite the clear benefits, the use of additive manufacturing for the production of end-use parts is still relatively uncommon.

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• Lack of understanding of the opportunities and requirements of design for AM.
• Limited knowledge of the fundamental principles which underpin the AM process.
• Lack of industrial case studies which demonstrate the benefits and limitations of the process.
• Low productivity of AM metal processes and poor part quality.

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AM for metals is not a single processing technology but subdivided into five sub classifications based on raw material format (wire or powder) material feed approach (blown powder, powder bed and wire fed) and heat source to fuse the metal (laser or plasma).

Metal AM processes split into two main process types; (1) powder bed processes where a thin layers of metal powder are deposited and then selectively melted using a laser or electron beam and (2) Directed energy deposition processes where a wire filament or stream of powder is fed into the path of a laser, electron beam or electric arc to form the part using a bead of semi molten of metal. Each approach has merits and limitations which make it suited to a particular application.

All five main process were covered in the AMAZE project. The overall objective being common to each processing route.

AIMS and Objectives of the AMAZE Project

The overall objectives of the AMAZE project are to:
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- Achieve a tenfold increase in process productivity.
- Enable a 50% cost reduction for finished parts, compared to traditional processing.
- Improve dimensional accuracy by 25%.
- Reduce scrap rates to less than 5%.

To achieve these objectives an end-to-end approach has been used, which covers the entire process chain for AM parts through 10 key activities:

1. DESIGN FOR AM
To extract the full benefits of additive manufacturing, parts need to be designed for the process. Often conventional parts are limited by the cost or difficulty of machining them, or the limitations of tooling to form the shape. The flexibility of AM allows designers unique freedom of creativity, allowing clever high performance parts to be designed, which not only offer significant performance benefits but are also quicker and cheaper to produce.

2. MATERIAL MANAGEMENT
Controlling the quality of materials used in the AM process is critical to ensuring consistent process performance and the integrity of the parts produced. In the AMAZE project we have developed specifications for both powder and wire feedstock to optimise its performance in AM specific processes. We have also developed a robust approach to material handling, storage and testing to ensure that it consistently complies with this specification.

3. AM PROCESS DEVELOPMENT
A key role is to take metal AM from lab scale development and rapid prototyping into production capable equipment. This includes increasing the productivity of the process by a factor of ten. To address the
diverse needs of industrial end users, a range of metal AM processes have been developed including:

- Powder bed fusion machines where a high power laser or electron beam is used to selectively fuse a fine metallic powder to form the part.
- Directed energy deposition where powder or wire is fed into a melt pool formed using heat from a laser or electric arc to ‘draw’ each layer of the part using a bead of semi-molten metal.

Powder bed processes are ideally suited to the production of small complex parts whereas direct energy deposition is able to offer the capability of producing larger parts and also undertake repair of high value components.

4. PROCESS MONITORING
Modern manufacturing processes require monitoring of key process variables, which are used to control the process. The aim of AMAZE is to develop AM processes with closed-loop feedback to provide precise and timely control.

5. IN-PROCESS AND POST PROCESS NDT AND INSPECTION
Defect-free parts are required for high performance applications. AM is a complex multistage process which can, if not properly controlled, result in defects and the risk of catastrophic failure of parts in service. Non-destructive testing methods (such as ultrasonic and eddy current) have been developed to detect the type of defects produced by traditional manufacture process but AM presents a challenge in terms of the new defect shapes generated and a relatively rough surface finish which often hampers conventional NDT methods.

In the AMAZE project new NDT methods are being developed, including non-contact laser ultrasonic methods. This work includes the potential to use NDT methods in-process to find defects as they happen, enabling the AM process to be halted or rectification to take place.

6. PROCESS MODELLING
This is vital to improve our understanding of the AM process and enable further optimisation to take place. Within the AMAZE project both powder bed and direct energy deposition processes have been modelled and the simulations validated using experimental results. This work will form the foundation of the future AM industry.

The combination of process monitoring, in-process NDT and process modelling offer the potential to drive down the level of defective components produced by AM, thus improving productivity and also confidence in the process.

7. PART FINISHING
AM processes are currently unable to produce parts with the surface finish required by industry. Moreover, the complexity of AM part geometry makes finishing using conventional methods very difficult. To overcome this problem, within the AMAZE project a range of new finishing methods, including the use of laser polishing, has been developed and evaluated against end user requirements.

8. PROCESS AUTOMATION AND STREAMLINING PRODUCTION
Like other modern manufacturing processes it is important to apply automation methods to reduce the cost
and variability associated with manual production operations. In addition, within the AMAZE project lean manufacturing principles have been applied to AM for the first time. The new streamlined production process offers significantly improved productivity. This new approach has formed the basis of four new AM factories established in the project.

9. PRODUCTION AND TESTING OF INDUSTRIAL DEMONSTRATION PARTS
To overcome the lack of industrial case studies and also highlight the developments made in the AMAZE project, a portfolio of demonstration parts (known as APODs) covering all of the sectors represented by the end users in the project have been manufactured and evaluated.

10. SUPPORTING THE DEVELOPMENT OF STANDARDS
AMAZE is supporting the development of critical standards, which will underpin the introduction and exploitation of AM technology. This work includes the development of a suite of test artefact parts and NDT methods for AM, which form the basis of new international standards being developed under a joint ASTM/ISO activity, which will also feed into European standards.

11. EXPLORATORY RESEARCH, NOVEL DESIGNS AND PROPERTIES
Supporting the technical and commercial objectives is a whole work package covering the whole duration of the project and accounts for a quarter of the work. There are six main objectives to advance scientific understanding of Additive manufacturing:

• To reveal the critical scientific links between alloy composition, powder/wire production, additive processing, microstructural evolution and the final properties of metallic AM parts.
• To understand, control and reduce defect formation and fully ascertain the extent to which defects can be tolerated, so that final component rejection is less than 5% (typical rejection is 25-40% at present);
• To investigate the fundamental issues for achieving homogeneous melting, controllable melt-pool behaviour and grain refinement, with the use of adaptive systems and external stimuli.
• To link this information with models of microstructural and thermo-mechanical evolution during AM production;
• to conduct advanced materials characterisation (physical, chemical, mechanical) for the entire programme and to reveal the degree of scatter, homogeneity and anisotropy of data, especially for mechanical properties;
• To undertake exploratory investigations in the areas of eco-friendly alloy development, cellular structures (e.g. lattices/auxetics), novel metal matrix composites (MMCs) and other smart materials than cannot be conventionally made.

Project Results:
The project has been carefully structured to address all of the critical aspects required to develop a robust end-to-end AM process chain. Work packages in the AMAZE project:

• WP1 Design for Additive Manufacturing
• WP2 Materials Management
• WP3 Additive Manufacturing Process Development
• WP4 Automated Post-Processing: HIPping, Heat & Surface Treatment
• WP5 In-process and Post-process Inspection
• WP6 Multi-level Process Simulation
• WP7 Pilot-scale Additive Manufacturing Factories
• WP8 Demonstrator Part Manufacture and Test
• WP9 Design Process and Materials Database
• WP10 Exploratory Research, Novel Designs and Properties

Throughout the project, case study parts referred to as APODs were selected in WP1 and used to
demonstrate the AM materials, redesign, AM process improvements, post processing and AM objective
improvements. In total 19 APODs were identified and used as a method of evaluating the technology
developed in each of the individual work packages. There was no one WP for the APODs and so they
occur throughout all WPs.

WP1 Design for Additive Manufacturing

The goal of the WP1 was to capture all relevant industrial end-user requirements related to:
• prototype selection, material choice, target properties, cost, material availability, supply-chain, the
  volume of components required for 2016+,
• in-situ monitoring, NDT, metrology, inspection, standardisation and certification
• analysis of environmental benefits of AM components.

Based on end users requirements from AVIO, BAE, BOMBARDIER, CCFE, EADS, ESA, THALES and
VOLVO, 10 initial Case study parts know as APODs were selected. Over the next 3 years these were
expanded to a final 16 APODs which were used to validate the improvements achieved by material,
process control, design, post processing etc.

The APOD parts covered a matrix of all 4 end users sectors i) Space, ii) Aerospace, iii) Energy and

Another important output has been the end-users’ definition of design sub-elements for the various APOD
parts. As a result of detailed component analysis, it has been observed that there are less than ten
commonly occurring features in engineering parts. These features include, for example, walls, ribs,
corners, T-junctions, angled junctions, cruciforms, curved sections, single and double-sided deposits, with
and without chamfers. It was vital to test these geometric sub-features well within the AMAZE project, in
terms of their build quality as well as mechanical properties.

