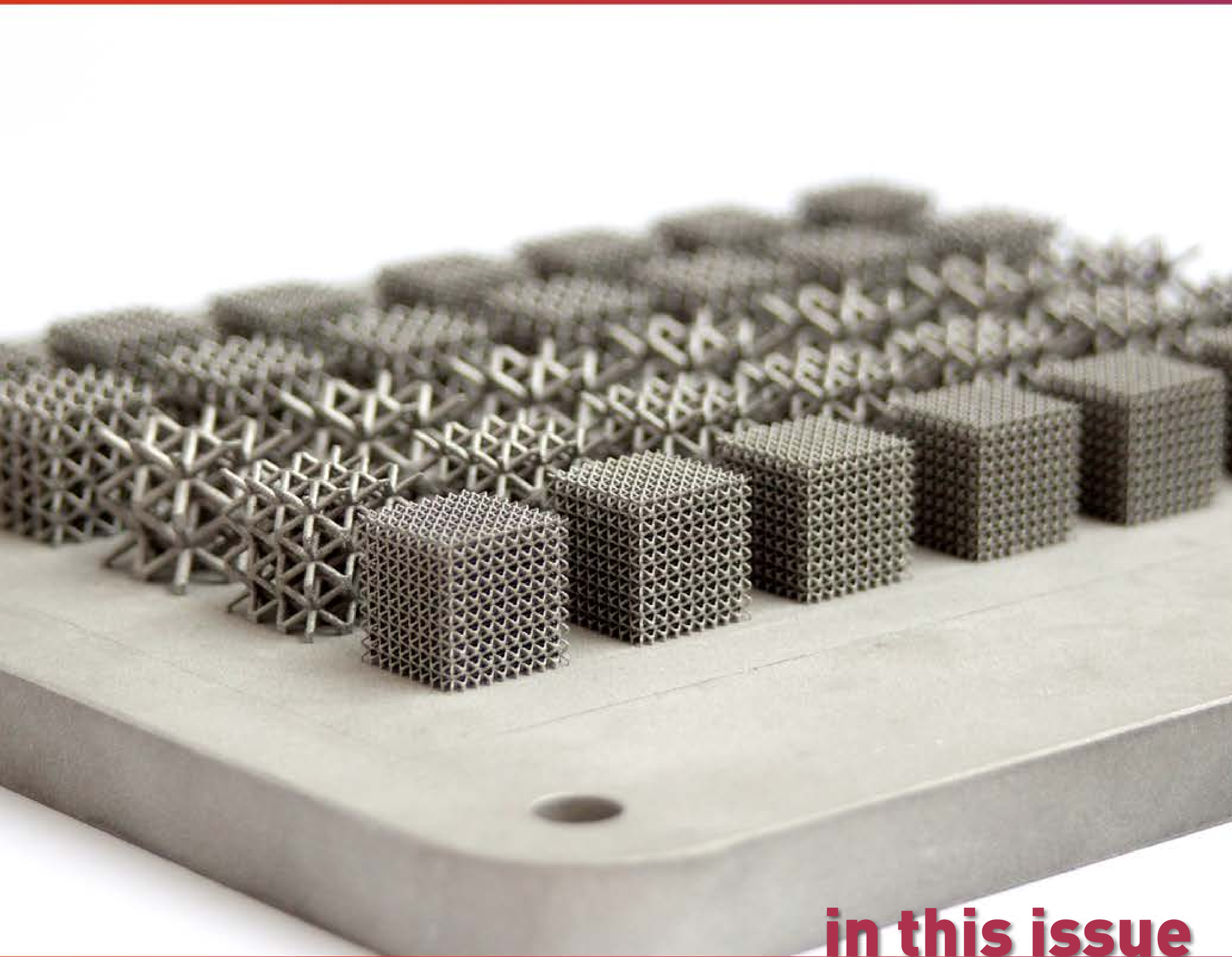
Vol. 2 No. 1 SPRING 2016

THE MAGAZINE FOR THE METAL ADDITIVE MANUFACTURING INDUSTRY

METAL AM



in this issue

PRODUCTION PLANNING IN AM

COMPANY VISIT: RENISHAW

HANDLING TITANIUM POWDERS

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METAL
ADDITIVE
MANUFACTURING

Additive Manufacturing: An industry and a community

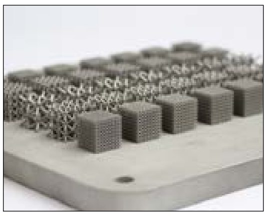
Writing this editorial it's hard to believe that this is only the second year of *Metal AM* magazine. Our first year exceeded all our expectations and this was directly as a result of the enthusiastic support and encouragement that we received from those in the industry. As a publishing company long focused on the processing of metal powders into finished components, we have tracked the rise of metal Additive Manufacturing for a number of years. Today, we are both excited and privileged to have been so warmly welcomed into this community.

For an industry that is relatively young, AM already has a number of unique and highly respected institutions. One such institution is the Additive Manufacturing Users Group (AMUG), whose annual conference takes place in St Louis, Missouri, USA, from April 3-7. Over a thousand people are expected to attend and *Metal AM* magazine will be there for the first time. We are thrilled to be able to attend an event that is held in such high regard by so many in the industry.

Looking further ahead, this issue of *Metal AM* magazine will also be distributed at a number of other important international events including Hannover Messe, Rapid 2016, PM China 2016 and AMPM2016, the Additive Manufacturing with Powder Metallurgy conference. The latter, co-located with the long running annual POWDERMET conference and exhibition, is establishing itself as a key conference for the presentation of the latest technical papers relating to the powder-based metal AM technologies.

The *Metal AM* team hopes to see you in 2016!

Nick Williams
Managing Director



Cover image
Lattice test structures built on Renishaw AM250 metal AM system at The University of Nottingham, as part of the Aluminium Lightweight Structures via Additive Manufacturing (ALSAM) project (Image Renishaw plc)

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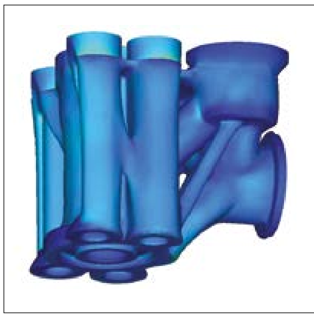

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39 Planning, preparing and producing: Walking the tightrope between additive and subtractive manufacturing

Delcam's Kelvin Hamilton explores the current possibilities for design, topology optimisation, simulation, process planning and process preparation in metal AM. Exploring the three Ps, Plan, Prepare and Produce, all the processes involved in transforming three airbrake bracket designs into final products are revealed.

59 Renishaw: Global Solutions Centres offer end-users an alternative route to develop new metal AM applications

This year the UK's Renishaw plc will further expand its global network of Solutions Centres for metal AM. The centres are designed specifically to provide a secure environment for end-users to trial the company's metal powder bed fusion technology and establish the viability of a project before committing to major capital investments. We report on a recent visit to Renishaw's flagship Solutions Centre in Stone, Staffordshire.

67 Titanium powder pyrophoricity, passivation and handling for safe production and processing

As AM moves out of the prototyping space and into production facilities with multiple machines, the importance of handling and processing powders, particularly titanium, becomes ever more relevant. Dr Andrew Heidloff and Dr Joel Rieken, from Praxair Surface Technologies, Inc., review best practice when handling and storing titanium powders for AM. Titanium powder can be safely produced, processed, stored and shipped using appropriate precautions, however under certain conditions it can become quite hazardous.

73 Process and quality control for AM: Sigma Labs PrintRite3D® methodology for overall quality assurance

Despite the outstanding promise of metal AM technologies, inconsistent quality, process reliability and speed are currently holding back industry growth and impacting on the cost-effectiveness of new applications. In the following article Sigma Labs' Dr Vivek R Dave and Mark J Cola review the technical challenges that are faced in enabling metal AM to reach its full potential and the systems that are currently available to address a number of critical issues.

81 Metal AM in Finland: VTT optimises industrial valve block for Additive Manufacturing

VTT, based in Espoo, Finland, is one of Europe's largest research and technology centres with a long track record in metal powder processing technologies. The centre's Erin Komi reviews the development of an AM valve block for demanding industrial applications. The project looked at the optimisation of the valve block in terms of size reduction, weight saving and performance gains..

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industry news

Sciaky introduces innovative closed-loop process control for its Electron Beam Additive Manufacturing systems

Sciaky, Inc., a subsidiary of Phillips Service Industries, Inc. based in Chicago, Illinois, USA, has announced it has introduced a patented closed-loop control system for its Electron Beam Additive Manufacturing (EBAM) systems. The Interlayer Real-time Imaging and Sensing System (IRISS) provides consistent process control for part geometry, mechanical properties, microstructure and metal chemistry for large-scale AM parts.

This innovative closed-loop control, which is claimed to be exclusive to Sciaky EBAM systems, monitors the metal deposition process in real time and makes adjustments to the process parameters that compensate for variation throughout the build process.

Sciaky's EBAM systems utilise wire feedstock which is available in a variety of metals such as titanium, tantalum, niobium, tungsten, molybdenum, Inconel, aluminium, stainless steels, nickel alloys and more. Sciaky can produce parts ranging from 203 mm to 5.79 metres in length.

EBAM is currently the fastest deposition process in the metal Additive Manufacturing market, with gross deposition rates ranging from 3.18 to 9.07 kg of metal per hour. The process also allows the use of a dual wire-feed option, where it combines two different metal alloys into a single melt pool to create custom alloy parts or ingots. In addition, users can change the mixture ratio of the two materials to create graded parts or structures.

"Sciaky's IRISS closed-loop control is in a class by itself," stated Mike Riesen, General Manager of Sciaky, Inc. "It is a big reason why EBAM is the most advanced metal Additive Manufacturing processes in the market for large-scale parts."

www.sciaky.com

Sciaky has introduced a closed-loop control system for its Electron Beam Additive Manufacturing systems

Airbus APWorks purchases first MetalFAB1 system

Airbus APWorks, a 100% subsidiary of the Airbus Group, has placed an order with Additive Industries for its first industrial metal AM system, MetalFAB1. Airbus APWorks is the first confirmed Beta customer for Additive Industries and brings a broad range of experience with metal Additive Manufacturing.

"We are proud to team up with Airbus as our first customer to further develop the process, new materials and applications as well as verifying the performance of the MetalFAB1 system. Their commitment emphasises the potential of our new metal Additive Manufacturing system for industrial series production of functional parts," stated Daan Kersten, co-founder and CEO of Additive Industries.

"With the integrated MetalFAB1 solution, we believe we are able to simultaneously improve the product consistency and lower the cost price for metal Additive Manufacturing," added Joachim Zettler, Managing Director of Airbus APWorks.

www.additiveindustries.com

Hoeganaes Corporation announces AS9100C Certification

Hoeganaes Corporation, Cinnaminson, New Jersey, USA, has achieved AS9100C Quality Management System certification for its Innovation Center facility in Cinnaminson. The AS9100C Quality Management System provides the basic quality framework necessary to address both civil and military aviation and aerospace needs.

This enhancement to Hoeganaes's quality systems follows a multimillion-dollar investment in 2015 for the commercialisation of advanced powders for AM. The production, design and distribution of its AncorTi™ range of gas atomised titanium powders are now certified under the scope of this rigorous aerospace quality standard. "The attainment of AS9100C certification further demonstrates our long term commitment to delivering high performance powders for AM to world class customers operating in aerospace markets," stated Mike Marucci, Global VP, Advanced Technology. Hoeganaes continues to be certified under the ISO/TS 16949 for automotive quality management, ISO 14001 environmental management and OHSAS 18001 safety management systems.

www.hoeganaes.com

Optomec partners with Dragonfly to expand Italian Additive Manufacturing market

Optomec, a global supplier of production grade metal Additive Manufacturing systems based in Albuquerque, New Mexico, USA, has announced it signed a distribution agreement with Dragonfly to expand sales of its products into Italy.

Optomec LENS printers use the energy from a high-power laser to build up structures one layer at a time directly from powdered metals. The LENS process can completely build new metal parts or add material to existing metal components for repair and hybrid manufacturing applications. LENS technology is available in standalone system configurations or as a modular print engine for integration with existing CNC automation platforms and robots.

"We are very excited about our partnership with Dragonfly to expand sales of Optomec products in Italy," stated Michael Kardos, Optomec Vice President of World Wide Sales. "Dragonfly is solely focused on the Additive Manufacturing sector and a perfect fit for introducing innovative products such as our LENS and Aerosol Jet systems to an untapped marketplace in Italy. Their consultative approach and experienced team will help ensure a successful customer base."

www.optomec.com

XJet secures $25 million investment

XJet, based in Rehovot, Israel, has secured a further $25 million investment in its nanoparticle metal Additive Manufacturing technology from private equity fund Catalyst CEL and design software company Autodesk through its Spark Investment Fund. XJet's technology is claimed to bring new levels of detail to the production of metal parts. The company's patented NanoParticle Jetting™ technology makes use of solid metal nanoparticles within a liquid suspension. The system's print heads deposit an ultra-fine layer of these liquid droplets onto the system build-tray.

Inside the system's build envelope, extremely high temperatures cause the liquid 'jacket' around the metal nanoparticles to evaporate. This results in strong binding of the metal with what is stated to be virtually the same metallurgy as traditionally-made metal parts. In addition, the metal part needs to undergo a sintering process, with the supports removed simply and with almost no manual intervention.

The current round of funding will be used to complete the development of XJet products and launch them into main international markets.

www.xjet3d.com

AP&C adds new atomisers and plans to triple capacity

Arcam AB, Sweden, has announced that its metal powder manufacturing subsidiary AP&C in Montreal, Canada, is significantly expanding its capacity with the commissioning of three new plasma atomisers. It was stated that the investment follows a surge in demand for AP&C's titanium powders and, when completed, production capacity will reach at least 500 tons per year.

"With this investment we are committing to supply our present and future customers with superior quality materials to meet the high manufacturing standards of the biomedical and aerospace industries. With the new reactors and atomising technology advancements, AP&C will triple production capacity in 2016," stated Alain Dupont, President of AP&C.

Plasma atomisation produces spherical powders of reactive and high melting point materials such as titanium. The process offers the highest purity possible and can produce powders of particle size distribution ranging up to 250 μm with highly spherical particles and minimal satellite content.

"The need for high end titanium powder is driven by the fast growth and adoption of AM. Arcam is determined to serve the industry through cost efficient solutions thus converting traditional manufacturing into AM. A requisite is to offer highest quality powder for production at competitive cost," added Magnus René, CEO of Arcam.

www.advancedpowders.com | www.arcam.com

GE Global Research latest to join 3MF consortium

The 3MF Consortium has announced that GE Global Research is the latest company to join the operating software development group. Scientists and engineers at GE have developed a number of AM components made with metals and ceramics. The company currently has production AM parts in two different jet engine platforms and is the world's largest user of metal AM technologies.

"With the successful integration of 3D printed metal parts in two different jet engine platforms and the construction of GE Aviation's $50 million state-of-the-art high-volume additive production plant in Auburn, Alabama, we achieved major milestones with our additive program in 2015," stated Prabhjot Singh, Manager of the AM Lab at GE Global Research. "But we have only scratched the surface on additive's potential. With even better design tools, machines and new materials, we can dramatically expand the additive industry's footprint in manufacturing. That future will arrive faster through the strong ecosystem that 3MF is building to bring the right stakeholders together to accelerate new innovations and breakthroughs in this space."

www.geglobalresearch.com | www.3mf.io

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Two technologies – one provider

Cooksongold launches platinum metal powder for the jewellery industry

Cooksongold, Birmingham, UK, has announced it has added platinum to its range of metal powders suitable for the Additive Manufacturing of jewellery. By combining the new 950Pt/Ru (platinum) metal powder with the company's established Direct Precious Metal Additive Manufacturing system, the Precious M 080, Cooksongold has enabled AM technology to become a viable commercial opportunity for the platinum jewellery industry for the first time.

The Precious M 080 is equipped with a 100-watt fibre laser and a powder management process developed for the jewellery and watchmaking industries

Launched in collaboration with the Platinum Guild International (PGI), an organisation funded by leading South African platinum producers and refiners, Cooksongold's Pt/Ru alloy has been specifically developed for Additive Manufacturing. This ensures that once the designs have been printed in the Precious M 080 they can be post processed, milled and polished to the high standards required without any of the common problems associated with other Pt alloys.

David Fletcher, Business Development Manager at Cooksongold, stated "This is one of the most revolutionary developments for the 3D printing technology. Helping to eliminate the common problems associated with casting platinum, it will become vital for bespoke and low volume platinum jewellery production."

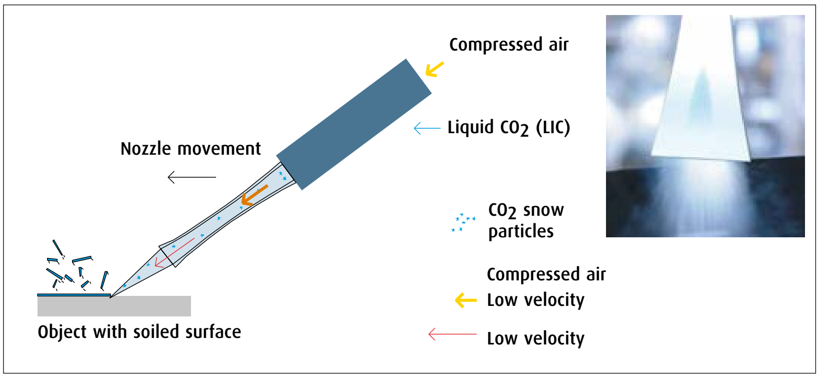
The 950 Pt/Ru powder will be added to Cooksongold's existing portfolio, which consists of 18k 3N yellow gold, 18k white gold, 18k 5N red gold and Brilliante 925 silver. Further new powders, such as base metals and other carat gold alloys, are currently being developed and scheduled for release during 2016.

Cooksongold's advanced metal powders have been optimised to work with the Precious M 080 system from EOS, which in turn has been developed with two key criteria in mind: accountability of materials and quick changeover times between jobs and materials. The powder range is also suitable for a number of other applications including Metal Injection Moulding (MIM) and press and sinter Powder Metallurgy.

Cooksongold is part of the Heimerle + Meule Group, one of Europe's largest refiners and processors of precious metals.

www.cooksongold-emanufacturing.com

Cryoclean Snow for cleaning AM parts



Snow particles are shot onto the surface with compressed air

BOC, the UK's largest supplier of industrial gases and medical gases, officially launched its Cryoclean® Snow+ industrial cleaning process at the company's Manufacturing Technology Centre in Wolverhampton.

Developed by BOC and its parent, The Linde Group, Cryoclean is a completely dry cleaning process in which liquid CO_2 is pressurised to 60 bar, creating tiny dry ice crystals known as snow. When the snow is accelerated onto the component, using compressed air, contaminants become brittle. The gas jet then permeates cracks and lifts the contaminant off the surface, after which it is expelled through exhaust systems.

As well as being used to clean industrial products such as machinery, process equipment and conveyor belts, Cryoclean Snow+ is also finding application in the Additive Manufacturing sector, where it can be used to remove oxides from the surfaces of a number of materials including steels and aluminium along with the removal of unfused metal powders.

By changing the ratio of CO_2 and abrasive material, the operator can adjust the intensity of the cleaning process to match the condition of the surface. This is particularly useful where cleaning challenges vary within a process flow, with relatively clean areas followed by heavily soiled, chemically altered or even corroded zones.

"BOC is delighted to introduce Cryoclean® snow+ to the UK and Ireland industrial cleaning market. This innovative new technology delivers the same standard of cleaning faster and more efficiently than traditional wet cleaning. It is also more environmentally friendly and requires a smaller footprint," stated Stuart Wilders, BOC's Market Sector Manager for Advanced Manufacturing.

www.boconline.co.uk

SLM Solutions to begin aluminium powder production

SLM Solutions Group AG, a provider of metal-based additive manufacturing systems based in Luebeck, Germany, has announced it is entering into a cooperation venture with PKM Future Holding GmbH to manufacture aluminium powders. PKM is the main shareholder of TLS Technik GmbH & Co Spezialpulver KG, a manufacturer of gas atomised metal powders in Bitterfeld, Germany.

"At the time of our IPO we had clearly stated our three-column growth strategy: alongside research and development, as well as distribution and service, the planned expansion of our metallic powder business was to represent a decisive building block," stated SLM Solutions' CFO Uwe Bögershausen "We are pleased to have now found the right partner in PKM, enabling us to offer our customers tailored solutions in the consumables area. Together with TLS's main shareholder, we will invest a mid-range, single-digit million euro amount to this end."

The development, production and distribution of aluminium alloys for metal-based Additive Manufacturing systems is intended to form the core of the cooperation between PKM Future Holding GmbH and SLM Solutions Group AG, within a joint venture that will be formed. According to the contract, SLM Solutions intends to acquire 51% of the share capital of this planned joint venture.

"We are starting off with aluminium, an important material for us, and we are planning – along with actual production – to also implement refining steps for the powder. This will enable us to adapt consumables even better to customer requirements," stated CEO Dr Markus Rechlin. "We are planning a total production capacity of more than 100 tonnes of aluminium powder per year for Additive Manufacturing purposes. We aim to offer other materials than aluminium at a later point in time."

SLM Solutions intends to bundle the powder business within a separate organisational unit, together with further services for the Additive Manufacturing of metal components such as training, consulting and financing, in order to take the particularities of the business into account.

"By generating continuous sales over the course of the year, expanding the powder business should help us offset the strong seasonality of our system business," added Bögershausen. "Over and beyond this, the consumables area is also interesting for us due to the fact that attractive margins can be achieved through developing and marketing metallic powders."

www.slm-solutions.com

Carpenter expands metal powder facility

Carpenter Technology Corporation, Wyomissing, Pennsylvania, USA, is reported to be spending an additional $23 million to add titanium furnace equipment to its new superalloy powder facility in Limestone County, Alabama. The purchase will raise Carpenter's investment in the plant to $61 million.

The new plant's titanium powder product offering will increase Carpenter's reach into aerospace and medical markets and offer growth opportunities in transportation, Tony R. Thene, Carpenter President, Chief Executive Officer told the Decatur Daily. Carpenter is close to completing its second Limestone County plant. The company's first Limestone County plant, a $518 million superalloy metal plant, began production in early 2014.

www.cartech.com

Prodways and Nexteam to form metal AM business for aerospace sector

France's Prodways Group has announced the signing of a major partnership agreement with Nexteam Group to develop a metal AM business for the aerospace sector. The partnership will lead to the creation of a joint company called Prodways-Nexteam.

Nexteam Group is a key player in the machining of complex and hard metal parts for the aerospace market, with operations in France, Poland and Romania. The group boasts expertise in the design, manufacture, assembly and maintenance of both large and small precision mechanical parts in all types of metal alloys meeting the demands of the aerospace sector.

Prodways Group has 20 years' experience in the manufacture of parts for the aerospace industry using Additive Manufacturing, through its INITIAL subsidiary, and has a fleet of around ten machines covering all metal AM technologies.

Philippe Laude, Deputy Managing Director of Prodways Group, stressed the partnership "reflects Prodways' aim to become the leader in the design and production of mechanical aerospace parts using 3D printing. This partnership with Nexteam Group, which will provide its expertise in the areas of machining and finalisation, will ensure that we can scale up our manufacturing processes to an industrial level that meets the technical requirements of the major players in the aerospace market."

Ludovic Asquini, Chairman of Nexteam Group, stated, "With this agreement, we are adding a new skill that will enable us to offer our customers an integrated range of products and robust optimisation solutions, backed by a leading player in the sector."

www.prodways.com
www.nexteam-group.com

UL opens Additive Manufacturing centre at University of Louisville and signs deal to train EOS customers

UL, a global safety science organisation, and the University of Louisville, have announced the official opening of a newly established Additive Manufacturing training centre named the UL Additive Manufacturing Competency Centre (UL AMCC). Developed for established AM technical and business professionals, the end-to-end training centre, located on the University of Louisville campus, aims to be a hub for advancing AM knowledge and workforce expertise.

UL also announced the signing of a Memorandum of Understanding with EOS in which the two companies will collaborate to provide joint AM training, conformity advisory services and facility safety management to EOS customers. The goal of the relationship is stated as being to promote the proper usage and advancement of AM technologies to the manufacturing industry.

"As the world-leading industrial 3D-printing solution provider, EOS forms strategic partnerships to strengthen our core competencies of systems, process and materials. Our partnership with UL allows us to join with our customers – both current and future – to push advancements in innovation, safety and quality," stated Glynn Fletcher, President, EOS of North America, Inc.

The UL AMCC offers hands-on training in Additive Manufacturing for metals and curriculum covering design set up, design corrections, machine set up, part production, post-processing and parts inspection, testing and validation. The training will allow professionals to understand how to produce metal parts and emerging materials through Additive Manufacturing, and establish safety systems, identify hazards from materials and machines and manufacture parts with safety built into designs.

The UL AMCC joins the University of Louisville's global advanced manufacturing campus, the Institute for Product Realisation (IPR), and collaborates and shares knowledge with other corporate residents, including GE and Local Motors' FirstBuild.

"The UL AMCC is a first-of-its-kind facility with the technical and educational expertise to not only progress Additive Manufacturing but also contribute to the future of manufacturing transformation."

"We see the intersection of industry information, UL's training, certification and safety knowledge and the University's AM expertise and academic research creating a manufacturing environment unlike anything else," added David Adams, CEO of the IPR.

www.ul.com/amtraining

LPW commences Plasma Spheroidisation of AM metal powders

LPW Technology has announced that its Plasma Spheroidisation equipment is now operational and processing metal powders for use in the Additive Manufacturing industry. The process uses high energy plasma to produce cleaner, highly spherical and dense metallic powders with greater flowability, reducing down time on the machine and speeding up the manufacturing process.

"We are hugely excited to have this next generation equipment on site for the benefit of our customers. LPW are constantly reacting to solve our customers problems and ensure that we have the right solution to keep them on track," stated Mike Ford, LPW's Sales Director. "Our Plasma Spheroidisation can produce the best metal powders on the market. They are more spherical and cleaner than those currently available."

