Vol. 2 No. 4 WINTER 2016

THE MAGAZINE FOR THE METAL ADDITIVE MANUFACTURING INDUSTRY

METAL AM

in this issue

COMPANY VISIT: GKN AEROSPACE

MODELLING CELLULAR STRUCTURES

IN-PROCESS MONITORING

Published by Inovar Communications Ltd

www.metal-am.com

Publisher & Editorial Offices
Inovar Communications Ltd
2 The Rural Enterprise Centre
Battlefield Enterprise Park
Shrewsbury SY1 3FE, United Kingdom
Tel: +44 1743 454990
Fax: +44 1743 469909
Email: info@inovar-communications.com
www.metal-am.com

Managing Director, Features Editor
Nick Williams
Tel: +44 1743 454991
Email: nick@inovar-communications.com

Publishing Director, News Editor
Paul Whittaker
Tel: +44 1743 454992
Email: paul@inovar-communications.com

Advertising
Jon Craxford, Advertising Sales Director
Tel: +44 207 1939 749
Fax: +44 1743 469909
Email: jon@inovar-communications.com

Production
Hugo Ribeiro, Production Manager
Tel: +44 (0)1743 454990
Fax: +44 (0)1743 469909
Email: hugo@inovar-communications.com

Subscriptions
Metal Additive Manufacturing is published on a quarterly basis as either a free digital publication or via a paid print subscription. The annual print subscription charge for four issues is £95.00 including shipping. Rates in € and US$ are available on application.

Printed by
Cambrian Printers, Aberystwyth, UK

ISSN 2057-3014 (print edition)
ISSN 2055-7183 (digital edition)

Vol. 2. No. 4 Winter 2016

This magazine is also available for free download from www.metal-am.com

METAL ADDITIVE MANUFACTURING

Truly exciting times for Additive Manufacturing

There is no doubting that for those of us lucky enough to be involved in the metal Additive Manufacturing industry we are going through some truly exciting times. Having spent a week exhibiting at, and exploring, the spectacular exhibition hall at formnext, the energy and excitement surrounding the future of metal AM was clear for all to feel.

Many of the conversations in the exhibition hall naturally focused on GE's recent investments in the AM arena in which the firm, after some considerable obstacles with its planned acquisition of SLM Solutions, made its final move to invest in Arcam and Concept Laser. The very fact that GE had options in terms of other targets in this sector must be regarded as an indication of the growing maturity and capability of the industry. Companies looking to adopt AM as a manufacturing technology can today chose from a broad selection of credible and experienced technology providers, be they under the umbrella of a global mulitnational or independent. What is certain is that GE isn't the only industry giant positioning itself to play a greater role in metal AM.

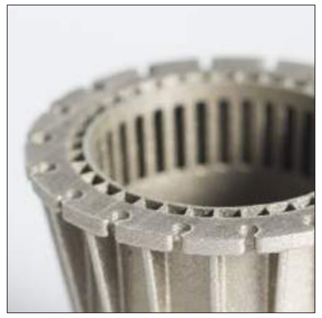
It would, however, be doing a disservice to the rest of the industry to suggest that the buzz at formnext was solely as a result of GE's activities. New and seemingly highly credible technology providers were making waves, whilst the trend towards automation - and with it high volume serial production - was one of the key themes.

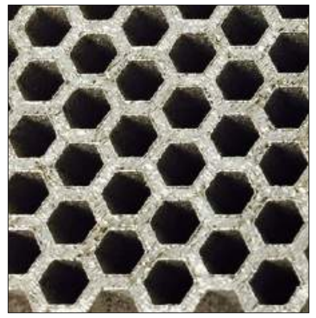
For companies small and large, huge opportunities still remain for those who are able to drive forward the industry's expansion with innovations in production technology, software, materials and applications.

Nick Williams
Managing Director

Cover image
In the foreground the Vulcain 2 demonstration nozzle stands with over 50 kg of Laser Wire AM deposition. In the background is the Vulcain 2 nozzle for the Ariane 5 rocket (Courtesy GKN Aerospace)

METAL ADDITIVE MANUFACTURING





Contents

industry news

GE Additive: New business targets sales of $1 billion by 2020 and 10,000 machine sales in ten years

GE has announced that GE Additive, a new business group focused solely on Additive Manufacturing, is targeting sales of 10,000 metal AM machines over the next ten years and sales of $1 billion by 2020. The news follows GE's purchase of controlling shares in Sweden's Arcam AB and an agreement to acquire a 75% stake in Germany's Concept Laser. The latter followed GE's failed bid for Germany's SLM Solutions. The total investement in Arcam and Concept Laser is estimated to be in the region of $1.2 billion.

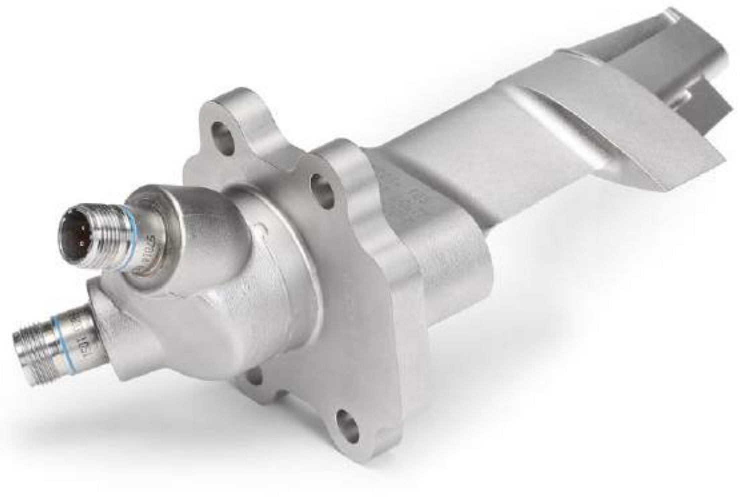
GE has already invested approximately $1.5 billion in manufacturing and additive technologies at its Global Research Centre in Niskayuna, New York, in addition to building a global additive network of centres focused on advancing the science. Now, in addition to being a pioneer in the development and use of AM technologies, GE is focusing on becoming a leading supplier of additive machines, materials and software for a wide range of industry segments, including aerospace, power generation, automotive, medical and electronics.

In addition to building a portfolio of additive machines, GE anticipates that 25% of the advanced metal powder used in manufacturing will be in the Additive Manufacturing space. Arcam owns Canada's AP&C, a leading manufacturer of metal powders for Additive Manufacturing and related technologies such as Metal Injection Moulding. This therefore gives GE access to industry-leading metal powder production technologies.

Commenting in relation to Arcam, David Joyce, GE Vice Chairman and President and CEO of GE Aviation, stated, "GE's strong position as a controlling shareholder of Arcam is a key step in our overall additive strategy. We are delighted with our relationship with Arcam, which follows our recent announcement with Concept Laser. GE is becoming a key player in the additive space."

Commenting on the Concept Laser deal, Joyce added, "Concept Laser founder Frank Herzog and his team are true pioneers in metal laser melting technology. We are committed to enhancing Concept Laser's technologies and product offerings across a well-established customer base."

Frank Herzog, Concept Laser's CEO, stated, "GE shares our vision regarding the potential for Additive Manufacturing to lead the digital



GE's pioneering AM housing for the T25 sensor provides pressure and temperature measurements for the GE90 engine's control system (Image GE Aviation) transformation of industrial production. We are delighted that together we will be able to accelerate development of the technology to the benefit of our customers. We have some exciting new product offerings due to come to market, including our innovative AM Factory of Tomorrow modular concepts and, with GE's support, we will be at the centre of Industry 4.0." Herzog will continue as CEO of Concept Laser and will also assume a senior leadership position within GE.

As a leading end user and investor in additive technology for several years, GE is well positioned to advance the Additive Manufacturing revolution across numerous industry sectors. AM is regarded as a key part of GE's evolution into what it calls a 'digital industrial' company and its AM production technologies are expected to leverage the company's Predix platform as part of GE's Brilliant Factory initiative. GE's industrial businesses are already heavily involved in design and producing components using Additive Manufacturing.

$10 million educational investments targets next generation of industrial designers

GE has also announced a $10 million investment over the next five years in two educational programs aimed at developing a pipeline of future talent in Additive Manufacturing. The company believes that enabling educational institutions to provide access to AM technology will help accelerate its adoption worldwide.

Mohammad Ehteshami, Vice President of GE Additive, stated, "We want to build an ecosystem that drives Additive Manufacturing across multiple industries. GE is committed to this space for the long-term. A new world is coming and we want future generations to have exposure to it from an early age." Two global programs have been launched, one for primary and secondary schools and one for colleges and universities. GE will invest $2 million over two years to subsidise up to 2,000 desktop polymer printers for primary and secondary schools, districts and systems around the world. Priority will be given to institutions serving ages 8-16 with a strong commitment to Science, Technology, Engineering and Math (STEM) education.

GE will also invest $8 million over five years to subsidise up to fifty metal additive machines for use in colleges and universities around the world. Priority will be given to institutions with curriculum and/or research underway in the area of Additive Manufacturing. Applications for both programs will be accepted from January 2017, enabling printers to be available to schools and universities during 2017.

www.geadditive.com

GE tests AM parts in demonstrator engine for Advanced Turboprop

General Electric has completed testing a demonstrator engine designed to validate additive manufactured parts in its Advanced Turboprop (ATP) system, which will power the new Cessna Denali single engine aircraft. The test engine contained 35% AM parts, which reduced the ATP's weight by 5% while contributing to a 1% improvement in specific fuel consumption (SFC).

GE's Advanced Turboprop (ATP) system will power the new Cessna Denali single engine aircraft

The ATP will utilise more additive parts than any production engine in aviation history; 855 subtractive manufactured parts will be reduced to 12 additive parts. Additive components constitute 35% of the ATP's total part count. The 12 additive ATP parts include: sumps, bearing housings, frames, exhaust case, combustor liner, heat exchangers and stationary flowpath components.

"With subtractive manufactured parts and assemblies, you traditionally use bolts, welds or other interfaces to attach the parts together, which adds weight to the engine," stated Gordon Follin, ATP Engineering GM at GE Aviation. "On the ATP, additive reduces weight by eliminating those attaching features while also optimising design of the parts."

An additional benefit to the ATP is an expedited engine certification schedule. GE recently completed ATP combustor rig tests six months ahead of schedule due to the faster part production speeds allowed by AM. For example, the combustor liners were printed in merely two days.

"A huge benefit of additive is expedited test schedules," added Follin. "For a program like ATP, one of our big philosophical points of emphasis is getting hardware to test faster instead of spending too much time with models on a computer. By putting real hardware on test as quickly as we can, we can use the resultant data to help us design the next iteration for a better product, and we get that product much faster than if we were to use conventional manufacturing methods."

www.ge.com

ExOne reports continued growth

The ExOne Company, North Huntingdon, Pennsylvania, USA, has reported financial results for the third quarter and nine months ended September 30, 2016, which showed continued growth for the global supplier of three-dimensional printing machines and 3D printed products, materials and services. Consolidated revenue for the 2016 third quarter was reported up 47% compared with the prior-year period. Machine revenue grew by more than two and a half times, driven by recognition of large, indirect machine sales. Non-machine revenue, which was consistent with the prior year, was impacted by lower pricing on consumables, partially offsetting increased consumables volume due to the larger installed base.

For the first nine months of 2016, revenue was up 37% over the 2015 period, also driven by the sale of large, indirect machines. Machine revenue more than doubled and non-machine revenue grew 8%. "We're pleased to see continued growth in the third quarter and year-to-date periods, with sales of more of our larger, indirect machines. Underlying this momentum are customers who are indicating that our S-Max® platform is setting the standard for industrial applications, evidencing growing adoption of our binder jetting technology," stated Jim McCarley, Chief Executive Officer.

"We have also made significant progress in 2016 with continued technological advances. The beta testing of our Exerial™ has not only resulted in enhancements to that machine but also improvements that we anticipate applying to our other indirect machine platforms to facilitate adoption. Furthermore, the strides we have made with finer powders for our direct machines are significantly broadening our addressable market for potential applications. Given customer feedback, we are confident that these investments will drive future results," added McCarley.

www.exone.com

Oerlikon acquires citim and plans new powder production facility

Oerlikon, headquartered in Pfäffikon, Schwyz, Switzerland, has announced that it has signed an agreement to acquire Germany's citim GmbH, a service provider specialising in the design and production of metal AM components. Oerlikon also announced that it will be building a new $50 million state-of-the-art manufacturing facility in Plymouth Township, Michigan, USA, dedicated to producing advanced materials for AM and surface coatings.

citim's core expertise lies in metal Additive Manufacturing for small-series production and functional prototypes. The company operates production sites in Europe and in USA, serving high-tech industries such as aviation, automotive and energy. In 2015, citim generated CHF 12 million (US $11.8 million) in sales and has around 120 employees. Both parties agreed not to disclose the financial details of the transaction.

"The competencies and team from citim will serve to consolidate our position in the Additive Manufacturing business, marking the acquisition as an important move for us to drive the industrialisation of Additive Manufacturing and to become an independent service provider for the production of additively manufactured components," stated Dr Roland Fischer, Oerlikon's CEO.

Oerlikon stated that it expects the demand for advanced materials for AM to increase rapidly in the coming years, making it one of the key growth areas in metal-based Additive Manufacturing. The new Michigan facility will produce the latest materials, such as advanced titanium alloys for the AM market and certain high-end thermal spray powders. The site will be fully equipped with next-generation VIGA technology, which combines vacuum induction melting with inert gas atomisation systems.

In addition, the facility will house a state-of-the-art research and development lab for further developments of titanium and other alloys (e.g. nickel, copper, iron and cobalt) for joint R&D projects with customers and will have the ability to produce customised powders in small batches. The facility is expected to be operational by the end of 2017.

www.oerlikon.com

SAP and Stratasys to establish network of 3D Printing Labs

SAP SE, in conjunction with Stratasys Ltd, has announced it is establishing a global network of 3D printing co-innovation labs to educate and enable customers, employees and partners on the adoption of Additive Manufacturing as an integral part of the manufacturing production line. Digital manufacturing and co-innovation sites are currently being rolled out across Paris, France; Johannesburg, South Africa; Walldorf, Germany; and Newtown Square, Pennsylvania, and Palo Alto, California, in the United States.

"SAP and Stratasys share a common vision of the tremendous value distributed manufacturing brings to customers' supply chains," stated Pat Carey, Senior Vice President, Sales, North America, Stratasys. "Harnessing this potential fully requires that 3D printing be seamlessly integrated with enterprise workflows for certification, planning, procurement and production. By participating in this initiative, it's now possible to combine SAP's leadership in these areas with our premier 3D printing solutions and services ecosystem. We look forward to further driving 3D printing adoption with these co-innovation customers."

www.stratasys.com
www.sap.com

Fives Michelin Additive Solutions introduces new systems under AddUp brand

The FormUp™ 350 machine is capable of mass producing complex parts

Fives Michelin Additive Solutions, a joint venture launched by Fives and Michelin in April 2016, has introduced a range of metal Additive Manufacturing solutions under its new AddUp brand. The company can now supply a complete industrial based system built around its new FormUp™ 350 Additive Manufacturing machine, as well as offering support and advice on part production.

"AddUp stands out because we provide personalised support to industrial businesses in order to find the optimum technical and economic solution. Furthermore, we pay particular and unprecedented attention to operator safety and respect for the environment during the industrial use of powders and metal Additive Manufacturing machines," stated Bruno Bernard, CEO of Fives Michelin Additive Solutions.

The FormUp™ 350 machine is said to be a flexible and modular industrial Additive Manufacturing machine and can be used for mass production of parts and prototypes. The system has a build area of 350 x 350 x 350 mm and utilises either single or dual 500W Yb fibre lasers. It is claimed to have unrivalled powder tolerance as well as being designed to limit inter-batch contamination and allowing quick changes between powders.

AddUp also offers a unique approach to health, safety and environment (HSE) issues. Through its Flex care System, AddUp provides a flexible solution of one or more transportable plug-and-play HSE units. The controlled-atmosphere, scalable, compact and portable solution aims to protect operators and surrounding buildings from the risks linked to the industrial use of powders and metal Additive Manufacturing machines.

www.addupsolutions.com

GKN Sinter Metals begins automotive series production of metal AM components

GKN Sinter Metals has announced it has begun series production of additively manufactured precision automotive parts at its plant in Radevormwald, Germany. The company is using its MetalFAB1 system from Additive Industries to produce complex engine and transmission components for the original equipment and replacement parts markets. Customers are said to include most of the leading automakers and their system suppliers.

The MetalFAB1 can simultaneously print hundreds of parts on a single build plate. "Depending on how many data sets we feed into the MetalFAB1, these can be 300 identical or 300 different parts. This gives us unprecedented production capacity and flexibility," stated Dr Simon Hoeges, GKN AM Director.

In addition to the AM build process, the MetalFAB1 also incorporates stress relief heat treatment and automated handling. The system uses powder bed fusion with multiple lasers. In a joint development programme the technology is further optimised for the needs of the automotive industry.

GKN Sinter Metals is the world's largest producer of precision powder metal products, the company offers extensive technical expertise in design, testing and various process technologies. GKN Sinter Metals offers a full range of complex shapes and high-strength products for automotive, industrial and consumer markets worldwide. With the MetalFAB1 system, GKN Sinter Metals stated that it is in a position to offer its customers around the world a range of complex and creative product solutions in next to no time.

www.gknsintermetals.com

Simon Hoeges, GKN AM Director, with the MetalFAB1 (© GKN Sinter Metals/Photographer/Ralf Bille)

EOS expands consulting and knowledge transfer under new Additive Minds brand

EOS GmbH, headquartered in Krailling, Germany, has expanded its consulting and knowledge transfer services to form an 'Additive Minds' division. Incorporating the company's Consulting, Innovation Centre and Additive Minds Academy, a team of experts from EOS will aim to directly educate staff in order to help more companies benefit from Additive Manufacturing technology.

EOS stated that, although many global technology corporations have realised the potential of industrial 3D printing and are strategically investing in the area, to succeed these enterprises must go beyond just developing new applications. There is a need for faster help for customers during additive transformation.

"Our Additive Minds services cover the customer's complete lifecycle – from Additive Manufacturing fundamentals and the choice of correct component or application, to the engineering process and development of the application, right down to planning the industrial production, qualification and validation," stated Güngör Kara, Director Global Application and Consulting at EOS.

As a catalyst in development projects, advisors for strategic questions or technological experts, the Additive Manufacturing Consultants address each customer's individual requirements. The range of topics on offer covers the complete cycle: from technology fundamentals, component choice for AM production, design and AM compatible engineering, to production scaling and validation. This means that customers can enlist Additive Minds at every step of their 3D printing journey.

"The huge innovation potential of this technology makes a key contribution to the current and future transformation process in industrial manufacturing. Based on our technology and extended consulting and training offers, customers can achieve the next level of innovation sooner," added Kara.

With its Additive Minds Innovation Centre, EOS extends its range of services in the field of counselling and creates a central hub of innovation. Companies can send a team of engineers and technicians to EOS with experts from Additive Minds overseeing their education and development for 6-18 months, with the potential to develop new applications through to a production stage. At the end of this phase, the team can begin production in their own company immediately, thus gaining a huge time advantage over their own competition. A Centre of Excellence model, deployed on the customer's premises, is also available.

The Additive Minds Academy will soon offer Additive Manufacturing courses and workshops. EOS has also developed its own training programme in collaboration with the University of Wolverhampton, UK, and the SRH Hochschule Berlin, Germany. Participants can qualify as an AM Application Engineer within six months through intensive learning modules and practical exercises. The first participants will begin their course in February 2017.

www.eos.info

InssTek to ship world's largest metal DED Additive Manufacturing system to Russia

South Korea's InssTek has signed a US$2.3 million contract to ship one of its MX-Grande metal Additive Manufacturing systems to a customer in Russia. With a working envelope of 4000 x 1000 x 1000 mm and a 5 kW Ytterbium fibre laser, the six-axis MX-Grande is claimed to be the largest Directed Energy Deposition (DED) type system in the world. The company also announced it will supply a German university with an MX-450 system in a $1.2 million deal.

InssTek produce a number of metal AM systems ranging from a compact desktop model to its flagship MX-Grande model. The company was founded in 2001 and has developed its own patented Direct Metal Tooling (DMT) technology, classified as Directed Energy Deposition in the ASTM standard. The technology can be applied in electronics, automotive, medical, aerospace and defence industries.

www.insstek.com

InssTek's MX-Grande has a build envelope of 4000 x 1000 x 1000 mm

Arcam announces CoCr option for its Q10plus AM system

Sweden's Arcam AB has announced that its latest Q10plus Electron Beam Melting (EBM) Additive Manufacturing system can now process Cobalt Chrome (CoCr) metal powders. CoCr is, together with titanium, the prime material for the orthopaedic industry and it is also a commonly used material in the aerospace sector.

The company stated that the availability of CoCr for the Arcam Q10plus system will now allow users in the orthopaedic market to take full advantage of the production capabilities of its EBM technology. Arcam added that its CoCr process provides parts with high resolution, production level productivity and impeccable material properties. The process has also been supported by an animal study undertaken at Gothenburg University, showing bone interaction with CoCr.

The newly released Arcam Q10plus is the latest iteration of Arcam's EBM technology designed specifically for cost efficient production of orthopaedic implants. The system offers a range of key features including the company's xQam™ X-ray based detection system for automatic calibration and improved beam control, along with its new EBM Control 5.0 software platform to add functionality for more efficient and accurate beam control as well as new melt strategies, improving build speed and precision.

www.arcam.com

Trumpf and Siemens to streamline AM process

German laser systems manufacturer Trumpf and engineering systems provider Siemens have announced a partnership in which they will aim to help industrialise laser metal fusion technology and make the Additive Manufacturing process for metal parts an integral part of the production process. The two companies are pooling their strengths and working together to develop a software solution for the design and preparation of metal AM parts.

The aim is to integrate and streamline the entire powder-bed based laser metal fusion (LMF) process for Trumpf printing machines into Siemens NX™ software. The comprehensive offering will address part design and engineering for Additive Manufacturing as well as 3D print preparation with integrated Trumpf build processor technology.

"Our combined solution will offer customers a high degree of process reliability thanks to its use of smart product models through all phases of the process," stated Tony Hemmelgarn, President and CEO, Siemens PLM Software. "There will be no need for data conversion because the tools for design, simulation, 3D printing and NC programming of metal parts are integrated into one system."

"These are decisive factors in making Additive Manufacturing a realistic proposition for industrial applications," added Peter Leibinger, Head of the Trumpf Laser Technology/Electronics Division. "Our partnership will result in an optimum interaction between machine and software so customers can move forward with designs optimised for Additive Manufacturing."

www.plm.automation.siemens.com
www.trumpf.com

Automated handling systems from Swisslog and Concept Laser

Concept Laser has announced it has entered into a strategic development partnership with Swisslog, a member of the KUKA Group, to deliver an innovative Automated Guided Vehicle (AGV) system for industrial Additive Manufacturing environments. The demand for automation is a further step in Concept Laser's development of its 'AM Factory of Tomorrow' utilising the company's M Line Factory systems.

Concept Laser stated that it will become the first manufacturer of machines and installations for metal Additive Manufacturing to embrace an automation solution for moving modules between the different machine units and within the production environments. The company is seeking to implement automated solutions as part of the process of manufacturing additive metal parts.

"The ambitious concept of the M Line Factory ensures a high level of automation and flexibility in 3D metal printing. The AGV system from Swisslog is the next stage in the development toward consistent automation of the processes embracing the basic idea of Industry 4.0," stated Dr Florian Bechmann, Head of Research & Development at Concept Laser.