WP2 Development of Additive Manufacturing Powder Specifications

This WP had a number of objectives to build confidence in the powder and wire materials used for AM
throughout the project by:
• developing and demonstrating alternative feedstock production routes using advanced and
  environmentally clean processing, such as energy-efficient wire drawing, melt-less alloying or inert gas
atomisation

- to procure and provide very high-quality powder and wire feedstock (Ti, Fe, Al, Mg, Cu, Ni, Co and composites) to AM partners in WP3 and later to the 4 pilot-scale AM factories in WP7, including handling protocols,
- to capture feedstock specifications from end-users; and to develop and demonstrate automated quality assurance (QA) techniques that can rapidly assess feedstock compliance,
- to design a safe, optimised, automated and space-efficient system for feedstock material production that fits well within a modular factory layout.

One of the main results was tasked with completing a market assessment to identify European powder suppliers capable of producing the required alloy compositions.

Procured powders were submitted to the MTC’s advanced powder characterisation laboratory for analysis to fully quantify the differences between powders procured from various suppliers.

The analysis was based on:
(1) Bulk packing and flow behaviour;
(2) Particle size and morphology; and,
(3) Chemical composition.

To ensure equivalent testing conditions all samples were conditioned prior to testing, and testing was conducted in a relative humidity controlled environment.

Assessment of powders procured from various European powder suppliers has demonstrated that powder characteristics do vary from supplier to supplier, even when powders are atomised via the same method and supplied as ‘nominally’ the same grade.

The initial powder characterisation work was used to inform the development of powder specifications. All incoming powders, which are accepted for AM processing, have been quality assured against these specifications ensuring that a consistent raw powder feedstock is used throughout the programme.

The specific benefits of this work have been:

- Detailed understanding of the natural variation observed in powder batches procured from different suppliers.
- Supply chain solution, which identified suppliers consistently atomising in-specification powder, provided to customer.
- A benchmark powder specification ensures consistent quality of input powder used for AM process.

Figure 1 Comparison of SEM micrographs (200x magnification) for three powder batches procured from three separator powder suppliers. All powder batches have a chemical composition consistent with Grade 5 Titanium and nominal size distribution 15-45 microns.

Figure 2 Quantitative particle morphology assessment of powder batches from three suppliers; Black – Supplier (a), Red – Supplier (b), and Blue – Supplier (c).
In summary:
• AMAZE powder specification addresses the critical KPVs for AM powder. (a specification for wire feedstock was also generated).
• Down selection of powder suppliers based on adherence to the desired properties outlined in the specifications.
• All powder used in the project was checked for compliance with the specification (including reused powder)

WP3 Increasing the capability of AM processes

The development of higher performance additive manufacturing processes is central to the AMAZE project. The work undertaken encompasses a wide range of metal AM processes including powder bed fusion and directed energy deposition (DED) processes.

WP3 is a complex work-package covering a range of technologies and objectives. To make the management of the WP simpler, it has been sub-divided into five smaller, more focused sub-work packages.

WP3a Component Design. - Several approaches to design optimisation have been explored in the AMAZE project. These include free material optimisation (FMO) and design extraction using NURBS supersets, such as T-Splines; an automated optimisation process to allow for rapid design iterations and topology optimisation using custom tailored micro-lattice structures for combined activities. The most effective routes such as FMO and T-splines were then used to redesign some of the demonstration parts in the project. The use of lattice structures is still somewhat problematic in design and analysis due to the enormous size of digital data trace, thus limiting its application in an automatic fashion.

WP3b Powder Bed Processing – to significantly increase in build rate and achieve high density parts (>99.5%). A comprehensive programme of research has been performed covering all of the main metal AM processes.
Powder Bed Fusion Processing; This work includes increasing the build rate of laser powder bed fusion through the use of higher power and multiple lasers at Concept Laser and Renishaw. The development of an optimal adaptronic build chamber for the Electron Beam Melting process to improve build time and material utilisation. The development of more effective build strategies including novel hull and core approach developed at FhG-ILT and in-situ shelling at UoBirmingham which allow larger bulky parts to be processed more effectively.

This has been achieved through the development of an optimal adaptronic chamber for A2AA Electron Beam melting system b MTC and Manchester Uni. plus the further development of in-situ shelling parameters by U of Birmingham. Renishaw has investigated multiple laser melting systems to increase build rate and part performance.
WP3c, Blown Powder Processing – has looked at developing new processing conditions to reduce residual stress. Irepa laser has developed a new build up strategy using an adapted raster strategy. Fraunhofer ILT focused on reducing deformation and increasing build performance through nozzle design increasing deposition rate from 2kh/h to 5kg/h. Trumpf developed new high rate laser deposition heads including a novel scanning head for adding features to existing parts or for repair.

WP3d, Wire Feeding Processing – by Norsk Titanium achieved best practice guidelines and procedures for critical sub elements using Rapid Plasma Deposition. Whilst Tecnalia has deployed adaptive in process monitoring during AM builds and repairs, in order to control and correct defects and to demonstrate on-going compliance with end user specifications.

WP3e Use of Adaptronics, In-situ Sensing, In-situ Process Monitoring and Embedded Sensors. - Collaboration by UoB, Trumpf and BCT on a hybrid AM part using availability of a measuring system inside the LMD processing chamber, able to capture the geometry of the part build to improve dimensional build accuracy. UoB and BCT worked on the LMD process optimisation by adjusting several/relevant LMD parameters related to the result of the previous build process through algorithms to develop in process feedback adjustment software.

In summary

The project partners have focused on four key tasks;
1) increasing the build speed,
2) improving part quality to reduce defects,
3) increasing the size and complexity of parts which can be made and
4) widening the range of materials which can be processed to enable new industrial applications to be addressed.

Build speed improvements have largely focused on increasing the power and number of fusion sources used and the development of more effective build strategies, including radical approaches based on in-situ shelling where only the skin of the part is formed in the process with final consolidation to form a fully dense part being undertaken in a secondary heat treatment process.

This work has helped to increase the build rate tenfold providing deposition of more than 10 kg of material per hour for some processes.

Larger build envelop machines have been developed and tested in the AMAZE project to enable the production of large structural components, including the largest metal AM part at Cranfield University, manufactured using a high rate DED process. Improved build strategies have been developed to improve the mechanical properties of a wide range of high performance materials and also reduce risk of defect formation.

The productivity improvements are not limited to the AM build process, developments to streamline other
parts of the overall process chain will also be presented, including handling and testing of powder feedstock material.

These developments have provided the platforms for the development of the new AM factories and production of the industrial demonstrator parts presented in WP7.

Figure 4 Geometric plot of in-situ shelled canister. Courtesy of the University of Birmingham.
Figure 5 Laser + powder DED. Courtesy of Fraunhofer ILT.
Figure 6 Microstructure of hull and core build strategy in laser melting powder bed fusion. Courtesy of Fraunhofer ILT.

WP4 Automated Post-Processing: HIPping, Heat & Surface Treatment

The new AM technologies overcome technological restrictions of traditional manufacturing processes, offering a nearly unlimited design freedom, leading to efficient but complex geometry which can be difficult to finish. The consequences for the surface finish of AM parts means that they still required mechanical post-processing of the parts to meet end use requirements. This may be the whole surface finish or specific locations where connection is made to other surfaces. Therefore mechanical post processing have been examined, and sample fixtures have been realised to process a number of AMAZE parts and demonstrate various options available.

In the AMAZE project the post-processing group has collaborated on a range of topics. The MTC and BCT have worked on fixture design and adaptive machining. Fraunhofer ILT has investigated the use of a laser for novel finishing methods, including laser polishing at FhG ILT and innovate fixturing methods at MTC which enable complex AM parts to be held rigidly and accurately. The main objective of this work has been to develop automated post-processing and inspection steps as the surface finish achieved with AM is not suitable for final application. A range of post processing techniques including laser polishing, milling and grinding were compared. AM and HIPping was investigated to increase component build rates and throughput by a factor of 10. For post processing of AM parts that have some dimension variation, adaptive fixturing is required for conventional machining to be applied.

In addition to this, the benefit of including a measuring process in the process chain has been demonstrated. To improve the precision, the software developments now allow to adjust the best-fit method to the degree of freedom provided by the fixture.

Fraunhofer ILT’s work has been focused on a new surface treatment method using a laser. The impact on the microstructure as well as on the mechanical properties has been examined in depth. Specific process developments which concentrated on a dedicated technology module have led to an intelligent laser power adjustment enabling the use of this technology even on curved surfaces. These developments have led to a specific strategy consisting of two different runs and the corresponding parameter set for IN718.