The most significant benefit of this novel technology is perfectly spherical powder with no satellites, which increases the flowability and packing density of the powder, especially on AM machines where finer powder is required. Levels of surface contamination, compared to conventional gas atomised powders, are also reduced.

www.lpwtechnology.com

Pilot plant for the production of nano-structured powders

The UK's Centre for Process Innovation (CPI) and nine other European partners are collaborating in the design, scale-up and build of a high energy ball-mill (HEBM) pilot plant for the production and validation of innovative nanostructured powders. These advanced powders will be able to be used in a number of high value manufacturing applications such as cutting tools, medical implants and a range of aerospace and automotive components.

The work is part of a four-year European research and development project titled 'PilotManu' which began in 2013. The €5.3 million project is partially funded by EU's Framework Programme Seven (FP7) and involves ten partner organisations. The project partners include CPI alongside MBN Nanomaterialia, IMDEA Materials Institute, +90, Putzier, INOP, Manudirect, IMPACT INNOVATIONS GmbH, Matres and Diam Edil SA.

PilotManu is manufacturing the nanostructured powders using a proprietary high energy ball milling technology developed by lead partner MBN Nanomaterialia. The technology will allow for the manufacture of powders with ultrafine crystalline structures, meaning that products can be optimised to enhance strength, reduce weight or provide excellent wear, corrosion or thermal resistance.

Dr Charanjeet Singh, Innovation Manager at CPI stated, "We are delighted with the progress of the PilotManu project so far. The consortium has been able to design and scale-up the manufacturing process. The pilot plant will come online in the next few months and we anticipate the production of some truly innovative powders which will be validated for their suitability and performance in a number of value adding applications."

"The pilot plant and the associated products developed by the consortium will significantly reduce the current productivity and cost barriers that are in the way of the market adoption of advanced powders. Once concluded, the consortium will demonstrate the technological and economical viability of the pilot line by incorporating the powders into advanced materials targeted at a number of applications such as wear resistant coatings, abrasive tools and Additive Manufacturing applications."

Project Coordinator Prof Paolo Matteazzi from MBN Nanomaterialia added, "We expect that the High Energy Ball Milling pilot plant being developed in the PilotManu project will enable MBN Nanomaterialia to overcome the productivity and cost barriers that are currently preventing the commercialisation of the advanced nanomaterials. The new pilot manufacturing line, based on the upscaling of a current HEBM facility, will increase production by ten times and allow us to enter the market for three main lines of innovative products and technologies; the diamond tool industry, CerMet and alloys for wear resistant coatings and new mechanical alloyed composites for Additive Manufacturing."

www.uk-cpi.com

Equispheres to produce metal powders for Additive Manufacturing

Equispheres Inc, based in Ontario, Canada, has announced the successful commissioning of the company's flagship proprietary atomisation reactor to produce metal powders for Additive Manufacturing and metal spray applications. The company will begin marketing spherical metal powders specifically engineered for aerospace and defence applications in early 2016.

Equispheres states that its patent-pending atomisation technology consistently produces free-flowing, uniform, monograin, agglomerate-free spherical metal powders, which bring superior control and performance efficiencies not currently available. The company's metal powders have a narrow particle size distribution, excellent sphericity and flowability and consistent microstructure as produced without sieving or classification.

"With the successful commissioning of our first commercial atomisation reactor, we have demonstrated our technology can successfully produce metal powders with superior performance characteristics compared to powders currently available in the marketplace," stated Equispheres' President and Chief Executive Officer, Kevin Nicholds

Equispheres intends to be producing metal powders in commercial quantities by the end of the first quarter 2016. "Once the commissioning of the reactor is finalised, we will scale-up production capacity and convey materials to our aerospace industry partners for further testing and validation. Equispheres' metal powders enable us to better support the manufacturing needs of aerospace and other industries," added Nicholds.

www.equispheres.com

AMPM conference programme published

The third annual AMPM Conference on Additive Manufacturing with Powder Metallurgy, organised by the Metal Powder Industries Federation, takes place in Boston, USA, June 5-7, 2016. The popular event will feature worldwide industry experts presenting the latest developments in metal AM. The programme has now been published and includes two days of technical sessions that cover topics such as materials, metal powder production, powder characterisation, modelling and processes.

The event is co-located with POWDERMET2016, MPIF's International Conference on Powder Metallurgy & Particulate Materials, and is essential for anyone interested in metal components produced via metal Additive Manufacturing.

www.ampm2016.org

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DUAL-WIRE FEED FOR MULTI-ALLOY/FGM, THICK & THIN LAYERS AT SAME TIME, AND ACHIEVING EVEN HIGHER 3D PRINTING SPEEDS

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- DEPOSIT TWO DIFFERENT ALLOYS AT THE SAME TIME WITH PRECISION CONTROL
- CREATE FUNCTIONALLY GRADED METAL SURFACES OR COMPONENTS
- EXACTLY CONTROL THE % OF EACH DIFFERENT ALLOY IN THE FGM
- WIRES FEED RATES MANAGED BY UNIQUE ADAPTIVE CLOSED LOOP CONTROLLER
- THIRD WIRE-FEEDER CAN BE ADDED WITH FULL CNC CONTROL

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Sinterex opens first metal AM facility in Middle East

Sinterex has opened for business as the first specialist provider of Metal Additive Manufacturing services in the Middle East. From its new premises in Ras Al Khaimah, United Arab Emirates, Sinterex will offer market research, consulting and manufacturing services to clients in the region.

"We are delighted to commence operations in the UAE and excited to support clients in the Middle East region with our innovative and high-tech services," stated Julian Callanan, Business Development Director at Sinterex. The Middle East was estimated by the IHS World Industry Service to have consumed some $42 billion of metal products and parts in 2014. This is expected to grow by over 40% to reach $60 billion by 2019. Despite consuming large volumes of metal products and parts, the Middle East has lagged behind Europe and the US when it comes to adopting metal Additive Manufacturing. The region has historically been a trading hub, attitudes towards new technologies are often conservative and the last twelve months have seen the challenges of low oil prices impacting all areas of the economy. However, Sinterex states that it is embracing these challenges. "Metal Additive Manufacturing offers a new and compelling value proposition for companies purchasing metal products and parts in the Middle East," stated Dr Alaa Elwany, Technical Director at Sinterex. "In the current slow economic and low oil price environment companies are under increasing pressure to identify areas for cost reduction and value enhancement. These goals can now be achieved through metal Additive Manufacturing."

www.sinterex.com

Largest titanium part from Puris

Puris LLC, based in Bruceton Mills, West Virginia, USA, has announced that it has successfully produced what it claims is the largest complex additive manufactured titanium part for commercial use. The part was produced using ExOne binder-jetting technology and was processed to 100% density. Measuring an estimated 48 x 48 x 28 cm with a cross-section thickness of 9.5 mm, the part weighs approximately 14 kg.

"There is a lot of activity in this arena and larger parts have been printed, but we believe this is the largest complex titanium part to be printed to date," Puris' CEO Craig Kirsch stated. "The milestone was achieved by the combination of our team's deep metallurgical and powder-production expertise and ExOne binder-jetting technology."

www.purisllc.com

Orbital ATK successfully tests additively manufactured hypersonic engine combustor at NASA facility

Orbital ATK, headquartered in Dulles, Virginia, USA, has announced it has successfully tested an additively manufactured hypersonic engine combustor at NASA's Langley Research Center. The combustor, produced using a powder bed fusion process, was subjected to a variety of high-temperature hypersonic flight conditions over the course of twenty days, including one of the longest duration propulsion wind tunnel tests ever recorded for a unit of this kind. Analysis confirms the unit met or exceeded all of the test requirements.

One of the most challenging parts of the propulsion system, a scramjet combustor, houses and maintains stable combustion within an extremely volatile environment. The tests were, in part, to ensure that the additively manufactured part would be robust enough to meet mission objectives.

"Additive Manufacturing opens up new possibilities for our designers and engineers," stated Pat Nolan, Vice President and General Manager of Orbital ATK's Missile Products division of the Defence Systems Group. "This combustor is a great example of a component that was impossible to build just a few years ago. This successful test will encourage our engineers to continue to explore new designs and use these innovative tools to lower costs and decrease manufacturing time."

The test at Langley was an important opportunity to challenge Orbital ATK's new combustor design, made possible only through the Additive Manufacturing process. Complex geometries and assemblies that once required multiple components can be simplified to a single, more cost-effective assembly. However, since the components are built one layer at a time, it is now possible to design features and integrated components that could not be easily cast or otherwise machined.

Additive Manufacturing is one of several manufacturing methods currently being explored by Orbital ATK and its technology partners. Final assembly of the test combustor was completed at the company's facilities in Ronkonkoma, New York, and Allegany Ballistics Laboratory in Rocket Center, West Virginia.

Orbital ATK was formed in 2015 following the merger of Orbital Sciences Corporation and ATK Aerospace and Defence. The company designs, builds and delivers space, defence and aviation systems for customers around the world, both as a prime contractor and merchant supplier.

www.orbitalatk.com

FKM Sintertechnik orders LaserCUSING systems from Concept Laser

Germany's FKM Sintertechnik GmbH has announced expansion of its production facility in Biedenkopf and further investment in a number of metal Additive Manufacturing systems from Concept Laser. FKM has been a user of Selective Laser Sintering (SLS) systems since 1994 and, according to the company, it is one of the largest providers of additively manufactured products in Europe.

Adjacent to its existing 3000 m^2 site, a new 700 m^2 production hall is being built to meet the growing demand for additive products made of metal. FKM has ordered several machines from Concept Laser in the medium and large build-chamber range.

"The market is currently developing toward batch production of 3D metallic products. In addition to the classic small batches and prototypes, industrial production lot sizes with a distinctive serial character are appearing now as well. With the strategic expansion of our 3D printing capacity, we want to be able to respond to increasing demand in a very flexible way and also to get in on increasing product dimensions," stated Harald Henkel, Managing Director of FKM Sintertechnik GmbH.

FKM Sintertechnik GmbH based in Biedenkopf

Harald Henkel, Managing Director of FKM Sintertechnik GmbH, and Oliver Edelmann, Vice President Sales & Marketing at Concept Laser GmbH, in front of the newly installed M2 cusing Multilaser

The FKM Sintertechnik facility already features the Mlab cusing and M2 cusing models from Concept Laser, as well as models from other suppliers. They were accompanied by a new M2 cusing Multilaser last winter and, as Harald Henkel explains, there is more to come, "We have ordered another M2 cusing Multilaser for 2016. Build rates and the suitability of Multilaser technology for batch production fit very nicely with our business strategy and we also want to be involved with very large build chambers. A new X line 2000R from Concept Laser featuring the world's largest build envelope for powder-bed-based laser melting with metals will be delivered to us here in Biedenkopf in Q1 2016."

The new M2 cusing Multilaser features a fully integrated design, which means that satellite solutions are no longer used for laser sources and filter technology. This closed solution is advantageous to the user thanks to the accessibility of system components and a reduced space requirement. The new M2 cusing also features a new filter concept with a filter surface five times greater in size, having increased from 4 m^2 to 20 m^2. The new filter module was designed with fixed piping and to be fully integrated into the system.

The new X line 2000R from Concept Laser features the world's largest build envelope currently available at 800 x 400 x 500 mm (L x W x H) and boasts high build rates using Multilaser technology.

The X line 2000R increases build volume in comparison to its predecessor model by nearly 27% from 126 L to 160 L and works with two 1,000-Watt lasers. This enables exposure of the build area from two positions simultaneously. The X line 2000R also has a rotating mechanism which allows two build modules to be used reciprocally, thus guaranteeing constant production with no downtimes.

www.fkm-lasersintering.de
www.concept-laser.de

Tantalum used in biomedical implants

Metalysis, based in Rotherham, UK, has collaborated with the UK's TWI in Cambridge, to demonstrate the feasibility of its tantalum powder in metal Additive Manufacturing for biomedical applications such as bespoke hip joints. The joint study successfully produced both uniform and randomised tantalum lattice structures that are bio-inert, replicate the structural stiffness of bone and allow for extensive integration with bone cells, so that the new joint is readily accepted by the body.

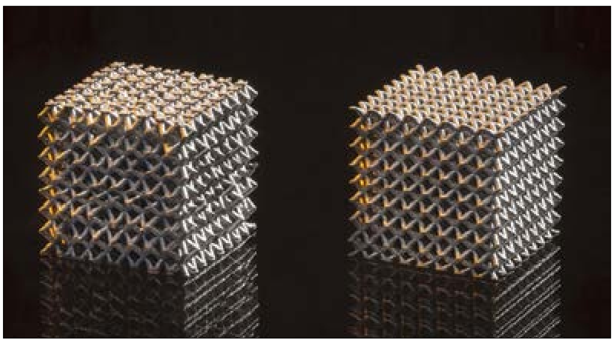
"It is tremendous to be partnering with TWI, a company that has so much knowledge in the manufacturing and medical industries. TWI has great expertise, particularly in the use of lasers in Additive Manufacturing, which we hope will help to bring individual joint replacements into the mainstream of mass manufacture," stated Dion Vaughan, Chief Executive of Metalysis.

Metalysis has developed a process that produces metal powders directly from their respective oxides in a single step, lowering the environmental impact of its manufacture.

"We have already seen the great success Metalysis has had printing automotive parts. Our analysis suggests these metals are incredibly versatile and highly suited to the medical industry. Metal 3D-printed hip replacements could be a huge step forward, allowing patients to have a tailor-made joint by scanning their other hip and matching it with a metal 3D-printed replacement, rather than being restricted to the choice of standard sizes now available," added Richard Pargeter, a technology fellow at TWI.

The study claims that the durability and inertness of this highly versatile metal are retained through the production process. It has demonstrated the significant potential of creating lattice structures using selective laser melting for use in hip joints, implants and other new biomedical products that will both benefit patient wellbeing and bring cost savings to the wider market. Since the launch of its commercial plant in 2015, Metalysis has been supplying tantalum powder to its clients globally, working in collaboration with LPW Technology to serve its Additive Manufacturing customers.

www.twi-global.com | www.metalysis.com



Examples of the lattice structures. The structure on the left is randomised, the one on the right uniform

Numanova Srl to manufacture metal powders

Italian investment group Italeaf has announced it has established Numanova Srl to produce metal powders suited to a range of Additive Manufacturing and Powder Metallurgy applications. The production plant will be located at Italeaf's facility in Nera Montoro, Rome.

Investment of some €12 million has been announced and the company will be equipped with gas atomised powder production technology. It will also use plasma atomisation and total production capacity is expected to be around 500 tons/year. "The production of metal powders and the R&D activity to make new alloys are attracting interest and growing expectations on the global market," stated Paolo Folgarait, Numanova's Executive Director and General Manager.

www.italeaf.com

Renishaw and BioHorizons collaborate to offer custom dental abutments

Renishaw plc has announced collaboration with dental implant producer BioHorizons to produce custom metal additively manufactured abutments known as LaserAbutments™. The joint initiative enables dentists to offer cost effective custom abutments for restorations, providing exceptional function and aesthetics.

The process provides a technologically advanced custom abutment made by Renishaw's hybrid manufacturing systems, where the abutment is additively manufactured to capture fine occlusal details and then precision machined to achieve precisely fitting interface geometry for screw-retained implants.

Following an ISO 13485 approved quality management system, the abutments are made from CoCr that has been biocompatibility tested according to ISO 10993. This enables

standard porcelains to be bonded to the surface without a separate coping/crown, providing a screw-retained crown which can later be temporarily removed for hygienic maintenance or work on adjacent teeth.

Using Renishaw Dental Studio (RDS) software, dental labs design their abutment in-lab and submit it digitally to Renishaw central manufacturing. LaserAbutments are supplied with a pre-polished emergence profile, helping to save laboratory time, and with a titanium screw for each abutment.

www.renishaw.com/dental

AM watch cases bring life to vintage pocket watches

US watchmaker Vortic Watch Co, based in Fort Collins, Colorado, is combining vintage pocket watch movements with metal additively manufactured watch cases to form a unique collection of wristwatches. The company claims to be the only watchmaker to currently utilise metal Additive Manufacturing for final product parts.

Each movement in Vortic’s American Artisan Series is salvaged from antique pocket watches destined to be scrapped. The pocket watches were originally made in the late 1800s or early 1900s by American watch companies such as Elgin, Waltham, Hamilton, Illinois, Hampden, etc.

Each case is custom designed to fit the antique pocket watch movements. Using a two-piece design, the case encapsulates each movement between two custom made Gorilla Glass crystals. Each case is additively manufactured from stainless steel and bronze and is coated with a patina or plating to provide a unique finish.

An insert in the watch allows the movement to seemingly float inside the case. This part is individually designed to fit each unique movement and is manufactured using a photopolymer resin on Vortic’s own Formlabs Form 1+ stereo-lithographic machine.

All watches are assembled by hand at Vortic. After completion, the watches are tested on a professional timing machine for accuracy.

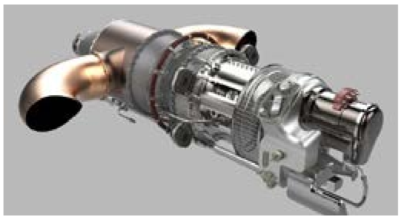
www.vorticwatches.com

GE turboprop engine to include additive manufactured structural components

GE Aviation has unveiled a new turboprop engine aimed at business and general aviation that will achieve up to 20% lower fuel burn and 10% higher cruise power compared to other engines in its class. GE states that a key feature of the new engine is that it includes additive manufactured structural components that reduce weight and improve durability. The new 1,300 shaft horse power (SHP) rated turboprop engine has been selected by Textron Aviation Inc., the world's largest maker of business propeller planes, to power its single engine turboprop (SETP). GE expects to conduct the detailed design review for the new turboprop in 2017 followed by the first full engine test in 2018.

"Our single engine turboprop will combine the best of both clean-sheet aircraft and new engine designs. Selecting GE as our engine partner reflects the best fit for the mission of the aircraft and our commitment to reliably deliver best-in-class performance capabilities to our customers," stated Christi Tannahill, Senior Vice President, Turboprops and Interior Design at Textron Aviation.

GE state that new design and manufacturing technologies developed for its latest military and commercial engines, such as Additive Manufacturing capabilities pioneered by the CFM LEAP turbofan, will help the advanced turboprop to extend time between maintenance overhauls by up to 30% more than existing engines. Development, testing and production of the new turboprop engine will occur at GE Aviation's recently announced turboprop Centre of Excellence to be located in Europe. The new facility will represent an investment of over $400 million and ultimately support up to 1,000 new jobs.



The new turboprop engine is the same size as its peers but produces nearly double the overall pressure ratio (Image GE Aviation)

"For the past five years, GE conducted design studies and actively researched the turboprop market to identify and integrate the best of our next-gen commercial and military technologies at the lowest cost and risk to our business aviation customers," stated Brad Mottier, VP and General Manager of GE Aviation's Business & General Aviation and Integrated Systems division. "We're honoured to be selected by Textron Aviation for its newest turboprop program and look forward to growing aircraft applications in the coming years with our new turboprop engine."

www.ge.com

Northwestern team develop innovative method for metal Additive Manufacturing

A team of engineers at Northwestern University, Illinois, USA, has reportedly created a new way to print three-dimensional metallic objects using rust and metal powders. The new rapid method is said to expand the type of metals, alloys and architectures that can be additively manufactured. The new process involves a liquid ink made of metal or mixed metal powders, solvents and an elastomer binder which then allows rapid printing densely packed powder structures using a simple syringe-extrusion process, in which ink dispenses through a nozzle, at room temperature. Despite starting with a liquid ink, the extruded material instantaneously solidifies and fuses with previously extruded material, enabling very large objects to be quickly created and immediately handled. The part is then sintered, allowing the powders to fuse together without melting.

The research is described in a paper published in the journal *Advanced Functional Materials*. The researchers' process open doors for more sophisticated and uniform architectures that are faster to create and easier to scale up than existing processes. After the object is printed, but before it is sintered, it is flexible due to the elastic polymer binder containing unbonded metallic powders. "We used a biomedical polymer that is commonly used in clinical products, such as sutures," stated Ramille Shah, Assistant Professor of Materials Science and Engineering in the McCormick School of Engineering and of surgery in the Feinberg School of Medicine, who led the study. "When we use it as a binder, it makes green bodies that are very robust despite the fact that they still comprise a majority of powder with very little binder. They're foldable, bendable, and can be hundreds of layers thick without crumbling. Other binders don't give those properties to resulting 3D printed objects. Ours can be manipulated before being fired. It allows us to create a lot of different architectures that haven't really been seen in metal 3D printing."

Another innovative component of their process is that it can be used to print metal oxides, such as iron oxide (rust), which can then be reduced into metal. Rust powder is lighter, more stable, cheaper and safer to handle than pure iron powders. The team discovered that they could first 3D print structures with rust and other metallic oxides and then use hydrogen to turn the green bodies into the respective metal before sintering in the furnace.

"It might seem like we are needlessly complicating things by adding a third reduction step where we turn rust into iron," David Dunand, Professor of Materials Science and Engineering, added. "But this opens up possibilities for using very cheap oxide powders rather than corresponding expensive metal powders. It's hard to find something cheaper than rust."

www.mccormick.northwestern.edu

BioArchitects receives approval for AM titanium cranial implant

BioArchitects has announced the 510(k) clearance by the US Food and Drug Administration for the company's additive manufactured patient specific titanium cranial/craniofacial plate implant. Designed for the repair of defects in the non-loadbearing bones of the head and face, each custom plate is permanently attached to the skull and/or face with self-tapping titanium screws.

As the first of its kind in the US, the implant takes advantage of the light weight and high tensile strength properties of the biocompatible titanium alloy and is made using Arcam's EBM technology. "We are extremely proud to contribute to what we consider another major advance in the trend toward personalised medicine." stated Mark Ulrich, CEO of BioArchitects USA.

Devices of this kind are typically used in the repair of bone defects resulting from trauma, disease, or congenital abnormalities. As each device is specific to the individual, its construction begins with the taking of a CT scan or MRI of the affected area. The scan or image is then imported into a computer design program which is used to create a template of the repair that becomes the model from which the AM system produces the titanium plate.

"BioArchitects is a prime example of how innovative organisations are using EBM technology to advance biomedical surgeries that truly affect people's lives," stated Magnus Rene, CEO of Arcam Group. "Arcam has been a strategic supplier to the orthopaedic market for over a decade and tens of thousands of implants are made yearly from our EBM systems."

www.bioarchitects.com

Methods 3D expands its technical centres

Methods 3D, Inc., based in Sudbury, Massachusetts, USA, has announced the addition of the new ProX™ DMP 320 from 3D Systems to its growing line of metal AM machines. The company is installing the ProX™ within multiple technology centres across the US to provide product demonstration, training, support and development of customer products.

Methods 3D is a newly formed subsidiary of Methods Machine Tools, Inc. a supplier of machine tools, Additive Manufacturing technology, automation and accessories. Methods Machine Tools, Inc., has been in operation for over 55 years and provides applications engineering support, installation, parts, service and training through a network of large technology centres and dealers throughout North America.

www.methodsmachine.com

Croft Additive Manufacturing to develop spacecraft mechanisms with ESR Space

Croft Additive Manufacturing based in Warrington, UK, has teamed up with ESR Space, also located in Warrington, to conduct a study into the use of AM to develop custom spacecraft components.

The research, funded by Centre for Earth Observation Instrumentation and Space Technology, aimed to exploit recent developments in manufacturing technology and create innovative, high-performance components for use in demanding mechanism applications. While the main emphasis of the study was on spacecraft applications, it also supported the development of supply chain capability in AM and the suitability of such processes in a range of markets, including telecommunications, science and robotics.

"During early discussions with Croft, we identified a number of synergies in the key skills it has developed as a business. It was an obvious choice to harness the process developments in this programme of work since Croft is well aligned with the technical objectives set out at the start of the programme," stated Grant Munro, Project Manager at ESR Space.

In space applications there are a number of disadvantages to using a liquid or grease-based lubricant, such as low temperature viscosity, evaporation, loss of lubricant and contamination of other parts of the spacecraft. To address these issues, two concept designs were developed using Croft's Realiser SLM-250 machine. These were both focused on managing the lubricant within the bearing system more effectively, with a particular emphasis on the challenges of the space environment.

Neil Burns, Director at Croft Additive Manufacturing, stated, "It is always advised to have several options when seeking to identify a bespoke solution using innovative technologies. Following the creation and analysis of the two prototypes in this instance, it was deemed more valuable to develop the lubricant retaining cage further."

While it is likely that the component developed will be initially used for spacecraft applications, the use of the technology in other industries such as nuclear, aerospace and medical will be explored in parallel.

www.croftam.co.uk

Materialise tour to promote metal AM across Europe

Materialise NV, based in Leuven, Belgium, has announced a series of events to promote metal Additive Manufacturing across Europe. With the Materialise Metal Tour, the company states that it aims to educate engineers and designers on the added value of metal AM. The tour started in March and will pass through ten European cities.

The Materialise Metal Tour is part of Materialise's 3DP ACADEMY, a series of half-day workshops providing in-depth information on technologies, materials and applications for AM. With the technology maturing and demand for metal parts growing worldwide, Materialise states that the timing is ideal to address engineers with a focused series of seminars on metal AM and how to make the most of it.

"At Materialise, we strongly believe that awareness of the possibilities and a deep understanding of design and engineering for AM is the key to success," stated Jurgen Laudus, Director Materialise Manufacturing. "With these events we want to provide engineers with the necessary know-how to find and develop the right applications for metal 3D Printing."

www.materialise.com/metaltour

Formnext on track for successful 2016 event

Formnext powered by tct, the international Additive Manufacturing and tool making show, will take place in Frankfurt, Germany, November 15-18, 2016. With over 70% of the previous year's exhibition space already booked, the organisers are on track for another highly successful event in 2016. "This enthusiastic response from our exhibitors is a continuation of formnext's outstanding development, which we laid the foundation for at our debut exhibition in 2015," stated Sascha F Wenzler, Vice President of formnext at Mesago Messe Frankfurt.