Swisslog brings its many years of expertise in the automation of material flow and intralogistics to this partnership. As a provider of flexible robotic and data-driven automated solutions for warehouses and distribution centres, Swisslog's AGV system is regarded as a key strategic element of the new M Line Factory from Concept Laser. Swisslog's task is specifically to integrate a driverless transport system with smart software for fleet management and power supply to ensure that modules can be moved between different machine units or within an AM factory. By contrast, Concept Laser is responsible for the set-up on top of the AGV in order to move powder or parts in an autonomous way. In addition, the company is also responsible for the docking including the receipt and transfer of the modules.

The planned approach pursues two objectives. Firstly, the AGV system should be capable of moving modules between the machine units or within a production environment,and, secondly, intralogistics in the factory established for the reliable and automated supply of powder material and preparation. "With this collaboration we see the opportunity to implement our highly efficient automated solutions for smart logistics networks in production," added Dr Christian Baur, CEO of Swisslog's Warehouse and Distribution Solutions division.

www.swisslog.com
www.concept-laser.de

BeAM to introduces new industrial metal AM machines

BeAM, a French manufacturer of industrial metal Additive Manufacturing machines using the Laser Metal Deposition process, displayed its new Magic 2.0 and Modulo machines at the recent formnext exhibition in Frankfurt, Germany, November 15-18, 2016. The company announced that it has also reached a milestone in the development of its Additive Manufacturing technology with the qualification of flight critical aerospace components.

BeAM stated that it had achieved this qualification with its first machines, Mobile and Magic 2.0, through its partnership with Chromalloy, a leading supplier of technologically advanced repairs, coatings and services for critical turbine engine components. Chromalloy is a global supplier to commercial airlines, the military and industrial turbine applications.

The Mobile and Magic machines are in use around the world, with customers including Safran, Chromalloy, Polytechnique ESTIA and others. The Magic 2.0 machine is in production and is being delivered to several customers, whilst the Modulo machine is available for pre-order and will be delivered in June 2017.

"Our philosophy at BeAM is not to integrate the DED processes in existing machines and then ask our customers to adapt to the limits of technology. On the contrary, we develop customised machines which harness the potential of our processes, nozzles and software. This is what allows us to innovate continuously with our R & D ecosystem. Our machines are constantly evolving to meet more industrial applications opportunities and this is what the market expects," stated Emeric d'Arcimoles, President of BeAM.

www.beam-machines.fr

BeAM's Magic machines are in use around the world

Ames and Oak Ridge in $5 million project to improve metal AM powders

Ames Laboratory and Oak Ridge National Laboratory have been awarded $5 million from the US Department of Energy's Advanced Manufacturing Office (AMO) to improve the production and composition of metal alloy powders used in Additive Manufacturing.

"There's a lot of intense interest focused on Additive Manufacturing with metal alloys, because there are so many potential applications," stated Iver Anderson, Project Leader and Senior Metallurgist at Ames Laboratory and Adjunct Professor in the Materials Science and Engineering Department at Iowa State University. "Industry has demands for prototyping parts, design development, reducing waste of expensive materials and efficiently producing custom and legacy components for their customers."

With those Additive Manufacturing processes using metal alloy powders as raw materials, the ability to control the properties and quality of the powder becomes paramount to the quality of the final product.

The project aims to improve powder production by further developing a high pressure gas atomisation process pioneered at Ames Laboratory. The team will design and customise alloys specifically for Additive Manufacturing processing methods. Modelling and simulation of gas atomisation process stages at Ames Lab will use a flow simulation code developed by National Energy Technology Laboratory for part of the work. The experimental gas atomisation work and alloy design calculations/verification also will be performed in the powder synthesis facilities at Ames Laboratory. Oak Ridge National Laboratory's Manufacturing Demonstration Facility (ORNL-MDF) will conduct the corresponding Additive Manufacturing experiments.

www.ameslab.gov
www.ornl.gov

FIT adds in-house CT scanning

FIT AG, headquartered in Lupburg, Germany, has announced the addition of a state-of-the-art computer tomography (CT) system to its growing inventory of advanced manufacturing technology. FIT claims to be the first AM manufacturer to establish an in-house QA department and stated that having in-house CT scanning provides customers with an even greater level of confidence in its AM parts produced.

Due to the non-contact and non-destructive measurement and analysis of inner structures, FIT is able to increase process stability for its manufacturing systems. The CT system allows FIT to identify or verify the existence of pores, cavities, fissures, form deflection, displacement, shape distortion etc. Evaluations such as design versus part comparison or analysis of wall thickness are visualised in colour and serve as proof of specified product requirements.

www.fit.technology

Schaeffler and DMG MORI look to Additive Manufacturing for development of rolling bearings

Schaeffler Technologies AG & Co. KG and DMG MORI have announced further cooperation between the two companies, signing an agreement that has the objective of jointly pursuing development work in the field of Additive Manufacturing for producing rolling bearing components. In addition, a marketing partnership that began in 2016 has been extended to see Schaeffler remain DMG MORI's marketing partner worldwide for rolling bearings and linear technology.

"Both partners complement each other perfectly to drive the future of machine tools as well as the continuing development of rolling bearing technology. Our joint "Machine Tool 4.0" development project has already demonstrated this with great success. Our cooperation in Additive Manufacturing means another very important strategic area for the future," stated Dr Stefan Spindler, CEO Industrial of Schaeffler AG.

The basis for the joint development work will be a Lasertec 65 3D made by DMG MORI, a five-axis machining centre including a laser metal deposition welding unit, that will be used at Schaeffler. The goal is to develop the laser metal deposition welding technology so that it can be used for the flexible manufacture of rolling bearing components for prototypes and for small batch sizes.

The focus of the development work is on process issues as well as on the materials used and their suitability for the process. In laser metal deposition welding, a material is simultaneously melted and applied to a surface. In this case, the material is metal

Schaeffler and DMG MORI will look to use Additive Manufacturing for producing rolling bearing components

powder and the heat source is a high-performance laser. This AM process is combined with conventional five-axis machining in the hybrid facilities developed by DMG MORI so that the resulting components can be finished immediately afterwards.

www.schaeffler.de

www.dmgmori.co.jp/en

3T RPD expands metal Additive Manufacturing capacity

3T RPD has a suite of 13 metal AM machines manufacturing parts for its customers around the world

3T RPD, one of the UK's largest Additive Manufacturing service providers, has opened a new metal Additive Manufacturing production facility near its current site in Newbury, Berkshire. The move follows recent investments in new AM machines and paves the way for further expansion of its metals and plastics AM production capacity in 2017. The company stated that the new facility triples its space for metal AM production and has given 3T RPD the chance to expand its finishing capability, bringing the whole metal AM production process in-house and creating a one-stop service for its customers around the world.

3T RPD's new site is already manufacturing metal AM parts and in addition to the current complement of AM machines it will shortly include an automated finishing machine, a laser marking machine, NDT, multi-axis CNC and a large vacuum furnace. The size of the site allows 3T RPD to continue to install more AM machines as demand for AM production ramps up.

"This expansion has three aims, firstly to increase our production capability, secondly to increase the consistency of our production output, and thirdly to provide our customers an AM service covering the complete process chain," stated Ian Halliday, CEO of 3T RPD. "As the demand for AM production builds, 3T RPD is determined to grow to meet customers' AM production requirements and to be their first choice for production metals and plastics AM. This expansion is part of a programme of investment and is the first of many planned AM production developments from 3T RPD."

www.3trpd.co.uk

OR Laser unveils new Orlas Creator metal AM machine

OR Laser, headquartered in Dieburg, Germany, unveiled its new Orlas Creator direct metal Additive Manufacturing system at the formnext 2016 exhibition in Frankfurt, Germany, November 15-18. Developed and designed specifically for small and medium enterprises, the new system is said to be an affordable 3D metal printing machine providing a full solution comprising a wireless control and an award winning CAD/CAM system.

When the company first began researching direct metal Additive Manufacturing more than three years ago, it stated that the main focus quickly became to make the technology's capabilities more accessible. Considerable market research demonstrated that metal AM had tremendous potential for small and medium sized enterprises (SMEs), particularly in the jewellery, dentistry and medical sectors as well as for smaller engineering firms and laboratories. This was precisely the type of organisation that OR Laser had in mind when developing the Orlas Creator and the ecosystem around it, the company added. The Orlas Creator is a contained hardware system, the build platform is original in design and functionality with an innovative blade design that ensures smooth operation and increased build speeds that produce parts up to 30% faster.

The Orlas Creator utilises a cartridge materials handling system to ensure safe operation in smaller facilities. Filled cartridges can be supplied by OR Laser, but the company keenly recognises the need for an open material system and operates accordingly.

OR Laser has also worked hard on developing the right operating system for the Orlas Creator, with sophisticated software and interface developments. This means that no third party software is required to run the machine and eliminates additional costs of running.

www.or-laser.com

Concept Laser announces new metal AM machines, software, peripherals and materials

The production unit and processing unit can be combined to suit the user (Courtesy of Concept Laser GmbH)

Concept Laser, Lichtenfels, Germany, has announced the commercial launch of its M LINE FACTORY, offering what is claimed to be a completely new approach in machine architecture with an unprecedented level of automation and innovation. At formnext 2016 the company also introduced its Mlab cusing 200R in the small machine segment and its X LINE PCG in the large machine segment as an option for the removal of powder. As well as the availability of new precious metal alloys, a new laser power meter, QM Cusing Power, was introduced that now enables the laser power to be measured directly on the build area.

Concept Laser stated that, for the first time, part production as well as set-up and dismantling processes will take place in two independent machine units, so that they can be operated separately from one another. This enables production processes to run in parallel rather than sequentially so that downtimes are reduced and the availability of the process chain is thus increased.

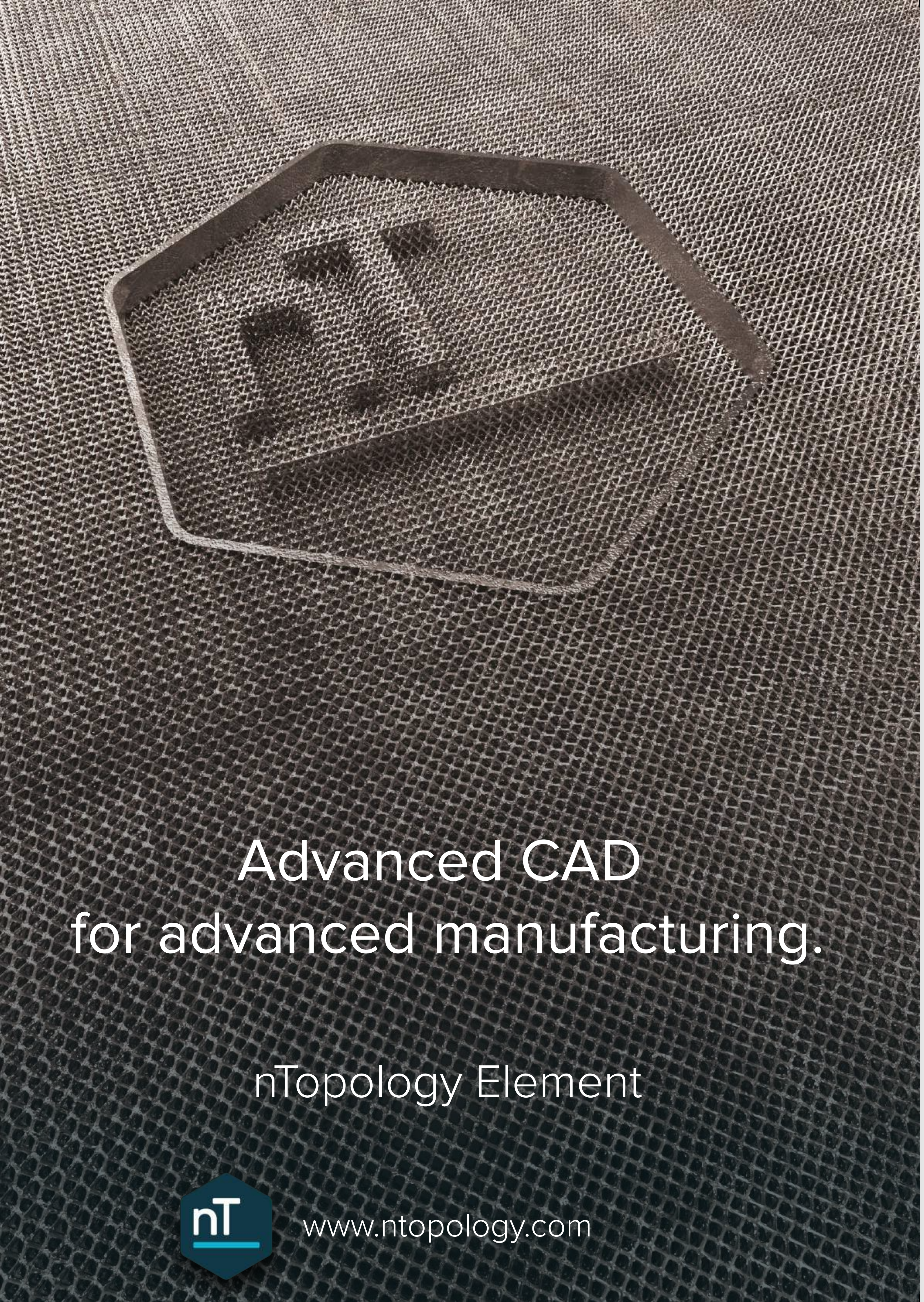
The M LINE FACTORY PRD, as the production unit, has a maximum build envelope of 400 x 400 x 425 mm (x,y,z) and is optionally equipped with one to four laser sources, each delivering 400 W or 1,000 W. The core of the unit is three independent modules, the dose module, the build module and the overflow module, which can be individually activated for the first time and therefore do not form one continuous unit. The individual modules are moved via a tunnel system inside the machine. Finished build jobs can now also be moved out of the machine with the dedicated module and replaced directly by a new prepared build module so that production operations can be resumed immediately. Furthermore, a new two-axis coating process has been implemented and this permits the return run of the coater to be performed alongside the exposure without the spatter problems that usually arise in the market today with systems that coat in both directions. This results in a substantial saving on time during the coating process in combination with a pursuit for the highest quality.

The separate, autonomous M LINE FACTORY PCG is available as the processing unit for set-up and disarming processes. This enables optimum use right through to the ideal of 24/7 availability of the machine technology. The new processing unit has an integrated sieving station and powder management. There is now no need for containers to be used for transportation between the machine and sieving station. Unpacking, preparations for the next build job and sieving therefore take place in a self-contained system without the operator coming into contact with the powder. An automated material flow allows self-contained modules for transport and material provision.

In addition to the long-standing Mlab cusing R, Concept Laser unveiled the larger Mlab cusing 200R. This makes it possible to manufacture even larger parts with much greater productivity, without the machine losing any of its compactness. Highlights include the doubling of the laser power to 200 watts, an expanded build area covering 100 x 100 mm^2(x,y) and 54% more build volume overall thanks to a z-axis of an equally enlarged 100 mm making it possible to manufacture even larger parts.

For the Mlab cusing 200R, Concept Laser offers an inertised sieving station as a stand-alone unit (QM Powder S). QM Powder S enables independent and automated sieving alongside the production process. The user can apply a variable number of sieves (1-3 units). A three-dimensional sieving motion enables optimum utilisation of the open sieve surface area.

www.conceptlaserinc.com



Trumpf launches TruPrint 3000 and TruPrint 5000 systems for metal AM

Laser manufacturer Trumpf, based in Ditzingen, Germany, has launched two new metal Additive Manufacturing systems. The new TruPrint 3000 and TruPrint 5000 sytems are based on laser metal fusion (LMF) technology and are capable of manufacturing components up to 400 mm in height and 300 mm in diameter. With a tool change cylinder concept that allows the construction chamber and supply cylinders to be switched out quickly and an industry-ready periphery, these new machines are said to be geared towards the large-scale production of complex metal parts.

"With the TruPrint 3000, we are shifting the focus onto the industrialisation of Additive Manufacturing based on the whole process chain. That means that we consider not only the manufacturing technology itself, but also – and this is quite in the spirit of Industry 4.0 – the work steps that precede and follow it," stated Peter Leibinger, Head of Trumpf Laser- und Systemtechnik GmbH.

Trumpf's TruPrint 3000

Both the TruPrint 3000 and TruPrint 5000 systems can be used to manufacture parts out of metal powders such as steel, nickel-based alloys, titanium or aluminium. The TruPrint 3000 is equipped with two supply cylinders providing up to 75 litres of powder for each job, around two and a half times the construction volume, allowing the user to complete the entire manufacturing process without having to stop for refilling. The system is designed so that the supply and overflow cylinders can be changed out without interrupting the manufacturing process. This reduces downtimes while also increasing the machine's productivity.

Trumpf utilises both Laser Metal Fusion (LMF) and Laser Metal Deposition (LMD) technology in its range of sytems, allowing customers to select the best machine to suit

Complex interior structures can be built using laser metal fusion

the manufacture of components for a variety of sectors. LMF allows the user to manufacture complete parts layer by layer in a powder bed, whereas with the LMD process the laser forms a melt pool on the surface of a component and fuses the powder, applied simultaneously and coaxially, to create the desired shape.

"Since we launched our new LMF and LMD solutions at the end of 2015, we have been seeing a significant upwards trend as well as interest from all areas of industry," added Leibinger. "More and more customers are using additive technologies not just to manufacture prototypes, but in full-scale production as well."

www.trumpf.com

Optomec showcases its new LENS metal AM machines

Optomec, based in Albuquerque, New Mexico, USA, displayed its new LENS Machine Tool series for 3D printed metals and Aerosol Jet 3D printers for functional electronics at the formnext 2016 exhibition held in Frankfurt, Germany. The new LENS Machine Tool Series integrates the company's LENS metal Additive Manufacturing technology into conventional CNC vertical milling platforms, resulting in what it claims are breakthrough price points as well as the industry's first hybrid Vertical Milling Centre (VMC) controlled-atmosphere system.

"Optomec's Machine Tool series leverages LENS industry-proven technology to provide high-performance metal additive and hybrid manufacturing capabilities at an incredible price point, making Additive Manufacturing a viable solution for the machine tooling industry," stated David Ramahi, President and CEO of Optomec.

The new LENS Machine Tool series combines CNC platforms from Fryer Machine Systems with Optomec's LENS Print Engine technology. It includes three standard configurations, all designed to reduce manufacturing process times while enabling improved end product performance and rapid design changes.

Optomec's metal hybrid VMC system

"This new product line complements our existing LENS systems and fills specific gaps for low cost additive only and hybrid CNC inert systems. We are working with machine tool vendors to make production-grade metal Additive Manufacturing more affordable and accessible," added Ramahi.

www.optomec.com

First US surgeries performed with curved TLIF device

4WEB Medical based in Frisco, Texas, USA, announced at the annual meeting of the North American Spine Society that the first surgeries utilising the company's Curved Posterior Spine Truss System (PSTS) for transforaminal lumbar interbody fusions (TLIF) procedures have now been performed. Additively manufactured from titanium, the company's curved PSTS implants offer numerous advantages over other designs.

"The Curved TLIF device from 4WEB provides yet another viable treatment option that leverages the company's patented truss implant technology. I have tried several of the new titanium implant designs on the market produced with additive manufacturing and the 4WEB technology has provided the best clinical outcomes for my patients," stated Cameron Carmody, MD, of Texas Spine Consultants in Dallas. "In addition to excellent clinical results, the 4WEB implant portfolio stands above the rest with the widest range of devices for ALIF, TLIF, Cervical, PLIF, and Lateral spine procedures."

Jeffrey Wise, MD, Blue Ridge Orthopaedic and Spine Center, who also utilised the Curved TLIF PSTS upon its market release stated, "With virtually every company now promoting a 3D printed porous titanium implant with stimulative surface roughness, it is refreshing that 4WEB continues to innovate with implants that are uniquely differentiated. While 4WEB's truss implants have at least three times more surface area for cell adhesion and differentiation than competitive products, the most important feature is found in the structural mechanics associated with the truss design. The kinetic load distribution throughout the entire fusion column delivers microstrain to adjacent cellular material which can aid in healing by capitalising on the concepts described by Wolff's law."

Curved Posterior Spine Truss System implant from 4WEB

The successful launch of the Curved TLIF system adds another important strategic milestone to 4WEB's string of achievements in 2016. "New product launches have made a significant contribution to 4WEB's growth and expansion this year," stated Geoffrey Bigos, 4WEB Medical's Vice President of Spine Sales.

www.4WEBMedical.com

Additively manufactured titanium fountain pen and nib

Additive Manufacturing has been adopted by Dutch designer Rein van der Mast to produce a series of complex and innovative fountain pen designs under his Pjotr brand. Having started using the technology in 2013 to design unique titanium fountain pens, van der Mast has now incorporated a fully functional additively manufactured nib in his latest design.

The new Spica Virginis fountain pen's body and nib are additively manufactured from titanium powder. "It is amazing what one can create by 3D printing. The nib is printed in titanium with the slit included. The current model is rather straight forward. This way, however, I can create very complex ink channels and precisely affect the way the nib interacts with the paper as well as the pen's user. And, of course, this way one can also create very complex shapes for aesthetic reasons," stated van der Mast.

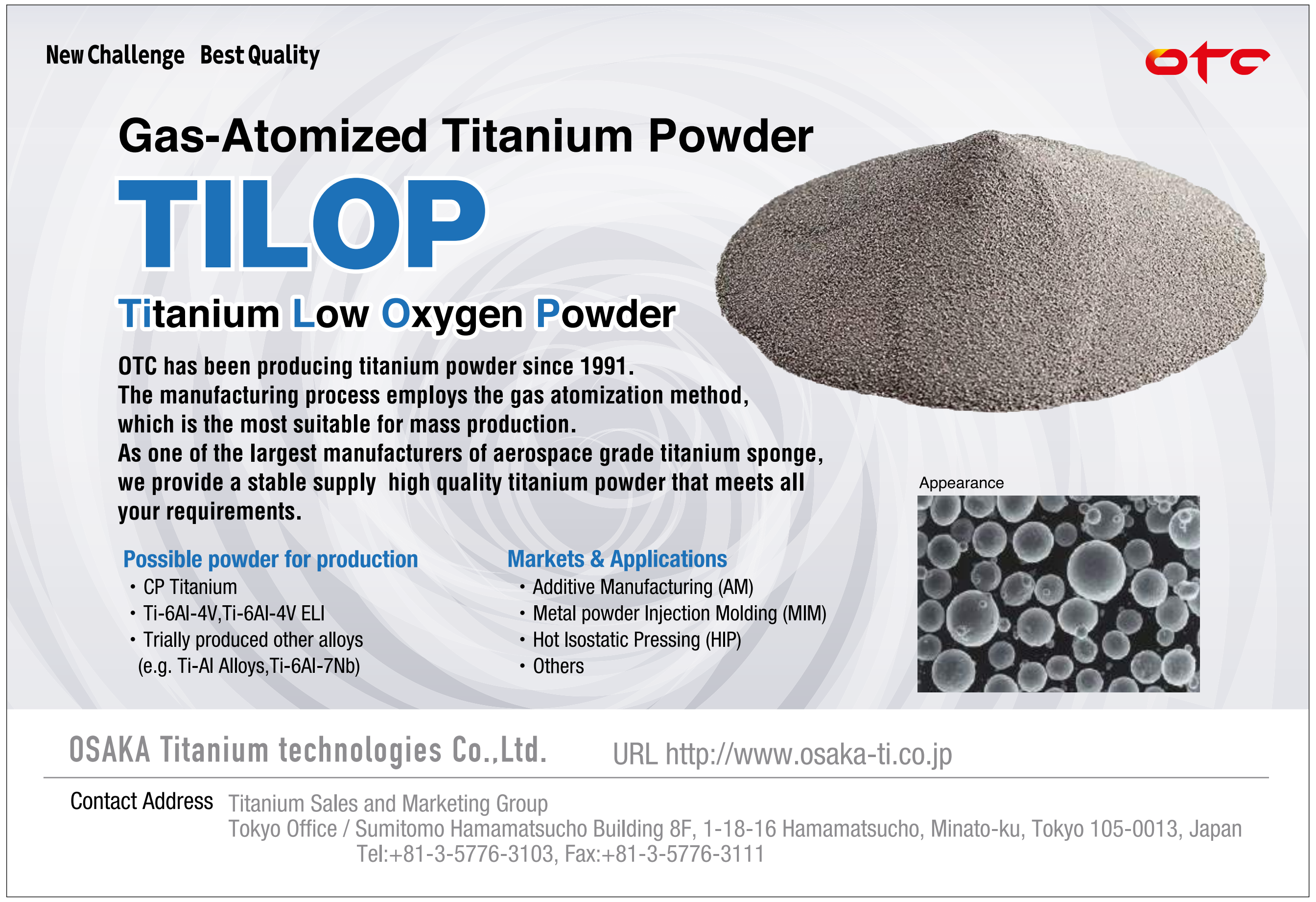
Van der Mast originally produced one-off pen designs to demonstrate the potential for customisation in AM, however a small series production run of the latest pen has been undertaken. "In the case of the Spica Virginis, design has priority over technology. Back in 2013 it was the other way around," added van der Mast, "Having only one piece to carry the design effort results in a pricey object." Although multiple copies of the Spica Virginis pen are produced, each piece has a unique serial number included in the 3D print.