Figure 7 Adaptive Fixture by the MTC, Thales Alenia sun sensor bracket.
Figure 8 BCT System concept – adaptive machining
Figure 9Fraunhofer ILT laser polishing of IN718 compared to Am as built part.

WP5 Adaptronics, in-situ sensors, NDT and metrology

The work on adaptronics, in-situ sensors, NDT and metrology covers a wide range of topics with the main focus of achieving closed-loop control in AM, so that (i) overall quality levels are improved, (ii) dimensional accuracy is increased by 25% and (iii) industrial scrap rates are reduced. By investigating and demonstrating new techniques for in-situ sensing (e.g. pyrometry, thermographic videography, piezoelectrics, electric signals etc) to gain real-time information about temperature and defect that can be fed back into the AM processes. There is also a requirement to make the critical links between in-situ information and ex-situ metallography, microstructural evolution, defects and properties.

The project successfully demonstrated in-situ sensors and adaptronics in the following processes:

- Wire + arc additive manufacturing (WAAM) DED process, from Tecnalia has been prepared to conduct in-situ monitoring, by means of several external sensors:
  - Camera: a Redman MCS 500 weld camera to view the wire melting process
  - Pyrometer: measuring the temperature of the deposited cord behind the arc
  - Laser scanner: scanning the deposited geometry cord by cord, offering the possibility of correcting the deposition strategy (height measurement)
  - Oxygen meter: measuring the O2 residual level to achieve a controlled atmosphere into the watertight chamber full of Argon

  Additionally to those signals of external devices, other internal signals of the machine are also monitored:
  - Plasma parameters (voltage and current): read by the machine from the plasma equipment
  - Machine axes positions (position measurement): duplicated from the machine encoders and registered by an FPGA

- The Rapid plasma deposition (wire + arc DED) process from from Norsk Titanium using interpass temperature measured ahead of the melt pool to control mechanical properties. Lowering the interpass temperature increasing the cooling rates and leads to a refined microstructure and high hardness which ultimately should translate to higher yield strengths of Ti-6Al-4V structural components made using wire-arc additive manufacturing.

- Laser + powder DED deposition from IREPA LASER using PRECITEC head to analyse the process stability during the process and to observe visual defects of the deposited material.

- Laser metal deposition (Laser + powder DED) from BCT/TRUMPF using laser line scanning technology to correct build positioning by Feed & Height adjustment based on the previous scan.

- Wire feed laser beam process (Laser+ wire DED) analysis from Airbus Group Innovations was carried out to assess post HIP treatment , the work showed that in micro-section for zx plane in polished and etched condition; almost perfectly dense material manufactured, only few pores of less than 10 µm were detected - these small imperfections have no influence on the material properties.
• Laser powder bed fusion (L-PBF) from Renishaw to focus on laser power study from 200W to 500W to decrease build time whilst maintain mechanical performance. A spectroscopy investigation into the optical emissions from the powder bed melting of grade 1 Titanium was undertaken. A correlation was shown between beam diameter on the powder surface and plasma electron temperature. Peak temperature corresponded to minimum beam diameter, and therefore maximum energy density. Work was also carried out using in-situ camera for the detection and handling of wiper damage; if wiper damage is present in one area of the build, stop building affected parts, reducing waste. Short dosing; if insufficient powder is introduced to the bed, re-dose before sintering to prevent defects occurring. It also allowed the monitoring of other visually discernible errors e.g. parts rising above the surface of powder bed.

Work on NDT and metrology, covered:
• X-ray CT limits of detection and demonstrator part metrology, metrology system comparison and laser ultrasound and non-linear acoustics highlights from the MTC, to provide reliable and rapid methods of assessing part integrity, including the potential to undertake inspection of parts as they are being built.
• Reference frame fixturing and phased array ultrasound inspection for (RPDTM) from Norsk Titanium.
• Applications of XCT/lattice structures from the University of Manchester.

Figure 10 Integration of different in-situ monitoring systems into the WAAM machine head.
Figure 11 Image from blown powder thermal camera.
Figure 12 LMD process and measuring head.
Figure 13 Integration of thermal camera in the IREPA blown powder system

WP6 Multi-level Process Simulation

WP6 looked at the developing sophisticated multi-level computer models capable of simulating and predicting AM processing, component properties, performance and life-time – including the optimised design of any support structures, and then validate the models against benchmark data coming from WP5 sensors. The ultimate goal is to integrate these different models into a commercial software package for AM quality prediction.

Modelling additive manufacturing processes is a complicated task because of the widely disparate length scales involved. The powder particles are a few microns in diameter but the heat source trajectory can be several hundred metres long. The spatial computational grid needs to span eight orders of magnitude in size differences. Also the time scale is challenging: whereas the heat source interacts with powder particles within micro seconds, the build time can be several hours or days.

ESI developed a complete suite of tools covering the multiphysics aspects of numerically predicting the quality of additively manufactured metals, the manufacturability and the characteristics of the final work piece (distortion and residual stresses).
Powder scale models resolve the heat source powder interaction, revealing details of the thermal cycles involved and how material consolidates to give dense material. The input to these models includes detailed analysis of how the feedstock is provided during the manufacturing process.

Figure 14 Powder bed supply interacting with coaxial laser in powder bed processes.
Figure 15 Surface roughness of molybdenum processed via powder bed fusion.
Figure 16 Component scale models resolve the large-scale processes providing insight on manufacturability and whether the final product will be conformal to the original design.

WP7 Pilot-scale Additive Manufacturing Factories

Additive manufacturing is emerging from the confines of single-unit batches towards higher volume production. To this end a key objective of the AMAZE project was to establish 4 modular, pilot-scale, industrial factories for the additive manufacturing and Tier-1 supply of metal components, for the first time in Europe and in the world. These factories would scale-up industrial AM techniques (from WP3) and demonstrate the capability of producing very high-quality components, up to ≈200cm in size, especially with unique designs that could not be produced using conventional methods. In addition there is a target to demonstrate the ability to produce 10 components within one working day.

Within the AMAZE Project, four European organisations, Irepa laser, Norsk Titanium, Avio Aero and the MTC demonstrated a production status, growing their operations and developing their processes to achieve a consistent discipline required to manufacture multiple identical components.

Four pilot scale factories have been established in the project over the project period with different AM process and material handling expertise.

- The factory operated by Avio Aero in Cameri, Italy carries the capacity to produce high quality aero-engine components from additive powder bed technologies.
- The operations at IREPA LASER in Strasbourg, France have the capacity to manufacture components from laser, blown powder CLAD® machines. The CLAD® process can manufacture functional parts ranging from a few millimetres up to one metre, repair worn or damaged components, and build functionality by adding features on existing parts.
- The MTC in Coventry, UK carries the unique capability of building AM pilot facilities using electron beam melting (EBM) physically and through simulation.
- Norsk Titanium in Hønefoss, Norway, can now deliver components fabricated by Rapid Plasma Deposition™ – a form of wire-plasma arc additive manufacturing – to major aircraft original equipment manufacturers. It operates 24h operation and has the capacity to produce 15 ton per year of components.

A key success of the project is the demonstration AM can dramatically reduce the number of assembly steps during component production and repair, and to achieve 50% cost reduction for finished parts, compared to conventional processing. Norsk titanium demonstrated 10 parts per day production within the project. The simulation work at the MTC provided factory requirements to achieve a 10 parts per day operation for APOD 2 brackets manufactured by EBM.
A key driver for each factory has been Waste elimination, to this end the four modular factories incorporate measures to reduce non-added value operation.

- Norsk Titanium: Closed deposition cell to eliminated filling time between builds.
- IREPA LASER: Dual powder feeder to eliminated powder refilling time and In-house substrate cutting.
- Avio Aero: In-house powder atomizer. Streamlined powder procurement to in-house quality control.
- MTC: Developing discrete simulation events for quick identification of bottleneck operations.

Figure 17 Four AM factory locations.
Figure 18 Norsk Titanium AM Machine Rapid plasma deposition
Figure 19 AMAZE APOD 12 ESA Cylinder Laser Blow Powder by Irepa Laser

WP8 Demonstrator Part Manufacture and Test

Building on the demonstrator parts made in earlier work packages and the end user specifications agreed at the start of the project, WP 8 covered the full industrial assessment. This covered:
- validate all specifications and procedures for process quality control, including in-process sensing and monitoring, destructive and non-destructive testing with the final objective of certifying the various AM processes;
- end-user rig-testing of AM demonstrators
- assess quality control standards by means of dimensional inspection, non-destructive testing (NDT), metallurgical examination of surface and bulk defects, dye penetration, X-ray and residual stress measurements.