An array of key international companies have already committed to attending formnext 2016, including 3D Systems, Additive Industries, Alphacam, Arburg, Autodesk, Bikar, EOS, Heraeus, Hermle, Knarr, Listemann, Materialise, Realizer, SLM Solutions and many more.

Formnext is also proving popular with newcomers to the exhibition state the organisers. Those set to attend for the first time in 2016 represent a wide range of topics and include exhibitors from China, France, Germany, Italy, the Netherlands and the United States.

The 2015 exhibition attracted a large number of decision-makers and developers from all over the globe with visitors from many world market leaders, renowned OEMs and key suppliers.

www.formnext.com

Powder flow measurement kit available from LPW

LPW Technology has announced the launch of a new powder flow measurement kit that allows the quick and full characterisation of powder flow to a number of ASTM standards. Aimed at those in the metal Additive Manufacturing industry, LPW's POWDERFLOW™ kit will help to distinguish between powder and machine problems, resulting in significant time and cost savings.

Measuring powder flow allows the user to determine whether or not the powder is changing within the AM process. The new kit allows operators to determine apparent density (ASTM B212), angle of repose, Hall flow (ASTM B213) and Carney flow (ASTM B964).

"LPW has produced this comprehensive kit to enable its customers to monitor the health of the powder they are using in their Additive Manufacturing processes, quickly, simply and cost effectively. I'm sure all users of metal powders will find the POWDERFLOW™ kit a useful addition to their testing regime," stated Phil Kilburn, LPW Commercial Director.

www.lpwtechnology.com

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Planning, preparing and producing: Walking the tightrope between additive and subtractive manufacturing

In the following article Delcam's Kelvin Hamilton explores the current possibilities for design, topology optimisation, simulation, process planning and process preparation in metal Additive Manufacturing (AM). Exploring the three Ps, Plan, Prepare and Produce, all the processes involved in transforming three airbrake bracket designs into final products are revealed. As well as explaining how important it is to appreciate and plan for the significant amount of subtractive manufacturing in metal AM, a number of the lessons learnt in this project are discussed as the author reflects on the experience of planning, preparing and producing parts.

If you ask anyone involved with metal Additive Manufacturing, they will tell you that producing quality parts always requires some kind of post-processing operation. AM should therefore be understood as one of the many processes that can be utilised to manufacture a part, not an end-to-end solution that stands alone. At Delcam, we have been involved with the production of metal AM parts for some time. Yet, time and again, we see the same mistakes preventing manufacturers from achieving the part geometry that they are trying to create.

Our experience tells us that the key to successfully producing quality metal AM parts lies in creating a comprehensive process plan [1]. This requires expertise not only in Additive Manufacturing, but in every process required to manufacture the finished parts. Understanding how to account for subtractive implications on the additive process at both the design and build preparation stages must be built into the process plan.

For the parts discussed here, we started by looking at the role of software within the process chain. More specifically, we looked at the tools available within Delcam and Autodesk to see how we can best incorporate this exciting process in anticipation of what the World Economic Forum calls the fourth industrial revolution [2].

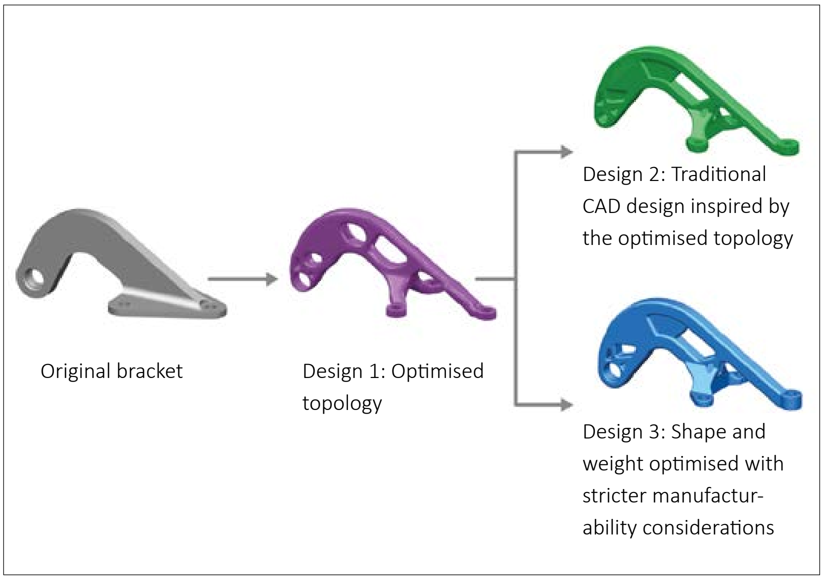

Fig. 1 Overview of the evolution of the airbrake hinge bracket

Why an airbrake hinge bracket?

The airbrake hinge bracket designed and built in this project was inspired by Bloodhound SSC, a unique, high-technology project to design and build a car that will break the 1,000 mph speed barrier. The bracket produced in our project was completed independently of the Bloodhound team [3].

Image: Flock and Siemens

What is an airbrake?
Commonly found on aeroplanes, an airbrake is simply a movable flap that helps to reduce the speed of a moving object. In order to stop the Bloodhound car within a distance of 5.5 miles, the brakes must virtually double the cross-sectional area and drag of the car. Consequently, Bloodhound's airbrakes are the biggest ever seen in land speed racing. The original part was milled from a solid block of titanium.

Reaction forces:
> 800 mph wind, > X: 128.3 lb force / 46.73 lb force in, > Y: -87.02 lb force / 31.37 lb force in, > Z: 93.16 lb force / -34.63 lb force in

Objectives

In order to understand the possibilities and limitations of the wide range of tools available to us, we took a known geometry from design all the way through to manufacture and post-processing. The aim was to explore whether the design and manufacturing software and processes available today could be used coherently to enable the additive and subtractive manufacture of quality metal parts.

At worst, we would identify roadblocks that prevent coherent workflows and explore how we could facilitate seamless workflows between design, preparation and post-processing.

The part

We took the design load cases and part requirements of an existing hinge bracket for an airbrake (see Fig. 2, top). The current design weighs 430.3 g and was conventionally machined from solid titanium. Working with colleagues at Autodesk, a topologically optimised shape was created using Inventor's Shape Generator tool. The redesigned part, called Opti-Opti (Design 1), respects the weight and stiffness constraints required by the airbrake (Fig. 2, middle). The shape was smoothed and re-simulated against the original loads using Fusion Simulation to verify the lightweight design, which must hold while the brakes are being applied at 850 mph. The optimised design, when realised, would deliver a 22% mass saving compared to the original, machined-from-solid bracket.

However, with its crow's feet design and cavities, it is not an ideal shape for manufacture. A number of the surfaces cannot be machined, meaning that some of the AM support fixtures would be impossible to remove and it would be difficult to achieve the required surface finish. Additional thought about the manufacturability of the optimised shape and its effects on downstream processes was therefore required.

Consequently, the Opti-Opti shape was used as a design template to produce a geometry that is more acceptable for manufacture. This resulted in the Opti-Trad (Design 2), a traditional CAD design using topology optimisation to explore design concepts (Fig. 2, bottom). Inventor's mechanical analysis and simulation tools were again used to verify that the new design meets load and stress requirements.

The as-designed mass of Opti-Trad was 438.3 g, a 2% increase compared to the machined-from-solid bracket. Although the shape inspiration of the optimised design has been kept, the Opti-Trad foregoes all the mass saving initially seen. There certainly is a happy middle ground to be achieved and this is discussed over the following pages.

With our final designs approved for manufacture, we moved on to process planning, manufacturing preparation and production. These are iterative phases: you cannot define a process plan in isolation before moving on to preparation and production. If only it were that simple. In reality, the process plan must be adapted to reflect the real decisions and compromises that have to be made as you consult with individual process experts and embark on each step.

Inexperience is, without doubt, the worst enemy of anyone who is starting to combine AM with other manufacturing processes. We were not immune to this and our learning was accompanied by some painful experiences. Ultimately, as we gain more experience of combining AM into the mix of manufacturing processes and as more CAE software tools become available, we will see more sharing of best practices and the normalisation of these iterative steps.

As a side note, the mindset and the actions involved in this iterative process of planning and manufacturing preparation will differ slightly, depending on which material (titanium vs. aluminium vs. steel, etc.) you are working with, which AM technology (SLM, EBM, DED etc.) is being used, the quantities, and the strictness of the industry standards with respect to part and process quality (aerospace vs. Formula 1 etc.).

Process planning

Process planning is without doubt the most important step. We have identified eight key issues that the process planner must consider. This is not an exhaustive list but it is a good starting point for any project. Planning is iterative and a comprehensive process plan emerges only by consulting with individual process experts and thinking about how each step in the process affects every other step. The principle of 'rinse and repeat' applies here. The key considerations of process planning include:

1. Manufacturing and product requirements
What standards does the product have to conform to? This can include, but is not restricted to, material, quantities, tolerances, mechanical and surface properties.

2. Technology choice
What technologies are required to realise the requirements - additive, subtractive, or other processes in some combination?

3. Process choice
What processes are needed for each technology? This can be AM-powder bed, milling, turning, wire EDM or other processes such as thermal and surface treatments.

4. Machine choice
What machines are needed and available for each process choice? This can be laser/EBM-based powder bed AM, 3-5 axis milling, mill-turn, turn and/or submerged wire EDM machine.

5. Sub-processes
What sub-processes are involved for each of the process choices? This can be face or surface milling, drilling, boring, threading, wire cutting, powder and support removal etc.

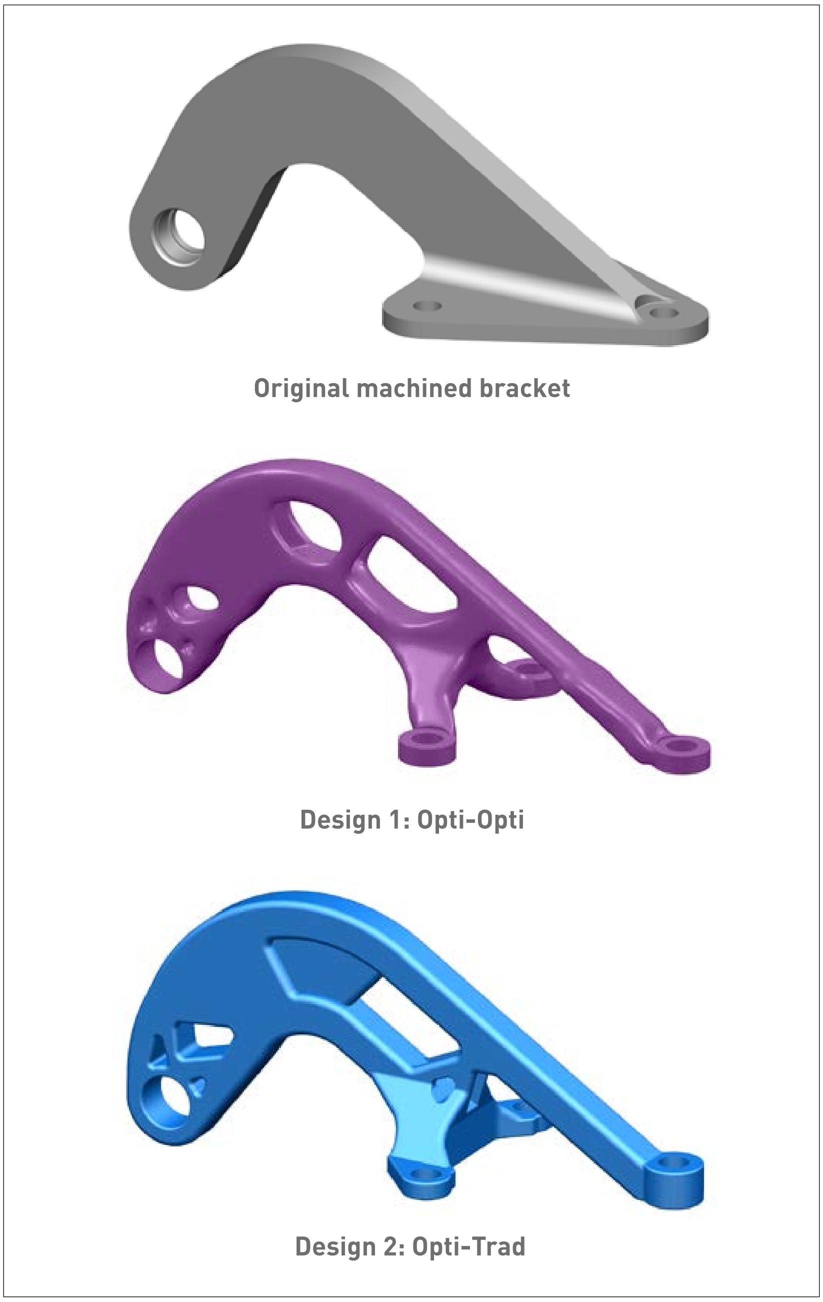

Fig. 2 Top: the existing bracket. Middle: Design 1, the Opti-Opti bracket, a full topology optimisation of the original part. Bottom: Design 2, the Opti-Trad bracket, shape inspired by the topology optimised bracket

6. Setups
What set-up does each machine, process and sub-process need? For example, three setups on a 3-axis mill or only one if a 5-axis machine is used.

7. Work holding
How will the part be held and fixtured in each setup? Perhaps the baseplate or some surfaces on the part itself are suitable, or it may be the case that standard clamps are enough. Alternatively, special machining fixtures may be required.

8. Execution sequencing
What is the execution order of each operation? It could be: first build on a powder bed machine, then clean excess powder, then machine holes with the parts still on the baseplate, then wire EDM a profile, or some other more complex mix of operations.

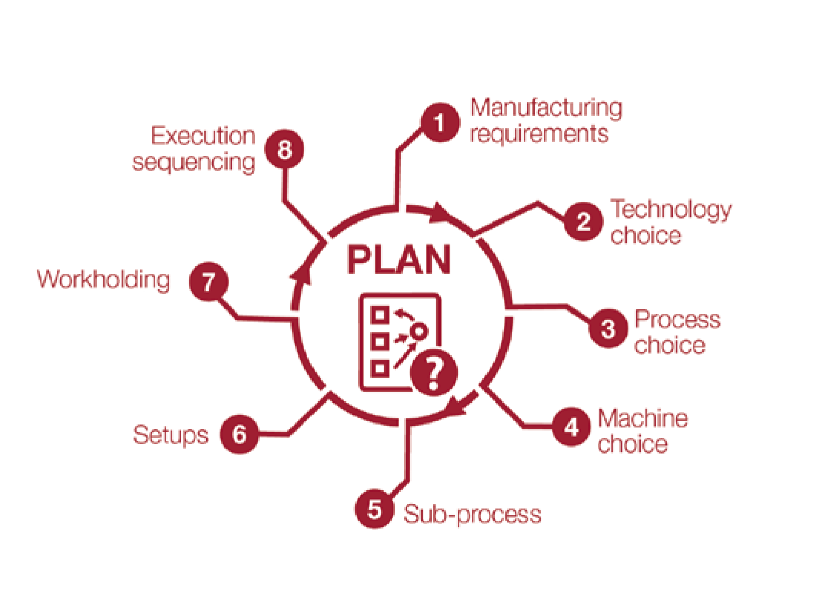

Fig. 3 A typical metal AM project plan

With these considerations in mind, our starting point for Designs 1 and 2 was to build both brackets, heat treat to relieve stresses, machine only the interfaces and holes while on the baseplate, wire EDM the bottom profile and clean up. This is just the high-level view of the manufacturing processes that we would have to use. It does not provide the level of detail necessary for a comprehensive plan. To achieve this, we had to walk through each process to see where things overlap and where potential problems might occur.

Compromises are always required and this activity highlights where these compromises had to be made. For example, if we had decided to machine while the parts were still attached to the baseplate, this would have implications on the downstream processes. Surfaces of the baseplate could be used for clamping during machining, but we had to think about how the parts would be nested relative to the baseplate, which surfaces could be used as datum references, tool access and so forth.

Conversely, we could have decided to wire EDM the parts from the baseplate before machining. In such a case, we would have had to worry about how to hold the parts and how to obtain datum references. It may even have necessitated the production of special machining fixtures to hold the parts.

This highlights how seemingly simple decisions have significant downstream impacts on the preparation stage and on subsequent processes. There are also cost implications to consider. In some cases, alterations to the original design may be required to accommodate the chosen manufacturing process.

Decisions about post-build processes need to be made as early as possible, even as early as the design stage. A true understanding of how each decision will affect the build means that involving each member of the supply chain, from the designer right through to those involved in the finishing processes, is critical to success. Unfortunately, there is currently a lack of cross-pollination and interaction between AM experts and other manufacturing experts, which makes this process more difficult. Our final process plan is shown in Table 1.

Steps		Description
1	**Manufacturing preparation**	Create the deposition model
2	**AM preparation**	Create platform layout/nesting, orientation, fixturing, laser paths & export
3	**AM build**	Build the brackets
4	**Stress relief heat treatment**	Reduce residual stresses
5	**3D scan inspection**	Confirm part dimensions after AM build and heat treatment
6	**Milling preparation**	Create machining data, cutting trajectories and instructions
7	**Machining**	Achieve the required dimensions and surface finish of mating faces and holes
8	**Wire EDM preparation**	Create wire EDM cut profiles, machining data and instructions
9	**Wire EDM**	Cut parts from baseplate and shape final geometry, remove support fixtures
10	**Fixture removal & clean-up**	Remove remaining support fixtures
11	**Vapor blasting**	Smooth out the surface and achieve a uniform finish

Table 1 The final process plan

Manufacturing preparation

There are many parallels to be drawn between what is typically done for castings and what is needed for AM. Since cast parts always require further processing, one of the golden rules of casting is to consult with each process expert before finalising the design for manufacture.

Many casting foundries have complementary processes in-house, since processes such as heat treatment, shot blasting, machining, tooling, polishing and coating, as well as non-destructive testing, are commonly used in combination with casting to produce finished products. It has taken years to build this expertise and production is guided by industry standards and best practices, allowing casting to sit as a fundamental manufacturing process.

The same expertise and understanding of multiple processes is required by those involved in producing metal AM parts, particularly when we speak about manufacturing preparation. Manufacturing preparation means thinking about each process and sub-process in the planning phase to visualise how they impact the final part. These impacts are countered by applying design for manufacture and manufacturability principles.

At Delcam, we call this activity Modelling for Manufacturing (MfM). This activity has a pivotal role in minimising throughput time, the number of setups and the pitfalls of each process, while maximising part fidelity and the benefits of each process. Practically speaking, this can mean transforming the final CAD geometry into a deposition model, which is typically called the near net shape (NNS). This transformation usually involves simplifying or suppressing features that cannot be created satisfactorily using AM and adding features such as fixtures and datum references to aid downstream processes.

Consideration must also be given to platform layout, part orientation and the data export from the preparation environment to the machine. For our brackets, preparation involved the following: creating the deposition models, preparing for wire EDM, milling, additive, work holding and other processes.

Deposition model

Creating the NNS is often overlooked - or only done partially by those using AM to create metal parts. What is more, it is not clear who should be responsible for doing this – the designer/customer or the machine operators. Any build project needs to clarify this responsibility and confirm its completion.

To make another parallel with casting, typically the final part geometry is created by the customer needing the part. Subsequently, the relevant MfM rules are applied to create a NNS that accommodates the needs of casting and subsequent processes. This can mean adding excess stock material for machining, draft angles and part identification, defining parting lines, managing hot spots and compensating for shrinkage, to name but a few.

If the customer has the capabilities and expertise, they will undertake this activity. Otherwise it is done in collaboration with the casting foundry. Consultation is key here; otherwise, the likelihood of mistakes is very high. MfM rules must also be applied to create the NNS for AM. However, such rules are scarce or incomplete and typically are not sufficiently far reaching to cover the complex multi-process requirements of combining AM with other manufacturing processes.

In our experience, creating the NNS for AM typically involves the four actions outlined in Fig. 4. These actions cannot be carried out in isolation but must occur in the context of each process and sub-process involved and consideration given to their interaction. For these brackets, we used our MfM software, PowerSHAPE, to complete the required direct modelling tasks, such as feature suppression and feature modification. The deposition models emerged as a combination of all the impacts and decisions taken while preparing for wire EDM, milling, additive, work holding and other processes. As we go through the preparation for each process below, it will become clear where these actions are performed and in which context.

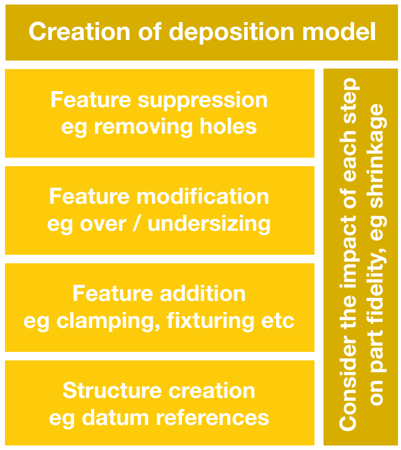

Fig. 4 Actions to perform when creating the deposition model

EDM preparation

Preparing for wire EDM is challenging because there are strict conditions that must be satisfied, leading us to ask ourselves the following questions:

- Is there enough additional stock material to cut through without damaging the parts?
- Are the surfaces appropriate for EDM?
- What setups are necessary?
- How do we orientate the parts so that cutting does not damage the baseplate or other parts on the platform?
- What cutting profiles are needed?
- How can datum references be obtained and how reliable will they be?
- Will any loose powder be released that could interrupt the cut?
- How can cutting information and surfaces be communicated effectively?

The answer to some of these questions will have a significant impact on how the AM preparation is performed, particularly part orientation and nesting. This demonstrates how the individual processes are intricately linked.

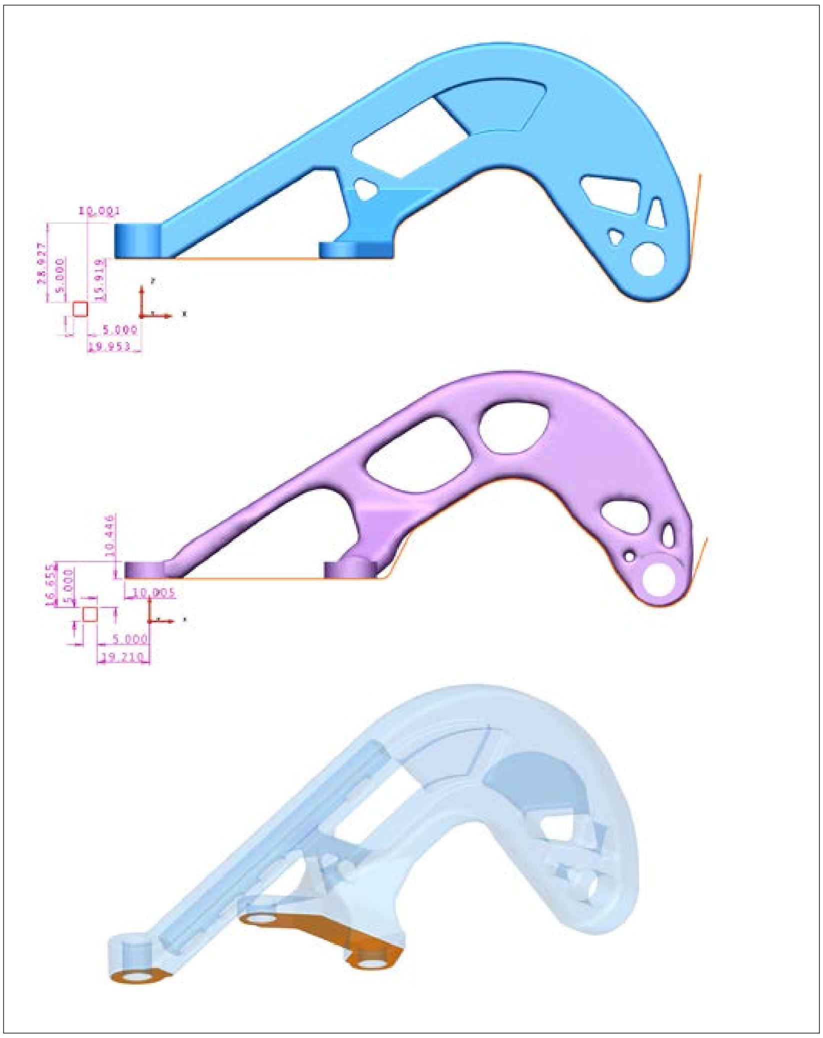

Fig. 5 Wire EDM preparation: the orange lines are the cut lines and orange surfaces are stock additions

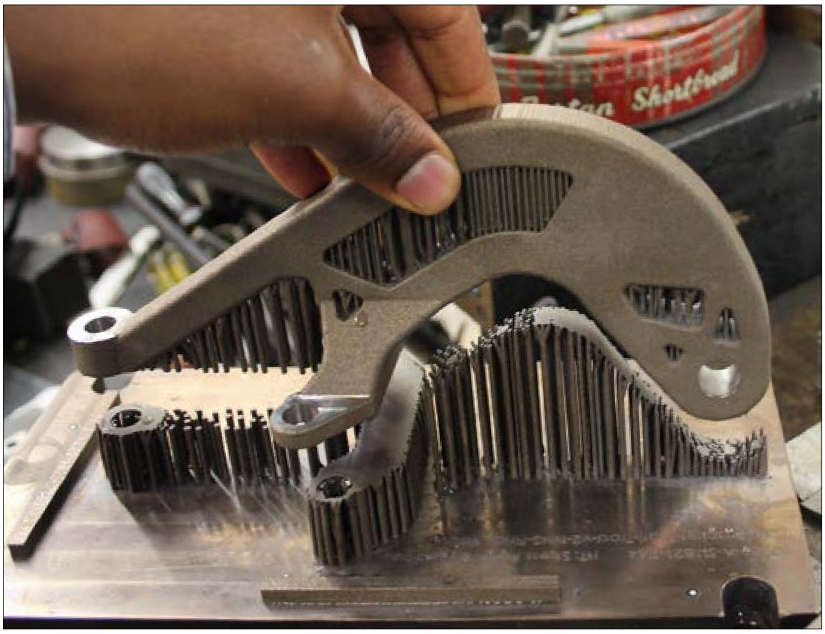

Fig. 6 The wire EDM process removes a number of the AM fixtures from the bracket

Asking these questions for our brackets led us to add 0.2 mm stock allowance to surfaces that would be cut by wire EDM. These surfaces are shown in orange in Fig. 5. The cut profiles, shown in relation to the reference datum bar, will create the shape of the final part. This step will also remove a large amount of the support fixtures (Fig. 6).