A total of 100 copies of the Spica Virginis pen will be made available and can be purchased for €2,490 from La Couronne du Comte in Tilburg, The Netherlands.

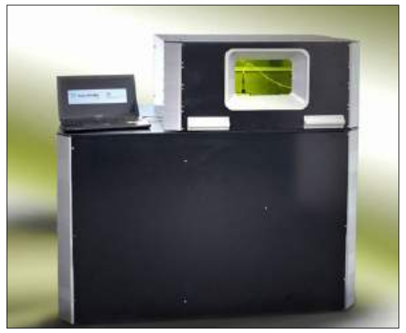
www.lacouronneducomte.nl

www.pjotrpens.com

The fountain pen's body and nib are additively manufactured from titanium



New low cost system offers easy access to metal Additive Manufacturing



FH Aachen/Fraunhofer ILT SLM unit will retail for around €30,000

Germany's FH Aachen and Fraunhofer Institute for Laser Technology ILT have announced the development of a new low-cost Selective Laser Melting (SLM) system. Built jointly with the GoetheLab at FH Aachen, the unit is intended primarily for small and medium-sized enterprises.

Employing a Cartesian coordinate system, the first functional prototype of the new system uses a 140 W laser diode with a focus diameter of 250 µm to produce complex metal components with a maximum height of 90 mm and a maximum diameter of 80 mm. The machine's footprint measures 1.3 m x 0.8 m x 1.4 m. According to Dawid Ziebura, Project Engineer at Fraunhofer ILT, a unit with a comparable installation space would cost at least €100,000, whereas the FH Aachen/Fraunhofer ILT SLM unit will retail for €30,000. The unit is said to be easy to use, with entry-level users only requiring a few hours to learn how to operate it. All of the components in the system allow users to maintain the unit themselves and are easy to replace. "The low-cost unit makes it easy for entry-level users getting into 3D printing of metal components," Ziebura added.

The components that the unit can produce are suitable for many applications, ranging from prototypes and sample parts to functional components. Users can select the speed and the production quality at which the unit operates. It was stated that the system can produce a medium-sized (55 cm^3), stainless steel part at a density of more than 99.5% within 12 hours.

In addition, the unit offers the option of producing lattice structures for large-volume areas in order to shorten the construction time of less stressed areas. Selecting a lattice density of 20% (corresponding to 20% of the original volume) reduces construction time by 60%.

The engineers in Aachen now want to shorten process times and optimise exposure strategies in order to improve component quality. They are also planning to manufacture components made of aluminium alloys and tool steel.

www.ilt.fraunhofer.de

Methods 3D opens new US Additive Manufacturing labs

Methods 3D has announced the completion of seven AM labs across the US

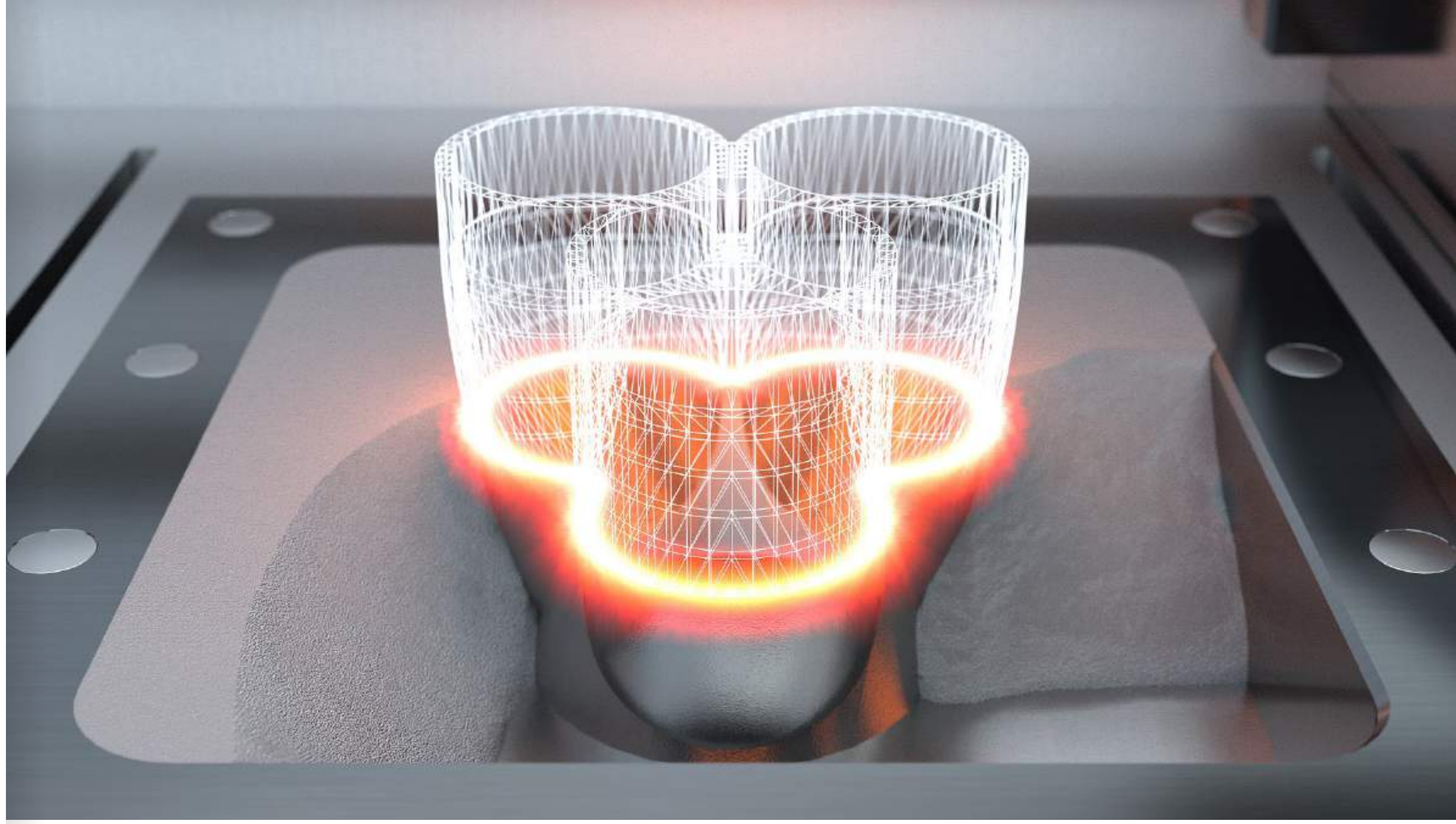
Methods 3D, Inc., a newly formed subsidiary of Methods Machine Tools, Inc. based in Sudbury, Massachusetts, USA, has announced the completion of seven Additive Manufacturing laboratories strategically located across the US. The new AM laboratories are equipped with 18 production machines including Direct Metal Printing (DMP), Select Laser Sintering (SLS), Stereolithography (SLA) and Multi-Jet models running 14 different materials.

A full complement of post-processing equipment such as EDM, CNC machining, automation and inspection is also onsite and each location is fully staffed by a dedicated team of sales, application engineers and service technicians. The Additive Manufacturing labs are in each of Methods Machine Tools' technology centres located in Sudbury (Boston), Detroit, Charlotte, Chicago, Phoenix, San Francisco and Los Angeles.

"Our new additive labs are ideal for manufacturing professionals to consult our experts and explore ways to design and produce their components using the latest 3D technology integrated with conventional machining, automation and more," stated James Hanson, Chief Operating Officer. "Engineers have been bringing their application challenges to us and we have been working with them to implement this technology into their manufacturing operations"

"By partnering with 3D Systems, whose core competencies complement Methods' suite of metalworking machining and automation solutions, we will provide our customers the most advanced 3D printing available, in addition to the highest level of service, support and solutions that Methods Machine Tools is known for. We are at the front end of this innovative technology that is poised to grow exponentially," added Hanson.

www.methodsmachine.com



Additive manufactured permanent magnets from Oak Ridge said to outperform conventional versions

Researchers at the US Department of Energy's (DOE) Oak Ridge National Laboratory, Tennessee, USA, have demonstrated that permanent magnets produced by Additive Manufacturing can outperform bonded magnets made using traditional techniques while conserving critical materials.

Scientists fabricated isotropic, near-net-shape, neodymium-iron-boron (NdFeB) bonded magnets at DOE's Manufacturing Demonstration Facility at ORNL using a Big Area Additive Manufacturing (BAAM) machine. The result, published in Scientific Reports, was a product with comparable or better magnetic, mechanical and microstructural properties than bonded magnets made using traditional injection moulding with the same composition.

The AM process began with composite pellets consisting of 65%vol isotropic NdFeB powder and 35% polyamide (Nylon-12) manufactured by Magnet Applications, Inc. The pellets were melted, compounded, and extruded layer-by-layer by BAAM into desired forms. "While conventional sintered magnet manufacturing may result in material waste of as much as 30 to 50%, Additive Manufacturing will simply capture and reuse those materials with nearly zero waste," stated Parans Paranthaman, principal investigator and a group leader in ORNL's Chemical Sciences Division. The project was funded by DOE's Critical Materials Institute.

Using a process that conserves material is especially important in the manufacture of permanent magnets made with neodymium and dysprosium – rare earth elements that are mined and separated outside the United States. NdFeB magnets are the most powerful on earth and used in everything from computer hard drives and head phones to clean energy technologies such as electric vehicles and wind turbines. "The printing process not only conserves materials but also produces complex shapes, requires no tooling and is faster than traditional injection methods, potentially resulting in a much more economic manufacturing process," added Paranthaman.

"Manufacturing is changing rapidly, and a customer may need 50 different designs for the magnets they want to use," stated ORNL researcher and co-author Ling Li. Traditional injection moulding would require the expense of creating a new mould and tooling for each, but with AM the forms can be crafted simply and quickly using computer-assisted design, she explained.

Composite pellets are melted, compounded, and extruded layer-by-layer into desired forms

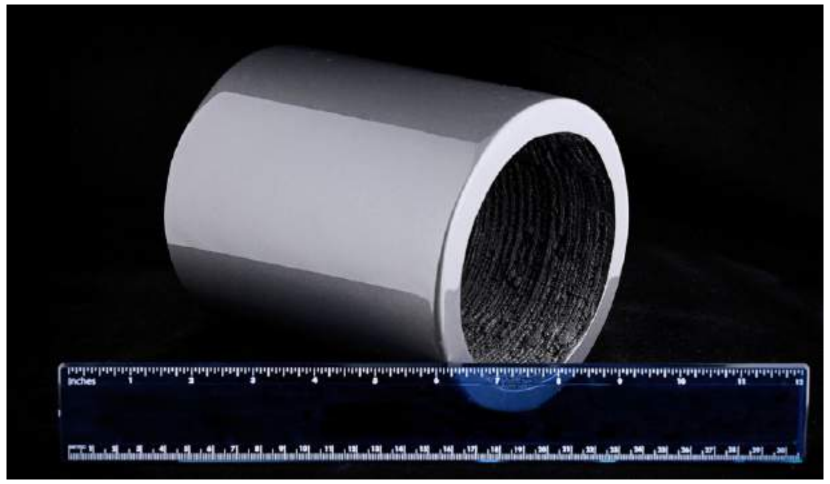
Future work will explore the printing of anisotropic, or directional, bonded magnets, which are stronger than isotropic magnets that have no preferred magnetisation direction. Researchers will also examine the effect of binder type, the loading fraction of magnetic powder and processing temperature on the magnetic and mechanical properties of printed magnets.

"This work has demonstrated the potential of Additive Manufacturing to be applied to the fabrication of a wide range of magnetic materials and assemblies," stated co-author John Ormerod.

Contributing to the project were Ling Li, Angelica Tirado, Orlando Rios, Brian Post, Vlastimil Kunc, R. R. Lowden, Edgar Lara-Curzio at ORNL, as well as researchers I. C. Nlebedim and Thomas Lograsso working with CMI at Ames Laboratory. Robert Fredette and John Ormerod from Magnet Applications Inc. (MAI) contributed to the project through an MDF technology collaboration. The DOE's Advanced Manufacturing Office provides support for ORNL's Manufacturing Demonstration Facility, a public-private partnership to engage industry with national labs.

The article is available to view on the Nature website at: www.nature.com/articles/srep36212.

www.ornl.gov



This isotropic, neodymium-iron-boron bonded permanent magnet was 3D-printed at DOE's Manufacturing Demonstration Facility at Oak Ridge National Laboratory

formnext 2016: event affirms reputation as worldwide platform for AM

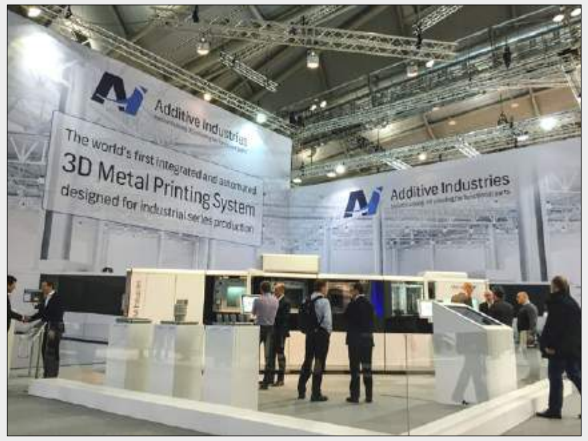
The second event in the formnext powered by TCT series, formnext 2016, took place in Frankfurt am Main, Germany, from 15 –18 November. In 2015 the very first formnext event firmly established itself as a leading international gathering for the AM industry and this second event built on this success, attracting visitors from across the globe to discover a diverse array of ground-breaking developments and world premieres. The organisers stated that the exhibition featured 307 exhibitors from 28 countries and attracted 13,384 attendees.

Sascha F. Wenzler, Vice President of formnext at event organiser Mesago Messe Frankfurt GmbH, commented, "formnext 2016 sends a clear statement. Already with the second edition it established a fixed place in the event calendars of the related industries. This success is underlined by a 50% increase in exhibitors and a 49% increase in trade visitors."

One contributing factor to the success of formnext 2016 was its international flavour, with 44% of visitors attending from outside of Germany. They included representatives from global OEMs and leading companies from a wide range of industries. The high level of visitor traffic and excellent overall atmosphere resulted in very positive feedback from exhibitors. Uri Resnik, CEO at OR Laser, Dieburg, Germany, stated, "During the first days our booth was completely crowded with international qualified visitors, among them representatives from OEMs such as Bosch and BMW. Overall an extremely positive trade show experience." In cooperation with tct, the formnext conference took a closer look at the future of Additive Manufacturing over all four days of the exhibition. Prominent speakers included German Paralympic champion Denise Schindler and numerous world-renowned experts from the field of Additive Manufacturing. The conference attracted a total of 647 participants from 25 countries

Two competitions organised as part of formnext, the Start-up Challenge and the Purmundus Challenge, also attracted considerable interest. The organisers stated, "The creative ideas submitted to these events from the world of Additive Manufacturing allowed attendees a glimpse of the future possibilities in additive production. In the Start-up Area, visitors also had the opportunity to marvel at exhibits of the year's winning entries from young entrepreneurs." The next formnext powered by tct will take place from November 14–17, 2017.

www.formnext.com



Renishaw and Dassault Systèmes team up to boost software

Renishaw has announced it is collaborating with Dassault Systèmes, a leading 3D modelling, simulation and industrial operations software provider, as part of a commitment to provide and enhance software for metal AM. Users of Dassault Systèmes' 3DExperience platform applications can now design, optimise, simulate and set up AM builds directly for production on Renishaw's AM systems. Dedicated Catia applications include a range of tools to develop and perform topological optimisation of parts. Delmia is employed to generate the process from build set up to generation of the necessary laser paths (scan paths). Simulation of the entire AM build, including stress analysis and distortion prediction, is carried out in Simulia.

Both Renishaw and Dassault Systèmes have software, which is accessible to authorised third parties, and this played a key role in the collaboration. It ensures the laser paths generated by Delmia are optimised for Renishaw metal AM systems and produce the best quality builds. This open ecosystem ethos enables collaboration with other experts working towards the common goal of creating a streamlined AM software experience.

"The 3DExperience platform coupled with QuantAM enables parts to be produced accurately from the outset, which is of tangible time and cost benefit to users. It marks the beginning of many enhancements we have in the pipeline to improve the AM user experience and streamline the front-end of the manufacturing process," stated Stephen Anderson, Renishaw's Director of Group Software.

This process control software is said to be part of Renishaw's wider mission to provide end-to-end solutions for innovative manufacturing and support the managed integration of AM into the production workspace.

www.renishaw.com/additive
www.3DS.com

Polygonica Software point cloud offering explained

MachineWorks Ltd, a manufacturer of component technology for processing polygon meshes based in Sheffield, UK, demonstrated its Polygonica 2.0 software at this year's formnext exhibition. The Polygonica Software Suite includes a complete array of tools for point cloud processing and meshing. Users can operate interactively and manipulate point cloud data according to the results on-the-fly.

Some of the new point cloud features include registration for aligning data sets from different scans, filtering to automatically remove outliers, smoothing for noise removing, sampling to reduce the size of point clouds, normal calculation and last but not least meshing of any part of the point cloud for further processing. Polygonica is said to offer great flexibility in manipulating point cloud data with users having infinite variations in which operations they apply to different sets of data.

"3D scanning is now common place and point clouds are at the heart of it. The potential for this exciting technology is tremendous and we will continue to focus our efforts on this area of development. It is only a natural step for our powerful solid mesh processing capabilities to be applied to the end result of point cloud processing" stated Dr Fenqiang Lin, MD of MachineWorks.

Polygonica 2.0 also contains a new algorithm for re-meshing. Other functions in the newest release are related to further development on geodesic paths, collision detection and handling open solids.

www.polygonica.com
www.machineworks.com

Cubichain brings blockchain cyber-security to AM industry

Cubichain Technologies, a Californian start-up focused on developing and deploying cyber-securing and anti-counterfeiting tools, along with CalRAM LLC., experts in the production of metal powder bed fusion components for aerospace and space applications, have announced the successful deployment of a blockchain network to protect the digital data stream for additively manufactured aerospace titanium parts.

Using the MultiChain private blockchain platform, based on Bitcoin Core, Cubichain Technologies stated that it is developing an application that interfaces with Additive Manufacturing industry processes to encrypt critical digital data associated with the binary part definition. It then stores that information on an internationally distributed private blockchain. The information stored on the blockchain provides an immutable copy of the original encrypted data that is used to verify that transmitted copies of the digital part data have not been altered, tampered with or otherwise hacked. The demonstration provided proof that the Cubichain technology can easily identify part files which have been tampered with by recognising the difference in a single data bit in the binary part file.

"Both Additive Manufacturing and blockchain networks are disruptive technologies; combining the two will undoubtedly revolutionise the future of manufacturing. We see the greatest threats to Additive Manufacturing as cyber-physical hacking and counterfeiting; the deployment of a blockchain can combat both. It's very exciting technology," stated Shane Collins, Director Additive Manufacturing Programs for CalRAM.

www.cubichain.com
www.calraminc.com

GKN Aerospace: The development of Additive Manufacturing at a global Tier 1 aerospace supplier

Metal Additive Manufacturing magazine was recently invited to visit the GKN Aerospace facility at Filton, Bristol, UK, to discover the business's global development activities in Additive Manufacturing (AM) and to view the company's on-site AM centre. Dr Robert Sharman, Head of Additive Manufacturing at GKN Aerospace, and Tim Hope, Manager of the Additive Manufacturing Centre at Filton, hosted the visit and outlined the company's current activities and future aspirations in the field of AM for aerospace applications.

GKN plc is a global engineering business with four divisions; GKN Aerospace, GKN Driveline, GKN Powder Metallurgy and GKN Land Systems, which operate in the aerospace, automotive and land systems markets respectively. Founded more than 250 years ago, the UK-based company has adapted, developed and grown into a business with 56,000 employees and 2015 sales in excess of £7.5 billion. It serves most of the world's leading vehicle, machinery and aircraft manufacturers.

Through the acquisition of strategic elements of leading aerospace manufacturers, GKN Aerospace has grown to establish itself as a world-class business. Prominent steps in this growth path, with particular relevance to the division's global AM development activities, date back to 2001 with the acquisition of the St. Louis, Missouri, USA, operation from Boeing. This acquisition created a strong partnership with Boeing in both metallic and composite technologies. This was followed in 2009 with the acquisition from Airbus of the UK's Filton operation, significantly enhancing the business's expertise in metallic aerostructure assembly. In 2012 GKN acquired Volvo Aero, Sweden, creating a market leader in aero-engine components and significantly expanding GKN's aero engine components business. The most recent acquisition, of Fokker Technologies, the Netherlands, in 2015 strengthened its market leading position, expanded its technology offering and increased content on key aerospace platforms, broadening its global footprint.