To turn additive manufacturing into a mainstream industrial process (up to TRL7), with a complete EU-autonomous supply chain, of multi-sectoral benefit to energy, aerospace, road transport and tooling sectors.

For each of the final 13 APOD parts selected to be taken forward at the month 38 meeting, detained AM build, post processing an testing rig design and testing plans were agreed to evaluate each parts end user requirements.

Taking APOD 3 as just one example, the work required extensive cross collaboration between multiple partners. For his case study eleven of the project partners were involved over an 3 year period. Contributors were: Thales Alenia Space, Avio, Renishaw, Concept Laser, University of Birmingham, University of Manchester, ESI, ILL, MTC, ESA, and Granta.

The objectives for the Space Sun Sensor and Antenna Support (APOD 3) designed to go on satellites were three fold:

1. Assess the benefits of the technology with an industrial point of view (design, performance, cost, impact, ...)

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2. To build the same part but with different suppliers (machine, strategy, powder...) to evaluate common performances despite some defects
3. Demonstrating the ability of a laser powder bed fusion process solution to meet the space applications requirements for medium mechanical loads.

Observation satellites include some sensors and antenna supports traditionally manufactured by bulk machining and assembly. For Thales Alenia Space, AMAZE allowed then to assess the compliance of an additive manufactured solution to the requirements of a satellite application and to identify the industrial benefits.

The selected sensors and antenna support are usually made of three aluminium machined parts bonded together with some drawbacks (necessary tool for assembly, loss of electrical conductivity due to the bondings). A lightweight single block aluminium solution became possible by a combination of innovative topological design optimisation and laser powder bed fusion process manufacturing for complex shapes.

Starting with re-design steps (TAS) for AM, covering - Definition of the optimization volume (CAD) - Topological optimization (weight / frequency) with Nastran - CAD model creation based on topological result (CATIA IMA) - Design adaptation to laser powder bed fusion process manufacturing – and Mechanical analysis (Nastran). The final solution achieved a weight reduction of – 52% over the current components and also included a single block design completed to 3 part assemble of current part, additional of the connector support function on to the antenna support.

Parts were manufactured by three partners using AlSi10Mg on laser powder bed fusion, Renishaw, Concept laser and University of Birmingham with different processing conditions, laser power. These were all machined in key locations by MTC using adaptive clamping system.

Testing was carried out by Thales, Manchester Uni and ESA covering 9 separate property assessments, - Mechanical Static behaviour, Mechanical Dynamic behaviour, Microscopic observations, Cleanliness, Thermal cycling, Electrical conductivity, CT Scan, Coefficient of Thermal Expansion and Stress Corrosion Cracking.

The residual stress of the parts has been demonstrated to be very low.
Random and sine vibration test with 3 dummy masses + 3 accelerometers + gauges > qualification requirements = success
Specification > 140Hz / Sine ~30g / low level comparison OK
Low damping compare to traditional bonded solution 0,6% instead of 2%
Similar dynamic behaviour for 3 parts (#2, #3 and #4)

Electrical conductivity Resistance < 5W on each parts, Pass

Particular cleanliness – after US cleaning
Some particles but < 50µm
Obscuration rate < 100ppm – Requirement 1000µm ppm – Pass
Thermal cycling - 10 cycles [-60°C/+60°C]
Comparison control 3D (before and after thermal cycling) deviations have been noted on the legs (0,1 – 0,6mm)

Life Cycle Analysis
Comparison between Additive Manufacturing and conventional process
Additive Manufacturing more than halves the environmental impact, (powder manufacturing impact was not taken into account).

A benefit analysis was also performed on this application case and demonstrated that for this part the AM process is cost-efficient from four to five parts, compared to traditional manufacturing. This study succeeded in demonstrating the ability of an laser powder bed fusion process solution to meet the space application requirements for medium mechanical loads, despite a necessary change of aluminium alloy and some potential defects in the parts, inherent of the AM process. The adequacy of a well-defined design strategy and laser powder bed fusion process complex shapes capacity lead to a viable industrial solution that Thales Alenia Space now applies for flight applications.

The APOD case study parts have allowed the project to demonstrate validation of the end user requirements for each of the 5 AM processes across the 4 end user sectors.

In summary:
For Space,
The APOD 3 Sun Sensor support from Thales has given Thales the confidence that L-PBF solution to meet the space application requirements for medium mechanical loads.

APOD 15 the Invar Space part lead by EADS in collaboration with Swansea University, University of Birmingham, Thales Alenia Space, has focused on Additive Manufacturing of Invar36 by powder bed laser fusion (PBLF) with the development of a Stable powder bed fusion process for Invar36 on different platforms and investigation of material properties and build of demonstrators.

Invar is an iron/nickel alloy with low thermal expansion that makes it ideal for space applications, which require a high thermal stability. Conventional manufacturing of Invar is time consuming, expensive and only offers a very limited design freedom. One area of work within AMAZE focuses on the possibility of manufacturing Invar36 additively by use of L-PBF. Therefore, a parameter set consisting of powder, laser and scan strategy needs to be investigated. AMAZE partners: the University of Birmingham, Swansea University and Airbus were able to develop a stable process for selective laser melting of Invar36. Different post heat treatments were tested according to the requirements of Airbus and Thales Alenia Space. Characterisation of the additive manufactured Invar36 material was undertaken to establish its mechanical and physical properties.

Generally an interesting round-robin exercise showing that complex parts can be successfully built. However, the trial also highlighted the importance of powder quality on final part properties, but poor powder quality and insufficient quantities (morphology/PSD) have contributed to difficult builds and less than optimal properties. UTS/Yield meet original specifications – Elasticity/elongation sometimes met
depending on tests. The measured CTE for as built parts was generally close to the required level but it was observed that heat treatment of parts increased the CTE.

Static strength and elongation properties are in the range of bulk material. The young’s modulus is significantly lower because of insufficient powder material, whereas the thermal expansion is in an expected and highly appreciated low range. Two possible applications in aerospace were identified by Thales Alenia Space and Airbus. The University of Birmingham and Swansea University were able to finalise this work by manufacturing the demonstrators.

For Aerospace:
APOD 2 Nacelle Hinge bracket for Bombardier Aerostructures in collaboration with Airbus Group, BAE Systems, BCT GmBH, The Manufacturing Technology Centre, and Renishaw, has demonstrated post heat treatment does not significantly affect the dimensional stability of AM parts. Final testing on mechanical performance of heat treatments and to directly compare the mechanical performance of laser powder bed fusion and electron beam powder bed fusion technologies through testing of a design optimised component is expected shortly.

APOD 7 AVIOAERO Shroud has demonstrated the build of honeycomb structures in CoCrMo7 with high precision.

For Energy:
APOD 14 Fusion Divertor Block for CCFE with collaboration with University of Birmingham, Cranfield University, University of Erlangen and Swansea University. The key objective being to demonstrate the commercial viability of AM for the building of components suitable for fusion energy, looking at - Facility build time and cost, Cost of electricity generation, Reliability, maintainability, safety.

For Plasma facing AM components they must: Survive high heat loads, Maintain their structural integrity, Offer resistance to neutron irradiation, Provide minimal impurities to the fusion plasma.

CCFE have investigated the feasibility and benefits of using both powder and wire-based AM techniques to manufacture a PFC concept prototype, demonstrating the feasibility of AM with refractory metals. High heat flux testing on the unique HIVE facility, built at CCFE under AMAZE, has highlighted the potential benefits of these techniques including novel cooling geometries, functional graded joints, and in-situ repair.

Comparative high heat flux testing has been carried out on conventionally produced and additively manufactured copper divertor prototype elements. The later included an electron beam melted copper substructure brazed to a tungsten armour tile and connected to conventional drawn copper pipes. Temperature measurements taken using thermocouples embedded in both samples show a higher maximum temperature for the same incident heat flux. Supporting finite element analysis suggests that this is due to a combination of increased heat transfer coefficient (~20%) and reduced thermal conductivity (0.5 x parent properties) of the additive manufactured copper. The former may be attributed to the increased surface roughness inherent in the AM process, while the latter – to be verified by pending material testing – may be due to impurities in the AM material. With further development it is expected that this deficiency
can be overcome.

For Automotive:
APOD 13 Volvo Truck suspension spring in collaboration with Cranfield Uni has been redesign for AM and key features were created with WAAM in steel. Problems controlling welding conditions to get defect free intersections was not possible with current WAAM technology at this time. However redesign has shown weigh saving over forged parts can be made.