As can be seen in Fig. 6, long rectangular bars were added to the baseplate as datum references for wire EDM. They were also used to set XY alignment of the part. These reference bars are aligned with the parts rather than the baseplate, meaning the part can be machined correctly even if the baseplate is misaligned. Of course, side effects of AM such as shrinkage should be accounted for, as these could change the dimensional accuracy and invalidate the datum references. This is discussed in more detail later.

Finally, the wire cut path should be carefully defined with thought given to the order of operations. This should prevent additional geometries such as datum bars from being damaged or accidentally cut before they need to be used by another process.

Milling preparation

To mill these brackets, we used a 5-axis machine with standard clamping and PowerMILL CAM software to generate the toolpaths for milling the surfaces and drilling the holes. 'Gentle' machining was specified for the part as we were uncertain how the support fixtures would react to machining. The fixtures might be strong enough to withstand machining loads in the z-axis but might not be strong enough when the loads are in the x-axis or y-axis. The main considerations that were of concern to us in relation to machining were:

- Is there enough additional stock material to cut through without damaging the part?
- What is the material condition and will it cut properly?
- What machine tool and cutting tools are necessary/available?

- What setups are necessary?
- How will the parts be held (work holding)?
- What cutting strategies (tool-paths) are necessary?
- Are the toolpaths safe and collision-free?
- What data are necessary for the machine?

We machined the interfaces and holes while the part remained attached to the baseplate. These surfaces are highlighted in yellow in Fig. 7. For the holes, we added 1.5 mm of additional stock and 1 mm was added to the planar faces.

AM preparation
Preparing for AM in this multi-stage process typically requires numerous iterations. The interactions of the processes culminate here because this is where every aspect needs to come together and be accounted for before the build starts. If anything needs to be changed after the part has started or finished building, this could mean scrapping the part. In order to prepare for AM and its interaction with the other processes, we asked ourselves the following questions:

- What is the build orientation of the parts?
- How should parts be nested (i.e. positioned relative to one another)?
- How does nesting affect dosing factors and powder utilisation?
- What type of recoater blade is to be used and how will that affect the parts and support fixtures?
- What additional geometries need to be built - datum references, travel specimen etc?
- What type of support fixtures are needed and where? Important considerations when designing support fixtures include the type of process and material, the size of the part, managing heat/distortion/stress, melt pool stability and managing part geometric fidelity

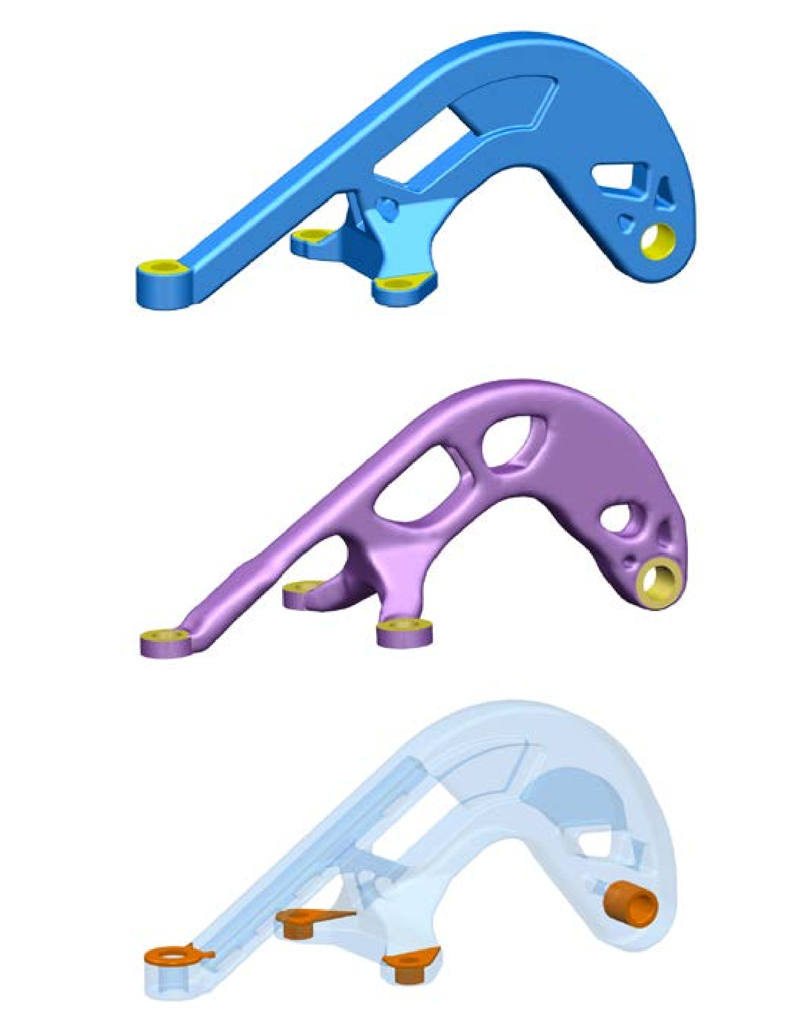

Fig. 7 Net shapes with the surfaces that require machining shown in yellow and additional stock material in orange

- How will the part be exposed? Important parameters include scan strategy, laser paths/power/focus/speed
- What data format does the AM machine need?

PartBuilder, our AM preparation software, was used for orientation, nesting, fixturing, the creation of reference data points and the exposure data for the laser (slicing and hatching). It was also used for exporting build data specific to the machine used. The process plan tells us to machine Design 1 and 2 parts on the baseplate, so this means the part orientation is already constrained. Due to the size of the parts and the build envelope of the machine we used, only two parts could be placed on the platform. This determined the part nesting.

Thinking about machining issues such as clamping and cutting tool access forced us to use two half baseplates, of 250 x 125 mm each, instead of the standard single 250 x 250 mm baseplate. This allowed us to build each part on its own plate, simplifying heat treatment, machining tool access and clamping as well as workpiece handling.

The next task was to create general support fixturing. PartBuilder can determine where fixtures are necessary, so we used it to automatically generate the majority of support fixtures (approx. 80%) required for the build (Fig. 8). For this build, we were working with titanium, a hard recoater blade and machining on the baseplate. However, the software cannot yet account for these variables. This requires manual intervention from an engineer with an understanding

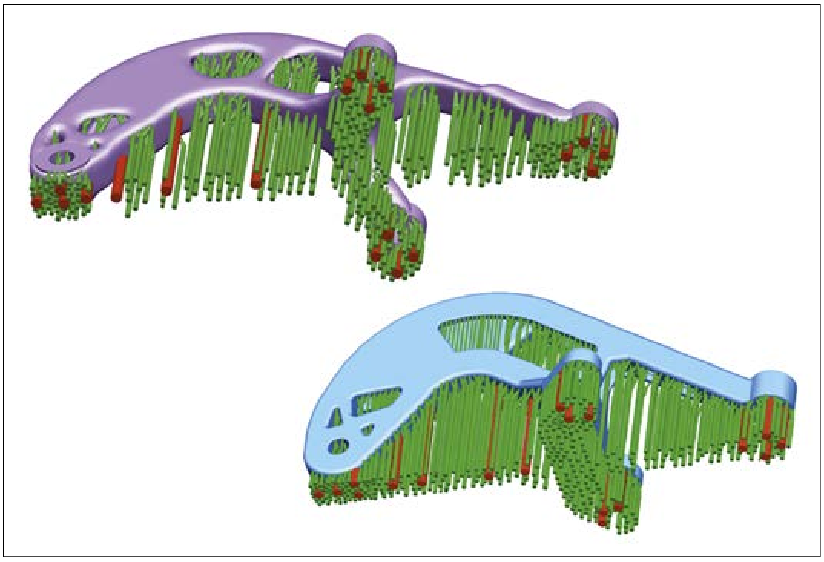
Fig. 8 Fixtures are added as the parts are prepared for additive manufacture

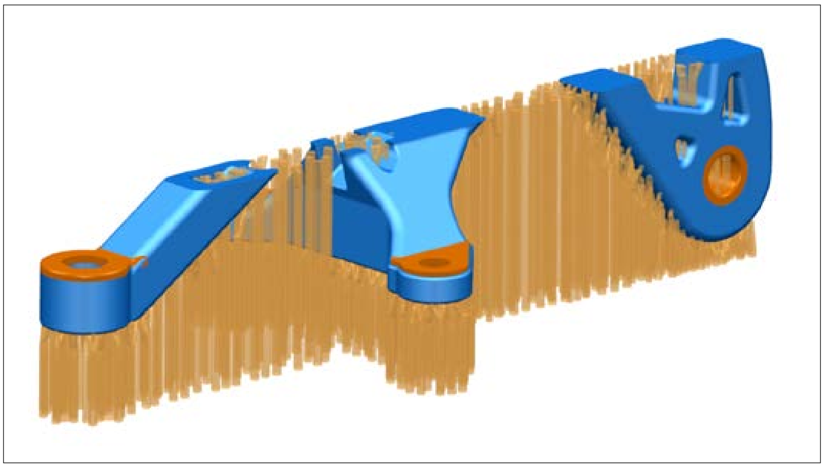
Fig. 9 Managing recoater contact and distortion

of the nuances of both AM and the subtractive processes to identify where problems could occur and take measures to prevent them.

Anticipating distortion and how this might impede the recoating action, special bracing support fixtures were added to critical areas (Fig. 9). At the layer height shown in Fig. 9 there were a number of individual overhanging material islands which had to be treated independently to prevent distortion. The number and size of exposed sharp edges in the recoating direction changes as the part is exposed and before individual islands of material join up. Therefore, additional cylindrical fixtures were added at key locations (the red columns in Fig. 8) to counteract cutting forces during machining.

Work holding preparation

Work holding for each set-up and each process should be given particular attention in order to avoid unexpected surprises. For each process, sub-process and their associated set-up, we needed to consider the following:

- What type of work holding/clamping do we need and where do we put them?
- Do we need to build additional geometries using AM, specifically for clamping?
- Do we need to design and fabricate special machining fixtures?
- What impact do these additions have on upstream and down-stream processes?

For machining Designs 1 and 2, only a single setup was used to machine all the holes and interfaces on the 5-axis milling machine. The baseplate was directly used for clamping, so no additional preparation was necessary.

It is also important to think about the sequence of operations with respect to work holding, as compromises could be necessary. For example, the nesting decision for AM will affect how and where clamps for milling can be placed if the baseplate is to be used. In this case, nesting should not interfere with clamping surfaces. Subsequently, and more importantly, when a part is separated from its baseplate, special care should be taken to ensure that clamping surfaces are available on the part and that there are surfaces appropriate for use as datum references. If the part has to be separated from its baseplate and is not a regular prismatic shape, then special machining fixtures will be required to hold the part.

Other processes

The remaining ancillary processes include heat treatment, surface treatment, manual fixture removal and any other steps identified in the process plan. Though they may not require any preparation, it is important to consider them and ask what additional geometry or data is necessary for these processes, and how should important information and work instructions be communicated.

Our process plan called for vapor blasting of the surfaces, so we had to communicate that machined surfaces should be masked to prevent damaging the as-machined surface finish.

The NNS that emerged for the Opti-Trad bracket after all the preparation steps had been followed is shown in Fig. 10. The final platform layout after nesting is shown in Fig. 11. Bracket Designs 1 and 2 are now ready to be built.

Preparing design 3

As stated earlier, the Opti-Trad bracket is slightly heavier than the original bracket after applying traditional CAD design techniques. Going further than simply using the optimised bracket as a shape inspiration, stricter MfM and manufacturability considerations were applied while maintaining the weight saving benefits of the topology optimised bracket. To arrive at this particular design, we started with the Opti-Trad bracket (as shown in Fig. 2, bottom) and changed the manufacturing objective from *machine only the interfaces and holes while on the baseplate* to *machine all surfaces*. This strict requirement means that all geometric elements added during the preparation stage must be removed. It also highlights the need for compromises in the part design stage to account for the limitations of the AM process.

Design changes were necessary to account for some of the manufacturability concerns. The purple additions shown in Fig. 12 are extra geometries constructed to eliminate the need for support fixtures in those areas as well as to close hollow cavities, which will be impossible to clean up.

The final result is shown in Fig. 13. Accounting for performance, shape and mass gains originally obtained by topology optimisation achieves a 19% mass reduction compared to the original machined-from-solid part. Adding a high manufacturability constraint forced us to think even more about the end to end processes. The final platform layout after nesting is shown in Fig. 14. Bracket Design 3 is now ready to be built.

A question asked when casting was maturing and which is very relevant today about AM is: can we define best practices/rules for experts and non-experts to make effective and impactful changes to part geometries without compromising part fidelity or negatively impacting manufacturability?

The activities performed before the AM build began, along with supporting software, are summarised in Fig. 15. This process includes design, topology optimisation, simulation, planning and all preparation activities.

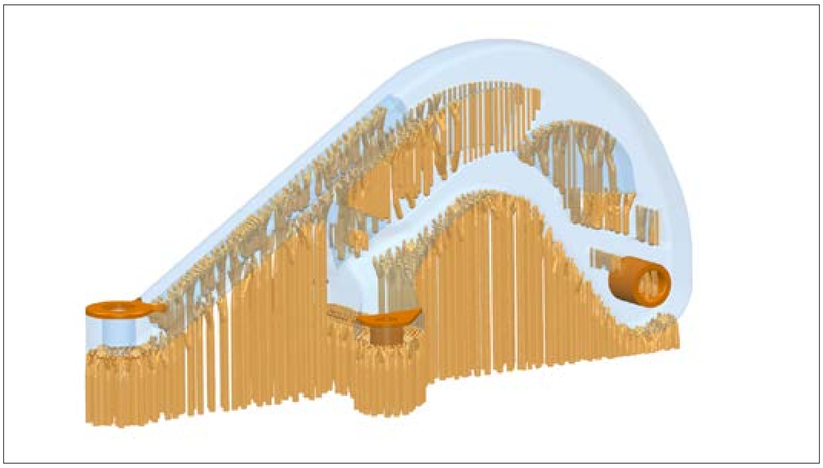

Fig. 10 Final deposition model for Opti-Trad including all transformations

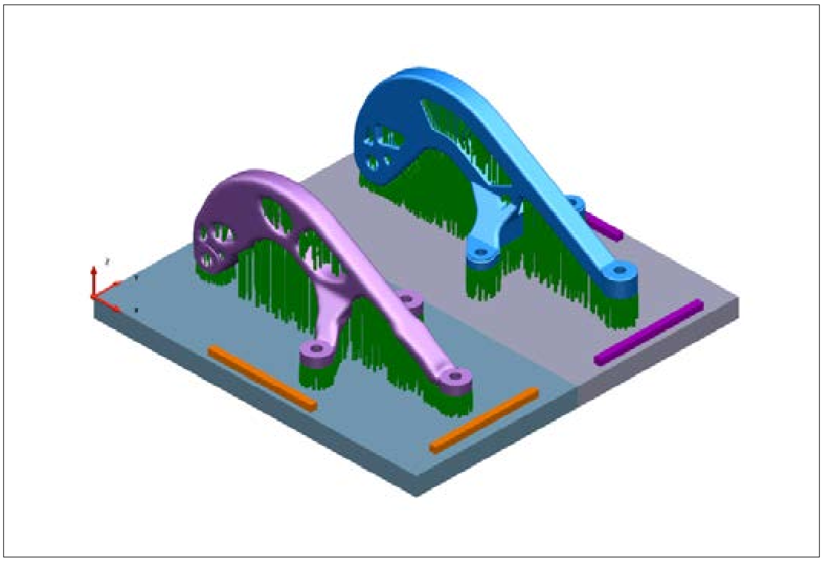

Fig. 11 Final platform nesting with datum blocks for wire EDM and support fixtures for additive and subtractive

Fig. 12 Design changes to improve manufacturability

Fig. 13 Design 3, mass optimised with strict manufacturability considerations

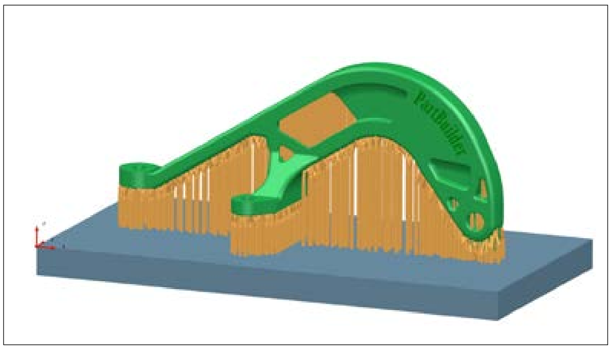

Fig. 14 Final deposition model for Design 3 including all transformations

Production

Production of the brackets revolved around physical actions to realise the process plan. Actions included setting up each machine, obtaining appropriate datum references and alignment, performing the necessary actions such as cutting or scanning until the final products emerged. Figs. 16-26 show the production stages for Designs 1 and 2 only.

Additive build and heat treatment

- AM machine set-up: manually installing and checking flatness of baseplate, manually cleaning the glass aperture of the laser, manually filling in powder and filling in 'holes' between the baseplate (Fig. 16)
- AM build and reveal: manually removing powder with a vacuum to reveal the parts (Fig. 17)
- Post heat treatment: brackets after heat treatment with a plastic mock-up of the original bracket (Fig. 18)

Metrology and machining

- 3D scan inspection: controlling part dimensions with 3D optical scanning (Fig. 19).
- Machine setup & Fixturing: Setting up the milling machine by defining part position and alignment, clamping and programs before cutting (Fig. 20).
- Machining & On-Machine Verification/Inspection: Machining interfaces and holes, verifying and controlling part dimensions (Fig. 21).

Wire EDM

- Machine setup & Fixturing: Setting up the wire EDM machine by defining part position and alignment before cutting (Fig. 22).
- Wire EDM to separate the part from the baseplate, remove the support fixtures and achieve final part dimensions on some surfaces (Fig. 23).

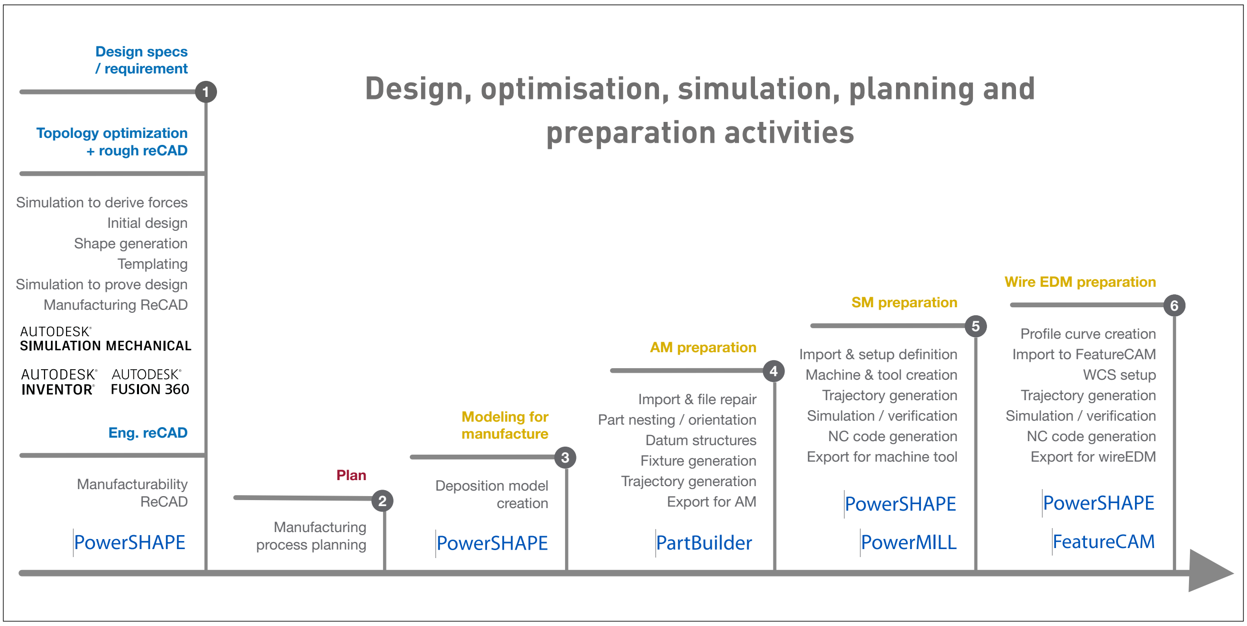

Fig. 15 Schematic of design, optimisation, simulation, planning and preparation activities used

Fig. 16 Machine setup. Top left, manually installing and checking flatness of baseplate; Top right, manually cleaning the glass aperture of the laser; bottom left, manually filling in powder; bottom right, filling in 'holes' between the baseplate

Fig. 17 Manually removing powder with a vacuum cleaner to reveal the parts

Fig. 18 The brackets after heat treatment with a plastic mock-up of the original part

Fig. 19 3D optical scanning

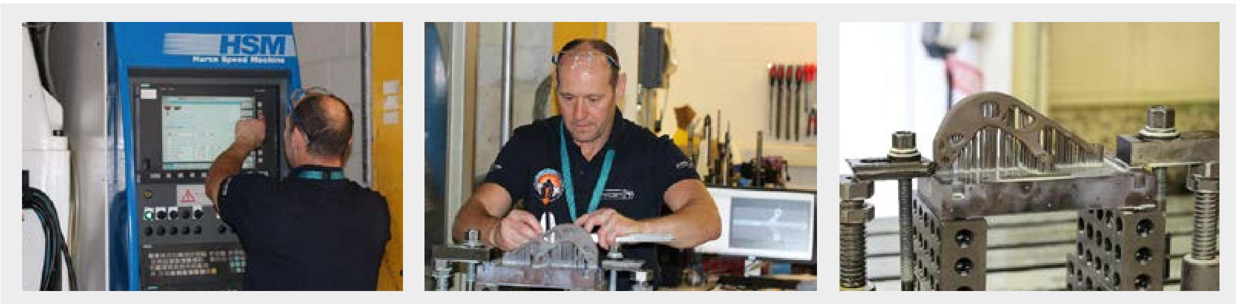

Fig. 20 Machine setup and fixturing: setting up the milling machine by defining part position and alignment, clamping and programs before cutting

Fig. 21 Machining interfaces and holes, verifying and controlling part dimensions

Fig. 22 Wire EDM setup and fixturing: setting up the wire EDM machine by defining part position and alignment before cutting

Fig. 23 Wire EDM to separate the part from the baseplate, remove the support fixtures and achieve final part dimensions on some surfaces

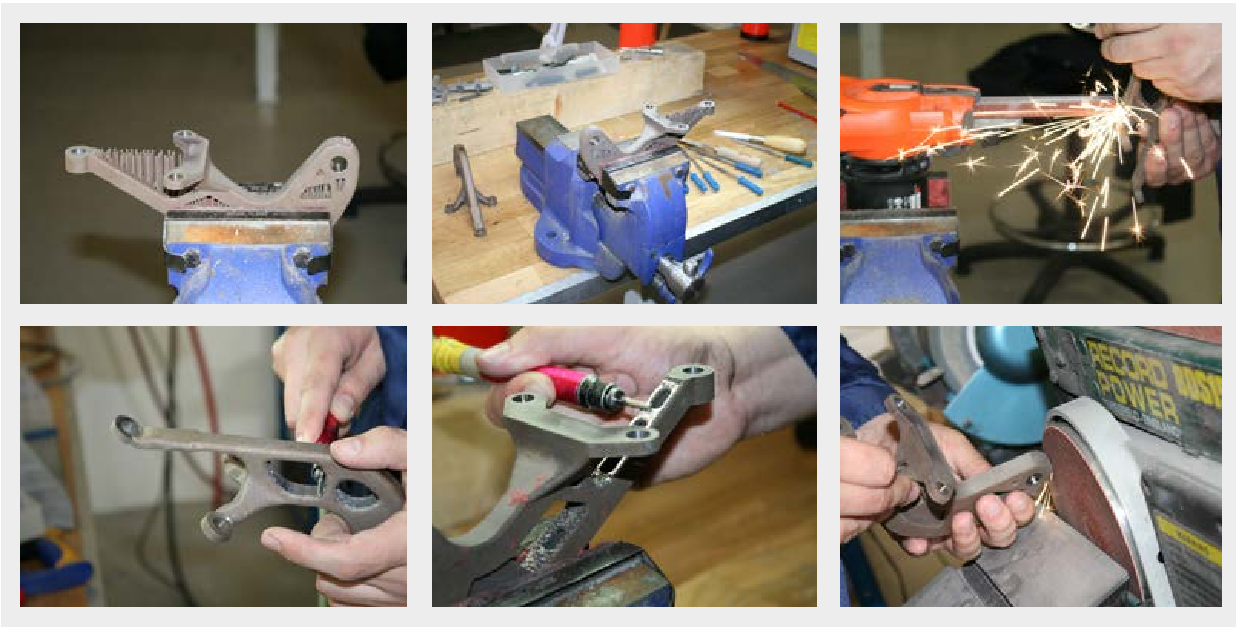

Fig. 24 Clean-up: manual fixture removal and clean-up of witness marks

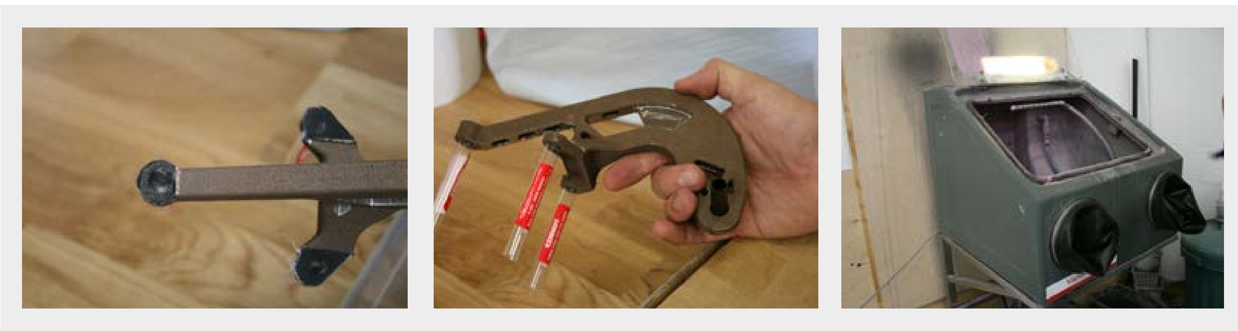

Fig. 25 Vapour blasting to produce a uniform surface finish. Machined surfaces and holes are masked to protect them

Clean-up and surface treatment

- Manual fixture removal and clean-up of witness marks (Fig. 24)
- Vapor blasting to produce a uniform surface finish. Machined surfaces and holes are masked to protect them (Fig. 25).