Fig. 1 An Arcam EBM machine in operation at GKN Aerospace's Filton facility

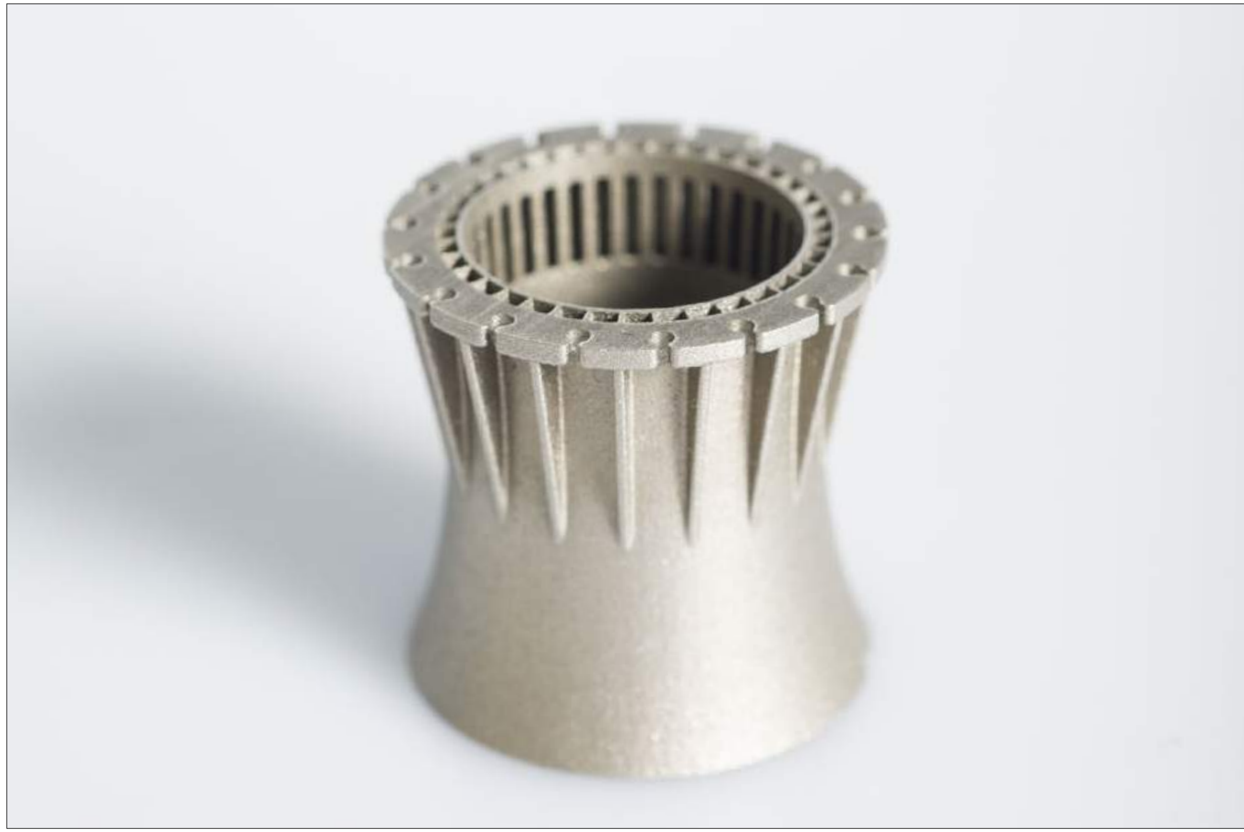


Fig. 2 A demonstration component developed by GKN Aerospace and produced using Selective Laser Melting

As a result of these acquisitions, GKN Aerospace can now claim to be the leading global Tier 1 aerospace supplier with an unrivalled breadth of capabilities in areas including:

- Aerostructures
- Engine systems
- Rocket engine subsystems
- Special products (e.g. window transparencies for flight deck and passenger cabins, ice protection systems, lightweight missile canisters)
- Landing gear
- Wiring interconnect systems
- Global services, including MRO (Maintenance, Repair and Overhaul), conversion and completion for mature and legacy aircraft

Today, GKN Aerospace has around 17,500 employees at 62 locations in fifteen countries. 2015 sales were around £2.5 billion, or approximately 33% of total GKN group sales.

Additive Manufacturing as a cross-divisional activity at GKN

Robert Sharman was keen to emphasise that GKN, as a group, sees Additive Manufacturing as a high priority manufacturing technology, stating, "AM development is a cross-divisional activity, particularly involving cooperation across a network of Centres of Excellence that span the Aerospace and Powder Metallurgy divisions of the group. In addition there is collaboration with a number of external parties such as equipment suppliers and research institutions."

AM related activities in the Centres of Excellence in Powder Metallurgy parts (GKN Sinter Metals, Radevormwald, Germany) and metal powder production (GKN Hoeganaes, Cinnaminson, New Jersey, USA) operations have been reviewed in separate reports [1, 2].

The focus of AM developments within these PM Centres of Excellence is largely on powder bed fusion and binder jetting technologies to produce series ferrous automotive components. In addition, GKN Hoeganaes has introduced the gas atomisation of titanium alloys to its powder making capability and this was further strengthened through the announcement of a joint venture agreement with the specialist German powder maker, TLS Technik [3].

Sharman stated that GKN Sinter Metals' interest in binder jetting was supported by its ability to leverage its expertise in Metal Injection Moulding, a technology that shares the process stages of debinding and sintering after the forming (or building) of the green parts. The potential of binder jetting to reduce AM part cost is of great interest for automotive applications. The binder-based AM technology is not, however, of interest to GKN Aerospace because of the inability of the process to achieve full density in the final product.

Global AM activities within GKN Aerospace

Sharman highlighted that the Aerospace division's focus is on metallic AM technologies and, specifically, on the processing of titanium and nickel-based alloys, although there is also polymer capability and application, as will be discussed later in this report.

GKN's AM developments began over fifteen years ago on rocket engine nozzle reinforcements through wire deposition. The company was also involved from a very early stage in EU-funded AM research programmes. The EU's Framework 6 VITAL project involved the Trollhättan, Sweden, operation (then Volvo Aero and now GKN Aerospace Engine Systems, AES), while the Regional Growth Fund ecoHVP project involved the Filton operation. The company continues to be involved in collaborative R&D programmes, including the Aerospace Technology Institute (ATI) funded Horizon project.

The Fokker acquisition also brought new AM capabilities and opportunities into the business, especially on the polymer side of AM, as well as opening up new applications for GKN's AM technology in wiring, landing gear and Maintenance, Repair and Overhaul. Consequently, the division's AM capabilities have grown significantly in scope to cover all of the major AM processing techniques and the entire value chain, from raw material to design, process and applications development.

Developments in the broad range of available AM technologies are led by the separate Centres of Excellence in GKN Aerospace and these encompass the following technologies:-

Fig. 3 Powder removal from in a protective atmosphere from a component produced in an Arcam EBM machine

Large-scale wire-based deposition

Large-scale deposition from a feedstock in wire form is undertaken using laser beams as the energy source. This is a high throughput process and is focused on large-scale (50 cm+) parts. Applications include large aerostructure components and the initial introduction of the technology is driven by the cost benefits arising from significantly enhanced buy-to-fly ratios. The North American Centre of Excellence is leading the development of this technology variant.

Fine-scale deposition

Fine-scale deposition is undertaken either from wire using a laser beam or from a powder feedstock using a laser beam with local atmosphere shielding. The focus is on titanium and nickel-based alloys and applications include the building of add-ons and features on welded structures, castings or forgings. This technology enables a reduction of part numbers, a reduction of the finish machining envelope, enhanced buy-to-fly ratios, high value component repairs and modifications and the building of a broad range of medium-sized aero-engine, space and aerostructure components and fabrications. The AM Centre of Excellence in Trollhätten, Sweden is leading this technology development.

Powder Bed Fusion

Powder Bed Fusion technologies use either a laser beam (Selective Laser Melting, SLM) or an electron beam (Electron Beam Melting, EBM) in a chamber to produce a part. The focus for EBM is on Ti-6Al-4V for highly net-shape small to medium

Fig. 4 A metal AM component inspected in the laboratory at GKN's Filton facility using a combined 3D micro coordinate measurement machine and surface roughness measurement system

parts. Selective Laser Melting is the lowest material throughput process of all of the available metal AM options. The focus here is on titanium and nickel-based alloys and on the building of intricate, complex, high-value components. The Filton Centre of Excellence takes the lead in the development of these powder bed processes.

Polymer processing

Polymer processing at GKN Aerospace involves either Selective Laser Sintering (SLS) in a powder bed or the deposition of extruded polymer, which solidifies layer-by-layer (Fused Deposition Modelling, FDM). The former process is restricted to a nylon feedstock, whereas the latter process is applicable to a wide range of thermoplastics. Both processes can deliver highly net-shape products and are applicable to tooling manufacture, rapid prototyping and component building. The Filton Centre of Excellence again takes the lead in the development of these processes.

Sharman stated, "All of these process options have both strengths and limitations and, therefore, they will all find a place within the AM processing scene of the future. Notwithstanding that the Centre of Excellence at Filton is specifically focused on powder bed processes, my view is that, in the future, the current dominant position of these processes will diminish to some degree and that the relative importance of the deposition technologies will increase."

As identified earlier in this report, an in-house powder supply capability is being developed in cooperation with the GKN Hoeganaes powder division, which has world-class capabilities in powder development, supply and handling.

Applications and developments are being pursued across the GKN Aerospace product portfolio in aerostructures, aero-engines and space applications. Examples of these application areas are cited in later sections of this report.

The perceived benefits to be derived from AM

The drivers for the adoption of AM were classified in three categories; delivery, cost and performance. Delivery drivers primarily relate to AM's ability to significantly compress application development lead times, from initial data release to first article production. An example was quoted where a lead-time of almost two years in conventional processing was compressed to less than twelve weeks with AM.

Cost drivers relate to the much higher material utilisation and energy efficiency levels offered by AM compared with conventional processing. Material wastage levels of 90% - or buy-to-fly ratios of 10:1 - are not untypical for parts fabricated from titanium plate, whereas material utilisation can be close to 100% in AM processes. This comparison becomes even more significant in times of material price volatility. While the above categories of drivers relate to situations where AM is in competition with other manufacturing technologies, performance drivers often relate to AM's ability to offer unique solutions, making its use an imperative. The use of topology optimisation to deliver component weight savings and the application of unique geometric capabilities for functional applications are both competitive advantages for AM in this category.

The adoption of bionic concepts in the design of AM components is an important aspect of GKN's developed capabilities, but there is a further concept that is borrowed from nature and that, as a metallurgist, holds particular attractions for Sharman. "Whereas the achievable microstructures in conventional manufacturing processes are largely constrained by the 'bulk' microstructures of the starting raw materials, AM has the ability to grow tailored microstructures 'in-situ' on a micro-scale. By judicious control over processing parameters, this offers the potential for placing the desired microstructures, and consequent properties/performance, precisely where they are needed in the built component. This implies the need for a detailed understanding of the relationships between AM process parameters, derived microstructures and consequent properties. The development of this understanding constitutes an important element of the development work in GKN's AM Centres of Excellence," stated Sharman.

As a further issue related to the tailoring of performance, it was noted that through the use of multiple feedstock wires, the wire-based deposition technologies in particular have great flexibility for local adjustment of chemical composition during a component build, enabling the direct building of functionally graded materials.

The requirement to control the levels of residual stresses in larger AM components often drives AM practitioners to the selection of processes such as EBM, which uses a pre-heated powder bed, or binder-jetting, which is a close-to-ambient temperature build process that therefore avoids residual stress generation. GKN Aerospace adopts a different philosophy through a modelling and prediction approach to define the required process parameter control to minimise stress generation. This builds on established expertise at the Trollhätten Centre of Excellence in the modelling and control of stress generation during welding.

Fig. 5 A test build is analysed using a high performance laser scanner

Fig. 6 Metal powder development and analysis is a central aspect of GKN's involvement in Additive Manufacturing

The AM Centre of Excellence at Filton

A tour of the facilities at Filton was provided by Tim Hope. The complement of AM machines in the centre was in the process of being increased from eleven to twelve, with the delivery of an additional polymer AM machine on the very day of the visit.

| contents page | news | events | advertisers' index | contact |
AM at GKN Aerospace

Fig. 7 A partly machined aerospace bracket produced using EBM

Fig. 8 An as-processed bracket prior to the removal of support structures

Fig. 9 A demonstration component manufactured by GKN Aerospace in Filton

The equipment is housed in three separate cells, two dedicated to EBM and one to laser powder bed processing. The work involved in the first of the EBM cells has a major target in developing an understanding of the relationships between build process parameters and the consequent microstructural and property/performance control. This information is then used to set process parameters in the second cell, which is dedicated to the series production of titanium components using EBM.

The centre also includes a dedicated materials laboratory for powder characterisation and quality control and an in-house metrology and materials testing facility. The centre works closely with conventional manufacturing techniques on the Filton site.

The focus at Filton is firmly on titanium and nickel-based alloys. On a case-by-case basis, the centre has been able to demonstrate significant cost savings in the replacement of conventional processing with the near-net shape AM approach. Part integration and structural optimisation have been shown to lead to higher performance and further cost reductions. Functional systems for acoustic liners and embedded anti-ice systems are examples of products that have been developed.

The Business Unit Space in Trollhättan

The Business Unit Space was one of the early adopters of AM, researching both fine deposition for its rocket nozzles and powder bed technology for its turbines. Today it works closely with the different GKN AM centres and several institutes. The first AM application in Europe that was hot fired on a rocket engine was GKN's Vulcain 2 demonstration nozzle. This had over 50 kg of fine deposition features added to solve a number of functions (Fig. 10). Today AM is implemented on the Vulcain 2.2 nozzle for the Ariane 6 rocket.

Fig. 10 In the foreground the Vulcain 2 demonstration nozzle stands with over 50 kg of Laser Wire AM deposition. It is not only used to reinforce the structure but also join to parts, which enabled significant cost savings. In the background is the Vulcain 2 nozzle for the Ariane 5 rocket

The AM Centre of Excellence in Trollhättan

The Trollhättan centre is based at the Innovatum Production Technology Centre (PTC) in conjunction with the city's University West. The development cells house:

- One 3 m size laser cell for AM and welding demonstrations
- One 1.5 m size laser cell for AM wire deposition
- One 1 m size laser cell for adaptive laser welding
- One 1 m size laser blown powder and welding cell
- One EBM system for nickel alloys

Laser wire AM is also used for feature deposition on large cast or forged titanium or nickel-based alloy components. This is a qualified process in GKN Aerospace Engine Systems for bosses and grow-outs and is also in use in space systems.

Powder deposition has been developed for feature deposition, component modification and component repair and has both titanium and nickel alloy capability. As previously mentioned, the centre has the capability for thermal distortion management and modelling, leveraged from its expertise in welding process control.

The US AM Centre of Excellence, St. Louis

The US Centre of Excellence in St. Louis is a collaboration with Oakridge National Laboratory. The division drives the development and application of large-scale deposition technologies that use a feedstock in wire form.

This technology is suitable for the production of large aerospace components and for the addition of features to large titanium forgings. The local deposition of flanges, details and sections for net or near-net preforms and the fabrication of entire components are possible options. GKN's St Louis facility pairs Additive Manufacturing technology expertise with the site's significant end-to-end manufacturing capability. As a secured facility, the development and implementation of AM for U.S. defence applications can be undertaken.

Future outlook for the exploitation of AM

Serial production of metal AM aerospace components is already underway at GKN Aerospace alongside each Centre of Excellence and, in relation to the future exploitation of the technology, Sharman anticipates that growth will be at a fast pace in-line with the current market and that even further acceleration will arise as new platforms are launched.


Fig. 11 This case study clearly demonstrates AM's material utilisation advantage compared to conventional processes

"The reality is that the aerospace industry recognises all of the benefits that can accrue from the use of metal AM and is embracing the wider adoption of the technology. As with all technologies, its adoption is more linked to the market opportunity for new products and so we expect to see each new aerospace platform to have an increasing AM content," stated Sharman.

In addition to the successful use of AM for the Vulcain rocket nozzles, the extension of GKN Aerospace's risk and revenue sharing partnership (RRSP) with Rolls-Royce on the Trent XWB-84 large aero engine will involve the use of a range of design methodologies and fabrication technologies, including AM processes, to create the lighter weight, higher performance Intermediate Compressor Casing (ICC). The supplier of the ICC will again be GKN Aerospace Engine Systems in Sweden.

"As with all technologies, its adoption is more linked to the market opportunity for new products and so we expect to see each new aerospace platform to have an increasing AM content"

In a sector where qualification issues for any new production technology are recognised to be extremely rigorous, Sharman stated that the biggest challenges in enabling the adoption of AM relate to concerns over the reliability, quality and repeatability of the processing equipment and the raw material supply. The company's strategy in responding to these challenges is to run test samples in builds and to ensure that the most rigorous controls and specifications are in place to ensure the necessary quality.

As GKN Aerospace seeks to leverage its expertise in metal AM, a number of options are potentially open, including the building of components for incorporation in its own assemblies and sub-systems, the contract manufacture of individual components for aerospace customers or the development of components, the manufacture of which could be sub-contracted. Sharman remarked, "All of these options are possible, depending on the application and the customer. However, in the immediate term, we would expect to keep most of the manufacture in-house because of the need for development and manufacture to be closely linked."

Currently, production is carried out alongside the company's Centres of Excellence but, in response to the question as to whether GKN Aerospace might contemplate the building of a dedicated AM factory as production volumes ramp up, Sharman remarked, "As with all business decisions, the timing, scale and location of future facilities would depend on a range of factors."

References

[1] "GKN Sinter Metals: Global Tier 1 automotive supplier anticipates opportunities for Additive Manufacturing", Schlieper, G, *Metal Additive Manufacturing*, Vol. 2, No. 2, p. 55-61. Available to download from www.metal-am.com.

[2] "Hoeganaes Innovation Centre: Technical support and powder development for the next generation of PM applications", Whittaker, P, *Powder Metallurgy Review* , Vol. 5, No. 3, p 47-56. Available to download from www.pm-review.com.

[3] Hoeganaes to form new joint venture to produce titanium powder in North America, www.pm-review.com, retrieved November 2016.

Contact

Marianne Mulder
Digital Communications & Media Manager
GKN Aerospace
Industrieweg 4
Papendrecht 3301LB
The Netherlands
Tel: +31 (0)78 6419848
Email: marianne.mulder@fokker.com
www.gkn.com/aerospace

Author

Dr David Whittaker is a consultant to the Powder Metallurgy industry.
Tel: +44 (0)1902 338498
Email: whittakerd4@gmail.com

Modelling the mechanical behaviour of additively manufactured cellular structures

One of the most promising aspects of Additive Manufacturing is the design freedom it enables. One manifestation of this design freedom lies in our ability to manufacture cellular structures such as lattices and honeycombs. Implementing cellular structures with AM, however, poses a range of design and manufacturing challenges. In this article Dr Dhruv Bhate, from Phoenix Analysis & Design Technologies, Inc. (PADT), focuses on a key area connecting design and manufacturing to final part implementation – the mechanical behaviour of these structures and the challenges and approaches to developing a reliable way to predict it.

It is now well appreciated that, within the several design possibilities enabled by metal Additive Manufacturing, cellular structures such as honeycombs and lattices are a particularly exciting research frontier. Cellular structures offer advantages that cannot be easily availed of from homogeneous structures. The better known examples of these advantages, particularly in the aerospace and transportation industries, include increasing stiffness-to-weight ratios, energy absorption and thermal performance. Medical implants also stand to benefit from improved bone integration and the ability to tailor mechanical properties spatially that come with the use of cellular geometries.

These advantages are essentially attained by leveraging the fact that cellular materials allow for tuning the allocation of material and space at a finer level than is attainable through traditional homogeneous structures and at a more accessible level of scale than at the microstructural level. While these advantages have been exploited even before AM arrived on the scene, AM technologies have made it significantly easier to manufacture these structures and explore geometries that were hitherto cost prohibitive or simply not feasible to manufacture.

This article focuses on the modelling aspect of successfully implementing cellular structures using AM technologies. While this is independent of the process used to make these structures, the vast majority of published literature on

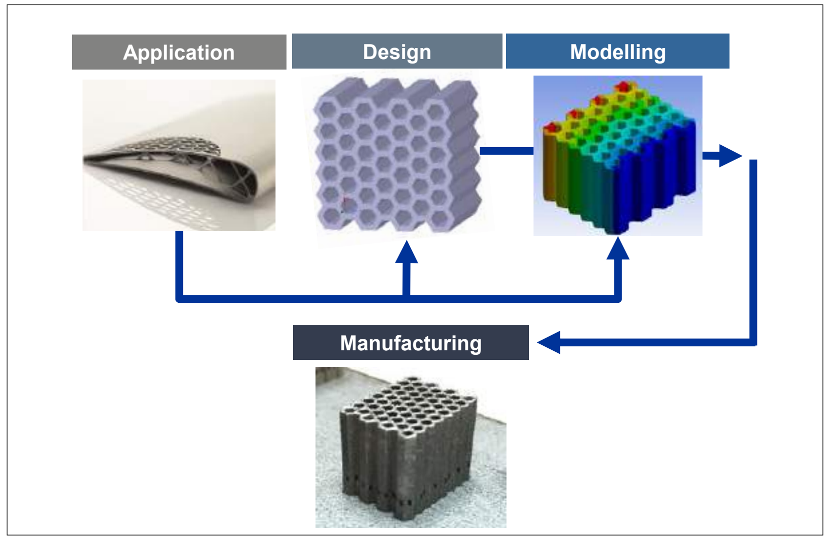


Fig. 1 Research and development areas in AM of cellular structures. The arrows are indicative of the fact that the application drives the design and modelling requirements, which in turn, taken together along with manufacturing constraints, inform the final production

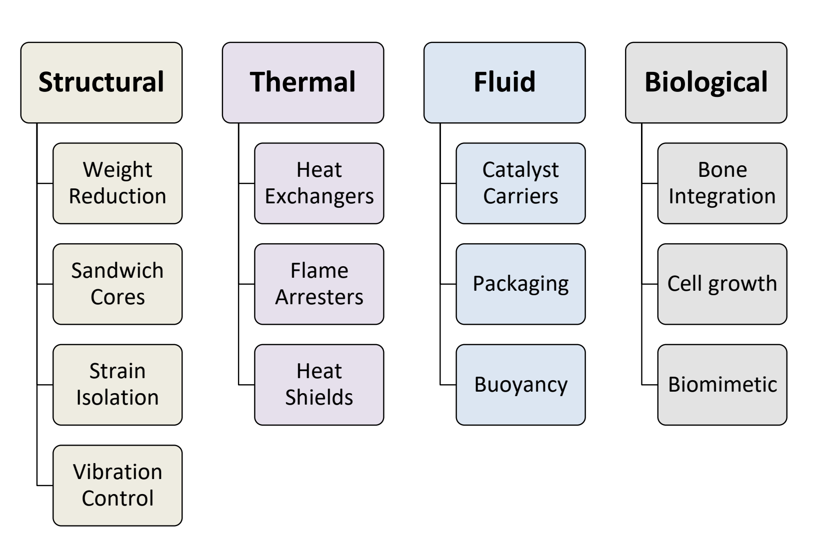


Fig. 2 Application areas for cellular structures that can leverage their special properties to enhance overall functional performance, adapted from [1]

"Without models that describe cellular structure behaviour, we are left with design tools that make structures that we can manufacture, but with little confidence in their ability to perform the desired function"

cellular structures is in metal AM, led by laser-based and electron-beam melting of metal powder. At the outset though, it helps to clarify the big-picture elements that need to come together to enabling production of cellular structures with AM, how modelling interfaces with the other elements and why it is a critical aspect in its own right.

Context: The role of modelling

The research and development in AM cellular structures can be broadly classified as belonging to one of four categories: application, design, modelling and manufacturing (Fig. 1). Modelling in this context is the analytical representation of material behaviour, primarily for use in predictive analysis. This is a critical aspect of enabling true simulation-driven design, where the design is the outcome of some objective such as stiffness-to-weight maximisation relative to an allowable stress, for example. From a more abstract point of view, modelling links up design and manufacturing capabilities to the application. Without models that describe cellular structure behaviour, we are left with design tools that make structures that we can manufacture, but with little confidence in their ability to perform the desired function in the end-application. While it is possible to certify components with cellular structures through rigorous testing, valid models and robust simulation together can both drive down qualification costs and also unlock untapped potential that a normal 'design-manufacture-test' cycle fails to uncover.

Modelling is thus highly dependent on information from the application and the available design and manufacturing options. A detailed discussion of each of these elements is beyond the scope of this current article, but a brief classification of the available options and tools is provided.