Figure 20 Plan for Thales – Sun sensor APOD
Figure 21 Final Design achievement for sun sensor – Thales Alenia space.
Figure 22 Non-destructive testing by neutron diffraction (ILL)

WP9 Design Process and Materials Database

One of the key objectives of the project has been to establish a comprehensive “AMAZE Design/Process/Materials Database” for high-quality AM production, in order to halve the design process and dramatically expand the use of different AM processes and materials.

The establishment of the Database schema was completed by Granta in the first half of the project and has steadily been populated by all partners since this time. The data base contains material powder characterisation to specification for a number of European powder suppliers. Mechanical test data from key build features identified in WP1, for a range of materials and processes. This is the most comprehensive materials/property database for AM in the world, with data on 778 parts and is still being added to with the APOD cases study parts. The data base is Searchable by Test/apOD Programmes, partner contributions, technical performance REACh, ROHS, Critical Materials, Eco.

Another key objective has been to draw on environmental, cost and socio-economic data, collected in WP1-8, and provide the means to assess the impacts and benefits of AM design/production throughout the entire EU industrial supply chain. With a target to lower the consumption of power, consumables (moulds, dies, tools, peripherals), raw materials and machining chip production by 50%, cf. conventional processing, and to substantiate this in a peer-reviewed Life Cycle Analysis (LCA).

Cost across the entire life cycle must be considered, as shown in the example of the Sun Sensor mount which realizes fuel savings during service due to the reduction in weight for €20,000 per launch. In addition the Thales Sun Sensor mount produced by Renishaw, produced cost estimates that do have the potential to reach ~50%, supporting this objective.

Conclusions from LCA work on Additive Manufacturing has shown that emissions and gross energy requirements from AM are smaller than machining for buy-to-fly ratios as low as 2:1, even when considering relatively high gas usage and support structure volumes.

In-service emissions dwarf the manufacturing emissions based primarily on weight reduction opportunities. Calculating in-service emissions is difficult enough for standard technologies (e.g. casting) so predicting
AM technology penetration into applications such as structural and aeroengine components is pure guesswork depending on many factors such as the re-usability of powder and acceptability of longer term fatigue strength data.

WP10 Exploratory Research, Novel Designs and Properties

WP10 covered 5 main topic areas through inter collaboration between partners:

- Modelling weld Pool Dynamics (ESIG, SWAN)
- Microstructural Control & Thermo-Mechanics (ESAE, CRAN, POLI, MANC, SWAN)
- Mechanical and Physical Property Assessment (EPFL, POLI, EADS, THAL, SWAN)
- Eco-Friendly Alloy Development (POLI, BIRM, EADS)
- Lightweight Lattices, Auxetic Structures, Shape Memory Alloys and Metal Matrix Composites (POLI, ERLA, BIRM, THAL, MANC, EPFL, SWAN)

MODELLING OF POWDER BED LASER FUSION WITH MEASURED MATERIAL PROPERTIES (ESI, Swansea University)

The generation of accurate and effective computation models is essential to provide the foundation of continued process and material development.

In AMAZE Swansea University and ESI collaborated to develop micro, macro and meso scale models for a range of metal AM processes laser - powder bed fusion (L-PBF), wire and powder DED processes.

Work at Swansea University concentrated primarily on modelling the L-PBF process. This has been accompanied with builds on a Renishaw AM250 and thermo-physical and mechanical property measurements of powders and processed material. The modelling has been done across multiple length scales, and capturing multiple levels of physics.

Commercial codes such as ANSYS FLUENT have been used, as well as new codes developed to simulate the melting of powders and solidification at the scale of the powder particles using 3D lattice-Boltzmann with free surfaces, discrete simulations of the powder deposition and 3D finite difference models based on the level of the hatch pattern with multiple layers, and more recently incorporating conduction/keyhole mode transition with a simplified ray tracing routine.

The work showed the fundamental aspects which could be addressed by modelling, such as whether keyholing is a concern in L-PBF when compared to other instabilities, such as Rayleigh-Plateau effects or to what extent do thermal and packing properties of the powder actually affect the quality of melt tracks. The results of this work have helped to answer the key question can simulation be used to predict process maps for any material and any machine, and how can this be verified?.

Figure 34

- Microstructural Control & Thermo-Mechanics (CRAN, THAL, POLI, MANC)

MICROSTRUCTURAL CONTROL OF TI AND AL ALLOYS AND LARGE-SCALE DEPOSITION OF REFRACTORIES (Cranfield University)
Cranfield University was able to alleviate residual stress and microstructural anisotropy (a common problem in high rate DED AM processes) in Ti-6Al-4V samples produced by WAAM, by adding a cold-working step in between layers. Cold-work was applied in a number of ways, including top and side surface rolling. Moreover, this approach resulted in mechanical properties that were better than conventional wrought alloy (proof strength = 980 MPa, ultimate strength = 1100 MPa, elongation = 13%). However, top rolling was not as effective as side rolling in reducing residual stress (measured using neutron diffraction and contour methods) and corresponding distortion.

In aluminium deposits (2024, 2319 alloys) rolling proved extremely effective in eliminating porosity, which did not appear, even after the solution and artificial ageing heat treatment. For these alloys, in-process cold-work also improved the strength. The addition of the T6 temper, on samples that were either cold-worked or not, produced properties that were also better than the equivalent wrought alloy.

Finally, Cranfield University successfully deposited large structures in tungsten, tantalum and molybdenum. For the first two, the density achieved was close to 100%. Further work is continuing to characterise the mechanical and thermal properties of samples. A graded structure between W and Mo was also created over a length of 4 mm. Work is ongoing to reduce the gradient to the 1 mm target.

Figure 23 Tungsten deposit.
Figure 24 In-process cold-worked titanium

LASER POWDER BED FUSION OF ALUMINIUM BASED MATERIALS (Politecnico di Torino)

In addition to work undertaken at Politecnico di Torino to characterise the interaction between laser heat sources and conventional aluminium alloys work was also undertaken to develop new high strength aluminium materials for Laser powder bed fusion.

Firstly, the feasibility of the production of aluminium matrix composites by laser powder bed fusion (L-PBF) was investigated.

A specific alloy that takes advantage from the fast cooling that arises during the laser scanning was selected. It was also observed that the laser scanning and the phenomena that arise in the melt pool result in an almost homogenous composition even when realising the alloy in-situ. Finally, the effect of a post-processing heat treatment on the microstructure on the mechanical properties of L-PBF aluminium samples was analysed.

For both composites and alloys, the laser-powder interaction and the consolidation phenomena were studied and compared by means of single scan tracks analyses which proved to be a promising approach to rapidly assess the behaviour of a specific material during the L-PBF process.
IN OPERANDO STUDY OF LASER-POWDER INTERACTION BY SYNCHROTRON X-RAY IMAGING (University of Manchester).

Powder consolidation phenomena govern the microstructure, properties and performance of parts produced by L-PBF. Their underlying mechanisms remain unclear due to the short laser-powder interaction times and complex molten pool behaviour. To provide an insight, trials were undertaken by Manchester University into the sequential thermophysical phenomena during the evolution of single layer and dual-layer melt tracks using a custom-built in-situ laser based additive manufacturing (LAM) device with high-speed synchrotron X-ray radiography.

The results revealed that dramatic changes in the molten pool, pores and spatters during the L-PBF process, including the vital model that Marangoni-driven flow plays in controlling the final melt track morphologies, as well as the evolution mechanisms of pores and spatters. This work also revealed a pore dispersion phenomenon during dual-layer L-PBF. Our results provide new insights into complex molten flow behaviour that are key ingredients for the development of the next generation metallurgical theories and simulation models which in turn will lead to improved machinery, materials and build strategies.

MICROSTRUCTURE AND MECHANICAL PROPERTIES OF ADDITIVELY MANUFACTURED METALLIC STRUCTURES (EPFL, POLI, EADS, THAL, SWAN)

The mechanical properties of additively manufactured TiAl6V4 are found to vary significantly depending on the AM process used. While tensile properties are essentially controlled by the cooling rate, which can vary significantly with the process, fatigue properties are strongly affected by the quantity and location of internal and surface defects (i.e. porosity and surface roughness). In general, defect-free AM parts exhibits tensile and fatigue properties at the upper end of conventionally produced TiAl6V4, cf. Figure. 28. However, Lack-of-fusion and spherical pores induced by overheating can be present which significantly reduce fatigue resistance, with the stronger influence exerted by a lack of fusion defects. Both defect types have a weaker, yet at times noticeable, influence on tensile properties.