The final parts are shown in Fig. 26. The activities performed during the production/execution stage are best summarised by Fig. 27, along with the supporting software tools used.

Fig. 26 The final parts

Reflections on the process

Our experience in designing, optimising, preparing and manufacturing these brackets has left us with many topics to discuss and reflect on. The following examples illustrate the need to consider how seemingly small decisions taken at each step of the process can affect the later stages. Until we can freely share and understand the black arts and artisanal secrets of AM, the process will not become a standard technique within the manufacturing family alongside casting, forging etc.

Metrology and quality assurance

Following the build, we heat treated the parts in a vacuum to reduce residual thermal stresses. When the parts were inspected with conventional touch probing and optical 3D scanning, this revealed non-uniform shrinkage in some areas. Scanning also confirmed the extent of delamination illustrated in Fig. 29. This could have been as a result of the scaling factor used and/or the heat treatment. Regardless of the cause, one thing is clear – at this stage in the development of metal AM technology, we need to introduce more measurements and quality operations into the production process in order to understand what is happening to the part and how each process affects the shape. Since we only scanned these brackets fully after heat treatment, we do not know what the geometric fidelity was like immediately after building. Additional measurements steps before heat treatment and after machining would have allowed us to track the shape changes more accurately and adjust the downstream processes accordingly. Without absolute certainty, cutting the parts could have resulted in costly damage. Looking at the planarity of the three holes shown in Fig. 28, had we machined without first verifying positions, these features would have been incorrectly machined.

Until we are at a point where we can reliably predict the shape of parts, such measurement activities are critical. We must follow quality assurance guidelines offered by committees formulating manufacturing standards as well as discussing openly how to account for the peculiarities of Additive Manufacturing.

AM build: issues observed

Currently, support fixture generation is one of the black arts of metal AM. Depending on the material, only the

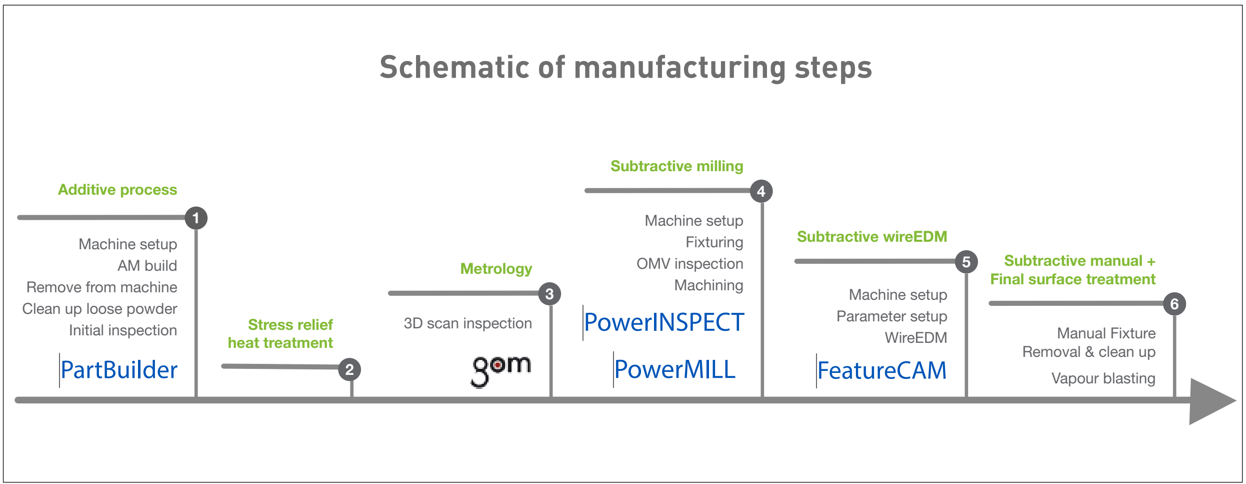

Fig. 27 Schematic of manufacturing steps from additive build to machining and finishing

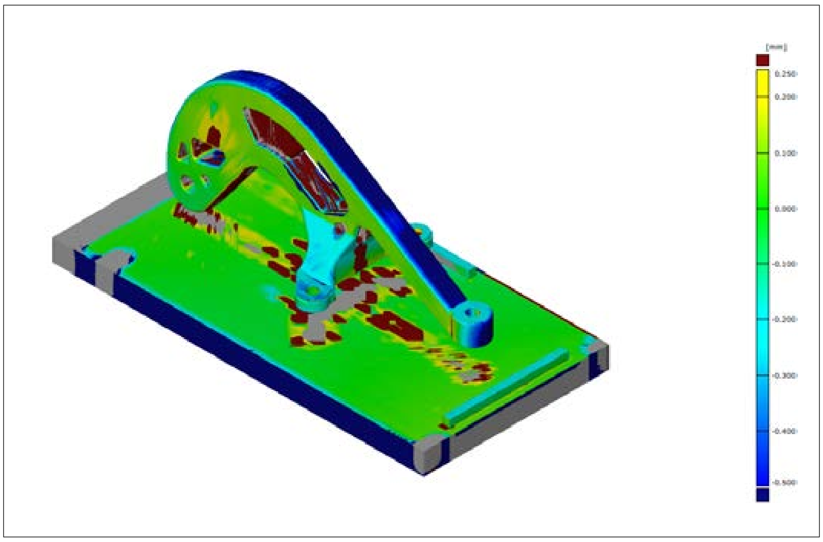

Fig. 28 The 3D optical scan results

most experienced and knowledgeable AM practitioners are doing this successfully and even they have no way of knowing whether what they have prepared is going to work. At Delcam, we are acutely aware of this issue and it is in the industry's interest to find a pragmatic solution. Despite considering a number of potentially problematic areas during the preparation of these brackets, we still encountered problems. "Titanium always finds a way to surprise" is a statement we hear often.

The support fixtures of our as-built parts were generally sufficient except around the back pivot hole where a separation between the part and its support fixtures can be seen (Fig. 29, bottom). This could be the result of high residual thermal stresses due to the shape of the part, uneven cooling rates and/or the large mass of material in this region. This fault had a number of downstream impacts. Firstly, a cosmetic error in the form of a horizontal line was observed on the Opti-Opti part (Fig. 29, top). Secondly, the part physically moved, directly affecting milling and wire EDM datum references as well as the positions of important features.

Additionally, consultation with the machine operators during the preparation phase raised questions about the efficacy of the trees and column support fixtures. The operators were not confident that they would be strong enough to withstand the machining loads while the holes were drilled into the solid material. As a compromise, the holes were undersized in the NNS before building, meaning that they could be milled to the correct size rather than drilled into the solid material. Additional stiffening fixtures were also added after understanding the operators' concerns. This is particularly important because using block supports is commonplace in AM, as is the practice of removing features such as holes to achieve more accurate positioning and tolerances. If parts are to be machined while still on their baseplates, the strength of these supporting structures should be assessed and provisions made to account for machining loads.

Compensation factors: build accuracy

How accurately parts are built depends on a number of factors. Through this process, we have uncovered a number of relevant factors for which published information is scarce.

Firstly, as a part is built, powder is transformed from loose powder to molten metal before solidifying. In each stage, there is a negative volume change that occurs, called shrinkage. This is a known thermal phenomenon. To counteract this, shrinkage compensation factors (SCFs) can be applied in order to change the nominal dimensions of the entire part. In casting there are established SCFs that are applied, depending on material, geometry and other considerations. However, as the complexity of cast parts increases, application of SCF becomes more complicated and requires careful consideration. Generally, experience, some guidelines and trial and error are frequently used. The emergence of casting simulation software to predict the extent of shrinkage and other thermal effects is helping to give more insight. It is not yet clear whether the factors and methods used in casting are directly applicable to Additive Manufacturing.

Currently, the shrinkage compensation factors used in AM and how they are determined is one of the other black arts and artisanal secrets. Usually the assumption is that there is homogenous shape deviation for a particular direction and therefore only a single SCF is applied to the nominal dimension in a given direction. This method is problematic because the effects of different geometric features, their sizes, locations and orientations are not taken into account. SCF based solely on the thermal expansion characteristics of additive materials are known to be insufficient when dealing with complex AM parts.

For shrinkage, the solution might be, as proposed by Ning [4] ,to compensate by changing process parameters or improved simulation and modelling tools, or applying careful distortion compensation. Whatever the solution, we need better understanding of the problem before new methods can be developed to rectify it.

Secondly, depending on how the machine has been calibrated, part dimensions can vary. Calibration factors, typically applied to XY dimensions per layer, depend on the machine and the defined build tolerance. Factors can also be varied from build to build, depending on the as-built dimensional requirements of a part. Since the part can be built slightly over- or undersized or exactly to CAD, special care and attention must be paid to dimensional accuracy requirements so that the part is built within tolerances.

Thirdly, the build strategy (and therefore the path that the laser follows as it builds the external and internal boundary contours of each layer) can have a substantial effect on the dimensional accuracy of the part. As each line is traced and melted by the laser, there is an effective welded track width. On these boundary contours, the part dimensions can be slightly over- or undersized or exactly to CAD depending on the build strategy and a parameter referred to as beam offset or beam compensation. Again, special care and attention must be paid to dimensional accuracy so that the part is built within the required tolerances.

Knowing about and discussing these important compensation factors can have a marked impact on the achieved dimensional accuracies of parts. For a machinist, for example, knowing the condition of supply of a part is paramount if they are to perform their precision finishing task well.

Part nesting: which way is up?

Everyone in the chain has their own priorities and is thinking about their individual step in isolation. In these bracket examples, the nesting angle of the parts (Fig. 30) was changed because the AM machine operator was not sure if he had enough titanium powder to complete the job. Consequently, the operator rotated the part 180° around its vertical axis as a means of bringing the highest portion of the part closer to the start of the recoater blade's course. This change was not communicated and therefore the process plan was not updated.

Such changes are commonly made by machine operators when powder levels are running low. After all, titanium powder is expensive and having unnecessary powder stockpiles represents a substantial investment for sub-contractors. This important build decision was

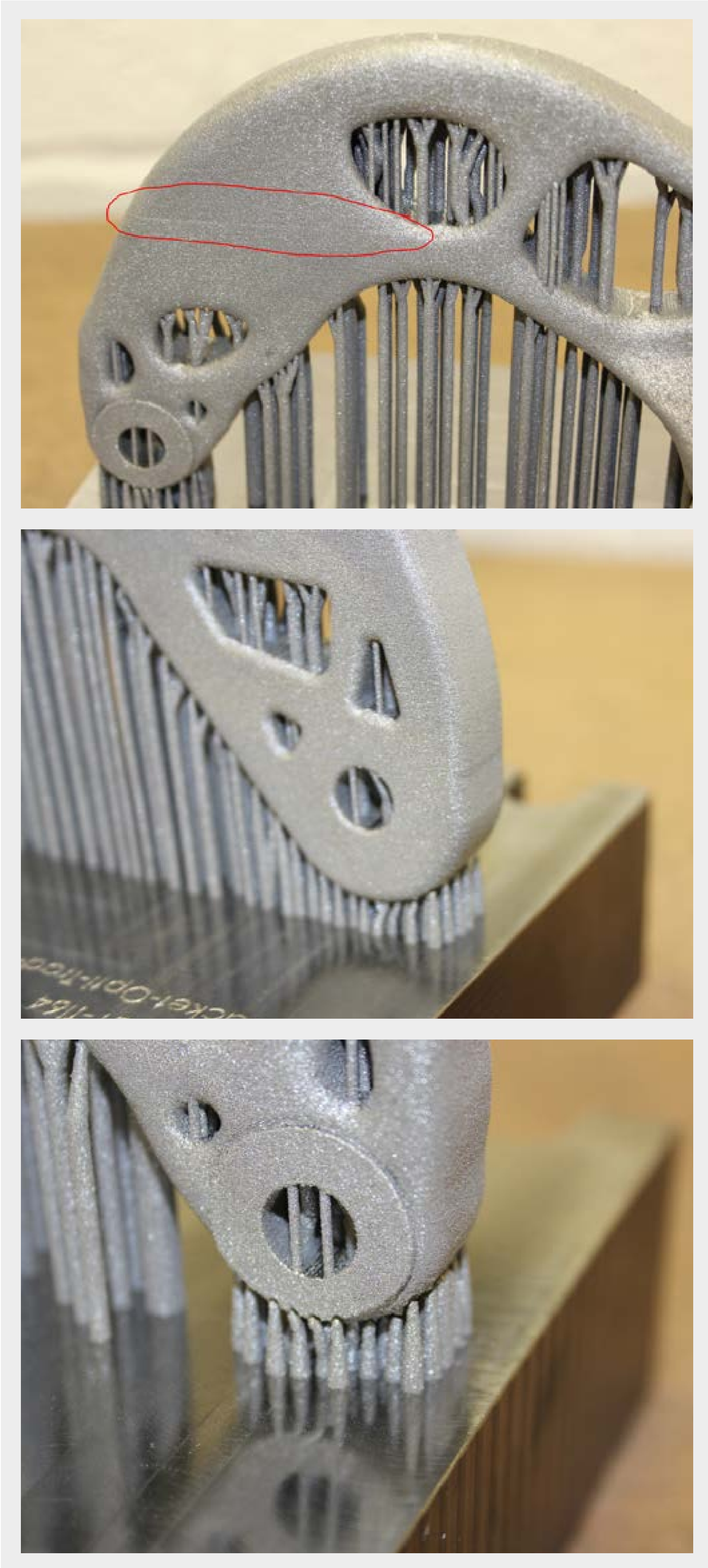

Fig. 29 Build issues observed

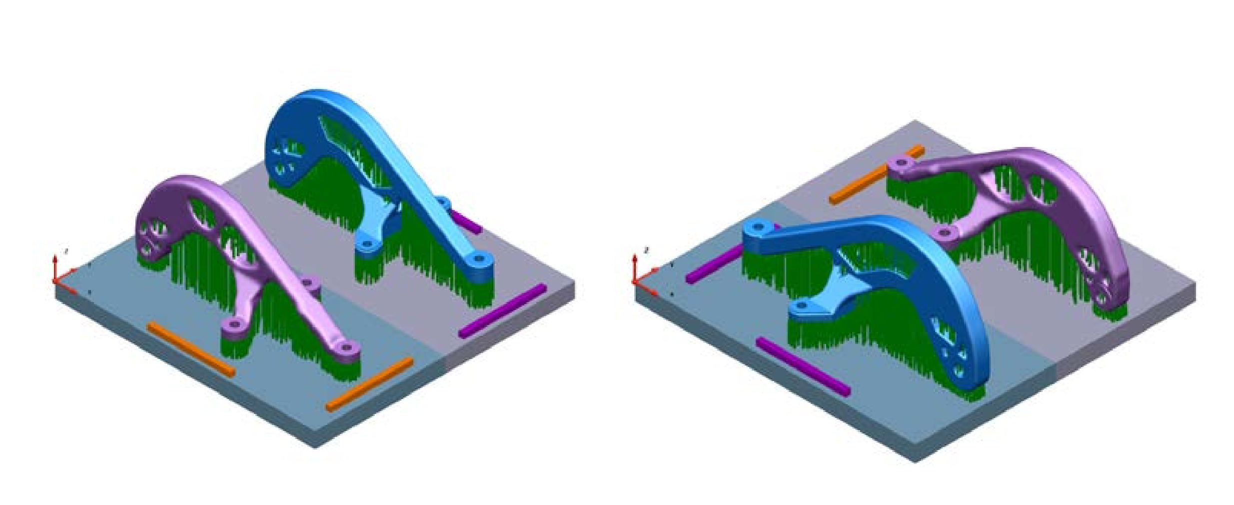

Fig. 30 Rotated parts, as-prepared vs. as-built

taken without consideration of the downstream processes and resulted in a number of issues.

First, during machining, surfaces that were required for clamping and work holding were noticeably reduced (Fig. 31). Compromises had to be made while setting up the milling machine to rectify this unexpected issue. The risk of collisions between the cutting tool and the clamps was suddenly increased because the CAD file and the machining work instructions no longer match the physical part.

Second, during preparation, it was anticipated that a hard recoater blade would be used. As such, if there was any distortion, there might be collision between the recoater blade and the part. To prevent this, special bracing support fixtures were added. During manufacture, however, a soft recoater blade was used to ensure a high probability of a successful build (the tree support fixtures used were not known to the AM machine operator and he had doubts about their effectiveness). Consequently, the parts were over-fixtured, resulting in additional material needing to be used and later cleaned up.

It is clear that, in any build project, the project manager (what we call the orchestrator) and the process planning team must be well versed in the ins and outs of AM and the other manufacturing processes. It is important to know and understand what the concerns are of each actor in the supply chain. It is only then that they would be able to mitigate any potential problems. Otherwise the actor will only do what makes their own lives easier, which may or may not be in line with the process plan.

The concern of the AM machine operator and his decision stemmed from the fact that he has no reliable way to know and effectively control powder use. There is a lack of tools to determine how much powder will be required for the entire build and to properly cover the exposure area of each layer without over or under dispensing powder. This is the dosage factor and some of the advanced systems available today are still only reactive, meaning that they compensate if powder is over or under dosed. Preparation software, such as PartBuilder could potentially be used to determine setpoints for the dosage factor of each layer and thus estimate powder need. Conversely, if the AM slice formats and machines were updated to support such setpoint parameters, this could improve the estimation of powder required for a build. Until the machines are able to do this or machines with powder conveyor systems are more commonplace, the machine operators have to guess and use their experience to determine what dosage factors to apply and when. Compounding this problem is the fact that the machine we were using, a top-of-the-range metal powder bed machine, cannot recover unused powder from its overflow bin during a build. Running out of raw material mid-build could mean the part would have to be scrapped if an identical batch of powder cannot be obtained. When a suitable powder is available, stopping the machine to restock powder levels can cause cosmetic errors, such as the visible horizontal line that formed across our part (Fig. 29). The commercial impact of lost production time and rebuilding parts could be costly.

Datum references and education

Additive parts are near net shapes and machining such parts is akin to machining castings or forgings, processes that also produce near net shapes. On such shapes, there are many ways to obtain datum references for setup and part alignment, but typically it is best if datum surfaces are features on the part. This ensures the highest reliability of the datum references. There is a lot of thought that goes into defining datum references and the associated work holding. These two important aspects are sometimes overlooked for AM and, even when they are not overlooked, they are incompletely provided. The cost associated with such oversight can be shocking.

For datum references, an observed practice in AM is to add blocks which are additional geometries built directly on the baseplate as seen in Fig. 6. To machine these brackets, we followed this same practice to see how different actors in our supply chain would deal with them.

For machining, we used Delcam's Advanced Manufacturing Facility in Birmingham, UK. The operators there refused to use these surfaces because they did not trust them. This was simply because they were not attached to the parts and this was an unfamiliar technique for them. The operators involved have not been exposed to many additive parts. They simply used their tried and trusted conventional methods i.e. touch probing the holes in the part and orthogonal surfaces for alignment and positioning to achieve the best fit to CAD. For wire EDM, these blocks were used for alignment and positioning without question. The operators here are relatively more familiar with cutting additive parts.

Where possible, any part that is to be produced by AM and further processed with other conventional techniques should ensure that proper work holding and datum references are considered. If the part to be machined is non-prismatic, one benefit of AM is that datum blocks could potentially be added during preparation and built with the part. Once the blocks serve their purpose, they will need to be removed.

It would go a long way in fitting AM into the manufacturing family if we all spoke a familiar language. Where necessary, existing geometric dimensioning and tolerancing standards (GD&T), such as ASME Y14.5, should be applied to minimise misinterpretations and mistakes.

Traditional supply chain actors may never have processed additive parts, so they will simply apply conventional thinking and familiar methods. Decisions taken during preparation must either be carefully communicated with them or already be in line with what they expect to see. As we grow as an industry, it is to the benefit of the existing manufacturing actors and the new actors to educate each other.

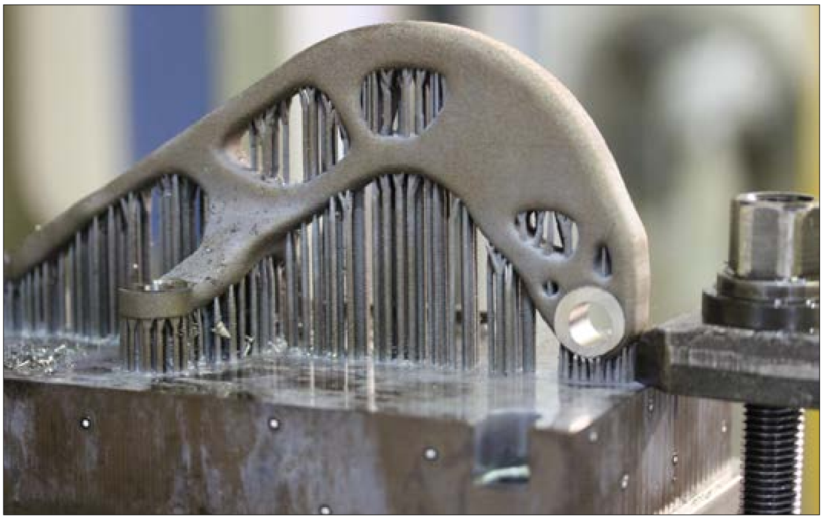

Fig. 31 Here the clamping area for the build plate has been noticeably reduced

Hardware: build volume

The quoted AM machine build volume, particularly the build height, is not a static value. Depending on the material that is to be processed, the thickness of the baseplate might need to be changed to prevent distortion when working with bulky titanium parts for example. This increase in baseplate thickness reduces the effective build height of the machine. Properly communicating this change in size to customers will go a long way to preventing unwanted surprises such as preparing a large part only to find out that the maximum part height cannot be attained due to the thicker baseplate. Doing this will increase transparency between machine vendors and machine users.

Predictability & repeatability

There are many variables to consider when working with metal additive processes from planning and preparation decisions to laser exposure parameters, material sourcing, thermal impacts and the limitations of AM machines. These factors together have a marked effect on the predictability and repeatability (P&R) of the as-built additive parts. Without measurable P&R, more uncertainty is introduced for later stage processes like wire EDM and machining. Even if problems are not easily corrected, being able to consistently reproduce and quantify them is very important.

Currently many AM practitioners, ourselves included, follow a trial and error approach. First build a part, see what goes wrong and apply lessons learnt to improve the next build. To quote Steve Hobbs, Development Director at Delcam, "It's not acceptable to make four parts and get only one good one. We need to be able to do better than that." This is not only wasteful and inefficient, but it represents a huge obstacle to taking AM beyond rapid prototyping. It is clear that, as an industry, we need more effort and tools to identify potential problems.

It is encouraging to see groups like 3DSIM, Additive Industries and Sigma Labs [5] working on addressing known quality assurance problems across the AM process chain. Indeed, we do not have years to wait for answers to these issues. We must take a realistic look at the problems to come up with pragmatic, reliable solutions for them. The lack of process understanding and other issues precluding metal AM from widespread use are difficult enough, but, when we add the complexity of multi-process production, the picture appears daunting. It is going to take an industrial effort to realise the true potential of this exciting technology. Everyone from process experts, planners, designers, machine makers, CAD-CAM vendors, supply chain actors and standards bodies are going to have to play their part. From what we have learnt, we know that Delcam and Autodesk also have a part to play.

Software

Going through the complete chain, from design and simulation to planning, preparation and production, shows that the current tools can enable additive and subtractive manufacture of quality metal parts. There is still work to be done to improve some of the workflows along the data chain to make them more coherent and seamless. This coherence is essential in order to increase productivity and quality assurance. We want to give practitioners the ability to realise their designs and ideas. If those designs are to reach production, they must be verified and prepared digitally in a safe environment. They should be able to predict problems and resolve them before ever going onto a machine. It is better that they see the failure in a software environment than in real life, where costs and consequences are much higher.

Thinking beyond AM, CAD and design, which are being covered by the 3D Manufacturing Format Consortium (3MF), it raises the question: what about the interaction of AM with other manufacturing processes? Drawing an analogy with the building and construction industry and the revolution seen there with the widespread use of BIM (Building Information Modelling), the author wonders if manufacturing, including additive, needs its own information model?

Conclusion

We started by looking at the role of software within the process chain. By working with various bracket shapes from design all the way through to manufacture and post-processing, we explored what is currently possible with the available tools and processes at our disposal. The potential of how software can be used to enable the additive and subtractive manufacture of production quality metal parts is discussed and the primary conclusion that we can draw is that there is still some work to be done if Additive Manufacturing is to reach its full potential. Everyone from process experts, planners, designers, machine makers, CAD-CAM vendors, supply chain actors and standards bodies are going to have to be involved to truly enable this exciting technology.