Applications

Generally speaking, the applications for cellular structures can be classified into structural, thermal, fluid and biological (Fig. 2). An understanding of the specific advantage being sought by using cellular structures ensures that the model developed is able to incorporate the relevant physics (or chemistry, biology) while also meeting other requirements needed of the part in question that incorporates them. One shared requirement of all manufactured parts is that they retain structural integrity for the intended application. Thus, understanding the mechanical behaviour of cellular structures is a shared area of interest independent of the ultimate reason why cellular structures were preferred to begin with. This is why this article and indeed the majority of the published research focuses on mechanical behaviour.

Design

Several design tools exist today in the form of stand-alone and integrated software solutions. Broadly speaking, these solutions fall into four categories, only two of which rely on analysis and therefore require material models. An approach that is purely geometric is the use of Boolean techniques common to most conventional CAD software, where a cellular structure is first designed and then added to or subtracted from another part. An improvement on this approach is to use what is referred to commonly as 'infill'. Infilling enables populating a part design with cellular structures and typically enables control on the skin of the part as well.

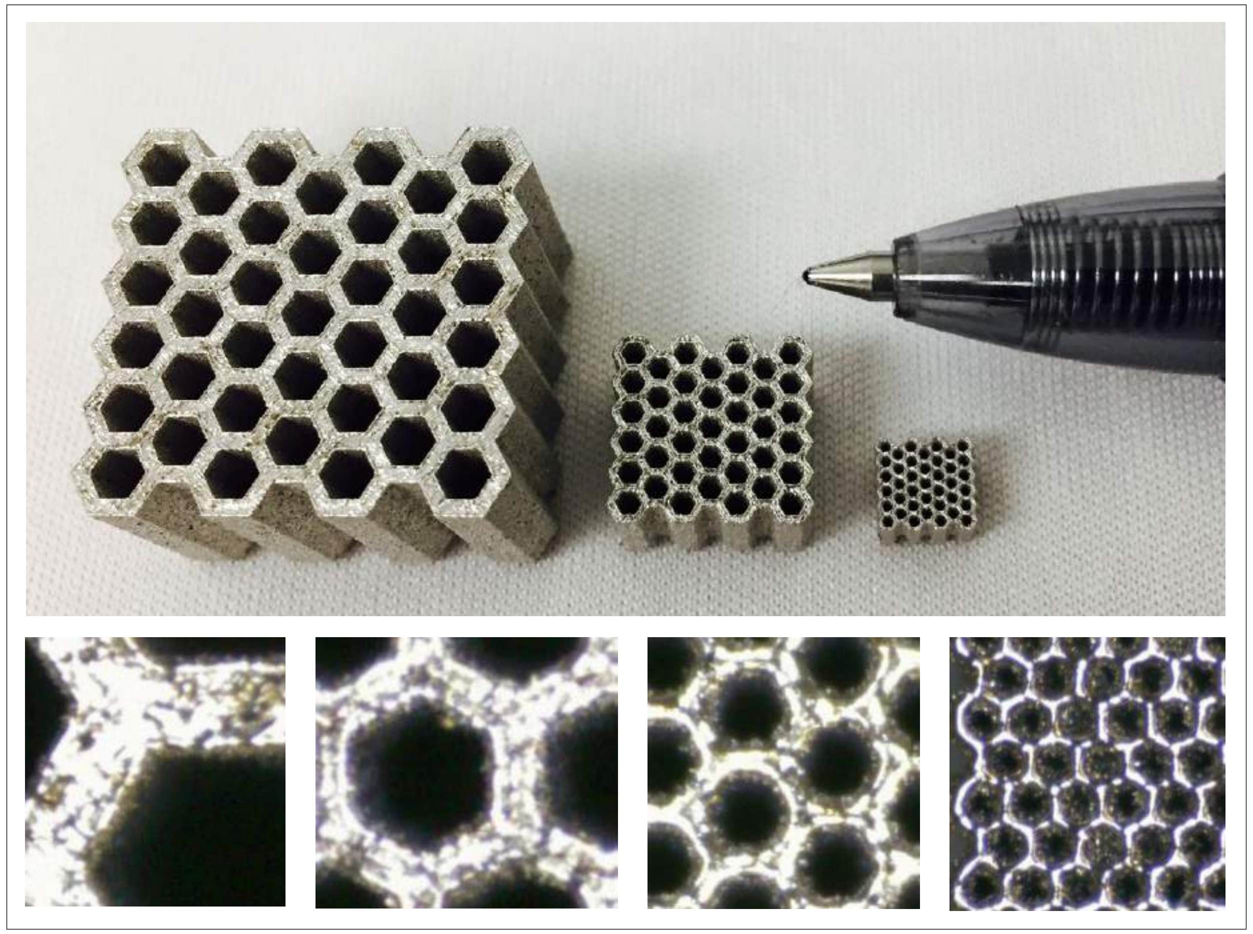


Fig. 3 Stainless steel 316L honeycombs manufactured with laser-based powder bed fusion. Gradually reducing wall thickness and edge length shows how, at a certain point, the cells no longer retain their intended shape

The two approaches that need a material model to be truly effective are topology optimisation based cellular structures and generative approaches. The former solves a topology optimisation problem, but, instead of allocating only material and space as is done conventionally, material densities can now be replaced with cells having equivalent density. Generative approaches, on the other hand, typically begin by defining nodes in space and building connections between nodes in response to an imposed problem, adjusting their thicknesses and distances through a combination of user-provided and analysis driven inputs.

Manufacturing

As mentioned previously, the majority of published literature in cellular structures with AM is in metals. In fact, in a recently conducted literature review of about fifty published papers on cellular structures and AM, it was found by the author that about 80% of these papers involved metal AM, the majority of them with laser-based powder bed fusion as the method of choice. The manufacturing process and material in question together are key inputs for modelling. Additionally, independent of the process used, there are three key manufacturing constraints that need to be considered:

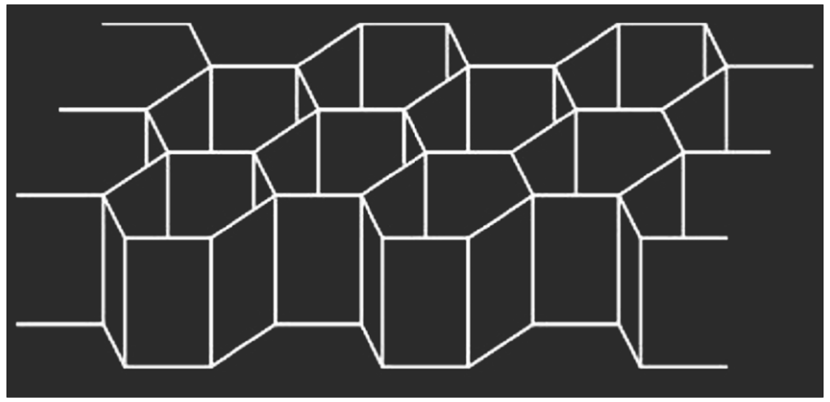


Fig. 4 Hexagonal honeycomb structure showing two-dimensional, prismatic nature (Attr: modified from the original by G.W. Herbert, Wikimedia Commons)

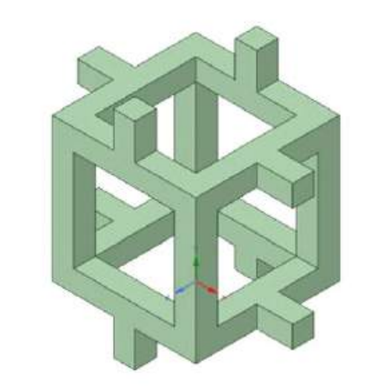


Fig. 5 Open cell foam unit cell

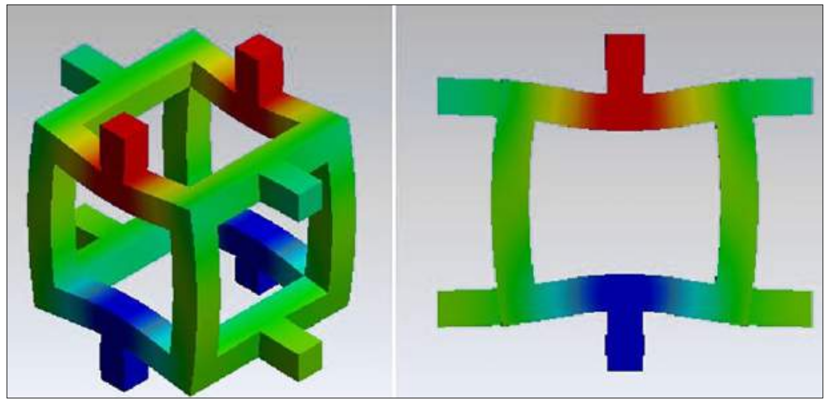


Fig. 6 FEA simulation of open cell foam unit cell under compression, showing predominant mode of deformation is on account of bending

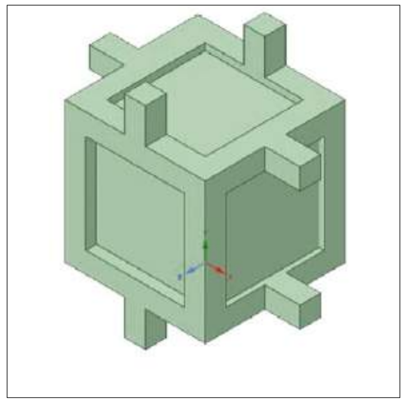


Fig. 7 Closed cell foam unit cell representation

- Minimum feature size: In the context of cellular structures, this refers both to the minimum thickness of the wall or strut and the minimum void volume that can be resolved within the members (Fig. 3). For powder bed fusion metal AM processes, the thinnest walls and struts that can be manufactured are typically in the range of 150-500 µm. The smallest volume that can be encapsulated varies strongly as a function of the specific cell in question.
- Support strategies: Most metal AM processes will require some form of support for mechanical and/or thermal reasons. With cellular structures, the structures must themselves provide this support.
- Accessibility: Another consideration is accessing both trapped powder and the structures themselves (for any finishing operations) – this may drive the need to provide escape holes for the powder, in the case of the former, and, in the case of the latter, defining minimum cell size not on the basis of the machine capability, but on the ability of the finishing agent to access the interior cells.

Classification of cellular structures

From a designer's perspective, the first step in implementing cellular structures in Additive Manufacturing is selecting the appropriate unit cell. The unit cell is selected based on the performance desired of it as well as the manufacturability of the cells. Seminal texts in the area of cellular solids and materials selection classify unit cells in the following four categories [2, 3].

Honeycomb

Honeycombs are prismatic, 2-dimensional cellular designs extruded in the 3rd dimension, like the well-known hexagonal honeycomb (Fig. 4). All cross-sections through the 3rd dimension are thus identical, making honeycombs somewhat easy to model mathematically. Though the hexagonal honeycomb is the most easily identifiable, the term applies to all designs that have this prismatic property, including square and triangular honeycombs.

Honeycombs have strong anisotropy in the 3rd dimension. In fact, the modulus of regular hexagonal honeycombs is transversely isotropic; equal in all directions in the plane but very different out-of-plane. The 2D nature of honeycomb structures means that their use is beneficial when the environmental conditions are predictable and the honeycomb design can be oriented in such a way as to extract maximum benefit. Examples of this include crash panels in the automotive industry, sandwich panels in construction and automotive radiator grilles. In all these cases, the direction of the environmental stimulus is known, whether it be the mechanical load or fluid flow.

Open-cell foam

Freeing up the prismatic requirement on the honeycomb enables a fully 3-dimensional open-cell foam design as shown in one representation of a unit cell in Fig. 5. Typically, open-cell foams are bending-dominated, distinguishing them from stretch-dominated lattices, which are discussed in more detail in a following section on lattices. Unlike the honeycomb, open cell foam designs are more useful when the environmental stimulus (stress, flow, heat) is not as predictable and unidirectional. The bending-dominated mechanism of deformation (Fig. 6) makes open-cell foams ideal for energy absorption – stretch dominated structures tend to be stiffer in comparison. As a result of this, applications that require energy absorption such as mattresses and

crumple zones in complex structures benefit from open cell foam designs. The interconnectivity of open-cell foams also makes them a candidate for applications requiring fluid flow through the structure.

Closed-cell foam

As the name suggests, closed cell foams are open-cell foams with enclosed cells, such as the representation shown in Fig. 7. This typically involves a membrane-like structure that may be of varying thickness from the strut-like structures, although this is not necessary. Closed-cell foams arise in a lot of organic processes commonly found in nature. In man-made entities they are commonly found in the food industry (bread, chocolate) and in engineering applications where the enclosed cell is filled with some fluid (like air in bubble wrap, foam for bicycle helmets and fragile packaging). The primary benefit of closed cell foams is the ability to encapsulate a fluid of different properties for compressive resilience. From a structural standpoint, while the membrane is a load-bearing part of the structure under certain loads, the additional material and manufacturing burden can be hard to justify. Within the AM context, this is a key area of interest for those exploring 3D printing of food products, for example, but may also have value for biomimetic applications with metal AM.

Lattice

Lattices are, in appearance, very similar to open cell foams, but differ in that lattice member deformation is stretch - as opposed to bending - dominated. This is important since, for the same material allocation, structures tend to be stiffer in tension and/or compression compared to bending. By contrast, bending-dominated structures typically absorb more energy and are more compliant. So the question is – when does an open cell foam become stretch dominated and, therefore, a lattice? Fortunately, there is an equation called Maxwell's stability criterion that addresses just this issue. The

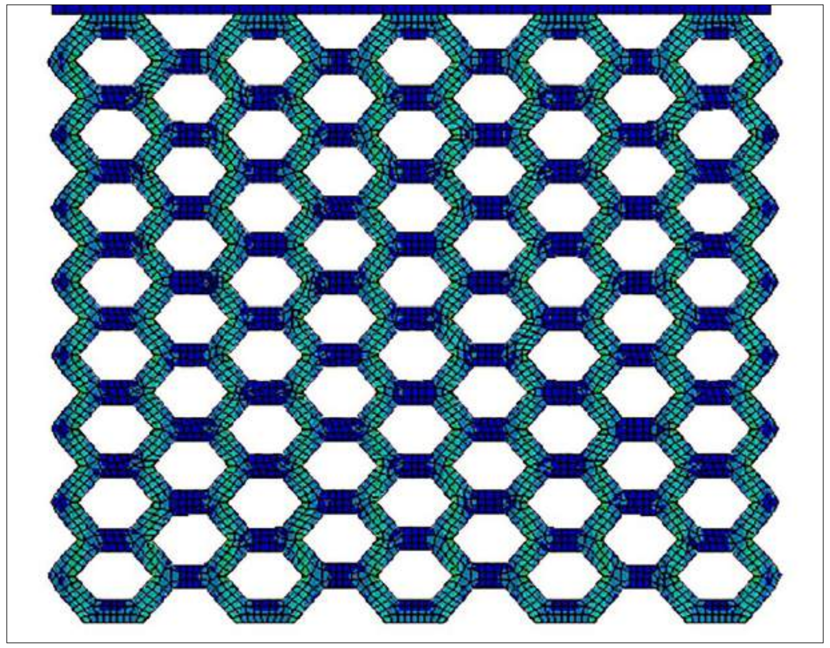


Fig. 8 Honeycomb structure under compression showing non-uniform local elastic strains

criterion involves the computation of a metric M for a lattice-like structure with b struts and j joints as follows:

In 2D structures: $M = b - 2j + 3$
In 3D structures: $M = b - 3j + 6$

With Maxwell's criterion and assuming the joints are locked (and not pinned), if $M < 0$, we get a structure that is bending-dominated. If $M \geq 0$, the structure is stretch dominated. The former constitutes an open-cell foam, the latter a lattice. There are several approaches to establishing the appropriateness of a lattice design for structural applications (connectivity, static and kinematic determinism etc.) and how they are applied to periodic structures and space frames. For a periodic structure to be truly space-filling, as is needed for AM applications, there is no simple rigid polyhedron that can accomplish this. A combination of polyhedra, such as an octahedron and tetrahedron that together make up an octet truss, are needed to generate true space filling rigid structures [4, 5].

Lattices are the most common cellular solid studied in AM. This is primarily on account of their strong structural performance in applications where high stiffness-to-weight ratio is desired (such as aerospace), or where stiffness modulation is important (such as in medical implants). However, it is important to realise that there are other cellular representations that have a range of other benefits that lattice designs cannot provide. Generally speaking, the following guidelines apply:

- Honeycomb structures for predictable, unidirectional loading or flow
- Open cell foams where energy absorption and compliance is important
- Closed cell foams for fluid-filled and hydrostatic applications
- Lattice structures where stiffness and resistance to bending is critical.

Considerations in the modelling of cellular structures

Selecting a particular unit cell design based on the functionality sought is the starting point for a designer. This must then be coupled with a model that describes the performance of that structure, which in turn requires

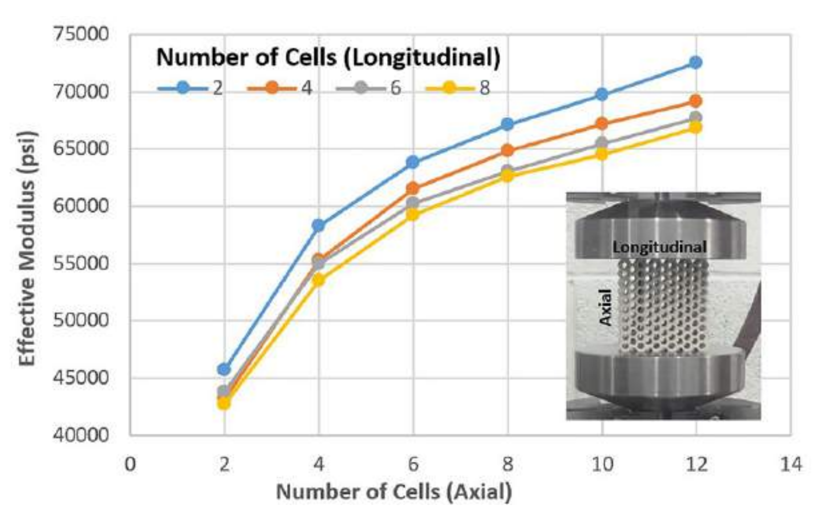


Fig. 9 Effective modulus under compression showing a strong dependence on the number of cells in the structure (Data collected by Thao Le, Arizona State University)

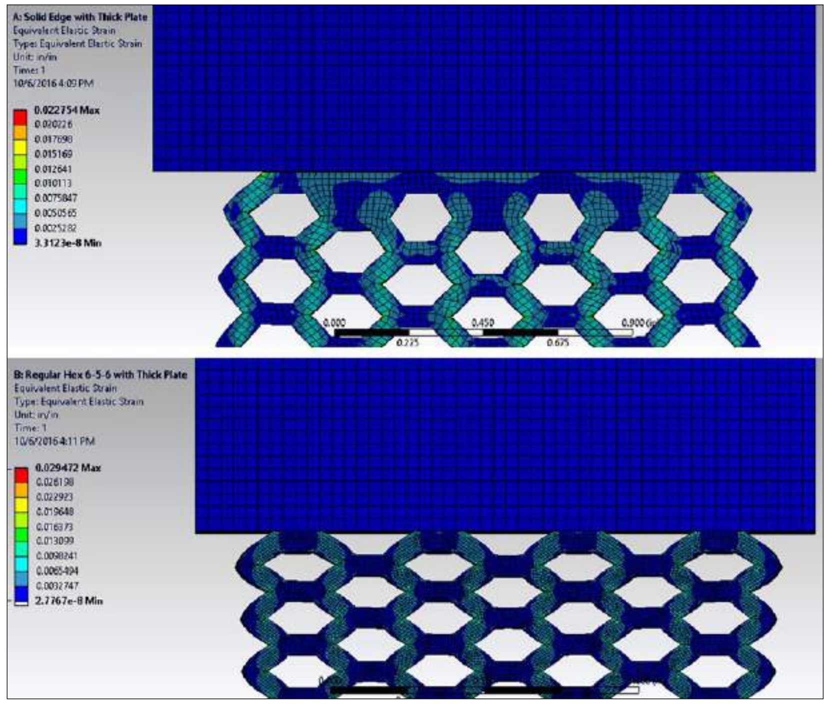


Fig. 10 Two (of many possible) contact conditions for cellular structure compression – both in terms of specimen design as well as in terms of the nature of contact specified in the simulation (frictionless vs frictional, for example)

the development of an analytical model and an experimental characterisation protocol that goes along with it. While there are standards for most mechanical testing, the standards for cellular structures are very limited. This is partly on account of the significant challenges associated with developing models for cellular structures, which are presented here.

Complex geometry with non-uniform local conditions

The first and most obvious challenge with cellular structures is that they are not fully-dense homogeneous materials with relatively predictable responses governed by straightforward analytical expressions. Consider a dogbone-shaped specimen of solid material under tension: its stress-strain response can be described fairly well using continuum expressions that do not account for geometrical features beyond the size of the dogbone (area and length for stress and strain computations respectively). However, as shown in Fig. 8, such is not the case for cellular structures, where local stress and strain distributions are non-uniform. Further, they may have variable distributions of bending, stretching and shear in the connecting members that constitute the structure.

Size effects

A size effect is said to be significant when an observed behaviour varies as a function of the size of the sample whose response is being characterised even after normalisation (dividing force by area to obtain stress, for example). For this discussion, size effects are limited to purely mathematical artefacts of the cellular geometry itself, independent of the manufacturing process used to make them. In other words this effect would persist even if the material in the cellular structure was a mathematically precise, homogeneous and isotropic material.

It is common in the field of cellular structure modelling to extract an 'effective' property; a property that represents homogenised behaviour without explicitly modelling the cellular detail. This is an elegant concept but introduces some practical challenges in implementation; inherent in the assumption is that this property, modulus for example, is equivalent to a continuum property valid at every material point. The reality is that the extraction of this property is strongly dependent on the number of cells involved in the experimental characterisation process. Consider the experimental data in Fig. 9 for honeycombs in compression, showing that the predicted effective modulus increases with increasing number of cells in the axial direction, but reduces (at a lower rate) for increasing number of cells in the longitudinal direction. The number

of cells in a sample being used to extract model data is thus a very significant consideration.

In addition to the number of cells, the actual size of the specimen as an entity can influence the results. For certain dimensions of the specimen being characterised (typically very tall aspect ratios), deformation in the macrostructure can influence what is perceived as cellular behaviour. It is essential to avoid very large aspect ratios since they tend to exacerbate these macrostructural effects.

Contact effects

In the compression test, shown in the inset in Fig. 9, there is physical contact between the platens and the specimen that creates a local effect at the top and bottom that is different from the experience of the cells closer to the centre. This is tied to the size effect discussed above, but needs separate consideration for two reasons. Firstly, it raises the question of how best to design the interface for the specimen: should the top and bottom cells terminate in a flat plate, or should the cells extend to the surface of contact (the latter is the case in Fig. 9). Secondly, it raises the question of how best to model the interface, especially if one is seeking to match simulation results to experimentally observed behaviour. Both of these ideas are shown in Fig. 10. This also has implications for product design – how do we characterise and model the lattice-skin interface? As such, independent of addressing size effects, there is a need to account for contact behaviour in characterisation, modelling and analysis.