Apart from the potential presence of porosity, the microstructure is characterised by elongated grains in the build direction and periodic microstructural inhomogeneity at the length scale of the melt pool size. While the former leads to some degree of anisotropy in mechanical properties, the latter leads to inhomogeneity in hardness and strain distribution during a tensile test, a fact that was quantified by digital image correlation (DIC), cf. Figure. 29. Subsequent β-anneal heat treatment and rapid cooling (≈1 °C/s) eliminates this microstructural inhomogeneity and leads to a more homogeneous strain distribution, yet leads also to slightly reduced yield stress and tensile strength while strain to rupture does not change significantly.
LASER POWDER BED FUSION OF LOW CTE ALLOYS (AIRB, THAL, SWAN, BIRM)

In the AMAZE project the University of Birmingham have investigated L-PBF of both Invar36 and AlSix. Both these materials have a low coefficient of thermal expansion (CTE) which makes them attractive to the space industry partners (Thales Alenia Space and Airbus) to provide dimensionally stable structures for parts subjected large temperature variations within in-orbit structures.

It was found that Invar36 could be successfully processed by L-PBF although to give the required CTE however processing parameters, including subsequent heat treatment were found to be critical. These trials also highlighted the importance of powder quality in generating acceptable AM parts. The parameters developed were used to produce demonstration components for Airbus and Thales.

The second approach studied focused on the blending of a standard Al-10Si-0.3Mg alloy and pure silicon powders to generate a material which has tailored properties including CTE. Microstructural investigations were been carried out which revealed how the silicon particles break down in the melt pool and bulk CTE testing has revealed good correlation between the experimental results and theoretical predictions.

SELECTIVE ELECTRON BEAM MELTING OF AUXETIC LATTICE STRUCTURES AND PURE COPPER (University of Erlangen)

In the AMAZE project, the Friedrich-Alexander University Erlangen-Nuremberg has been focused on two main subjects relating to the Selective Electron Beam Melting (SEBM) – the generic term coined for the Arcam EBM process. The first one aims at the development, of new fully auxetic lattice structures with a negative Poisson’s ratio. The mechanical and damping properties of these structures were measured and the underlining mechanisms analysed.

The second topic deals with the process development of pure copper and oxide dispersion strengthened copper powder. Pure copper is of particular interest because of its excellent electrical and thermal behaviour. SEBM offers the potential to produce complex, dense, parts with high thermal/electrical conductivity.

The results show the dependency between process parameters and the sample density, including the sample characterisation as thermal and electrical conductivity and the mechanical properties in terms of hardness and tensile tests. Furthermore, the powder ageing and the influence of the powder quality on the process and the sample properties were also assessed.
LASER POWDER BED FUSION OF REFRACTORY METALS (University of Birmingham)

The feasibility of producing net shape components directly from pure refractory metals has been investigated – these high temperature material are of particular interest for the production of components for nuclear fusion reactors.

Parametric studies have examined the relationship between process parameters and defect (porosity and crack) formation in pure tungsten, molybdenum, and vanadium. Optical microscopy and SEM examination of samples was used to assess the nature of these defects. Additionally the effect of powder (spherical and faceted) morphology on the formation of defects was studied.

Demonstration geometries have been produced to highlight the potential of this manufacturing process in components showing complex geometries. Additionally, test samples have been produced to support the CCFE prototype armour tile development for use in the HIVE facility and to establish baseline thermal and mechanical properties. Finally, several experimental methods to attach molybdenum (Mo) to tungsten (W) have been investigated in an effort to eliminate the need for subsequent brazing operations.

Summary of Technical Achievements

AMAZE is the most comprehensive metals AM projects ever undertaken. The scope of the data collected encompasses design data, feed-stock characteristics, AM processing parameters, heat treatment conditions, part finishing parameters, NDT and geometrical information, based around standard benchmark test artefact as well as industry demonstrators, and mechanical properties (static and cyclic loading) from a comprehensive test campaign, as well as witness sample built contemporaneously with the demonstration parts. This information is supported with the results of micro, macro and mesio scale multiphysics modelling.

This activity has been conducted over across all of the major direct fusion metal AM processes (Laser and electron beam PBF, powder and wire DED), using technology from a range of European suppliers and a suite of materials which address the needs of the key end-use applications, as illustrated by the demonstration parts (aPODS made in the project).

1. Feed stock specifications (wire and powder) have been developed specifically for AM, together with robust test protocols – this information will help Europe to develop a robust supply chain for AM feed-stock which is an essential precursor for successful commercialisation of metal AM.

2. Software tools have been developed which enable rapid and reliable design of parts to exploit the full
benefits of AM processes. Using topological optimisation has been used to redesign aPod demonstrators, such as the Thales sun sensor, yielding a 52% weight reduction which saves over €20,000 fuel saving for each satellite launched.

3. Enhanced metal AM processes and build strategies have been developed which have enabled build times to be reduced by a factor of ten. This work includes highpower, multi laser powder bed machines developed by Renishaw and Concept laser which have enabled a dramatic (5 fold) reduction in the fusing time for aluminium parts up to xxx. Integrated powder handling will help to reduce the risk of powder contamination and automated sample assessment methods developed by Renishaw have dramatically reduced parameter development lead-time for new materials. The technical feasibility and commercial/environmental benefits of adaptronic build chambers, tailored to the component size have been demonstrated in EBM machines - including a 79% and 50% reduction in material and preheat time respectively. New build strategies for laser powder bed fusion (hull/core and in-situ shelling) developed at FhG-ILT and university of Birmingham have been shown to increase productivity for larger bulky parts by more than 680%. ILT have increased the build rate for IN718 using laser+powder DED by 500% enabling more that 10kg/hr to be deposited, although a slight drop in mechanical properties was recorded. IREP A have improved both laser+powder DED hardware and process parameters to enable large, high integrity parts to be produced (aPOD9a - 1m length, 35kg of Ti6Al4V, 120h processing time). Trumpf has developed two new laser processing heads which allow deposition rates of over 600cm3/h to be achieved. Developments made at Cranfield on the WAAM (wire+arc) DED process have enabled the World’s largest AM (6m long) part to be produced.

4. Improved AM materials have been developed which exploit the benefits of the process and offer higher performance allowing AM to address new, more demanding applications. This includes novel aluminium alloys as well as composites and refractories which have never been processed before.

5. New flexible fixturing and finishing methods have been developed and tested in AMAZE which will enable the efficient and consistent post processing of complex AM parts. This work includes design and processing guidelines for laser polishing of IN718 yielding reduce surface roughness without manual finishing. To support this work improved adaptive CAM software (OpenARMS software from BCT) was developed.

6. New in-process monitoring methods have been developed to capture KPVs (key process variables) during part manufacture. This invaluable information is used to diagnose problems and introduce process improvements. The potential sources, as well as nature, of defects in AM parts has been studied and this information has enabled improved NDT methods to be developed and deployed. The combination of KPV monitoring and part quality assessment has already helped to understand the impact of processing conditions on ultimate part quality. This information will help to reduce defect formation and fully understand the extent to which defects can be tolerated, so that final component rejection is less than 5% (typical rejection is 25-40% at present) can be achieved.

7. Improved process models have been developed which will provide essential tools for future process and material development as well as improving part design and machine set-up to reduce the likelihood of
8. The developments made in the project have been used to design and manufacture demonstration parts which offer improved performance, lower weight, lower part count and significant cost reduction (up to 50% in some cases). Long term durability testing of the aPOD parts will continue well beyond the duration of the AMAZE project however, promising initial results have significantly boosted confidence in the AM process, leading to commercialisation, including demanding space and aerospace applications. The information from the demonstration parts has also helped to validate the meso scale process models. The manufacture of aPOD parts has helped to demonstrate that metal AM processes are becoming more reliable, although long term monitoring is required before it is possible to show than the down time has been reduced to the 5% target.

9. Four European AM Factories at Irepa laser (France), Norsk Titanium (Norway), Avio Aero (Italy) and the MTC (UK) have been established to enable the AM production to be demonstrated and showcase the developments made in the AMAZE project. The factories have been configured to provide a safe, optimised, automated and space-efficient (50% reduction in floor space) production environment. The process chains used in the factories have been streamlined through the use of Gemba Kaizen waste management principles and a highly disciplined production orientated approach has been established which is an essential step to gain industry confidence and achieve process qualification/certification. Indeed, Norsk Titanium have recently announced the delivery of the World’s first FAA-Approved, 3D-Printed Structural Titanium component. The ability to produce more than 10 components per day as been demonstrated.

10. Work in the AMAZE project has formed the basis of new standards development including a new benchmarking process based on a “suite” of test artefacts to assess: geometrical accuracy, surface finish, resolution, density, microstructure and productivity - ASTM-F42/ISO-TC 261 Joint Group 52 and standards for NDT of AM parts being developed in the - ASTM-F42/ISO-TC 261 Joint Group 59

Potential Impact:
Impact of AMAZE ....