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Delcam

Delcam is one of the world's leading suppliers of advanced computer-aided manufacturing (CAM) software. Headquartered in Birmingham, UK, Delcam's range of design, manufacturing and inspection software provides automated CAD/CAM solutions for a variety of industries, ranging from aerospace and automotive to toys and sports equipment. The company has more than 30 offices worldwide and approximately 700 employees. www.delcam.com

Autodesk

Autodesk is a leader in 3D design, engineering and entertainment software and acquired Delcam in 2014 as part of its expansion into manufacturing and fabrication. From additive to subtractive manufacturing and other related technologies, Autodesk now has the pieces needed to truly realize the Future Of Making Things for everyone from a maker to a major manufacturer. www.autodesk.com

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Renishaw: Global Solutions Centres offer end-users an alternative route to develop new metal AM applications

This year the UK's Renishaw plc will further expand its global network of Solutions Centres for metal Additive Manufacturing. The centres are designed specifically to provide a secure environment for end-users to trial the company's metal powder bed fusion technology and establish the viability of a project before committing to major capital investments. *Metal Additive Manufacturing* magazine's Nick Williams reports on a recent visit to Renishaw's flagship Solutions Centre in Stone, Staffordshire.

Headquartered in Wotton-under-Edge, Gloucestershire, UK Renishaw plc is one of the world's leading engineering, science and technology companies, with more than 70 offices in 35 countries employing over 4,000 people. The company is also an established and high profile metal Additive Manufacturing machine manufacturer.

It was following the acquisition of MTT Technologies Ltd (MTT) in April 2011 that Renishaw made the move into metal AM equipment production. Upon completion of the acquisition MTT was incorporated into a new Additive Manufacturing Products Division at Renishaw with a specific focus on the development and further commercialisation of metal AM technologies. MTT's heritage stretches back to the earliest days of the commercial development of metal AM with the first sales of systems in the UK in 2004. Since the acquisition the division has grown from 35 staff to over 250 AM employees.

The acquisition of was billed as a natural fit for Renishaw, most notably because of the company's leading market position in the world of metrology and process control, both complementary and necessary areas of expertise for anyone looking to enter the market for metal AM component production. At the time of the acquisition, Renishaw was already a user of AM technology for the manufacture of dental restorations, bringing both an understanding of the status of the technology and an awareness of its challenges and the potential.

Fig. 1 Rows of Renishaw AM250 machines building parts for customers in the customer builds and applications area in Stone, Staffordshire

Fig. 2 Robin Weston, Marketing Manager for Renishaw's Additive manufacturing operations (Image Renishaw plc)

Fig. 4 A Renishaw Equator™ comparative measurement and inspection system in the laboratory at the Stone Solutions Centre

Fig. 3 An Instron tensile testing machine in the laboratory at Renishaw's Stone Solutions Centre

When *Metal Additive Manufacturing* magazine visited the Renishaw facility in Stone, Staffordshire, in January it was nearly five years since the acquisition and over this period the company's AM operations have experienced dramatic growth. It was also a year to the day that the company acquired the building that is now home to the Renishaw's Additive Manufacturing operations. Alongside Stone, the division is supported by a large group of development engineers at the new Renishaw Innovation Centre at Wotton-under-Edge and by software teams in Pune, India, and manufacturing teams in Cardiff, Wales. The Solutions Centre in Stone encompasses the division's offices and R&D facilities and covers some 9000 m^2 of floor space.

The role of Renishaw's Solutions Centres

Renishaw's strategy for the development of its AM business is the establishment of metal AM solutions centres worldwide. Whilst not all will be the size of the facility in Stone, they will all serve the common purpose of providing an environment for potential and existing customers to develop and prove the viability of a specific metal AM application in a secure, confidential environment with the close support of Renishaw's technical experts.

To this end, the Stone facility today operates as a fully fledged metal AM manufacturing and development centre. Walking into the impressive main metal AM production hall is in many regards a glimpse of what one imagines the factory of the future might look like (Fig. 1). In a bright and immaculately clean hall, more than 40 Renishaw metal AM machines are in operation, silently manufacturing parts from various materials including aluminium, steels, superalloys and titanium alloys. Given the production capacity in the hall and the expertise on-site, Renishaw's Stone facility could rightly be considered as the UK's largest metal AM facility.

Air quality is monitored to help understand the environmental impact of metal AM operations and powder handling is extremely carefully controlled, with dedicated storage and handling rooms for each material type. Operators, when handling powders, wear advanced protective masks with powered air filtering systems for protection from powder inhalation.

Explaining the motivation behind the Solutions Centre programme, which will see a number of additional locations opening up worldwide this year, Robin Weston, Marketing Manager for Renishaw's AM operations, (Fig. 2), stated, "For companies who want to be able to manufacture a small number of components by metal AM, a service bureau can be a cost effective solution. However, if your aim is to move towards developing in-house AM production facilities, then by using a service bureau you may only learn a limited amount about how jobs are completed. Our Solutions Centres, on the other hand, aim to address this by allowing potential customers to use our software, production equipment and testing facilities over an extended period whilst working in close collaboration with our in-house experts."

"Solutions Centres offer a way to build up your knowledge of the AM process, whilst at the same time moving potential applications closer to commercial production. At the end of the process, you can make an informed investment in AM systems knowing that they can meet your requirements. Within the Solutions Centre there is a pre-production facility that customers can use once the initial development work is complete, whilst in parallel seeking or developing an alternative supply chain," stated Weston. "R&D activities can of course be undertaken in collaboration with researchers at university centres but there is always the challenge of competing for precious machine time with other projects. In our solutions centres, the large numbers of machines available can ensure that customer projects are completed within the agreed time, budget and quality expectations. Choosing an approach will depend on the scope of the project. We often work in close cooperation with Universities and customers to combine fundamental research with application expertise to achieve a successful outcome."

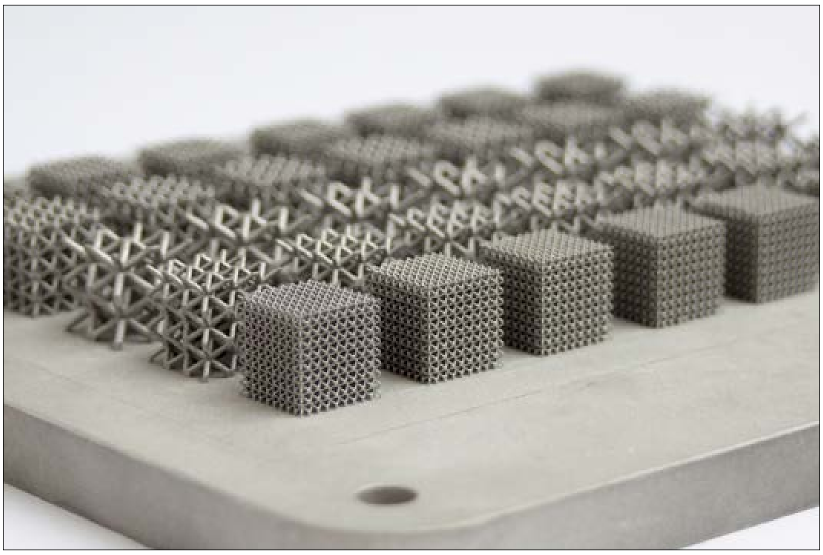

Fig. 5 Lattice test structures built on Renishaw AM250 metal AM system at The University of Nottingham, as part of the Aluminium Lightweight Structures via Additive Manufacturing (ALSAM) project (Image Renishaw plc)

In addition to the main manufacturing hall, an extremely well-equipped laboratory supports the projects undertaken at the Solutions Centre (Figs. 3 and 4). The laboratory includes SEM with EDS, high resolution optical microscopy, a state of the art Renishaw Equator gauging system, abrasive cutters and polishing equipment for optical and microstructural analysis, density and hardness testing systems and tensile testing facilities. Powder testing includes Hall flow for powder flowability, a powder rheometer for flow characteristics, a particle size analyser and a powder blender. A

Fig. 6 Worldwide locations of Renishaw's AM Solutions Centre (Image Renishaw plc)

Fig. 7 Renishaw's entry level AM250 system (Image Renishaw plc)

Fig. 8 The new RenAM 500M metal AM system from Renishaw (Image Renishaw plc)

vacuum furnace is also installed and there is also a dedicated area for the removal of components from build plates and subsequent machining operations. Dedicated private offices and meeting facilities are also available for customers to use whilst on-site that include separate secure computing facilities.

Commenting on the benefits of working closely with Renishaw's customers in such an environment, Weston stated, "The work undertaken at our Solutions Centre also gives us tremendous insight into the needs of our customers and the challenges that those new to this technology face. By being able to work in partnership on the development of a project, further opportunities for the application of metal AM in their business can be identified, thereby increasing AM's applications and market share."

In addition to the centre in Stone, Renishaw also has additional UK Solutions Centres in Bristol and Cardiff. Additional locations due to be opened during 2016 include Stuttgart in Germany, Dallas and Chicago in the US, Toronto in Canada, and Shanghai, China. The company's first Indian Solutions Centre has already opened in Pune.

Renishaw's AM machine range

The workhorses of Renishaw's AM range are the AM250 (Fig. 7) and AM400 systems. Both machines have build volumes of 250 mm × 250 mm × 300 mm, however whilst the AM250 has a 200 W laser the AM400 has a 400 W laser. Both systems have evolved from their initial configurations with enhancements that include larger filters, improved control software, revised gas flow and window protection systems. Both systems have a beam diameter of 70 micron ensuring the transferability of existing 200 W parameters to the 400 W system.

Renishaw's most significant machine launch since entering the market for metal AM systems is, however, its new RenAM 500M system (Fig. 8). As well as allowing an increased z-axis travel of 350 mm, the RenAM 500M has been specifically developed for the industrial production of metal AM parts. Upgraded to include a 500 W laser, the system features automated powder and waste handling systems to enable consistent process quality and reduced operator interaction.

Weston told *Metal AM* magazine, "A major difference between our AM250 and the RenAM 500M is that the majority of systems in the machine are developed in-house, in contrast to the AM250's extensive use of off-the-shelf components. This has not only offered far greater development flexibility, but also enabled increased in-house quality control."

"In addition to their technical capabilities, the concept and design of AM machines is evolving to meet the ever more sophisticated requirements of end-users. Our machines have a footprint that is as compact as possible in recognition of the fact that these machines are frequently used in high cost economies where space is at a premium. They are also being designed to make all operator intervention as efficient as possible. A simple example in the case of the RenAM 500M was to move the powder loading system to waist height, rather than at the top of the machine as on earlier models. The ultimate goal is to move to full automation, but to achieve this effectively it is our belief that this will require significant further advances in process understanding," added Weston.

In an area adjacent to the main metal AM parts production hall in

Stone is the development and testing area for new models of Renishaw's AM machines. Commenting on the current machine range and future machine developments, Weston stated that whilst the company is developing new multi-laser systems and systems with the next generation of process monitoring capabilities, it is not in the company's nature to rush such important developments to market. "We will not launch such a system until it is has been thoroughly tested and evaluated. As a major international technology company operating in a wide range of markets, we have a hard built reputation to protect."

Whilst most product development takes place in Stone, research and development is conducted across multiple sites where the relevant expertise exists, such as optical engineering, software, process and motion control and many other disciplines. The manufacture of the company's AM machines takes place at the 775,000 m^2 Miskin site, near Cardiff, South Wales.

Fig. 9 An intercooler for the Swansea University Formula Student (FSAE) race car, built in aluminium, using Renishaw AM250 system (Image Renishaw plc)

Italy: A success story in Metal AM

Whilst Europe as a whole is a major market for Renishaw's AM division, Italy is regarded as somewhat of a pioneer in terms of metal AM technology adoption and as such is a regarded as a unique market for Renishaw. The company's Enrico Orsi, Product Manager Italy, told *Metal AM* magazine, "Whilst Italy is a very active country in industrial and medical AM, some very large players for aerospace and energy already have manufacturing sites. A surprisingly high number of medical implants are additively manufactured and of course we host some of the world's most important motor racing teams. All of this is backed up by a history of excellence in manufacturing technology that places the country as the fourth largest machine tool manufacturer worldwide and one of the top in terms of machine usage, with over 300,000 metal working machines installed in machine shops around the country."

Orsi added, "With this background the expectations for the growth of Additive Manufacturing cannot be anything other than really positive and recent sales figures confirm this. In Italy we have a firm position in the metalworking business, not only with Additive Manufacturing technologies but also with Renishaw's other technologies that provide the link between the different stages that bring a product to life, from metal powder supply through to post-build inspection, machining setup, inspection and post-process certification. In this sense we're ideally placed to support the typical Italian mid-size machine shop, which likes to maintain the entire process in house to offer premium service to its customers."

Concluding, Orsi stated, "We're facing strong competition in Italy, no doubt. However, the whole sector is thriving. Renishaw in particular has advantages in terms of low entry barriers and significant application support, which are extremely important to new companies trying to integrate Additive Manufacturing in their machine shops and factories. The core of the Italian manufacturing sector is built on small and medium enterprises and the factors above are extra important for this type of companies, making us even better placed."

"Whilst Italy is a very active country in industrial and medical Additive Manufacturing, some very large players for aerospace and energy already have manufacturing sites"

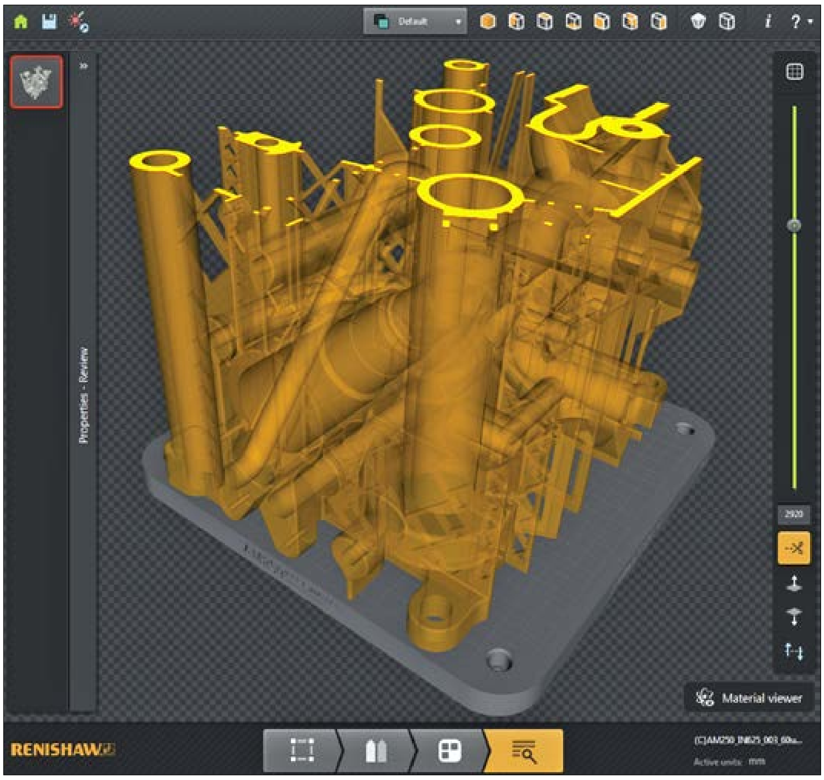

Fig. 10 A screenshot of Renishaw's QuantAM software showing a slice of a complex manifold (Image Renishaw plc)

The potential for metal AM in China

Renishaw has performed strongly in China in recent years across all its product ranges and the country remains the biggest market for Renishaw PLC. Jiandong He, AM Application Manager for Renishaw in China, continues to see great potential for AM technology in China.

> *"AM can't just be used with the expectation of getting equal or better performance compared to traditionally designed products unless there is significant topology optimisation and a re-design for weight reduction and improved mechanical properties"*

"The industry and the market trends are more or less the same as in Europe and the US, especially for the lower technical level AM adopters. with a higher level of expertise is, however, comparably less. There is limited understanding of how to design or optimise products for metal AM, or how to combine metal AM with conventional processes in solutions for aerospace, medical and tooling applications," stated He.

He also believes that expectations for metal AM in China are too high. "AM can't just be used with the expectation of getting equal or better performance compared to traditionally designed products unless there is significant topology optimisation and a re-design for weight reduction and improved mechanical properties."

Renishaw has high hopes that the nature of the services offered in its new Shanghai Solutions Centre will go a long way towards managing technology expectations and increasing process knowledge in this key global market.

Metal powder solutions

Renishaw, in line with other machine makers, also supplies metal powders to its customers. Whilst powders are not typically manufactured by the machine makers, powders are specified and qualified to guarantee optimum performance in a manufacturer's system. Commenting on the use of third party powders Weston stated, "Powders for AM have to meet very specific requirements and have to offer consistent properties from batch to batch. Any variation in powder size distribution or chemical composition will directly impact the stability of the process and the properties of the finished product. We therefore naturally encourage the use of our own certified powders in the development of new applications. Some experienced customers, in particular customers with a well equipped metallurgical department, are naturally in a strong position to experiment with powder from other sources and have the capability to do the necessary testing, analysis and classification of the incoming powder themselves, or with support from Renishaw as required."

One area of research at Renishaw is understanding the impact of recycling on metal powders. Weston stated, "We monitored the powder and mechanical properties of twenty builds in which a single batch of powder was used. After every build the unmelted powder in the overflow and build volume was sieved and returned to the hopper for the next build. Unused powder left in the hopper after each build was not disturbed. We found that there was very little change to the powder chemistry [interstitials] and tensile properties over the progression of the re-use. Component density was consistently measured at 99.9%

through all the builds. Data from a more rigorous version of this experiment is currently being analysed."

"It's important to note, however, that an aspect such as chemical composition is very much dependent on atmosphere control in the AM machine and this can vary significantly from manufacturer to manufacturer," added Weston.

Looking ahead

Whilst Metal AM technology has advanced dramatically in recent years, the process currently remains relatively slow and labour intensive, with limited useful process control capabilities. The industry is, however, continuing to move in the right direction at pace with a view to optimising the process for commercial production.

"The key to this is automation, however, effective automation requires advances in process control and monitoring to improve quality and repeatability," commented Weston. "A priority for the industry will be a major advance in software for AM. Integrated software tools need to be able to take the end-user from the CAD drawing to the finished component, including topology optimisation, the generation of support structures and quality control. A more connected process chain will be far more advantageous and bring huge benefits down the line."

In many cases the individual software components for each step exist or are in an advanced stage of development. QuantAM (Fig. 10), Renishaw's own dedicated build preparation package, provides a selection of tools for file preparation. "We have considerable software development experience and there are around 300 employees dedicated to software development within the company, so this area isn't new to us. We believe that this is just one aspect of our business that sets us apart from other AM technology developers," commented Weston.

It was also stated that another pressing challenge is that of education and training. "What is clear to us is that the skills ecosystem is too small. Training for the development of AM needs to move from high level research to practical industry-oriented training that can help support the growth of the industry." Renishaw is developing and maturing its customer education and training programmes for AM technologies to support subsidiaries and customers.

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Titanium powder pyrophoricity, passivation and handling for safe production and processing

As Additive Manufacturing moves out of the prototyping space and into production facilities with multiple machines, the importance of handling and processing powders, particularly titanium, becomes ever more relevant. In this article Dr Andrew Heidloff and Dr Joel Rieken, from Praxair Surface Technologies, Inc., review best practice when handling and storing titanium powders for AM. Titanium powder can be safely produced, processed, stored and shipped using appropriate precautions, however under certain conditions it can become quite hazardous. These hazards can be mitigated by following the suggested precautions reviewed below.

As companies enter the Additive Manufacturing sector, they are often for the first time introduced to the world of Powder Metallurgy. The following descriptions and recommendations are meant to acquaint those unfamiliar with Powder Metallurgy with the correct resources. For those that are new to this segment and are currently using or producing powder, they are encouraged to test the powder with a trusted and certified third party for pyrophoricity and explosibility characteristics, as this will form the foundation of many choices that will be made in order to operate a facility under safe conditions.

This testing approach consists of a screening test to determine if the powders are capable of initiating and sustaining an explosion (20 L chamber per ASTM E-1226), followed by: Minimum Ignition Energy (MIE), Minimum Ignition Temperature (MIT), P_{max}, K_{st}, Limiting Oxygen Concentration (LOC) and Minimum Explosible Concentration (MEC). All of these characteristics will aid in understanding what is important to safety in a given facility and scenario.

Why is titanium reactive?

Titanium is a well-known material to be characterised as flammable under certain morphologies. Titanium and its alloys have a

Fig. 1 Machine preparation at the AM laboratory at Praxair

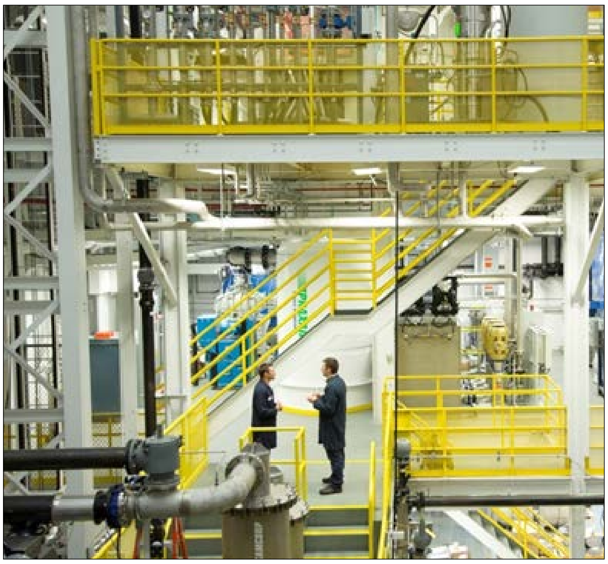

Fig. 2 An atomiser dedicated to titanium alloys at the Praxair Surface Technologies, Inc. powder plant, Indianapolis, Indiana, USA

great affinity for oxygen and will form a native 2-7 nm TiO_2 layer instantly if a clean metallic surface is exposed to air at room temperature. This film prevents further oxidation from taking place and protects the underlying metal powder. When heat is applied, either through a thermal source or a spark, the powder can generally or locally heat to the point of thermal runaway or burning. The consensus mechanism of self-sustaining thermal runaway of titanium powder occurs by means of ion diffusion through this native TiO_2 film on the titanium powder [1, 2]. As the micron size of the powder decreases, the specific surface area (in units of m^2/g) increases at a rate of 6/d where d=particle diameter. In context, to fill a typical AM machine with 45 kg of titanium powder, with an average particle size of 20 µm, this powder will have enough surface area to cover over 3000 m^2. Generally, titanium powders with a particle size < 45 µm are considered a flammability hazard.

When describing a reaction of any metal powder, there are three categories into which each reaction may fall: 1) stagnant, 2) freely aspirated and 3) conveyed. Stagnant powder reactions generally are a result of powder that collects on a horizontal surface and ignition is typically from a heat source, as a more significant source is necessary to ignite a stagnant bed of powder. When powder is dispersed in the air, the fine powders may stay aloft creating a cloud. Aspiration of powder, and specifically titanium powder, does not automatically mean the cloud will ignite spontaneously. However, if the temperature threshold or spark energy necessary for ignition is met, rapid oxidation of powder can occur as it mixes with oxygen from the air. This is a result of no thermal heat sink of other powders or materials in near proximity to the powder cloud allowing it to reach a much higher temperature and propagate to other powders, which may result in a large pressure increase and possible explosion.

Ignition can come from a variety of sources, which will be discussed throughout this article. Thermal exposure to temperatures of 300-700°C can cause ignition of titanium powder despite the native oxide layer (i.e., minimum ignition temperature or MIT). Spark ignition can come from a variety of sources including static electricity build-up, electric components and friction/impact of metal components. Titanium powder can have minimum (spark) ignition energies (MIE) of 3-30 mJ.

Powder production

After atomisation, powders are traditionally collected in a cyclone system. These powders are typically non-passivated. The transfer of these non-passivated powders from the atomisation cyclone to ancillary process containers is considered to present a high risk of thermal runaway, which may require breaking of the inert gas seal and exposure to oxygen with high potential for powder aspiration. To overcome this problem, non-passivated powder requires exposure to air (or a reactive gas) to passivate at room temperature, a very time consuming and potentially dangerous process. As an example, passivation of 215 kg of aluminium powder was conducted in a powder collection canister after atomisation, requiring a 20 hour cool down (below MIT), followed by a 1.5 hour passivation period [3]. While canisters can be isolated and moved for passivation, this process concentrates a large quantity of nascent surface powders (i.e. highly reactive) in a confined vessel, which is not ideal.

A novel passivation approach

As a solution to this problem, Praxair Surface Technologies, Inc. uses a novel in-situ passivation process that prevents further oxidation of the powder during exposure to air, thus minimising any exothermic reaction, thereby greatly diminishing the possibility of thermal runaway or burning of powder. Using Praxair's in-situ process, titanium powders are passivated prior to reaching the cyclone collection and are deemed safe to handle after dropping below the aforementioned MIT (300-700°C in air). This not only increases the productivity of titanium powder production, but also greatly diminishes the hazards of the powder.