Dimensional tolerances

While all manufacturing processes introduce some error in dimensional tolerances, the error can have a very significant effect for cellular structures. A typical industrial AM process has tolerances of approximately 75 µm (0.003"), whereas cellular structures (micro-lattices in particular) very often are 250-750 µm in thickness, meaning the tolerances

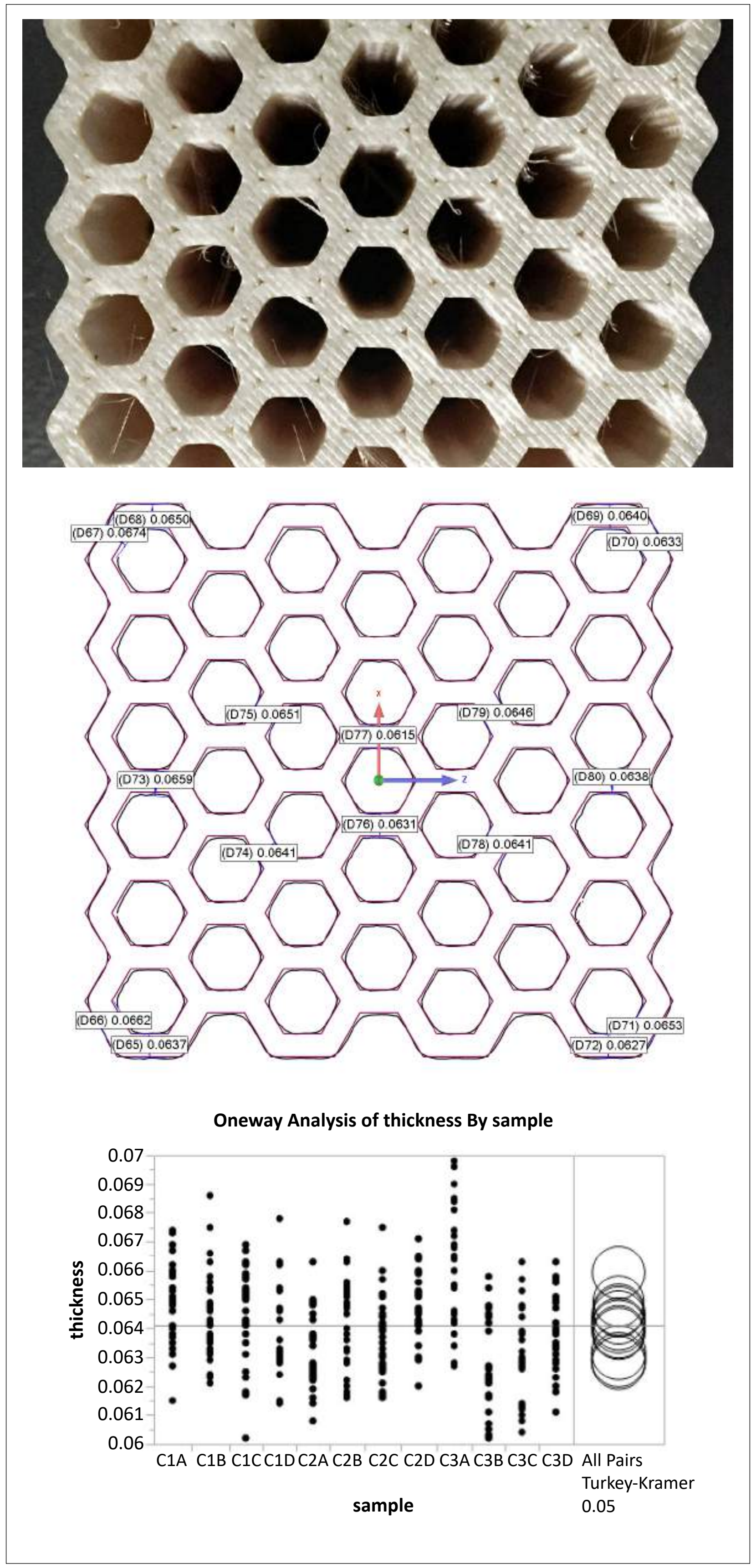


Fig. 11 (From top to bottom): A honeycomb sample, optical scan image, 12-sample data showing a mean of 1.625 mm against a designed value of 1.524 mm – a 7% error in thickness (Data collected by Thao Le, Arizona State University)

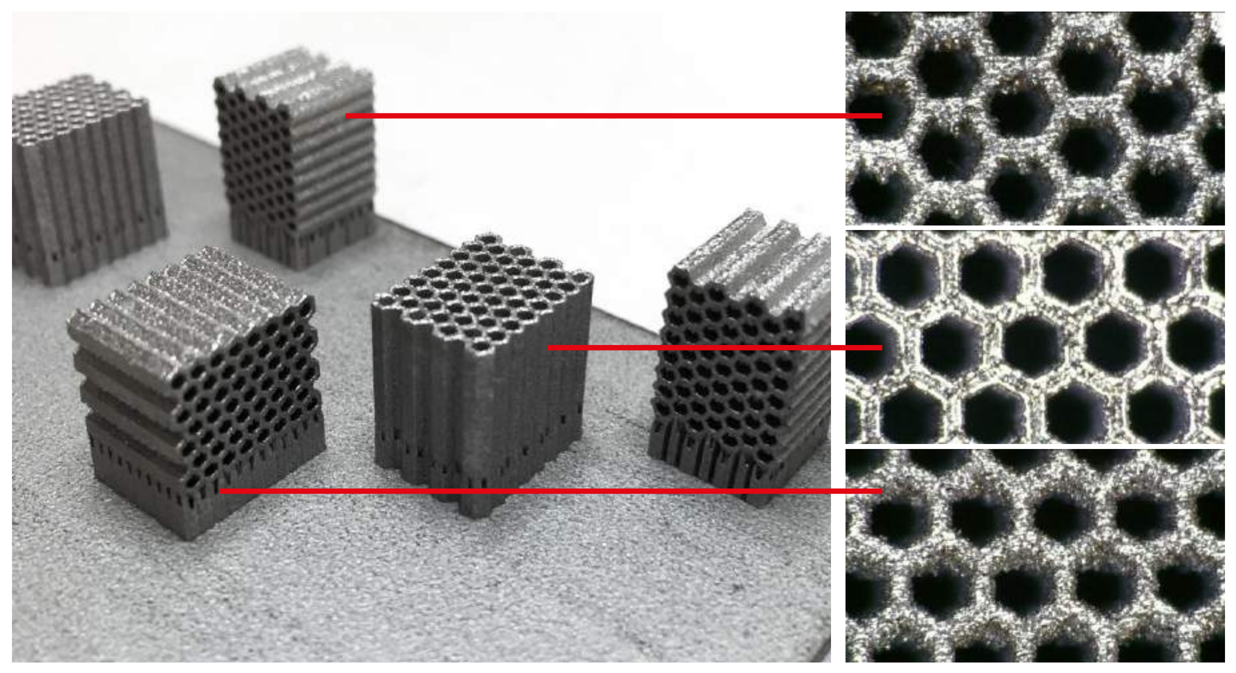


Fig. 12 3D Printed stainless steel 316L honeycomb structures showing orientation-dependent morphology

on dimensional error can be in the 10% and higher error range for thickness of these members (Fig. 11). Such large errors in thickness can yield a significant error in measured behaviour such as elastic modulus, which often goes by some power to the thickness, amplifying the error. This drives the need for some independent measurement of the manufactured cellular structure; made challenging itself by the need to penetrate the structure for internal measurements. X-ray scanning is a popular, if expensive, approach. However, the modeller then has the challenge of devising an average thickness for analytical calculations and, furthermore, the challenge of representation of geometry in simulation software for efficient analysis.

Mesostructural effects

The layer-wise nature of AM introduces a unique set of challenges, chief among which is the resulting sensitivity to orientation, as shown for the laser-based powder bed fusion process in Fig. 12 with standard materials and parameter sets. Overhang surfaces (unsupported) tend to have down-facing surfaces with different morphology compared to up-facing ones. In the context of cellular structures, this is likely to result in different thickness effects depending on direction measured. Thus, orientation and process parameters are variables that need to be comprehended in the modelling of cellular structures, or set as constants for the range of applicability of the model parameters that are derived from a certain set of process conditions.

"The layer-wise nature of AM introduces a unique set of challenges, chief among which is the resulting sensitivity to orientation"

Modelling approaches

The literature on the AM of cellular structures is vast and growing. While the majority of the focus in this field is on design and process aspects, there is a significant body of work on characterising behaviour for the purposes of developing analytical material models. These approaches fall into three different categories depending on the level of discretisation at which the property is modelled: at the level of each material point, or at the level of the connecting member or, finally, at the level of the cell.

Continuum modelling

The most straightforward approach is to use bulk material properties to represent what is happening to the material at the cellular level [6-9]. This approach does away with the need for any cellular level characterisation and, in so doing, does not have to account for size or contact effects described previously that are artefacts of having to characterise behaviour at the cellular level. However, the assumption that the connecting struts/walls in a cellular structure behave in the same way as the bulk material does can particularly be erroneous for AM processes that can introduce significant size-specific behaviour and large anisotropy. It is important to keep in mind that factors that may not be significant at a bulk level, such as surface roughness, local microstructure or dimensional tolerances, can be very significant when the connecting member is under 1 mm thick, as is often the case for cellular structures in AM. The level of error introduced by a continuum assumption is likely to vary by process: polymeric processes like Fused Deposition Modelling (FDM) are already strongly anisotropic with highly geometry-specific meso-structures and an assumption like this will generate large errors. On the other hand, it is possible that better results may be had for powder based fusion processes used for metal alloys, especially when the connecting members are large enough and the key property being solved for is mechanical stiffness (as opposed to fracture toughness or fatigue life).

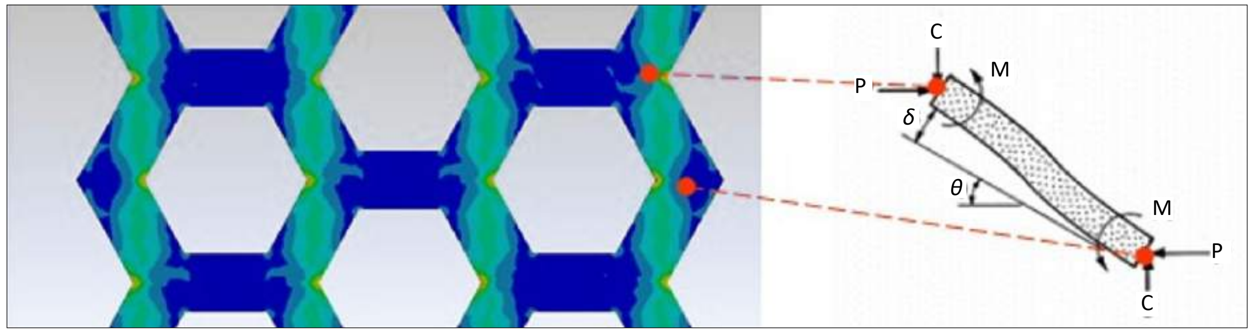


Fig. 13 Representation of cellular structures as an assemblage of connecting members such as the beam shown here, allows for utilising beam theory in the development of models

Cell level homogenisation

The most common approach in the literature that accounts for cellular behaviour is the use of homogenisation; representing the effective property of the cellular structure without regard to the cellular geometry itself. This approach has significantly lower computational expense associated with its implementation in simulation software. Additionally, it is relatively straightforward to develop a model by fitting a power law to experimental data [10-13] as shown in the equation below, relating the effective modulus E* to the bulk material property Es and their respective densities (ρ and ρ s), by solving for the constants C and n.

$$E^* = C\,E_s\left(\frac{\rho}{\rho_s}\right)^n$$

While a homogenisation approach is useful in generating comparative, qualitative data, it has some difficulties in being used as a reliable material model in analysis and simulation. This is first and foremost since the majority of the experiments do not consider size and contact effects. Secondly, even if these were considered, the homogenisation of the cells only works for the specific cell in question (e.g. octet truss or hexagonal honeycomb), so that every new cell type needs to be re-characterised. Finally, the homogenisation of these cells can lose insight into how structures behave in the transition region between different volume fractions, even if each cell type is calibrated at a range of volume fractions. This is likely to be exacerbated for failure modelling.

Member modelling

The third approach involves describing behaviour not at each material point or at the level of the cell, but at a level in-between: the connecting member (also referred to as strut or beam) (Fig. 13). This approach has been used by researchers including this author [14-16] by invoking beam theory to first describe what is happening at the level of the member and then using that information to build up to the level of the cells. This approach, while promising, is also beset with some challenges. It requires experimental characterisation at the cellular level, which brings in the previously mentioned challenges. Additionally, from a computational standpoint, the validation of these models typically requires a modelling of the full cellular geometry, which can be prohibitively expensive. Finally, the theory involved in representing member level detail is more complex, makes assumptions of its own (e.g. modelling the 'fixed' ends) and it is not proven adequately at this point if this is justified by a significant improvement in the model's predictability compared to the above two approaches. This approach does have

"The third approach involves describing behaviour not at each material point or at the level of the cell, but at a level in-between: the connecting member"

one significant promise. If we are able to accurately describe behaviour at the level of a member, it is a first step towards a truly shape and size independent model that can bridge with ease between, say, an octet truss and an auxetic structure, or different sizes of cells, as well as the transitions between them, thus enabling true freedom to the designer and analyst.

Conclusion

Additive Manufacturing with cellular structures is a justifiably promising field with many examples demonstrated from a software and manufacturing standpoint, as well as some successful applications. However, as this article has attempted to demonstrate, there is a real need for developing models that can allow us to truly leverage cellular structure designs in all additive parts, including those that end up in functionally critical applications. The research in this field, as with most of functional part AM, is relatively immature, especially when compared to the work on software solutions and manufacturing capabilities for cellular structures. More work needs to be done before we can truly unlock the full potential of using cellular structures as just another choice available to designers.

References

[1] Ashby, Evans, Fleck, Gibson, Hutchinson, Wadley, "Metal Foams: A Design Guide," First Edition, 2000

[2] Ashby, "Materials Selection in Mechanical Design," Fourth Edition, 2011

[3] Gibson & Ashby, "Cellular Solids: Structure & Properties," Second Edition, 1997

[4] Deshpande, Ashby, Fleck, "Foam Topology Bending versus Stretching Dominated Architectures," *Acta Materialia* 49, 2001

[5] Deshpande, Fleck, Ashby, "Effective properties of the octet-truss lattice material," *Journal of the Mechanics and Physics of Solids*, 49, 2001

[6] C. Neff, N. Hopkinson, N.B. Crane, "Selective Laser Sintering of Diamond Lattice Structures: Experimental Results and FEA Model Comparison," 2015 Solid Freeform Fabrication Symposium

[7] M. Jamshidinia, L. Wang, W. Tong, and R. Kovacevic. "The bio-compatible dental implant designed by using non-stochastic porosity produced by Electron Beam Melting®(EBM)," *Journal of Materials Processing Technology* 214, no. 8 (2014): 1728-1739

[8] S. Park, D.W. Rosen, C.E. Duty, "Comparing Mechanical and Geometrical Properties of Lattice Structure Fabricated using Electron Beam Melting", 2014 Solid Freeform Fabrication Symposium

[9] D.M. Correa, T. Klatt, S. Cortes, M. Haberman, D. Kovar, C. Seepersad, "Negative stiffness honeycombs for recoverable shock isolation," *Rapid Prototyping Journal*, 2015, 21(2), pp.193-200.

[10] C. Yan, L. Hao, A. Hussein, P. Young, and D. Raymont. "Advanced lightweight 316L stainless steel cellular lattice structures fabricated via selective laser melting," *Materials & Design 55* (2014): 533-541.

[11] S. Didam, B. Eidel, A. Ohrndorf, H.-J. Christ. "Mechanical Analysis of Metallic SLM-Lattices on Small Scales: Finite Element Simulations versus Experiments," *PAMM* 15.1 (2015): 189-190.

[12] P. Zhang, J. Toman, Y. Yu, E. Biyikli, M. Kirca, M. Chmielus, and A.C. To. "Efficient design-optimization of variable-density hexagonal cellular structure by Additive Manufacturing: theory and validation," *Journal of Manufacturing Science and Engineering* 137, no. 2 (2015): 021004.

[13] M. Mazur, M. Leary, S. Sun, M. Vcelka, D. Shidid, M. Brandt. "Deformation and failure behaviour of Ti-6Al-4V lattice structures manufactured by selective laser melting (SLM)," *The International Journal of Advanced Manufacturing Technology* 84.5 (2016): 1391-1411.

[13] R. Gümrük, R.A.W. Mines, "Compressive behaviour of stainless steel micro-lattice structures," *International Journal of Mechanical Sciences* 68 (2013): 125-139

[14] S. Ahmadi, G. Campoli, S. Amin Yavari, B. Sajadi, R. Wauthle, J. Schrooten, H. Weinans, A. Zadpoor, A. (2014), "Mechanical behavior of regular open-cell porous biomaterials made of diamond lattice unit cells," *Journal of the Mechanical Behavior of Biomedical Materials*, 34, 106-115.

[15] S. Zhang, S. Dilip, L. Yang, H. Miyanji, B. Stucker, "Property Evaluation of Metal Cellular Strut Structures via Powder Bed Fusion AM," 2015 Solid Freeform Fabrication Symposium

[16] D. Bhate, J. Van Soest, J. Reeher, D. Patel, D. Gibson, J. Gerbasi, and M. Finfrock, "A Validated Methodology for Predicting the Mechanical Behavior of ULTEM-9085 Honeycomb Structures Manufactured by Fused Deposition Modeling," Proceedings of the 26th Annual International Solid Freeform Fabrication, 2016, pp. 2095-2106

Author

Dhruv Bhate, PhD
Phoenix Analysis & Design Technologies, Inc. (PADT)
7755 S. Research Dr.
Suite 110
Tempe
Arizona 85284
USA
Email: dhruv.bhate@padtinc.com
www.padtinc.com
www.linkedin.com/in/dhruvbhate

Cost and practicality of in-process monitoring for metal Additive Manufacturing

Additive Manufacturing gives industrial designers the freedom to create ever more complex and customised products. However, with the increasing adoption of the technology by sectors such as aerospace, where product failure can have catastrophic consequences, component verification is becoming a critical issue. In the following article Dr Chris Hole, from the UK's TTP Group plc, reviews the challenges of verification in an industry that is associated with low volume runs of complex, often highly customised components with sophisticated hidden internal structures.

Much has been said about the new capabilities and scope for customisation that powder based Additive Manufacturing offers, but in many cases true customisation is less important than the 'complexity for free' factor - production runs that are short and where parts are complex but generally not unique. In aerospace, complex shapes often come from the need to remove weight. In medical prosthetics a complex surface enables biological cells to infiltrate the structure and form a strong bond with the host bone or organ. Similar situations exist in other industries including automotive, motorsport, energy and antenna design.

Complex components create a problem however: verification. In many applications targeted by AM, component failure is serious and parts cannot be used unless reliable and trusted non-destructive testing (NDT) techniques exist, or the production process is so well controlled that companies and certification authorities accept a given set of manufacturing parameters leads unequivocally to a given set of performance characteristics. AM currently struggles with both these routes to verification. For example, the geometrical complexity of parts makes the interpretation of ultrasound returns from parts difficult [1] and eddy current probes often cannot access every part of the component's surface. The alternative approach of strict process control faces the problem of the sheer number of process variables; Spears & Gold [2] list fifty important process parameters in metal AM and only twelve are typically under the control of the user. Roughly fourteen are largely controlled by the machine manufacturer, another fourteen by

Fig. 1 Geometric complexity can greatly improve the function of many components and this is often only possible using additive manufacturing (Image courtesy of 3T RPD)

Fig. 2 High performance cameras and lenses are available from a number of vendors as off-the-shelf systems (Images courtesy of Edmund Optics, Cognex & Flir (formally Point Grey Research))

the powder supplier and the balance are not reliably under the control of any single party in the supply chain.

Given the above it seems unlikely that either post-production NDT or open loop quality control will provide adequate component verification for AM parts in many key markets for the foreseeable future; consequently the attention of both industry and academia has turned to in-process monitoring both for NDT and process parameter control [3]. There is a growing body of literature on ideas for in-process monitoring and their technical effectiveness, but so far less has been said about likely cost and practicality in an industrial environment. This article seeks to look at several of the leading in-process monitoring techniques and discuss factors such as cost, effect on build times, and compatibility with existing AM machines and work flows. It also looks briefly at how another industry has solved similar problems in the past.

Cameras and image processing

This is the most mature process and already offered by both machine manufacturers, for example EOSTATE from EOS and 3rd party vendors such as Sigma Labs. High resolution digital cameras are now cheap, but the lenses required to image the small melt pool, the conditions in the build volume and the requirement for high dynamic range push costs up to the $1000-$3000 range. If cameras are bought as part of a package along with image processing and product support, prices rise to the $7000-$12,000 region at the time of writing (Fig. 2).

With regard to machine vision and digital processing technology, huge investments are being made by other industries which will benefit in-process monitoring for AM at almost no cost to the AM community. The bigger problem for vision systems is to know which visual cues, once identified, are important. Solving this problem will require a lot of research funding and time but will probably not add much to the cost of manufacturing AM equipment. The sheer complexity may however enable those who develop good data to charge heavily for the knowledge if it can be embedded in AM design software.

"huge investments are being made by other industries which will benefit in-process monitoring for AM"

Thermal imaging

One area where imaging costs have historically been high is thermal imaging at longer wavelengths (lower temperatures). Existing low cost CCD cameras have intrinsic sensitivity at wavelengths up to about 1.2 µm (if the IR filter is removed), which is enough for visible light spectroscopy [4] and for basic temperature estimation above about 400°C. Temperatures away from the centre of the weld pool however are too cold to be measured directly with a low cost camera, as are temperatures in polymer melt pools. True thermal imaging cameras have traditionally cost $10,000+ due to the high price of germanium lenses and sensor cooling, but new lens materials such as Cleartran (ZnS) can be bought for less than $200 even in one-off quantities. Improvements to sensors have also removed the need for cooling in all but the most demanding applications. As a measure of this cost reduction, companies such as FLIR and SEEK now produce room temperature thermal camera add-ons for smart phones for less than $200. Wavelength sensitivity of these systems goes out as far as 16 µm.

Melt pool spectroscopy

Spectroscopy techniques are well established in other industries and use signals from across the electromagnetic spectrum and also sound. Spectroscopic techniques are starting to be explored as a method for melt pool condition monitoring as well as material loss analysis of the plume above (Fig. 3). The cost of off-the-shelf industrial spectroscopy systems remains fairly high and the market for AM in-process monitoring is unlikely to be large enough to change this. However, the cost of the constituent parts has fallen substantially in recent years. Fingernail size spectrometers cost a few hundred dollars [5] and provide sufficient resolution for basic in-process melt pool monitoring in the visible light spectrum [4]. Today's low cost detectors and microprocessors are enabling very low cost spectrometers to be built by the open source community for under $100 [6] which could enable spectroscopy across a wide range of AM systems.