AMAZE is the most ambitious metal additive manufacturing research project ever undertaken. The higher productivity AM processes, higher performance materials, process monitoring and modelling methods, finishing and inspection techniques, as well as improved understanding of the fundamentals of the processes has strengthened Europe’s lead in metal AM and will provide a robust platform for future developments. The impact of the AMAZE project will not only be seen in academic knowledge but also in commercial AM hardware/software and new applications.

Although Additive manufacturing is still seen as a promising manufacturing method for some application and is not yet accepted as a main stream manufacturing process by the Space, Aerospace, Automotive or Energy sectors. A key objective of the project has been to tackle current issues to drive it from TRL 4-5 to
The AMAZE project has successfully achieved its key aim of “Building Confidence in Additive Manufacturing” as clearly demonstrated by the top 4 key highlights:

- Norsk Titanium through development of their Rapid Plasma Deposition (RPD) technology have increased process robustness, consistency and machine throughput. Leading to delivery of the world’s first FAA-Approved, 3D-Printed Structural Titanium component for Boeing.

- Over the course of the project Thales Alenia Space have gained knowledge and confidence in the metal AM processes to enable them to successfully deploy metal AM components (sun sensor brackets) on satellites which are now in orbit.

- Generation of the World’s most comprehensive metal AM database covering every aspect of metal AM from design, feed-stock quality, AM process parameters, post processing and inspection to provide an unparalleled resource for both research and exploitation of AM.

- Four European AM factories at Irepalaser (France), Norsk Titanium (Norway), Avio Aero (Italy) and the MTC (UK) provide a unique network of industry credible pilot-lines covering all of the major direct fusion metal AM processes.

Dissemination activities:
There have been some very positive developments in the way that AMAZE has presented itself to the outside world. Because non-confidential dissemination is an important part of R&D, the team has carried out some important actions to ‘spread the word’ about AMAZE.

In the first 3 years of the project ESA was the project coordinator and organised a successful media based project launch. This include:

a) Creation of a project website, targeting the online community;
b) Project launch via TV media and press at the British science museum
c) Technical lectures, targeting the academic and industrial community;
d) Public lecture at schools, targeting young children studying science at ESA;

Throughout the project Keynote lectures at conferences, targeting international aerospace executives and engineers; have been carried out by ESA, ESI, Swansea University, University of Birmingham, Erlangen University, FHG-ILT, The MTC, University of Manchester, Tecnalia, United Kingdom Atomic Energy Authority, Politecnico Di Torino and BCT.

e) Successful exhibition at the London Science Museum, targeting scientifically-interested members of the
general public (this has now been extended to Manchester’s Science Museum in M18);
f) Special AMAZE articles in trade magazines;
g) Engagement with ASTM, ISO and CEN standards bodies, in the realm of standards development and dissemination,
h) Development of an AMAZE Prize for Young Researchers;

At the start of 2016 the coordination of the AMAZE project transferred from ESA to the MTC, and the MTC took over responsibility for project coordination including dissemination activities.

During 2016, the MTC made representation of the AMAZE project at:
• Visit by Commissioner Carlos Moedas to Industrial Technologies Directorate 14th March 2016.
• Impact of the Factories of the Future PPP 14-15th April 2016 (Brussels).
• International Cooperation Additive Manufacturing Cluster 2nd May 2016 (Barcelona).
• FoFAM Experts meeting 26th May 2016 (Brussels).
• Euroscience Open Forum (ESOF) 23-27th July 2016 (Manchester).
• Nordic Powder Metallurgy conference Jernkontoret, Stockholm 17th November.

The culmination of Tear 3’s PR campaign was the press release from Norsk Titanium, highlighting the value of the project.

See: www.norsktitanium.no/amaze

In late 2016 the original Amaze project web site set up by ESA closed. A new web site was launched on www.amazeproject.eu. This also allowed the MTC to rebrand the project logo and create the strap line “Building Confidence in Additive Manufacturing”.

As the project was reaching a successful conclusion the level of public dissemination increased to allow the results of the project to be shared, this included a public open forum event and an introductory video explaining the structure and purpose of the Amaze project was created with work package leaders, which is available on Youtube and the project web site.

AMAZE Open Forum, the MTC – 7th June 2017

The AMAZE Open Forum workshop was hosted at the AMTC on the 7th June 2017. Over 175 people registered for the event from over 80 organisations. Interest was such that visitor included representation from South Africa (Prof Dimitri Domitrov, Stellenbosch University) and USA (Dr Anil Sachdev and Dr Tyson Brown, General Motors).

 Following an introductory presentation on the aim and objectives of the project parallel sessions were held with an industrial and academic focus.
The industrial sessions targeted decision makers, and AM part production, covering results from the project by taking the audience through the manufacturing process steps from
This was followed up in the afternoon by a case study session focused on sharing the experience gained from taking four of the industrial demonstration parts through design, manufacture and testing in the AMAZE project.

In Parallel with these sessions 10 presentations from Exploratory research, Novel design & properties session were given by the University partners within the project.

There was a single final session to conclude the event covering the key achievements of the AMAZE project and a future vision.

Through-out the day, company presentations and case study part display was held in the exhibition space showing parts from space, Aerospace, Automotive and Energy sectors.

To support the event a booklet summarizing the AMAZE project was designed and 500 copies printed (250 have already been given away). The booklet provides an overview of the aims & objectives of the project, introduces the partners. Provides a summary of the work undertaken and the major achievements and concludes with a list of the follow-on EU projects and impact of the project.

A suite of videos were produced to support dissemination, including videos of all of the presentations given at the Open Forum event and interviews with attendees. The AMAZE website has been populated with new information including the presentation given at the Open Forum event.

Exploitation of results:

The AMAZE Exploitable Plan was broken down into 7 themes based on different interest groups: 1, Academic Researchers, 2 AM feedstock, Hardware & Software providers, 3, Pilot scale AM Factories, 4, End-Users, 5 Policy Makers, 6 Standard Bodies, 7 Society.

Many of these themes contributed to activities carried out during the 4.5 years of the project and have already seen significant benefits to the AMAZE partners and European AM sector.

At the end of the project all partners were asked to list exploitable results they have identified, together with the activities carried out during the project.

These activities included - PhDs granted, numerous academic papers, improved AM techniques, new alloys and material structures, novel scientific data and “materials mapping for AM”, predictive computer models and software, promotion of multi-disciplinarily in materials science, new ideas for spin-off projects, educational content for students, joint patents and co-invention, new “Research Roadmap” pointing to new areas and challenges in AM and metallurgy.

Over the period of 4.5 years 17 PhD students worked on the project as part of their studies, and the work has contributed to over 60 published technical papers and presentations by the Academic partners. Further Articles are still planned beyond the completion of the project and this is estimated at a further 30+ technical papers and presentations over the next 2 years.


AM Feedstock;
AVIO have established a powder production capability as part of the integrated AM factory. Through an iterative approach, with AVIO generating batches of powder and MTC assessing its quality against the feed-stock specification developed in the project, the quality of powder produced has steadily improved and now comfortably meets the quality requirements. This gas atomising facility has the capability to produce more powder than AVIO requires for its own use and is supplying powder to external customers.

A wider review of the powder supply chain across Europe was also conducted by the MTC in WP2 and the feedback provided to the suppliers has enabled them to understand the requirements of the AM sector and tune their manufacturing processes to meet them.

In this way one important legacy from the AMAZE project is the strengthening of Europe’s feed-stock supply chain. The feed-stock specification and the test protocols developed in the AMAZE project will be embodied in the material test standards currently in development. As a result of the project MTC has strengthened its position leading the characterisation of AM feed-stock in Europe which has helping to secure additional research and industry consultation in this area.

AM Hardware;
Renishaw have developed higher power and multi laser powder bed machines which will have a direct input future products. Moreover, a new semi-automated method of developing optimised process parameters has been developed which is 15 times faster and yet provides a higher quality and quality of data. This has been used to develop new processing parameters for AlSi10Mg which have given a 5 fold
reduction in build time. These developments coupled with the case studies generated from the aPODS will help Renishaw secure additional sales.

Concept Laser has developed optimised processing parameters for several materials including AlSi10Mg which is key material for the range of large metal AM powder bed machines (Xline 1000R and 2000R). In addition an integrated powder recovery system was developed and tested in the AMAZE project which will be commercialised in the next 2 years.

FhG ILT and University of Birmingham have developed new build strategies (hull-core and in-situ shelling) which can dramatically reduce the time to build large bulky parts. Work to perfect these build strategies is continuing and the results will feed into the commercial domain over the next 2-5 years.