The ability to add a specific passivation layer to the titanium powder without greatly affecting the powder making process requires the formation of an oxide shell in-situ after the powders initially solidify and descend downwards within the atomisation chamber. The most important aspect of in-situ passivation is the generation of a layer similar (in thickness and chemistry) to the native oxide film that will form on the surface of titanium at room temperature (i.e., a 2-7 nm thick oxide) [4-7]. Oxide thickness becomes extremely important because of the extremely large surface area described above. Ideally, the total oxygen content should stay below 1300 ppmw (0.13 wt.%) for a 20 µm particle, which requires a target

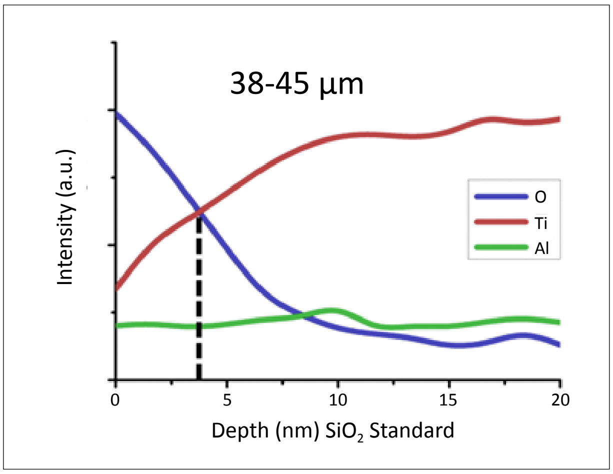

Fig. 3 Auger electron spectroscopy depth profile of Ti-48Al-2Cr-2Nb in-situ passivated powder showing a 3 nm oxide shell (adapted with permission from author)

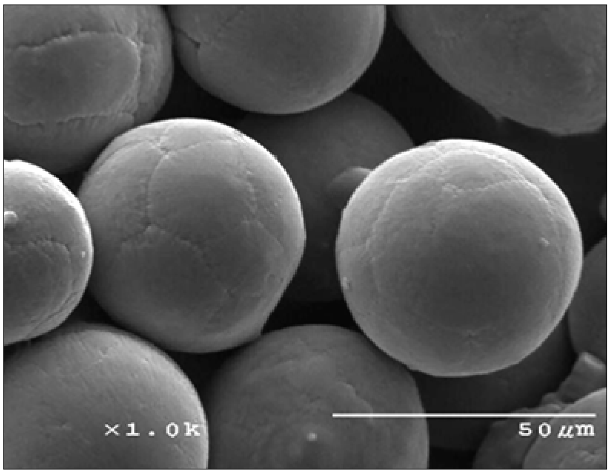

Fig. 4 SEM image of the passivated powder analysed in Fig. 3

titanium oxide thickness of ~2-3 nm if the bulk material contains less than 1000 ppmw of O_2. If the target oxide shell thickness of 1-3 nm can be produced then no additional oxidation should take place when exposed to air at room temperature for extended periods of time.

The production of a 1-3 nm oxide shell *in-situ* on atomised powders is accomplished by employing both thermal and physical energy balance models to accurately predict the temperature vs. distance profile of the atomised powders (as they proceed through the spray chamber). Passivation halos are used to inject a specific reaction gas (for example an Ar-O_2 mixture) at a predetermined vertical position within the atomiser in order to achieve ideal oxidation kinetics.

Fig. 3 shows an Auger Electron Spectroscopy depth profile of the in-situ passivated Ti-48Al-2Cr-2Nb powder (dia. 38-45 µm) shown in Fig. 4. The crossover point is the general consensus of an oxide thickness and is highlighted at ~3 nm. This analytical tool provides an example of the novel passivation process.

Post-production processing and handling safety

The post-processing of titanium powder undoubtedly will utilise electrical equipment from sieves, blenders, feeders, etc. This challenge also presents itself to users of AM equipment. When considering electrical installations involving any flammable substance, it is highly recommended to reference National Electrical Code, NFPA 70, particularly articles 500 to 504. These sections describe the recommended best installation practices for electrical equipment in the presence of a hazardous material. Class II is relevant to combustible dusts (e.g., metal powders) and, within Class II locations, there are Divisions I and II. To determine which division a process/material may fall into, the reader is directed to read these descriptions carefully.

Beyond electrical installations, certain procedures/guidelines should be considered when handling titanium powder.

Guideline I: Avoid any condition that will suspend or float powder particles in the air, creating a dust cloud

1) Minimise accumulation of dust on floors, walls and other surfaces by complying with good housekeeping practices in all areas where titanium powder is stored or handled.

2) In transferring titanium powder, dust clouds should be kept at an absolute minimum. Handling should be slow and deliberate. Both containers should be bonded together and should utilise a grounding strap.

3) All powder transfers and spills should use grounded, conductive and non-sparking tools; while synthetic bristle brushes and plastic should be avoided.

Guideline II: Eliminate all sources of ignition in powder handling areas

1) Avoid MIT personnel sources by not allowing open lights, smoking, lighters or matches in areas where titanium powder is present.

2) To prevent MIT sources of a processing nature, items such as blow torches, welding torches or other open flames are prohibited. No flame, spark-producing or propellant-actuated tools or activities should be carried out in an area where titanium powder is present. Where activities such as welding, cutting, grinding or use of portable electric tools is necessary, a "hot work" permit system is strongly recommended.

3) Avoid MIT sources by minimising friction sparks by avoiding metal-to-metal or metal-to-concrete contact of tools as these impacts can produce sparks that will ignite titanium powder. Non-sparking tools must be used where there is a possibility of impact sparks.

Material	d_{50} [µm]	P_{max} [bar(g)]	$(dP/dt)_{max}$ (bar/s)	MIE [mJ]	MIT [°C]	MEC [g/m³]	MEC [g/m³]	Ref.
Titanium	33 (≤20 µm)	6.9	420	<1	460	50		10
Titanium	33 (≤45 µm)	7.7	436	1-3	460	60		10
Titanium	113 (≤150 µm)	5.5	84	1-3	>590	60		10
Titanium	8			30				11
Titanium	20			30				11
Titanium	45			30				11
Titanium	10-75	3-8	40-770		330-700	40-80		12
Titanium	25	4.7				70		13
Titanium	10-104 µm			25	330-510	45	4-7	14
Titanium		3.5					1-2	15
Titanium	10				565			5
Titanium	1.25				350			5
Titanium	75				730			16
Aluminium	21	10.2	760	10	650	50	7.5	14
Data generated by the authors are in most cases conducted under ASTM methods: MIE: ASTM E2019, MIT: ASTM E1491, MEC: ASTM E1515, LOC: ASTM WK1680, P_{max} and $(dP/dt)_{max}$ ASTM E1226								

Table 1 Explosibility characteristics of titanium powder from various sources and a dataset for aluminium for comparison

Guideline III: Eliminate the generation of static electricity, where possible, and prevent static charge accumulations

1) Bonding and grounding of machinery to remove static electricity produced in powder operations are vital for safety. Bonding and grounding should be done in accordance with the latest versions of Recommended Practice on Static Electricity, NFPA 77, and Standard for Combustible Metals, NFPA 484.

2) All moveable equipment, such as bins, containers and scoops, should be bonded and grounded during powder transfer by the use of clips and flexible ground leads. Ground-conducting floors and/or mats in conjunction with static dissipative footwear/casters are an attractive solution for personnel and movable equipment. Care should be taken to ensure the proper resistance to ground for such designs.

3) During transfer, powder should not be poured or slid on nonconductive surfaces as this can lead to static electricity buildup. A static-dissipative or conductive liner is also recommended.

Guideline IV: Take steps to limit the size of a fire or explosion and to hold any resulting damage to the very minimum

1) The storage area for titanium powder is recommended to be separate from handling of powder. Rooms of noncombustible or limited-combustible construction are encouraged. Titanium powder should not be stored in areas containing incompatible materials such as flammable liquids, oxidisers, organics, fuels or other combustible materials due to the differences in firefighting methods. Storage methods should also be considered by stacking containers properly with ample aisle space and keeping stack height to a minimum.

2) Keep all titanium powder storage containers tightly sealed to prevent accidental dust generation and to prevent possible contamination from moisture or other dusts.

3) All containers in work areas should be closed and sealed. Only those in use for removal of material should be open at any time and should be closed and resealed as quickly as possible. This not only assures greater safety against fire from external sources, but also prevents possible entrance of tramp contamination material or water from the air.

4) Consider the use of an inert cover gas, which can replace air, as this can be valuable in minimising the hazards in many operations, particularly where it may be impossible to ensure that all sources of ignition are eliminated. Utilisation of an inert cover gas will be linked to the LOC determined during powder explosivity characterisation.

Regulation of dust

While practices are employed to prevent clouds during titanium handling, such as restricting compressed air or any other controls that are put in place, undoubtedly a certain amount of dust will be generated within a facility. Regulation of dust is necessary and, while dust control could be considered to fall into any one of the aforementioned guidelines, it is laid out separately here, as dust control is of primary importance.

Dust is one of the most likely sources when a safety incident occurs in a titanium powder facility. Standard industrial central vacuum systems/cleaners should not be used for cleaning as accumulation of dust on a dry filter can create a safety hazard. Dust ventilation systems should be rated for the proper NFPA environment class. Special explosion prevention systems, specifically approved for use with combustible metal dusts, are highly recommended. These systems maintain necessary ventilation air velocity to prevent powder settling in duct work, as well as utilising duct work that is P_{max} and K_{st} rated in the event of an explosion within the duct. These design considerations are another reason for combustibility and explosibility powder characterisation.

The role of personnel

Use of personal protective equipment (PPE) is vital for safely working with titanium powder. Personnel should ground themselves using a wrist strap or grounding plate with conductive shoes at workstations. When static-dissipative footwear and mats and/or flooring are used, testing preventative maintenance should be employed to ensure that the static dissipative properties have not deteriorated. Trousers and shirts should not have cuffs, where dust might accumulate, and should be made of closely-woven fire resistant/fire retardant fabrics, which tend not to accumulate static electrical charges. Respirators are highly recommended as inhalation of powders can easily happen, particularly if the proper dust regulation equipment is not installed. Full face or half face respirator choices should be made based on the personnel tasks and responsibilities. PPE should also include safety glasses, leather gloves and, potentially, face shields.

Safety must be a critical part of the facility culture. Continual efforts should be taken to educate personnel and improve equipment safety. If a highly safety-conscious workforce is combined with the execution of procedures, methods and equipment, such as those discussed here, titanium powder can be produced and/or used safely.

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Process and quality control for AM: Sigma Labs PrintRite3D® methodology for overall quality assurance

Despite the outstanding promise of metal Additive Manufacturing technologies, inconsistent quality, process reliability and speed are currently holding back industry growth and impacting on the cost-effectiveness of new applications. In the following article Sigma Labs' Dr Vivek R Dave and Mark J Cola review the technical challenges that are faced in enabling metal AM to reach its full potential and the systems that are currently available to address a number of critical issues.

Despite the outstanding promise of Additive Manufacturing for critical metal components, three basic limitations exist that will hold back growth and cost-effectiveness of current and future applications; consistent quality, process reliability and productivity or speed. In terms of quality, Additive Manufacturing for critical metal components such as those for aerospace and automotive still exhibits variability between runs, between machines, and over time. In terms of process reliability as determined by part geometry, Additive Manufacturing can only realise a dimensional accuracy of about 100 microns with a positioning accuracy of about 20 microns. Surface finish is also very rough as compared with aerospace requirements. Additionally, the geometry currently has to be measured by expensive post-process inspection methods such as x-ray CT scanning. In terms of productivity and speed, the typical output of an AM machine for metal is still below 20 cm^3/hour. The entire world's production capacity of metal AM machines running 24 hours a day, seven days a week for an entire year would still produce less material than a steel mill could produce in half of one daily shift.

Sigma Labs is addressing the first two issues, namely quality and geometry, with its patented PrintRite3D® Inspect™ and Contour™ in-situ process control, monitoring and inspection software for metal Additive Manufacturing. Specific sensing and measurement

Fig. 1 The process flow for the Sigma Labs process and quality control system

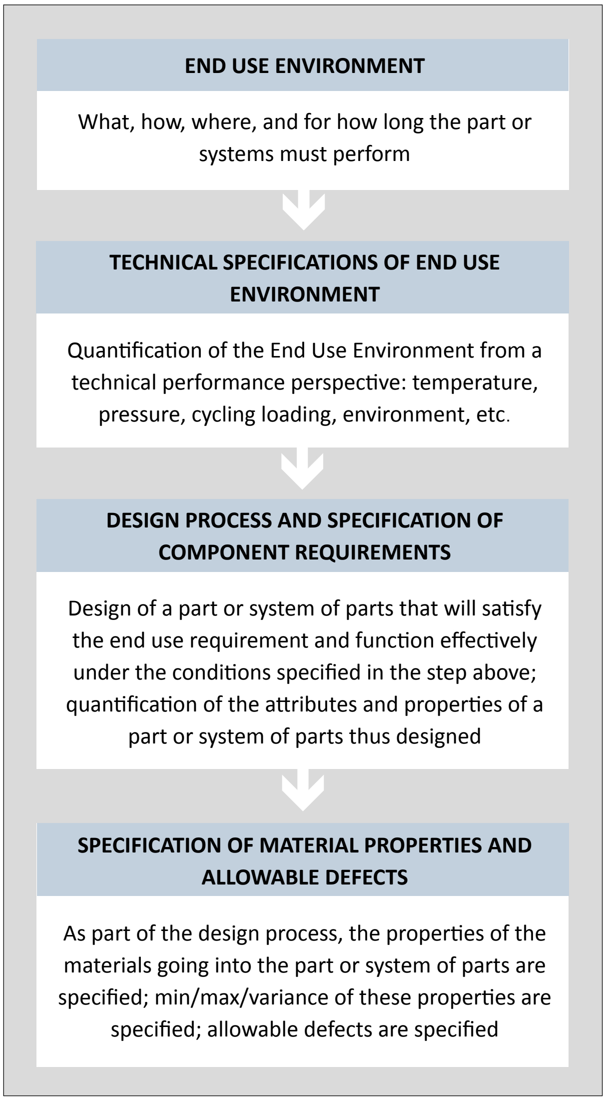

Fig. 2 Derivation of part and material properties and allowable defect attributes from end-use environment technical specifications

technologies will be discussed as well as the Big Data challenges of accumulating what can be terabytes of data per part and then analysing these data to produce actionable knowledge. The software to do this is Sigma Labs' PrintRite3D® Analytics™. Also, the reporting and interfacing requirements will be discussed to ensure that in-process, real-time on-machine process control and inspection data can be effectively integrated into existing and legacy manufacturing execution systems and enterprise data systems used by many large aerospace, medical and automotive suppliers.

One of the most important barriers to the wider adoption of metal AM is the qualification of AM-produced parts as made evident by the many programs on quality issues of metal AM [1, 2]. The criticality of this has been characterised by many as the single biggest challenge to broader acceptance of metal AM technology [3]. Many manufacturers have openly stated that they see three basic limitations with parts made by metal AM; consistent quality, process reliability and part strength. Until they can be assured of consistency, many manufacturers will remain reticent about AM technology, determining the risks of unpredictable quality too costly a trade-off for any potential gains [4].

From a technical perspective, there are three high-level steps that must be undertaken to design and implement a process control and quality control system for any manufacturing process including Additive Manufacturing. These are:

- The establishment of technical requirements linked to ultimate end-use performance,
- The development and implementation of a process control and quality control system, and associated destructive and non-destructive measurements, capable of directly or indirectly measuring attributes of parts or defects,
- The data analysis, correlation methodology and uncertainty quantification to show, in a mathematically rigorous manner, that the measurements and data gathered by the process and quality control system will in fact correlate with the technical requirements needed to meet end-use environment performance targets, and that the process and quality control system over time will support such objective evidence of compliance.

Each one of these high level steps may be further analysed and broken down into subtasks. Fig. 2 shows the steps involved in the establishment of technical requirements as derived from end-use performance targets. This is also the technical requirements list emanating from the part design process. The outputs of this first step are:

- A geometric specification of the part or system of parts, i.e., geometry,
- Materials properties including specifications of min / max / variance / distribution as applicable,

In-Process Quality Assurance™	Post-Process Quality Assurance
Measures attributes of the process	Measures attributes of the part
Real-time or near-real time	Not real-time
Able to sense process variations before they cause defects	Able to find defects with little information on root cause
Forward-looking	Backward-looking

Table 1 In-Process versus post-process quality assurance

- Other measurable properties or performance characteristics that are unique to the functioning of the part or system of parts (e.g. fluid flow rate in valves or testing of electronic circuits),
- Allowable defects and their attributes in terms of size, shape, distribution, frequency of occurrence, etc.

It is very important to understand the context of the term defect as it is used above. All materials are inherently imperfect. The term refers to lower level flaws, imperfections and irregularities in materials, not defective parts which are allowed to be sent downstream and incorporated into final assemblies. For example, at the atomistic level, lattices of atoms have vacancies where atoms are missing at some sites or interstitial atoms exist at other locations. On the one hand, these may be viewed as material defects, but, on the other hand, the science and technology of physical and mechanical metallurgy is based in no small measure on the creation and manipulation of such atomistic defects.

On a more macro scale, porosity can be considered a defect in powder metallurgical parts, for example. A perfect part without porosity might be possible, but could also be prohibitively expensive. Therefore, based on stress, temperature, fatigue life, etc. the design engineer may specify an allowable defect size, shape, distribution, etc. that will still allow the part to function reliably in its end use environment. So, from the standpoint of creating an acceptable part, these are not part-level defects, but rather allowable limits on material-level flaws and irregularities that will not compromise performance.

The next high level step in current quality control practice is the design and implementation of a quality control measurement and data collection system. This can be destructive or non-destructive, could involve the measurement of part and defect attributes, or could involve the measurement of part response in a variety of simulated mechanical, environmental or performance tests. There are extensive existing specifications, procedures and standards available for such measurements and therefore the measurement and data collection systems are seldom designed from first principles but rather follow industry standards and norms.

Similarly, there is a vast array of available measurement technology that results in measurements, which can be calibrated to known standards and can also be compared to known independent standards. Fig. 3 outlines in greater detail the steps and considerations that must be taken into account to design and implement such a quality control metrology system.

What is proposed in this article is Sigma Labs' In-Process Quality Assurance™ (IPQA®) methodology for process and quality control and quality assurance for Additive Manufacturing. The differences between in-process quality assurance and post-process quality assurance are outlined in Table 1.

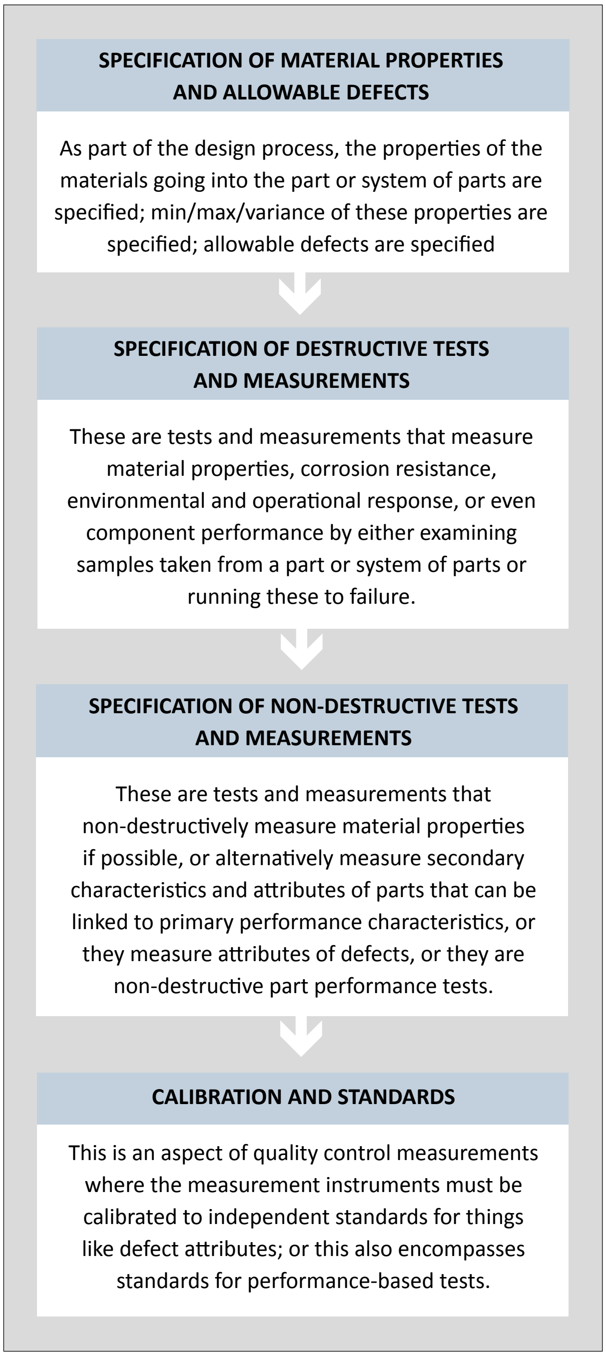

Fig. 3 Elements of a Metrology System to support Quality Control

Application to Additive Manufacturing of in-process quality

In this article we will principally refer to Additive Manufacturing processes in which there is a stationary bed of metallic powder and the heat source (laser or electron beam) scans rapidly over this powder bed so as to melt and consolidate the next layer. The underlying technology is however applicable to other Additive Manufacturing processes and is not limited to powder-bed additive processes.

Eulerian Sensors	Lagrangian Sensors
ADVANTAGES	
• Undistorted view of process • Simple to implement • Works with laser and electron beam processes	• Ability to see all locations in build • Ability to see all the time intervals
DISADVANTAGES	
• Limited viewing regions and times	• Difficult to implement for electron beams • Possible signal distortion

Table 2 Advantages and disadvantages of Eulerian and Lagrangian sensing schemes

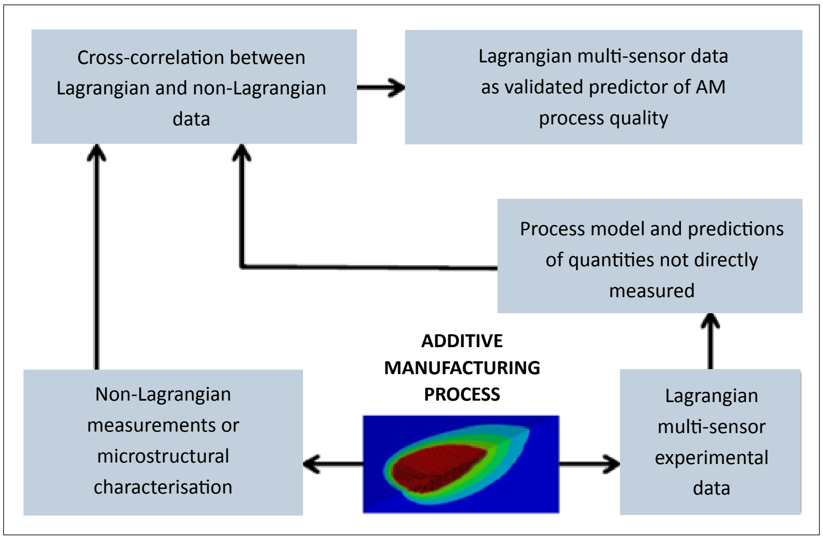

Fig. 4 Data analysis scheme incorporating Lagrangian and Eulerian data

There are several types of sensor data that could be gathered in such cases but they generally fall into two broad categories. The first sensor type is a sensor that is in the frame of reference of the moving heat source. For example, in a laser-based system, this could be a sensor that utilises back-reflected signals coming from the melt pool to various sensors in the scan head. Such sensors are called Lagrangian as they follow the heat source around the workpiece. The other type of sensor is stationary with respect to the moving heat source and therefore has a potentially broader field of view, or alternatively looks at a specific region in the part being built. This type of sensor is called Eulerian as it is in a stationary reference frame with respect to the moving heat source. Examples of both kinds of sensors could include but are not limited to:

- Pyrometers
- Photodiodes
- Spectrometers
- Imaging sensors such as CCD cameras
- Acoustic emission sensors (usually in Eulerian frame only)

Eulerian and Lagrangian sensors are both useful and they both have advantages as well as disadvantages. These are enumerated in Table 2. It is clear from Table 2 that it would be best to utilise both Eulerian and Lagrangian sensors and to perform a data fusion to arrive at a more accurate representation of the process dynamics of Additive Manufacturing processes. Fig. 4 shows one possible scheme by which this sensor fusion may be effected. Both Eulerian and Lagrangian data are collected. The Eulerian data could include post-process measurements such as microstructural measurements. The Lagrangian data may be additionally processed through various real-time or reduced order models to derive features that are not directly measured in the Lagrangian frame of reference.

In order to be really useful and produce validated results, the Lagrangian and Eulerian data must be cross-correlated. Then, based on this correlation, features can be assigned as In-Process Quality Metrics™ (IPQM®) which could be predictive of process quality. It is critical to emphasise that in-process measurements of this nature are not directly sensing the presence or absence of defects; rather they are sensing the process conditions under which such process defects are most likely to occur. Fig. 4 therefore offers a template by which in-process, real-time, on-machine data could be used to detect process conditions under which defects may occur. These data could be used for process intervention, i.e., stopping or altering the process before defects occur. Alternatively, if there is access to the real-time operating system governing the Additive Manufacturing process, then such in-process quality data could be used for real-time process control so as to completely avoid process conditions which may lead to defects.

Application to the in-situ measurement of geometry

As discussed earlier in this article, the control and measurement of as-built geometry is critical for metal components, especially those that will be introduced into critical applications such as aerospace or automotive systems. The high temperatures and non-linear thermal gradients in Additive Manufacturing processes contribute to significant thermal stresses which in turn cause distortion and residual stress. Therefore, the control of geometry is a critically important aspect of metal Additive Manufacturing. However, the measurement of merely the outside contour using contact or non-contact means may well be insufficient to fully capture part geometry as additively manufactured articles can have complex internal geometry. Additionally, the currently available methods for full geometric inspection of both internal and external geometry are based on tomographic scanning, such as x-ray tomographic scanning. Such techniques are slow, capital-intensive and involve the use of ionising radiation. Furthermore, as part geometry becomes larger and as the density and atomic number of elemental constituents of a metallic alloy increase, the x-ray energy required to fully penetrate such parts over large geometries becomes quite large indeed. This poses serious technical as well as radiation safety challenges in practice, if x-ray tomographic scanning had to be carried out with gamma rays with energies of several hundred thousand or even several million electron volts. Therefore, an in-situ means of scanning and detecting the as-built geometry is highly desired.

Fig. 5 shows the general process by which geometric data may be collected during an Additive Manufacturing build. There are several critical steps involving calibration, data collection, geometric feature extraction, data aggregation and, finally, rendering and analysis so as to compare the measured point cloud against the original CAD model that embodies the design intent.

Fig. 6 shows the results of such a process where the part solid model is shown with the various as-built measurement contours superimposed onto the part model itself. In this manner, the manufacturing engineer could quickly make a determination as to whether or not the geometric design intent of the part has been met [6]. Additional quantitative analysis can find specific regions which are out of tolerance and can automatically ensure compliance to blueprint / solid model dimensional tolerance requirements.