Laser Induced Breakdown Spectroscopy (LIBS) is a closely related technique to melt plume monitoring that has been developed by other industries, most notably the nuclear industry [7]. In LIBS a laser is fired at a surface which vaporises a tiny quantity of the surface material into plasma. The plasma is then analysed for its spectral content (Fig. 4). Researchers in metal AM are exploiting a similar process in the plume [2] and assuming useful information can be extracted the cost of existing LIBS systems gives a guide to likely cost in an AM context. A key factor here is that the main cost of LIBS systems is the cost

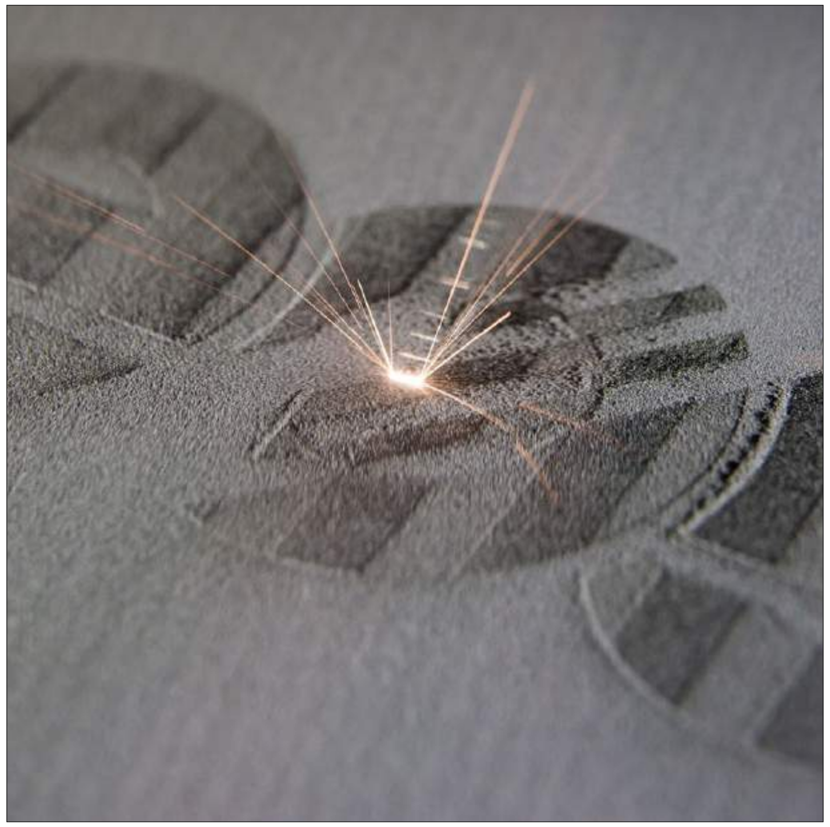


Fig. 3 Laser fusing of a powder bed generates both optical and infrared radiation. Cooling rates away from the laser spot can yield valuable information about the thermal connectivity of the fused surface to the layers below but quickly become visible only in the infrared (Image courtesy EOS GmbH)

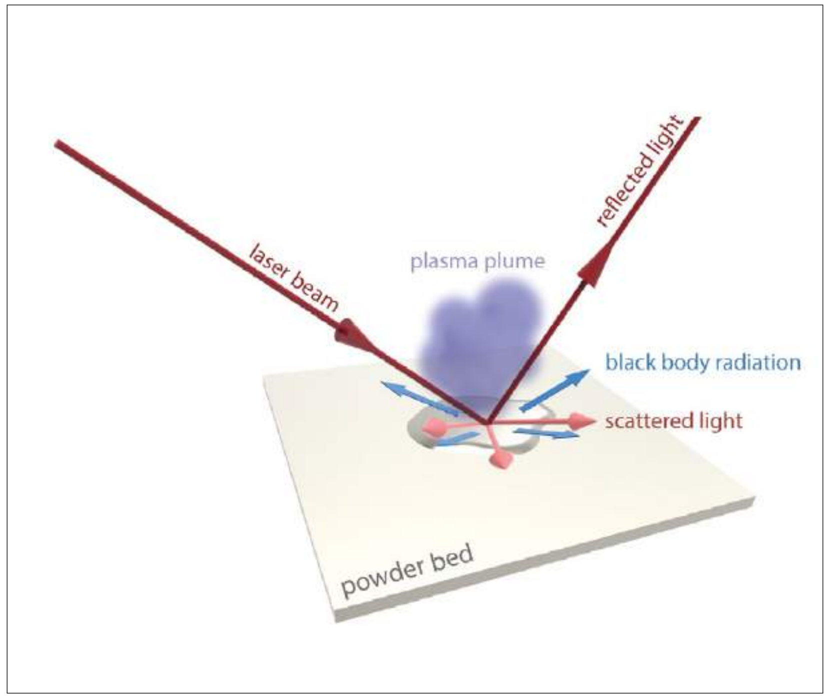


Fig. 4 The incident laser beam's energy is partly absorbed, partly scattered and partly reflected by the powder. The absorbed energy heats the powder causing it to emit black body radiation (i.e. glow) and to eject elements from the surface forming a plasma plume above the melt pool

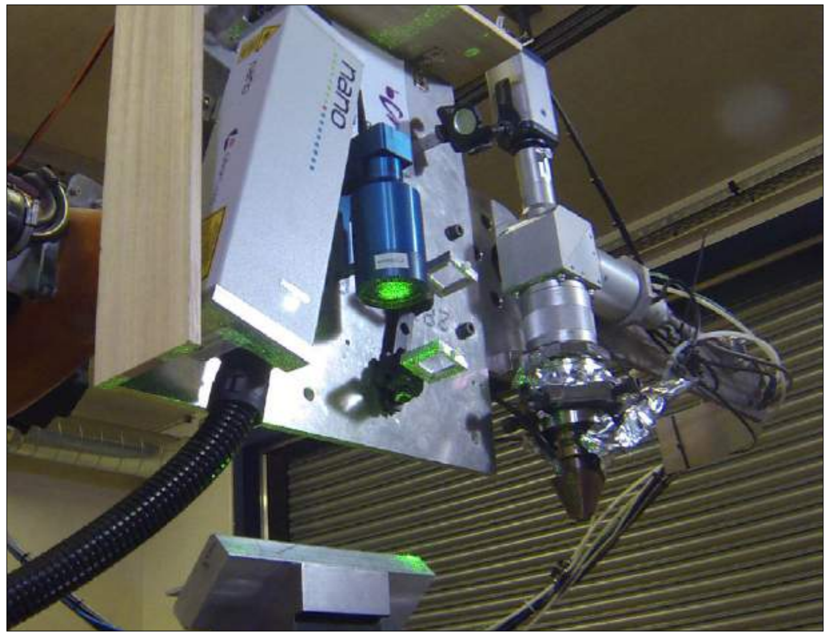


Fig. 5 Prototype non-contact (laser based) ultrasonic NDT system for in-process monitoring of Additive Manufacturing developed under the INTRAPID framework 7 project (Image courtesy of John Rudlin, TWI)

and safety issues associated with the high power laser needed to ablate the material from the surface. In AM these problems have already been paid for in the form of the laser which is at the core of most powder bed fusion systems. The only additional cost is the receiver spectroscopy system which can be, as noted above, 100s, not 1000s of dollars. LIBS can operate over a considerable distance (even 10s of metres) from the surface being analysed, so a plume monitoring system is unlikely to interfere with the build process in AM.

Ultrasound and eddy current NDT

Cameras and spectrometers are fundamentally surface observation instruments, but many of the important defects such as voids and delaminations do not exist until further layers are deposited on top and their initiators are difficult to detect with a camera [8]. For applications that are not safety critical the assumption that a visually correct weld pool surface will correspond to the desired bulk properties is likely to be a cost effective solution but customers seeking to manufacture safety critical parts are likely to want a more direct measure. As a result this author suggests that subsurface techniques must eventually be developed for AM if it is to be used in these high value applications. Both ultrasonic and eddy current testing are widely deployed, and trusted, in the NDT of conventionally manufactured parts but are hampered by problems in AM.

- Geometric complexity of parts makes ultrasound reflections difficult to interpret.
- Coupling sound across the rough surface of AM components is difficult to do mechanically without liquid couplant
- Eddy current probes do not require physical contact but must be placed close to every surface of the complex AM part, many of which may not be easily accessible post build.

Surface access and ultrasound reflection complexity are naturally solved by in-process monitoring and the cost of existing NDT systems can be used to estimate what they might cost when integrated into an AM machine. An in-process eddy current system can be similar to a conventional one [9] and should have a bill of materials (BoM) less than $200 - although coil winding, signal processing and mechanical integration into the AM machine will probably drive total costs over $2000 given the small production volumes. Extensive use of bought-out subsystems could add another $2000-$3000. The bigger problem however is likely to be the need for the coils to be physically close to the fused parts of the powder bed and this could slow build times by constraining the optimal laser path. Time represents a major cost when the interest payments alone on a $400,000 AM machine are about $5/hr.

Estimating the cost of ultrasonic NDT is more complex since true non-contact systems are not generally used in NDT today but would be required for practical in-process monitoring. Taking the system proposed by Liaptsis & Rudlin as an example [10], the cost is dominated by the interferometer and ultrasound generation laser.

Many different types of laser have been used to generate ultrasound but taking 8 ns pulsed as an example [10] high repetition rate lasers of this type are still tens of thousands of dollars but lower rep rate lasers used for tattoo removal are only a few thousand dollars and have adequate power. The price of this major cost reduction will be slower inspection rates which will impact build times significantly unless potential detector mitigation strategies are employed. The potential also exists to re-use the core AM laser to inspect each layer immediately after it is built. Again, this allows a major cost saving at the expense of longer build times.

Ultrasound waves are detected using a laser interferometer (Fig. 5). These can be fibre coupled; meaning most of the components could be installed away from high temperature parts of the AM machine but are very expensive if bought as scientific instruments. The system used by Rudlin and Liaptsis cost of the order of $100,000 but lower specification devices can be made for around

Fig. 6 High quality equipment is available for laboratory metal powder analysis of both size distribution and particle morphology but adapting these instruments for in-line monitoring would require significant development effort and current morphology measurement techniques are not suitable for 100% testing (Images courtesy of Malvern Instruments)

$10,000 depending on the required sensitivity. The signal processing, data processing and other components should be less than $300 if there is no requirement to store raw data long term. Integration into a reliable industrial system which yields clear and useful data will be a challenge, but on the positive side there is a huge body of knowledge on the ultrasound signatures of defects in metals, polymers and composites that can be applied to many, though not all, of the defects seen in AM.

X-rays and X-ray tomography

To the knowledge of the author no industry has ever adopted X-rays with enthusiasm. Health and safety issues, both real and imagined, have always discouraged adoption unless no practical alternative exists. Perhaps the most recent example has been the security scanning of airline passengers. The United States TSA set the maximum radiation dose for backscatter X-rays scanners at <0.1 μSv per scan - or the equivalent dose of about 2 minutes of flying time at normal cruising altitude [11] - but their use still remains controversial [12]. Dentists routinely leave the room when administrating a dental X-ray and this behaviour would be difficult to replicate for an operator of AM machines in a production environment.

Despite the above, electronic and mechanical component inspection is carried out using X-rays (e.g. GE's Phoenix range) but its use in NDT is declining relative to ultrasonics and eddy current systems. We suspect the industry would have to accept that no practical alternative exists before embracing the technique despite the high quality results from tomography in post-process inspection [13] and in porosity detection.

Powder characterisation

Particle size distribution is known to be a key parameter [2] strongly influencing the recoater process (forming each new layer) and minimum feature size of an AM process. Powder characterisation techniques are already well established in the Powder Metallurgy industry (Fig. 6) but many (e.g. avalanche angle and successive sieving) are slow and not suitable for in-process monitoring. Particle Size Distribution (PSD) measurement using laser light has been investigated by several researchers and can be implemented as a ring of low cost diode lasers and photodiodes around free falling powder for a few hundred dollars. In parallel a camera or shadow projection system could be used to estimate particle morphology one particle at a time, probably for a similar cost, but will only ever inspect a tiny fraction of powder grains. As a result this method is unsuitable for preventing point defects due to exceptional particles not caught by screening trays and neither method will detect changes in the flow of powder due to non-powder parameters such as humidity.

Given the above, direct machine vision monitoring of the powder flow during new layer deposition may be the only stand-off process capable of in-process monitoring of powder characteristics. If machine vision based melt pool monitoring is already implemented in a system then the additional manufacturing cost due to powder flow monitoring could be near zero since the melt and recoat processes do not occur at the same time.

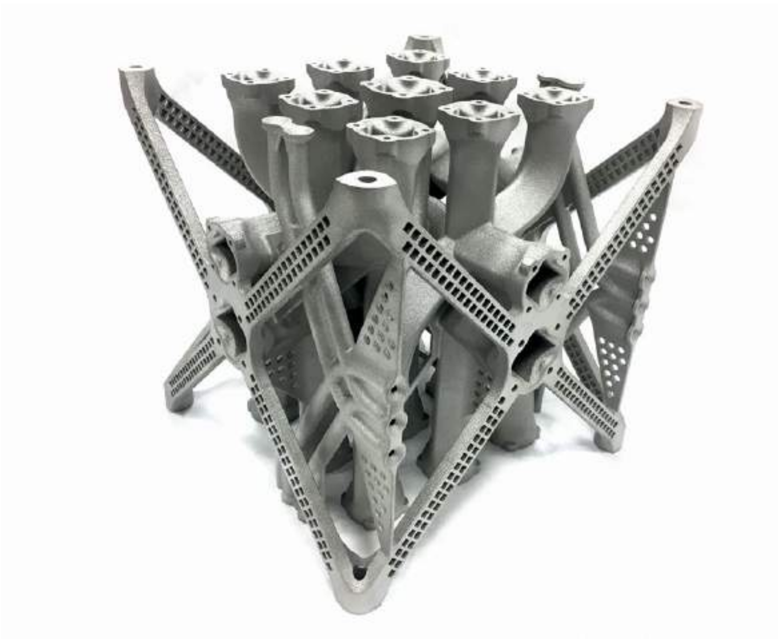


Fig. 7 The in-process monitoring of large, complex AM components results in the generation of a large amount of data that in some sectors will need to be archived for the lifetime of the component (Image courtesy of 3T RPD)

Validated blocks of laser movement – an alternative to in-process monitoring

Given the large number of process variables discussed in [2], and their fragmented nature, it may prove impractical to adequately control them all, even in the long term. A similar situation exists in the semiconductor industry where a large number of manufacturing parameters affect the performance of a transistor and further parameters affect the way each transistor works in a given integrated circuit. While process control and transistor behavioural models have improved greatly over the last twenty years the problem of accurate process control has been solved in part by companies such as ARM [14] developing huge blocks of transistors and associated components which carry out high level functions. What ARM sells is essentially a complex electronic circuit schematic that other companies can drop into their overall chip design rather than repeating ARM's design and testing work. Clearly the most obvious value to a customer is the avoidance of having to design something as complex as a microprocessor themselves, but the testing and validation ARM has done with each of the manufacturing processes it supports is crucial to ensuring the design works reliably and enables customers to slot together high level functional blocks like Lego to create a more complex product of their own that also performs predictably and reliably.

Another case of this is starting to occur in the area of molecular diagnostics, or 'desktop biology'; research has always suffered from an inability to reproduce published results from one lab in others due to a combination of high sensitivity to experimental conditions and the large number of experimental parameters. The move to highly automated biological research equipment, driven by TTP and others, has enabled complete experimental parameters to be built up from software style subroutines of procedures and published via weblinks in academic journals allowing precise replication in other labs. This helps the research community but is also benefiting the equipment vendors because equipment now needs regular calibration and it enables market leaders to cement their position using de facto instruction standards.

By analogy, companies may emerge in AM that sell a block of defined laser movements and power levels for a particular machine and powder supplier that they have demonstrated to result in a predictable high level functional object. Examples could be a cylinder or I-beam of known strength (and accepted by the Tier 1 airframe companies for a particular reliability level) or a complex surface shown to support in-growth of bone at a known rate based on accepted clinical trials. These IP blocks could then be assembled in the machine's build software to enable product companies to produce complex products with greater predictability and lower test and validation costs.

Data storage and traceability

The techniques discussed in the sections above all create very large data sets for useful resolution levels and there is concern across the industry that manipulation and storage will become a significant cost in their own right. To estimate costs we can take the most mature technology (visual/infra-red weld pool monitoring) and apply some fairly industry standard monitoring specifications for to estimate the volume of uncompressed data generated in a 300 x 300 x 300 mm build volume. Assuming an imaging resolution of 10 µm per pixel at 8 bit digitisation, 40 µm layer thickness and about 25% of the powder bed fused by the laser this equates to about 30 TB of uncompressed data.

Long term archival storage costs today can be as low as $1/TB/month (e.g. Oracle Cloud) creating a data management cost of about $4000 for ten year storage of a 300 x 300 x 300 mm build job, if no access to the data is subsequently required. This compares to a machine time cost of perhaps $10,000 – $20,000 plus post processing costs, so it is significant but not dominant. That said, cost remains a key impediment to the growth of this industry so there is a strong desire to reduce any cost of this size.

The AM industry cannot significantly influence the price of data storage so the only real route to cost reduction is data compression. Compression comes as two variants; lossy and lossless. Lossless data compression systems such as FLAC, LAGARITH and PNG essentially replace long patterns of numbers that repeat within the data with shorter labels that reference a single record of the long sequence. This can give high data compression where long patterns repeat exactly. Unfortunately the pixel brightness of successive weld pool images seldom repeats exactly which limits the magnitude of lossless compression to typically 3x but perhaps as high as 10x in some cases.

The scope for lossy compression is much greater. To give a sense of what is possible at the extreme, weld pool brightness can be approximated as a peak brightness in the centre falling according to a mathematical function to an edge. The shape of the pool edge can be modelled as an ellipse with given major and minor axes. Compression at this level reduces an entire image to just a few numbers (the coefficients of the mathematical fit functions) and enables compression ratios measured in thousands - more or less eliminating the cost problem. However, it is obvious that all information other than the general shape and temperature profile are lost and this would make detailed forensic investigation of the manufacturing process after a part failure impossible. A reasonable compromise may be to regard successive melt pool images as a movie and use algorithms such as those in the H264 video compression standard to give compression ratios of perhaps 150-300x in this application. H264 compression generally preserves the information needed for engineering analysis much better than the popular JPEG type algorithms which exploit limitations of human vision to hide the substantial artefacts they create in images.

Data management and access will create costs over and above the simple storage costs quoted above but overall we expect the data problem to be manageable in the long term - but some negotiation with aerospace and medical certification authorities over imaging resolution and the extent and type of data compression losses may be needed.

Conclusions

There are several in-process monitoring technologies which have the potential to enable AM to continue its growth into high value, safety critical, markets but cost will be a critical determinant of which get commercial traction. This article has sought to provide cost and usability estimates for the leading contenders. Overall we concur with many others that visible and IR light inspection, together with some form of machine vision, is the first system widely used for in-process monitoring but we suspect that eddy current and optical spectroscopy should become cheap enough to challenge the dominance of camera based monitoring in the medium term. With regard to ultrasonic systems we expect these to remain relatively expensive but fall over time to a cost range acceptable for high end metal AM machines given the value of the data ultrasonic NDT can provide. We are more pessimistic about the use of X-rays for in-process monitoring and suspect that powder condition monitoring will remain an off-line process because only the size spectrum can be measured easily in an on-line scenario.

Bibliography

[1] Inspection of additive manufactured layered components. Cerniglia, D. 2015, *Ultrasonics*, pp. 292-298.

[2] In-process sensing in Selective Laser Melting (SLM) Additive Manufacturing. Spears & Gold. 2016, Integrating materials and manufacturing innovation.

[3] NIST. Measurement science roadmap for metal based additive manufacturing. s.l. : National Institute for Standards and technology, 2013.

[4] Sensing defects during directed energy Additive Manufacturing of metal parts using optical microscopy. Nassar, A. R. s.l. : University of Texas, 2014. Solid freeform fabrication symposium. pp. 278-287.

[5] www.hamamatsu.com/jp/en/C12666MA.html

[6] www.myspectral.com

[7] www.appliedphotonics.co.uk

[8] High frequency ultrasound non-destructive testing evaluation of additively manufactured components. Karthik, N.V. Austin : University of Texas, 2013. Solid freefrom fabrication symposium.

[9] Inspection of laser powder deposited layers. Rudlin, J. Prague : European Federation for NDT, 2014. 11th European Conference on Non-Destructive Testing.

[10] Liaptsis, D. NDT activities in additive manufacturing. twi.co.uk. [Online] 24 September 2015.

[11] Radiation exposure and privacy concerns surrounding full body scanners in airports. Accardo, J. 2014, *Journal of Radiation Research and Applied Sciences*, pp. 198-200.

[12] Times, LA. [Online] 11 November 2011. http://latimesblogs.latimes.com/money_co/2010/11/body-scanners-pilots.html.

[13] Palmer, T.A. Computed tomography as an enabling technology for additive manufacturing. gemeasurement.com. [Online] 2016. https://www.gemeasurement.com/sites/gemc.dev/files/palmer_cimp3d_ct_for_additive_manufacturing_1.pdf.

[14] www.arm.com

Author

Dr Chris Hole is with TTP, a broad based technology development company active in the development of several aspects of Additive Manufacturing technology. He can be contacted at additive@ttp.com, Tel: +44 1763 262626

Additive Manufacturing at World PM2016: Advances in the processing of aluminium and magnesium alloys

WORLDPM2016 congress and exhibition

The Additive Manufacturing of light alloys was the focus of three separate technical sessions at the World PM2016 Congress, held in Hamburg, Germany, from 9-13 October, 2016. The event, which was organised by the European Powder Metallurgy Association (EPMA), covered all aspects of metal powder processing technologies. This report reviews three of the key papers from these sessions, two relating to the AM of aluminium alloys and the third to the AM of a magnesium alloy.

Investigations on aging behaviour of aluminium powders during a lifetime simulation for LBM

One of the seven designated Keynote Papers within the full PM2016 World Congress programme was presented by Dominik Bauer (Airbus Innovations, Munich, Germany). The paper was co-authored by Elisabeth Schwarzenboeck, Norbert Schupp and Frank Palm (also Airbus Innovations) and Ina Ludwig and Gerd Witt (University of Duisburg, Germany) [1].

The issues addressed, which act as current impediments to the building of aluminium alloy parts by AM techniques, include the susceptibility of these materials to hydrogen embrittlement and oxidation. Therefore, this reported work was motivated by the need to avoid the contamination of atomised aluminium alloy powders by oxygen and hydrogen during powder production, handling and storage, processing by powder bed Laser Beam Melting (LBM) and recycling of unmelted powder from the bed after the part build run.

Information from the published literature indicates that environmental conditions, especially temperature, humidity and pressure, play an important role in the appearance and composition of oxide and hydroxide layers on aluminium powders and these, in turn, affect defect formation in LBM parts. The effects of long term exposure to humidity must therefore be understood in more detail. In order to achieve high levels of mechanical properties in built parts, it is important to guarantee reproducible and high quality powder production, storage and processing.

Aluminium alloy powders produced and handled under dry conditions would be expected to be covered by a passive Al_2O_3 layer a few nanometres thick. However, in humid conditions, water reacts with the alumina layer, leading to AlOOH generation.

Fig. 1 More than 1900 participants attended the World PM2016 (©World PM2016 Andrew McLeish)

Alloy P1: AlSi10Mg0.45	Unit	
Si	[m%]	10.01
Mg	[m%]	0.26
Fe	[m%]	0.016
Mn	[m%]	<0.001
Oxygen	[m%]	0.028
Alloy P2: AlSi7Mg0.6	**Unit**	
Si	[m%]	7.1
Mg	[m%]	0.59
Fe	[m%]	0.01
Mn	[m%]	<0.01
Oxygen	[m%]	0.033

Table 1 Analysed chemical compositions of powders P2 and P1 [1]

	D_{10}	D_{50}	D_{90}
P1	16.4 µm	32.1 µm	53.2 µm
P2	9.6 µm	23.2 µm	45.5 µm

Table 2 Particle size distributions of the investigated powders [1]

No.	Temperature [°C]	Salt solution	Rel. humidity [%]	Duration [h]
A1	23.7	potassium chloride	84.2 +/- 0.3	72
A2	35	potassium chloride	83.0 +/- 0.3	72
A3	45	potassium chloride	81.7 +/- 0.3	72
A4	55	potassium chloride	80.7 +/- 0.4	72
A5	45	potassium chloride	81.7 +/- 0.3	168
A6	45	magnesium-chloride	31.1 +/- 0.2	72

Table 3 Parameters for the aging series of AlSi10Mg powder [1]

Finally, the hydroxide is reduced by aluminium, generating hydrogen bubbles at the metal/oxide interface. As soon as the hydrogen pressure in the gas bubbles exceeds the oxide's tensile strength, the passive layer fractures, exposing fresh reactive metal and further promoting surface layer formation.