Tecnalia have developed in-process monitoring methods, including meltpool temperature and the geometry of deposited material – this information can be used for process improvement and control, as well as forming an integral part of the QA procedure for parts. They intend to commercialise these developments within the next 2 years.

Trumpf Laser and Systemtechnik intend to exploit the developments made in laser+powder DED processing over the next two years; including new techniques to measure the position of substrates to enable precise placement of deposited material which is particularly important for repair applications. In addition, Trumpf also developed two new high rate DED heads (6kw line optics system as well as a scanning optics system for rapid deposition on to large areas, including nonplanar substrates (patent application WO 2017025148 A1).

University of Birmingham has undertaken research on new materials development in the AMAZE project including laser powder bed processing of low CTE (invar and AlSix) material which has been successfully used to build space demonstration parts. Work on and the processing of refractory materials has shown significant promise although further work is being undertaken (CCFC funded PhD) to perfect the process which could be used to produce critical parts for nuclear fusion reactors.

Cranfield University has developed an enhanced WAAM (wire+arc DED) cell with higher deposition rates (10kg/hr) and large part capacity - this has been used to produce parts upto 6m in length and will provide a key resource for both research and industrial evaluation of high rate DED processing going forward. Moreover, Cranfield University has recently formed a spin-out venture to offer the WAAM process commercially.

AM Software
ESI have improved their background AM tools for AM simulation using actual part build to verify their new models, They are working on Integration of AM modelling tools into a unified platform, with a prototype currently under review and will integrating these development into their current suit of tools within the next year.
BCT who specialise in adaptive CAM software solutions have identified several exploitable results, arising directly from their participation and collaboration in the amaze project.

1. Improved functionality of “best-fit” and other alignment methods as part of BCT’s software suit for all AM sectors. New functionality to adjust NC programs/processes to the individual position of parts. Restrictions presented by part fixtures can now also be considered. The developments will be directly be used within BCT’s software framework OpenARMS and it is planned to offer the functionality within a specialised software package in 2018.

2. Improvement of the alignment function to enable the remaining amount of stock to be readily checked to ensure that there is sufficient material for subsequent finishing operations. The function has been tested and will be integrated into BCT’s OpenARMS software framework after some further improvements. Function will also part of a separate software package in 2018.

3. Improved integration and functionality of laser line scanners has been developed and incorporated into BCT’s Software. Laser line scanning is now available as one module of BCT’s software application OpenARMS. Different sensor types are also supported.

4. Improved height control for DED processes has been developed based on using the the result of previous scans, by capturing the as-is geometry after adding a number of layers. Basic developments have been made within AMAZE, but more development effort is required to be able to offer the solution to customers. The first version will be ready mid to end 2018. Further improvement to the algorithms are being undertaken in collaboration with Birmingham University.

Post processing & Inspection

FhG Institute of Laser Technology (Fhg-ILT) has identified a number of areas where is can commercially exploit he results from the AMAZE project. In addition to the development of process strategies and parameters for high power laser powder bed and DED AM processing of IN718, Fhg-ILT has developed a novel laser polishing method which was used to process some of the demonstration parts in the AMAZE project. Research is ongoing to enable exploitation of this approach within the next 2-5 years. Applicable sectors are Aerospace, Tooling, Mechanical Engineering, Automotive, Turbomachinery through their current industrial support offerings.

MTC, supported by other partners in WP5, has studied the nature of defects in AM parts and used this information to develop improved NDT methods. These include rapid, low cost methods of checking part integrity using resonant frequency testing as well as X-ray CT methods which enable the precise size and location of defects to be found. This work has fed directly into the development of new standards.
Pilot-scale AM factories (involving Norsk Titanium, Avio, Irepa laser and the MTC).

Complete metallic AM supply chain developed in EU, through the establishment of 4 AM factory locations at AVIO, Norsk Titanium, Irepa Laser and the MTC capable of producing up to 10 parts a day,

Norsk Titanium has developed the Rapid Plasma Deposition (RPD) process – a form of wire+arc DED – through the project including the development of the new RPD Merke IV machines which have been installed into the new integrated AM factory. This work has culminated in the launch of the world’s first FAA-Approved, 3D-Printed structural titanium component for Boeing. The developments at Norsk Titanium are being exploited already.

IREPA have developed the enhanced Magic LF6000 laser+powder DED machine with increased power (500w fibre laser and 2kw diode laser) and improved accuracy. During the project the Macro clad 24Vx nozzle was developed with improved cooling to enable longer continuous operating times at high power. As well as perfecting processing parameters for large Ti64 space structures Irepa Laser has also developed a new aluminium powder (Product name CL32) for automotive applications and prototyping. All of the developments made in the AMAZE project can be exploited immediately.

Avio have developed the world’s first fully integrated AM factory, including powder production, under one roof. The knowledge and capability they have gained from the AMAZE project includes; I, Development and introduction of powder production technology. ii, Powder production process parameters , iii, AM innovations and alloys and iv, Higher throughputs and process efficiencies. All these developments are for the Aviation sector and already in place.

MTC has established a centre for additive manufacturing based around electron beam technology. The facility includes a powder characterisation lab which was used to test all of the powder used in the project as well as part inspection including advanced NDT methods. This facility has now been expanded to incorporate a suite of laser powder bed machines, DED and hybrid metal AM techniques as well as polymeric and ceramics AM technology. The centre is equipped with the largest range of AM technology under one roof in Europe. This world leading capability was recognised by ESA who selected the MTC as their Space AM benchmarking centre.

End-Use Applications (partners, involving Thales Alenia Space, Avio, Airbus, ESA, Bombardier, BAE Systems, Volvo and CCFE), covering the four main sectors of Space, Aerospace, Automotive and Nuclear Fusion Energy.

Key requirements to build confidence in AM technology for these sectors has been:
- Scaling-up AM from small to large 2m components
Nuclear Fusion;
The Culham Centre for Fusion Energy (CCFE) in the UK has recognised the potential of AM to produce parts for the nuclear fusion reactors. The primary focus for CCFE in the AMAZE project has been the development and testing of heat resistant and high conductivity materials. To support this work CCFE established the HIVE facility through the AMAZE project to enable high heat flux testing of components. This facility includes a high pressure and temperature (up to 200°C, 20 bar); closed loop water system (45 kW ~100 kHz); induction heating system, and custom control and instrumentation system connected to a custom UHV vacuum vessel into which test samples can be mounted. The parts produced in the AMAZE project have encouraged CCFE to pursue this work further including trials involving the Universities of Oxford, Leeds and Imperial College London in the areas of high temperature coatings, CFD validation and nanofluids. Plans are also in place for use with European Fusion sector for testing tiles, particularly applicable to the energy and aerospace sectors.

Aerospace:
Airbus: a global leader in aerospace, defence and related services including the aircraft manufacture Airbus sited Powder Bed Fusion Process of Invar36 as a key exploitable result particularly for Space Parts where thermal stability is needed. Further collaboration with University of Swansea and University of Birmingham is planned to commercially exploit this knowledge.

Space:
Thales Alenia Space have gained important information on design for AM, as well as material and mechanical test results from the AMAZE project. The work on aluminium powder bed processing which culminated in the production of the Thales satellite sun sensor bracket, represents the main exploitable result for Thales. In addition to technical performance data, LCA (Life Cycle Analysis), undertaken by Swansea University, and economic information, which showed a potential saving of €20,000, was also generated. This information has been critical to enable Thales to gain sufficient confidence to use AM to successfully produce parts deployed in commercial satellites which are now in orbit.

Other key exploitable results identified are:

Granta Design, specialists in materials engineering software, developed the structure (schema) for the AMAZE database which encompasses every aspect of metal AM from design, feed-stock quality, AM process parameters, post processing and inspection. The schema for the data base will be commercially exploited by Granta. In addition the AMAZE database has been populated with over 800 pieces of AM
data to provide an unparalleled resource for both research and exploitation of AM. The AMAZE consortium
have agreed to continue to share the test data for the next two years to give the project partners an
advantage over competitor companies. In the long term the consortium will also decide how to manage
wider access to the database for organisations outside of the AMAZE project.

List of Websites:
Public website address www.amazeproject.eu
Project coordinator
David Wimpenny
Chief Technologist
Component Manufacturing
MTC
Home of the National Centre for Net Shape & Additive Manufacturing
Tel: +44 (0)2476 701644
Mobile (preferred): +44 (0)7748591189
Email: david.wimpenny@the-mtc.org
http://www.the-mtc.org/

Related documents

final1-final-report-main-s-and-t-results-sestion-figures.pdf

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