Big data aspects of process and quality control for Additive Manufacturing

With the advent of IPQA®, the data collection, storage and analysis requirements increase by many orders of magnitude as compared with conventional manufacturing. There is a direct correlation between the information content of a manufacturing process and its flexibility, agility and adaptability to many different materials and geometries. Additive Manufacturing is highly flexible and adaptable and the information content involved in defining part models, translating these to build files, execution of actual builds and, now through IPQA® in-situ, real-time data collection and analysis, is formidable indeed. It is estimated that

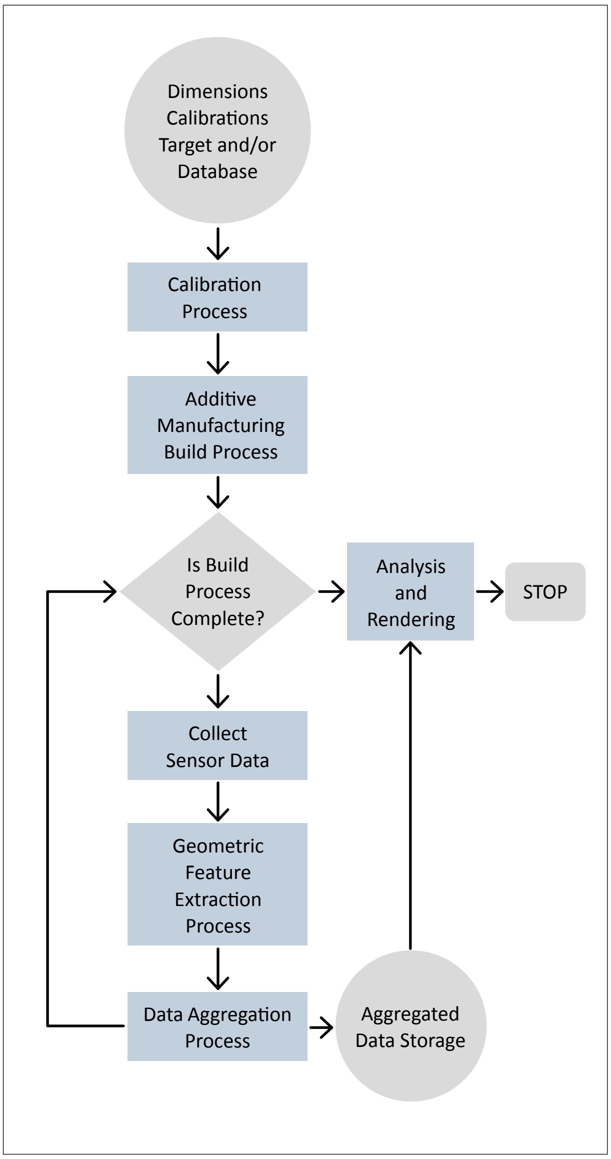

Fig. 5 Process for in-situ geometric data capture during Additive Manufacturing

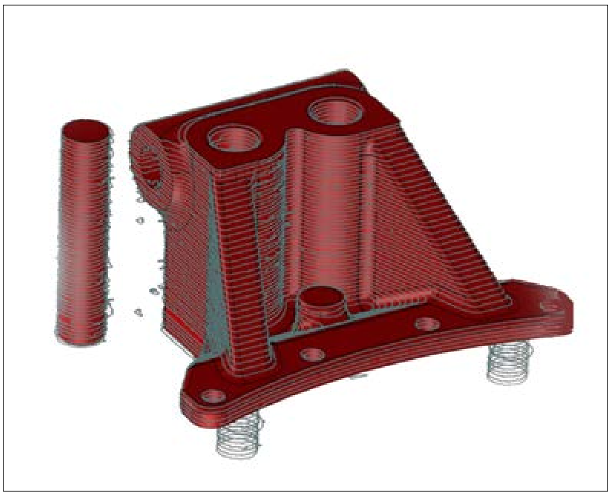

Fig. 6 Example of Actual In-Situ Geometric Data superimposed on Part CAD Model. (CAD model courtesy Honeywell Aerospace)

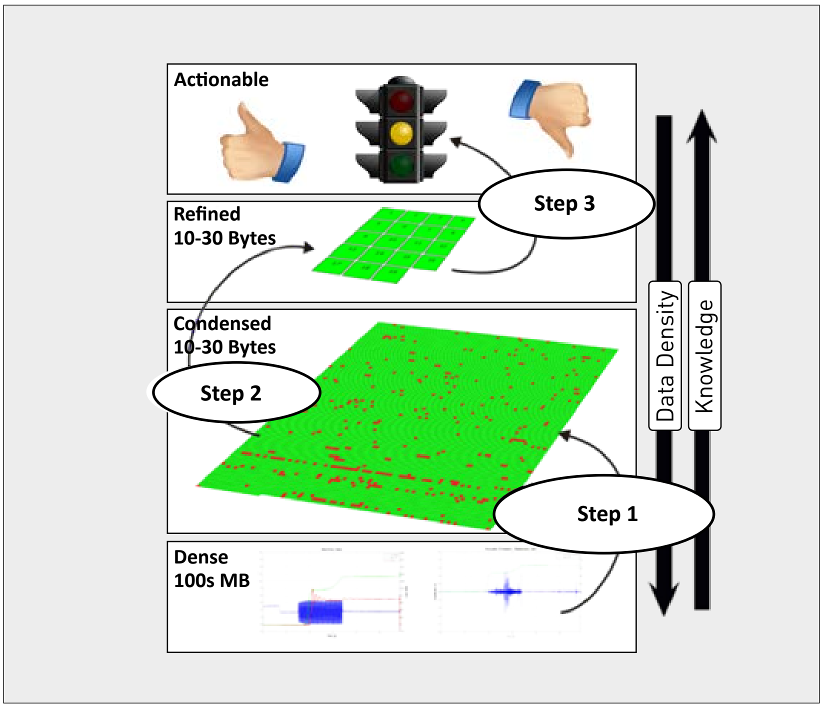

Fig. 7 Schematic of big data approach for Additive Manufacturing

the total data content of a metal Additive Manufacturing build using full IPQA® for the quality assurance will approach 100-1000 GB per build. If a typical machine performs 125 builds per year, this could translate to 10-100 TB of data per machine per year. It is clear that Additive Manufacturing will quickly overwhelm traditional data handling, storage and analytical tools without the benefit of Big Data Analytics. As with other Big Data solutions, the application to Additive Manufacturing will involve:

- Data compression, data mining and feature extraction,
- Careful consideration of hardware architectures to execute analytics,
- Efficient analytical approaches that would parse smaller subsets, perhaps on massively parallel commercial platforms, and extract meaningful, actionable information.

Just as with any other Big Data application, the central and critical challenge for Additive Manufacturing going forward will be BD2K, or Big Data to Knowledge. What is critically needed is not just Petabytes of raw data, but reduced order, intelligible and actionable process knowledge. This inverse relationship between actionable knowledge and data density is schematically shown in Fig. 7. Here, there are three levels of abstraction and analytics represented. In Step 1, we go from raw time-domain data to feature data. This typically represents a million-fold data compression. Features could be time domain, frequency domain, time-frequency domain, some attribute domain or some other variable domain altogether.

The critical aspect of features is that they preserve essential time domain process physics and are capable of discerning between nominal and off-nominal process conditions, i.e., they have the requisite sensitivity to indicate when potentially defect-causing process conditions occur. At Step 2, various correlations and further analytics are performed on the feature spaces themselves. These additional higher order analytics could take on the form of multivariate statistics, other statistical or non-statistical classification schemes, population of databases, training of expert systems, and various heuristic analyses such as neural networks, etc. The entire purpose of these higher order analytics is to enable pattern recognition and other correlations in the feature spaces. At the highest level of data abstraction, these secondary correlations are now queried and they must be further refined into answers to specific questions, for example, "Has the process drifted so as to be in danger of entering into a set of process conditions that could cause a defect?"

Therefore, in this schematic representation, it is seen that the overall data compression and data reduction as we move from raw data at very high densities to actionable knowledge could be as high a 100 million to one. This kind of a hierarchical approach will be crucial to effectively integrating Additive Manufacturing into an overall manufacturing system together with other processes which will be far less data intensive.

Conclusions

Additive Manufacturing is currently at less than 5% of its eventual market potential according to many analysts [7]. However, several significant challenges and technical problems remain that could prevent Additive Manufacturing from reaching its full potential. Additive Manufacturing has uncertain quality, unpredictable and difficult to measure geometry and rate-limiting speed. While the present work cannot address the manufacturing rate question, the following observations are valuable in guiding the future development of Additive Manufacturing and a rapid qualification approach for part certification.

- PrintRite3D® can be used in addition to, and eventually in lieu of, post-process inspection,
- IPQA® and PrintRite3D® is the only way to establish root causes for failures as it tracks every spatial region over every time step as the part is being made,
- IPQA® using PrintRite3D® is

a paradigm shift away from traditional post-process inspection and an enabling method for rapid qualification and part certification,

- Both metallurgical quality and process stability are possible to discern using PrintRite3D®,
- In another aspect of IPQA® using PrintRite3D®, as-built geometry can be directly interrogated without the need for expensive and time-consuming post-process inspection techniques such as x-Ray CAT Scan,
- The use of IPQA® automatically invokes issues relating to Big Data as the sheer amount of information that must be tracked, collected, stored and analysed is many orders of magnitude larger than for conventional manufacturing processes.

What is clear is that IPQA® and related Big Data tools such as PrintRite3D® ANALYTICS™ will be essential to enable the current expansion and future growth of Additive Manufacturing for critical metal components across a wide range of industrial applications.

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Metal AM in Finland: VTT optimises industrial valve block for Additive Manufacturing

VTT, based in Espoo, Finland, is one of Europe's largest research and technology centres with a long track record in metal powder processing technologies. In the following case study VTT's Erin Komi reviews the development of an additively manufactured valve block for demanding industrial applications. The project, in conjunction with industrial partner Nurmi Cylinders, looked at the optimisation of the valve block in terms of size reduction, weight saving and performance gains.

Additive Manufacturing (AM) offers many advantages over traditional manufacturing methods. The technology can produce very complex component geometries, gives designers and engineers unmatched design freedom and allows for a much more structurally efficient and lightweight design. Increasingly, companies in a wide variety of industries are looking to reap the rewards of Additive Manufacturing. They soon realise, however, that they can only gain the full benefits of the technology when the components to be produced are designed to meet the specific needs and constraints of the Additive Manufacturing process.

In 2015 VTT, the Technical Research Centre of Finland, conducted a research project to explore the feasibility of Additive Manufacturing in the country. The project was funded by several public and private organisations, including Tekes, a government funding body in Finland, VTT and several smaller Finnish companies.

VTT is the leading research and technology company in the Nordic countries, with a national mandate in Finland. For nearly 75 years VTT has provided expertise, top-level research and science-based solutions to domestic and international customers and partners in both the private and public sectors. The researchers at VTT develop new smart technologies, create innovative and profitable

Fig. 1 VTT in Espoo, Finland

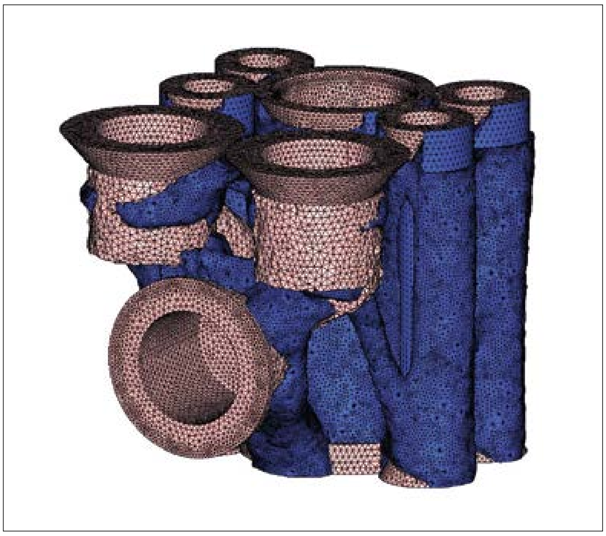

Fig. 2 Generating the valve block shape with OptiStruct

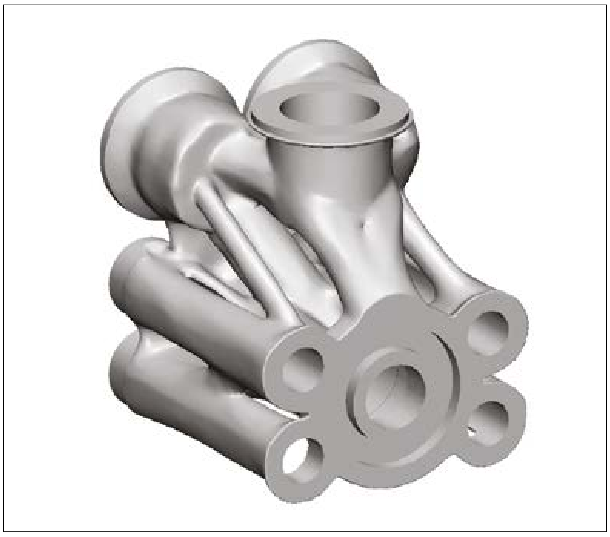

Fig. 3 Smoothing of the geometry with 3-maticsSTL to prepare model for Additive Manufacturing

solutions and cooperate closely with their customers to develop technology that benefits both the client companies and society in general.

For the Additive Manufacturing project, VTT engineers chose the example of a valve block from Nurmi Cylinders, a Finnish manufacturer of hydraulic cylinder products for offshore, industrial, marine and mobile hydraulics, and one of the project's funders. Together VTT and Nurmi wanted to showcase what a design specifically targeted for Additive Manufacturing had to look like in order to fully benefit from the manufacturing method. The goals were to use Additive Manufacturing to both reduce the size of the valve block and the amount of material needed, as well as to optimise and improve the valve block's internal channels to produce a better component for the customer.

The engineer in charge of the additively manufactured valve block project was Erin Komi, Research Scientist at VTT. Komi works with finite element acoustic simulations, making acoustic models of different products for VTT's customers. More recently, she also started to work on design projects for Additive Manufacturing, where she is applying topology optimisation and other design tools.

Finding the best printable design

Not every component or product is suitable for Additive Manufacturing, depending on its size, form and design, as well as the quantity needed. A valve block, however, is very well suited for Additive Manufacturing and has a high potential for improvements in weight and performance when additively manufactured.

Traditionally, the design of a valve block starts with a block of metal. After being formed by traditional manufacturing methods into the desired shape, internal channels must be drilled to accommodate hydraulic fluid flow. Drilling these channels accurately is difficult as they need to meet cleanly at certain points, but alignment issues are often caused by what is in essence 'blind' drilling. In addition, auxiliary holes are often drilled and then plugged, but this opens the door to potential leakage.

Employing optimisation techniques and Additive Manufacturing, VTT engineers hoped to replace this cumbersome method by improving the design and manufacture of the block's internal channels and ending up with a smaller, lighter, better final product.

To design, optimise and analyse the valve block, VTT used Altair Engineering's HyperWorks® CAE software suite. OptiStruct®, the optimisation tool and finite element solver in the suite, was VTT's first choice. "We went straight for OptiStruct," stated Komi. "We've used it in the past, so I understand the workflow and have been pleased with the results."

"There are other products available on the market that allow you to do topology optimisation," Komi continued, "but I think the result interpretation, which is in my opinion easier with HyperWorks, is also very important. The flexibility of OptiStruct, with many different possibilities to apply loads and to include responses as well as constraints, is very helpful."

Software tools speed design process, tackle challenges

A significant advantage to topology optimisation with a tool such as OptiStruct is that a CAD model is not really needed to design the component. Once the engineer defines the design space and its limitations, as well as loads and other boundary conditions, the optimisation tool proposes an optimal design. In the VTT project, the customer provided the boundary conditions as well as additional internal limitations, such as where the valve actually has to be placed and which machining tolerances had to be considered. The size, position and orientation of the

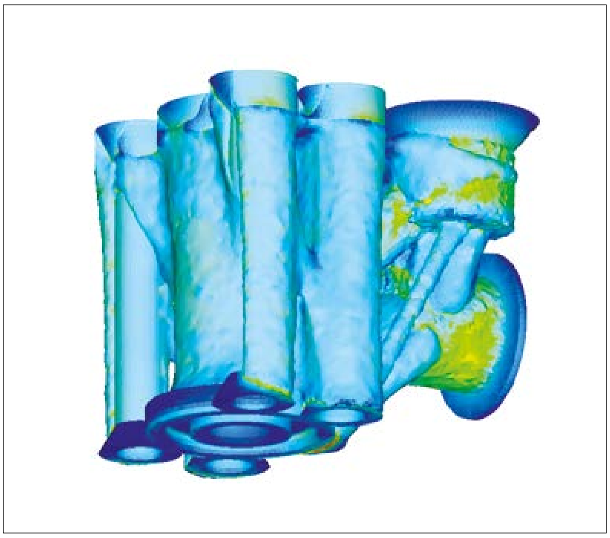

Fig. 4 Valve block design analysis with OptiStruct

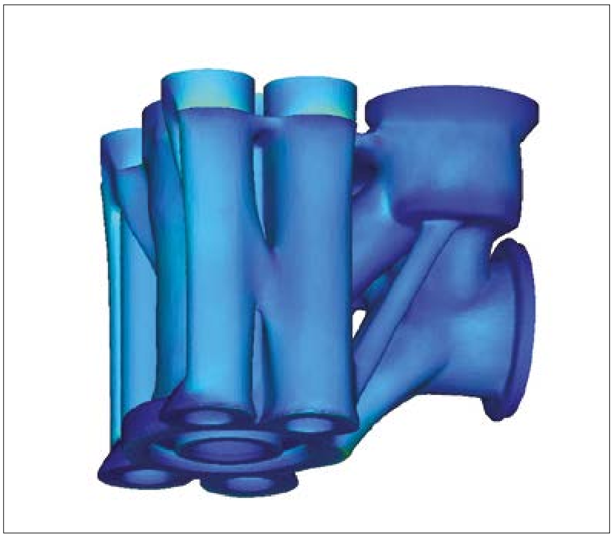

Fig. 5 Valve block design analysis with OptiStruct

internal channels were also chosen by the customer and were part of the non-design space. The design space in this case was a block, with some holes where connecting bolts would be placed. An important tool that helped VTT create the optimised design of the valve block was OSSmooth, one of OptiStruct's shape generation tools (Fig. 2). With OSSmooth, the engineer can automatically re-mesh the design and run a re-analysis to make sure that all initial design requirements are met and stress limits are not exceeded. At that point, the design is only a rough model and often has stress spikes which make it unsuitable for Additive Manufacturing.

To tackle that challenge, VTT used a software application called 3-maticsSTL from Materialise, offered under the Altair Partner Alliance. The Alliance gives HyperWorks customers access to third-party tools under their existing HyperWorks licence at no additional cost. The 3-maticSTL software enables design modification, re-meshing and the creation of 3D textures, lightweight models and conformal structures, all on STL (StereoLithography) levels. In this case 3-maticsSTL helped turn Komi's optimised mesh into a printable file (Fig. 3). "I learned about Materialise through Altair," explained Komi. "At some point in the development process I had tried to prepare a model for printing with HyperMesh, but it was very cumbersome. It was taking me days and the result wasn't all that great. Once I learned about 3-maticsSTL and tried it, what used to take days is done in hours and the results are so much better. An additional benefit is that we can access the tool via our HyperWorks licences, so we don't even have to invest in additional software."

The valve block went through several design iterations. In certain areas, the initial size of the design space provided by the customer was cutting into the result Komi had come up with. As it turned out, the customer had decreased the size of the design space, assuming that with a smaller design space a smaller final design would be the optimisation result. This is not necessarily the case. Given the natural flow of the stresses and forces, and by applying full freedom to the design, the engineer usually receives the best optimisation result, including the smallest and lightest design, with the highest stiffness.

To further optimise the valve block's performance, Komi changed the route of the internal fluid channels. Initially these channels were curved like an S, with the cross sections having a circular shape. To actually produce the valve block via Additive Manufacturing, VTT had to use SLM (Selective Laser Melting) machines. For the SLM method, the recommendation to add supports internally in the channels was unviable as they would have been impossible to remove. The solution VTT came up with, together with the customer, was keeping the same cross sectional area but changing the shape and path of the channels.

One of the major goals of the project was to create design rules for SLM. These include guidelines such as designing an oval or diamond shape channel instead of a circular one, since this design does not need support structures and will result in an overall structure that can be better printed with the SLM method.

It is commonly recognised that in SLM processing 45° is more or less a limiting angle for overhangs to be produced without adding supports. To optimise the design VTT made the assumption that the outer structure would more or less follow the route of the inner channels, and thus if the internal channels run at ~45° angle to the base plate, the number of external supports needed could be reduced, saving time and money spent on support removal in the post-processing phase. Based on these kinds of best-practice design rules for the SLM machine, VTT could define a set of design rules which were consequently recommended to the customer.

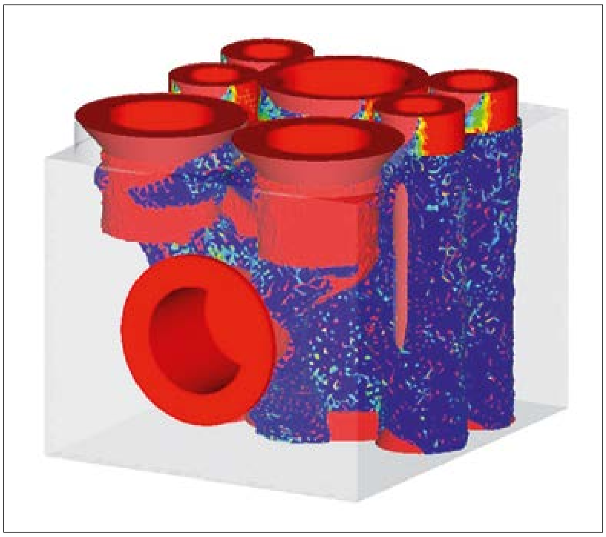

Fig. 6 Topology optimisation results

Fig. 7 The additively manufactured valve block

Optimised design creates smaller, lighter, improved product

The result of this new approach to the valve block design and its production were striking: an overall reduction in the component's size and weight, improved fluid flow in the internal channels and all stress and strength requirements met. A similar valve block made with traditional drilling techniques is estimated to weigh over 2.5 kg. The new optimised and additively manufactured valve block weighs less than 600 g, a 76% weight reduction compared to traditional design and manufacturing methods. The Additive Manufacturing process also results in less material waste. The success of the research project has benefitted not only the customer, Nurmi Cylinders, but VTT as well, Komi stated.

"Everybody involved in the project is really pleased with the results. Because it was a public project, we can show and talk about our results and the solution path we took. It was also an interesting project because with the valve block you have a well-defined load case, which is important when trying to optimise a structure. The topology optimisation resulted in a really interesting looking, complex, organic shape design, which was challenging to print and made planning for the printing process a very good learning experience (Fig. 7). In detail we had to consider the print orientation on the platform, eliminate the need for internal supports, minimise the need for external supports and much more. It has also been a nice learning process for us to explore Additive Manufacturing."

"VTT has had an SLM Solutions printer for roughly a year and we were still evolving our design process to learn what a design targeted for Additive Manufacturing would look like. Having this focus on actually designing for Additive Manufacturing has been a learning experience. We could see the benefits of Additive Manufacturing early in the design phase and take that into consideration. This project gave us the opportunity to use it successfully."

Komi believes that without the application of topology optimisation tools it would have been difficult to reach the same design. The valve block now has a natural organic shape, proposed by optimisation with OptiStruct and refined with 3-maticsSTL. Simply looking at the initial block of material, without the insights provided by the Altair HyperWorks tools, it is doubtful anyone could have created a similar design.

"The Altair tools were crucial to the success of this project," Komi stated. "We need OptiStruct for the topology optimisation and to define the optimal placement of material within our design space. We need a tool like OSSmooth to interpret the optimisation results and produce a feasible solution. In addition a tool such as 3-maticSTL is needed to smooth the resulting mesh and turn it into a shape you can and want to print. In the end you need OptiStruct again, to re-analyse the final smoothed design. With this process, you obtain a reliable design ready to be printed."

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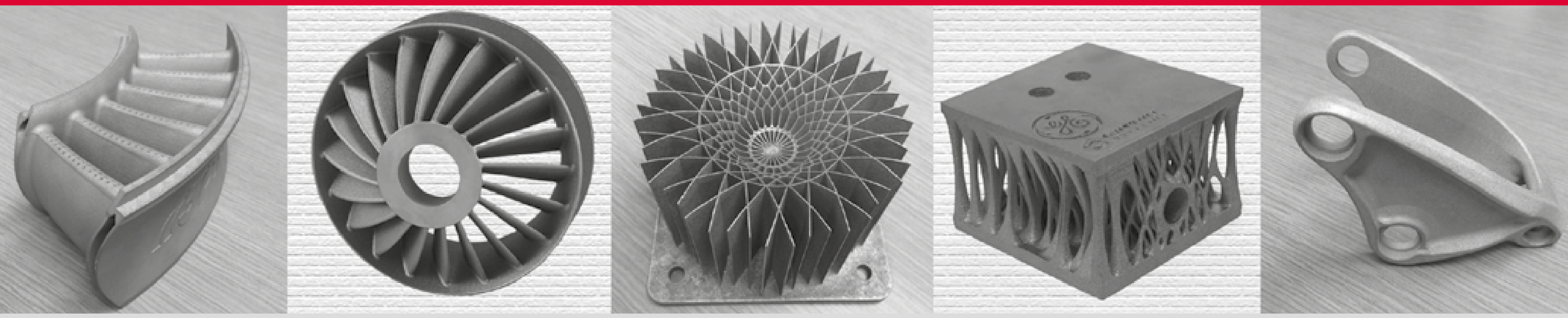

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