Two different atomised powder grades were investigated in the study, the alloys AlSi7Mg0.6 (P2) and AlSi10Mg0.45 (P1). These powders were produced by Electrode Induction Melting Gas Atomisation (EIGA) with an inert gas as the atomising medium. All atomised powders were separated by air and then sieved to give a particle size distribution between 20 and 63 µm.

The chemical compositions of powders P2 and P1 are shown in Table 1 and these lie within the allowable limits defined in ENAC–43400 and ENAC–42200 respectively. The elemental analysis was carried out using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), the silicon content was examined by gravimetric measurement and carrier gas hot extraction was used to analyse the amount of oxygen contamination in the powder. Both powders complied with the authors' observations from earlier work that a high-quality LBM powder must be covered by a thin oxide layer and that the oxygen content should not be higher than 500 ppm.

The values for particle size distribution were measured by laser diffraction and are shown in Table 2. Powder P1 had higher values for D_{10}, D_{50} and D_{90}, compared with powder P2. SEM observations indicated that both powder types were predominantly spherical in shape, but that powder P2 exhibited higher levels of agglomeration and satelliting.

Powder aging due to handling and LBM process simulation was assessed using a climate chamber, comprising containers equipped with a moisture barrier. A salt solution in the container provides a nearly constant value of the moisture content for defined temperatures. To create defined moisture levels, potassium chloride and magnesium chloride were used for the aging investigations.

The chosen parameters for the series of aging trials are shown in Table 3. Parameter set A1 was chosen to mimic typical ambient conditions in the German summer period. Considering the LBM process, the temperature of the atmosphere in the build chamber climbs to ~50°C during a build job. Consequently, the parameter sets A3 to A6 in Table 3 were chosen to bracket this approximate temperature. The powder P1 (AlSi10Mg) was used for these aging simulations.

SEM observations of the powder after the A1parameter set showed no visible differences from the starting powder and the same was true of the material subjected to parameter sets A2 and A3. The SEM micrographs in Fig. 2 show the results for aging parameter set A4. Around this parameter set, all particles show characteristics such as whisker growth on their surface. Fig. 2b shows, for a higher magnification around the marked area, a puckered structure for the surface and whiskers on the surface. Fig. 2c shows whiskers that have grown out from the particle surface and are

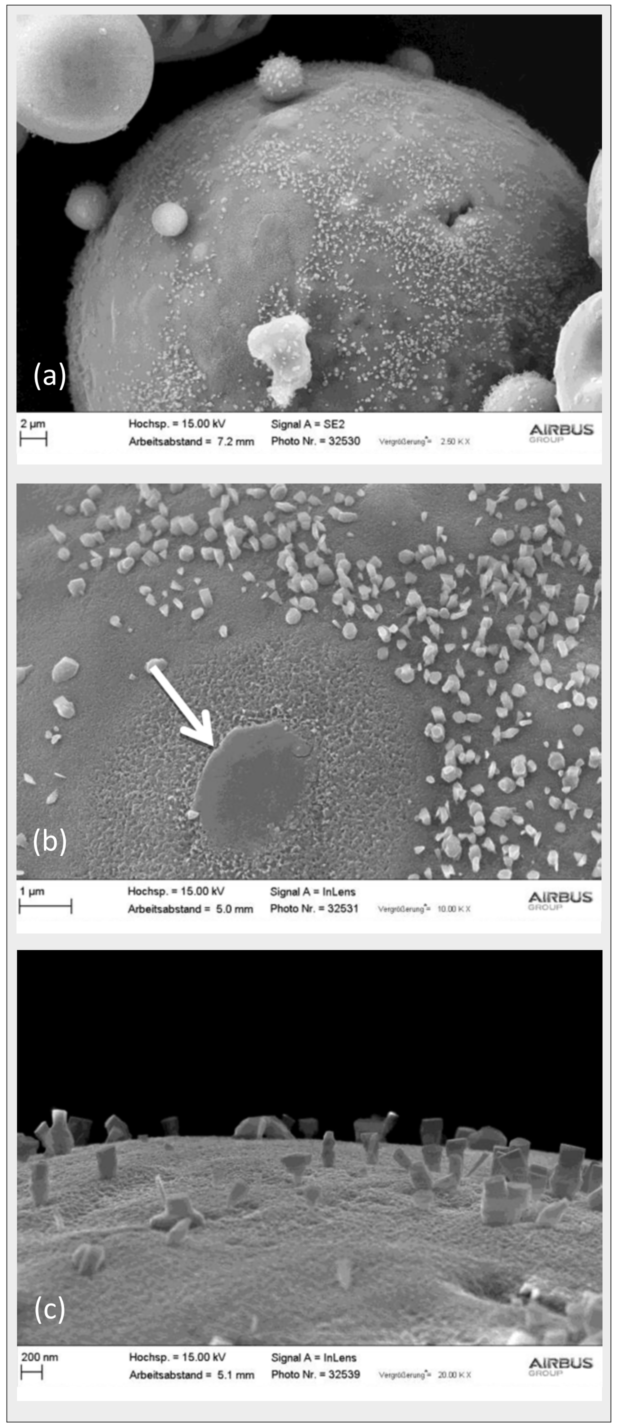


Fig. 2 SEMs of powder aged at parameter set A4 [1]

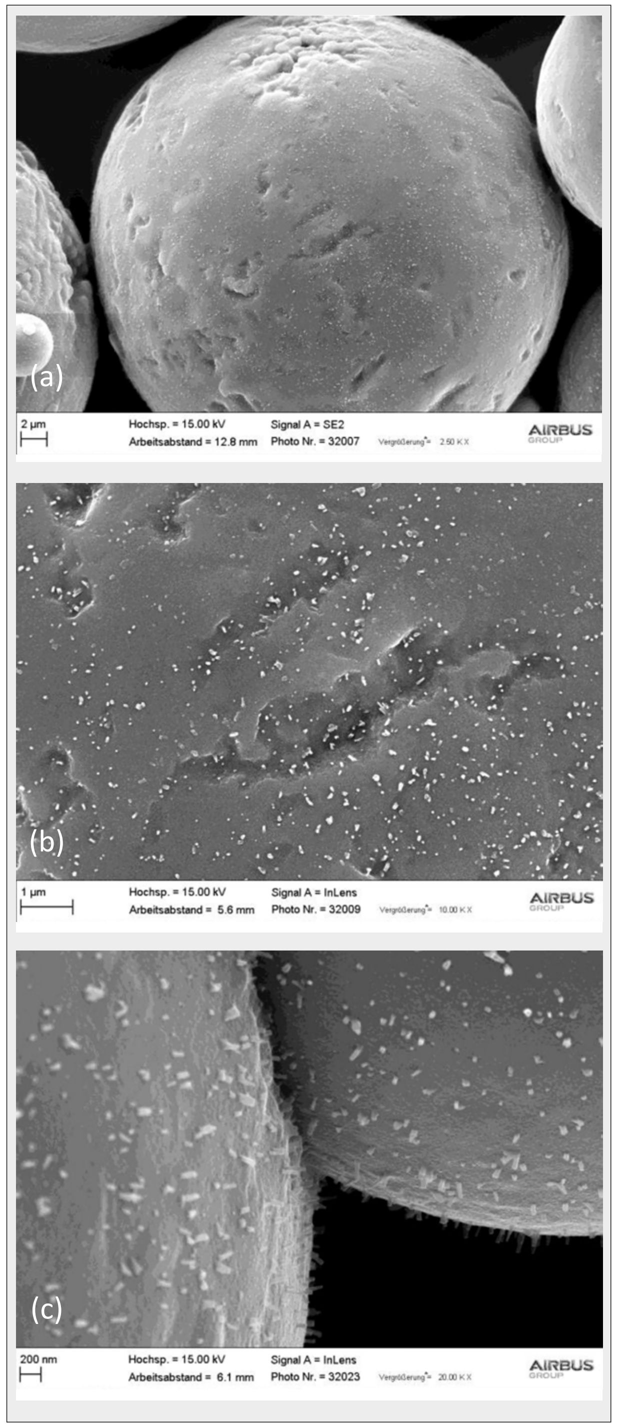


Fig. 3 SEMs of powder aged at parameter set A5 [1]

thinner nearer to the surface. For the parameter set A5, Figs. 3a-c show that the formed whiskers are thinner and, compared with parameter set A4, they are formed homogenously and distributed evenly. The duration of aging for parameter set A5 was longer, but at a lower temperature and, because of this, the growth of the whiskers and grains was slower. Overall, it was concluded from these trials that the influences of humidity level and temperature on whisker growth are more significant than that of exposure time.

The final powder characteristic assessed was flowability and this characteristic was dynamically measured with a Revolution Powder Analyser. In this test method, 100 ml of powder is filled in a drum between two glass fronts. Due to the rotation of the drum, the powder begins to form avalanches. These avalanches are then described by the average angle, as an indicator for the powder flowability. To ensure an initial homogenous state of each powder, 315 avalanches are generated before the test series. Then, each test series is carried with five test cycles, each with

Conditions	~ 23.7°C/ 72 h ~ 42.5 +/- 2.5% rH	~ 23.7°C/ 72 h ~ 84.2 +/- 0.3% rH	~ 25°C/ 4h ~ $2*10^{-2}$ mbar
C1	X		
C2	X	X	
C3	X		
C4	X		X
C5	X		
C6	X	X	X

Table 4 Climate atmosphere investigations for flowability of powder P2 [1]

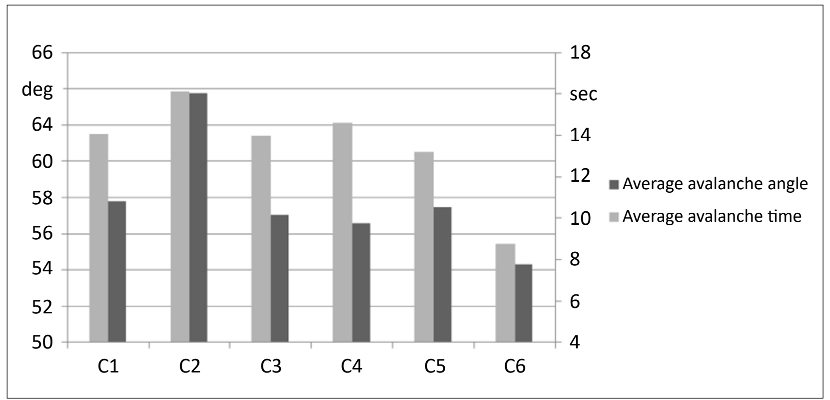


Fig. 4 Powder flowability measurements for powder P2 [1]

150 avalanches. For each powder, the avalanche angle and avalanche time are measured and average angles and times are calculated based on all the test results.

The flowabilities of the P2 powder (AlSi7Mg0.6) were measured for the various conditions shown in Table 4. The climate conditions were chosen to generate no changes on the surface, such as the growth of whiskers, and to avoid oxidation of the particles. Powder samples C1, C3 and C5 were exposed to the same starting climate, followed by flowability measurement. Powder samples C2 and C6 were additionally exposed for 72 hours at room temperature and a humidity of ~85% rH. For powder samples C4 and C6, the powders had been dried under vacuum at a defined temperature of 25°C.

Fig. 4 shows the flowability test results for the powder samples C1 to C6. As anticipated, samples C1, C3 and C5 showed virtually the same values for average avalanche angle and average avalanche time. For the increasing humidity arising from condition C2 compared with C1, the avalanche angle and time increased significantly. This can be related to a higher agglomeration rate, caused by the higher moisture content and hydrogen bond. Due to the high number of fine particles, this powder material is sensitive to agglomeration. The average avalanche angle decreases slightly from condition C3 to C4, where the powder was only dried from the starting condition without exposure to a higher humidity. Powder condition C6 was dried after exposure to a higher humidity. Compared to condition C5, the average avalanche angle and average avalanche time were both lower and the flowability increased. The results of this investigation showed that the average avalanche time is more sensitive to moisture than the average avalanche angle.

From these tests, the authors concluded that there is a potential to dry the powder and, consequently, recondition the flowability. Drying of the powder was also expected to reduce the agglomeration rate and to achieve a higher bulk density in the deposited powder.

Finally, the authors indicated that further work should be directed at investigating the direct influence of the various powder conditions on mechanical properties. There is a possibility that, for sensitive powders, defined storage conditions and an expiry date may have to be established.

Microstructural and mechanical properties of Al-Si-Ni alloy produced by Direct Metal Laser Sintering

In the study presented by Alberta Aversa (Politecnico di Torino, Italy) and co-authored by Sara Biamino, Paolo Fino and Matteo Pavese (also Politecnico di Torino) and Massimo Lorusso, Francesco Trevisan, Diego Manfredi, Flaviana Calignano and Elisa Ambrosio (Istituto Italiano di Tecnologia, Italy) the effects of the introduction of nickel on the microstructure and mechanical properties of aluminium alloy components, built by Direct Metal Laser Sintering (DMLS) were investigated [2].

	Si Wt %	Fe Wt %	Cu Wt %	Mn Wt %	Mg Wt %	Ti Wt %	Ni Wt %	Al Wt %
AlSi10Mg	9-11	≤0.55	≤0.05	≤0.45	0.2-0.45	≤0.15	<0.05	Remainder
Al-Si-Ni	8.5-10.5	≤0.55	<0.05	<0.45	0.18-0.42	≤0.15	5.1	Remainder

Table 5 Nominal chemical compositions of the powder batches [2]

The laser powder bed processing of aluminium based powder faces challenges related to a number of its physical characteristics, such as high reflectivity, high thermal conductivity and low powder flowability. From the broad range of available aluminium alloys, the AlSi10Mg casting alloy has emerged as the most attractive for AM processing, because of its high fluidity in the molten state and its narrow solidification range due to its near-eutectic composition.

The extremely high cooling rates that arise during laser powder bed processing (~10^6 K/s) allow the creation of fine and new microstructures and hence unique mechanical properties. To-date, however, there has been limited research activity aimed at taking advantage of this fast cooling to create novel microstructures, such as supersaturated solid solutions, metastable intermetallic phases and metallic glasses. Published studies, however, have reported that high strength can be achieved by the introduction of transition metals, such as nickel, to rapidly solidified Al-Si alloys. Therefore, this reported study was aimed at investigating the microstructure and mechanical properties of Al-Si-Ni samples processed by laser powder bed fusion.

An EOS M270 Xtended system was used to build all samples. This system uses an argon atmosphere with oxygen content lower than 0.1% and an ytterbium fibre laser with a power up to 200 W to melt thin layers of metal powder. An AlSi10Mg gas atomised powder, supplied by EOS GmbH, was mixed with a spherical pure nickel powder. The nominal chemical compositions of the powder batches are reported in Table 5. The mixing ratio for the Al-Si-Ni material was chosen to obtain a chemical composition close to the ternary eutectic (567°C at 4.9 wt.% Ni and 10.98 wt.% Si).

	Min	Max
Power (W)	120	195
Scan speed (mm/s)	600	1200
Hatching distance (mm)	0.1	0.17
Stripe length (mm)	1	10

Table 6 Range of build parameters used [2]

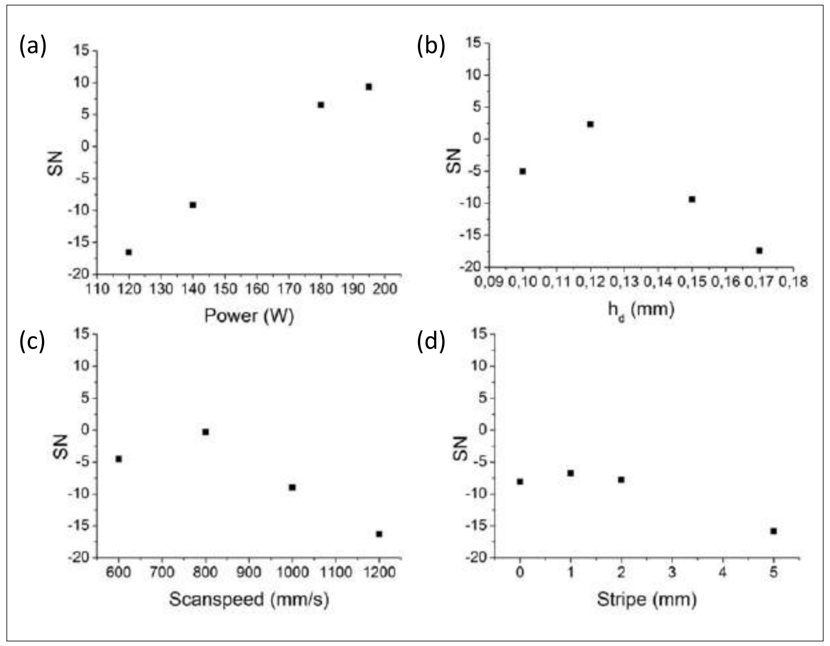


Fig. 5 Signal to noise values [2]

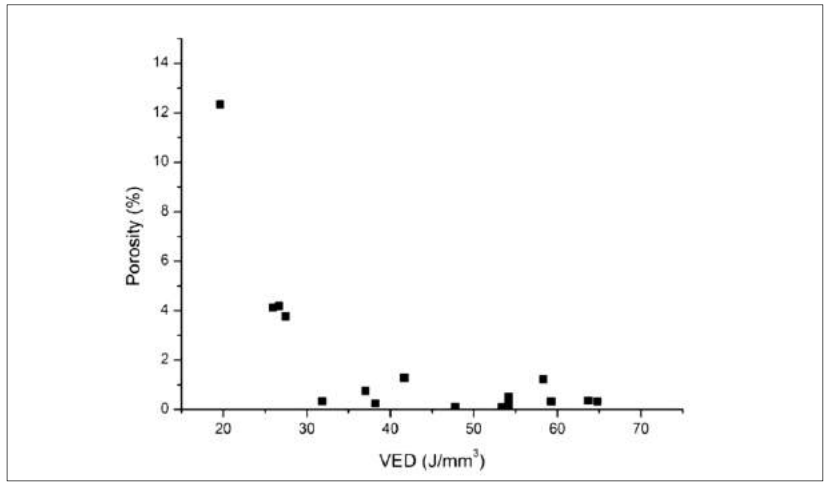


Fig. 6 Porosity versus VED graph for the Al-Si-Ni samples [2]

The powders were dry mixed in ceramic jars for 48 hours without any grinding medium and were sieved using a 230 mesh sieve (63 μm) to eliminate the larger powder fractions. Cubic samples with 10 mm length were built using the EOS stripe scanning strategy by varying the main building parameters laser power (P) scan speed (v) hatching distance (h_d) and stripe length (s) on a 100°C platform using a 30 μm layer thickness. The building parameters were varied in the range shown in Table 6.

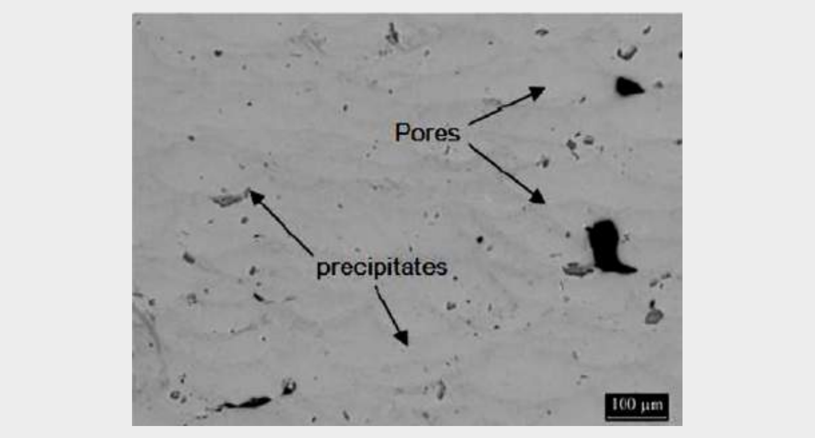


Fig. 7 Optical micrograph of the Al-Si-Ni sample built with the optimised parameters [2]

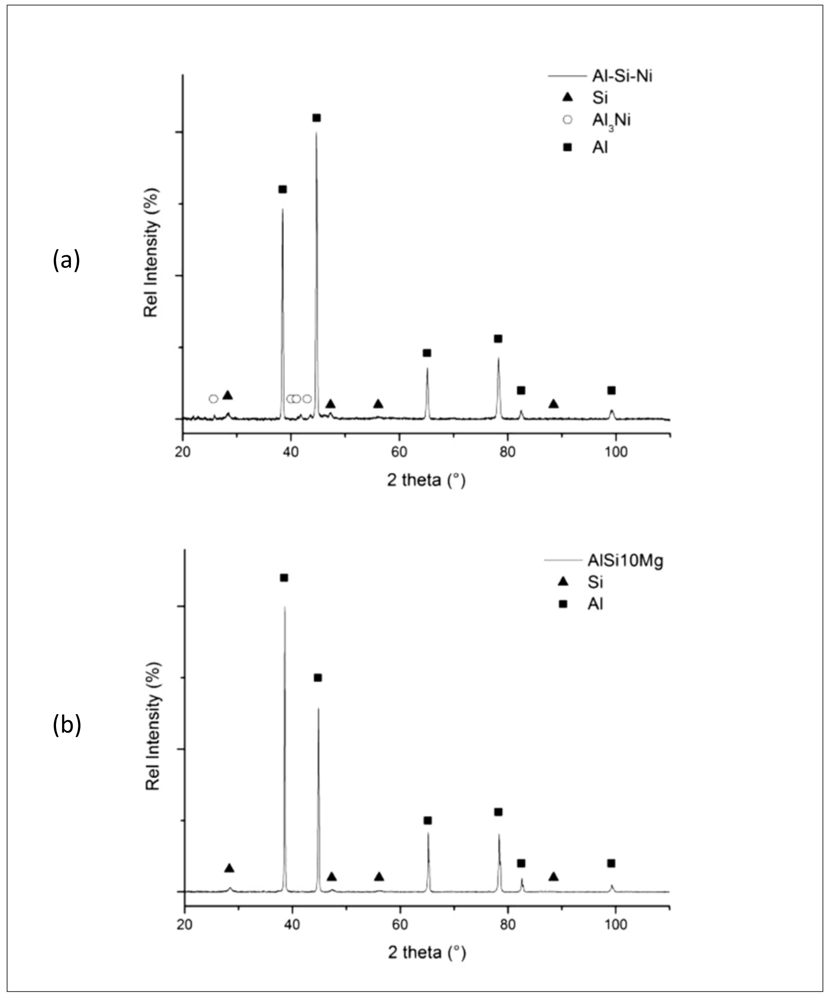


Fig. 8 XRD patterns of a) an Al-Si-Ni and b) an AlSi10Mg sample [2]

	Al Wt %	Si Wt %	Ni Wt %	Mg Wt %
Point 1	37.0	4.2	56.9	0.07
Point 2	81.2	10.3	4.5	0.32

Table 7 EDX data corresponding to the points shown in Fig. 8a [2]

To select the most suitable building parameters, two main approaches were used. Firstly, the Volumetric Energy Density (VED) parameter, calculated using the equation below, was employed to select the minimum value that can generate a low porosity level.

$$VED = \frac{p}{vhd}$$

Secondly, the Taguchi statistical approach was used to understand the effect of each building parameter on the consolidation. For the various parameters, the signal to noise values (*SN*) were calculated by means of the following equation, using the porosity as the quality factor:

$$SN = -10\log(\frac{1}{n}\sum y^2)$$

where *y* are the porosity values and *n* the number of trials.

The signal to noise values, based on the porosity data, are reported in Fig. 5. It is evident that *P*, *v* and h_d have the most significant effects on sample consolidation. The porosity versus VED graph for the Al-Si-Ni samples is shown in Fig. 6. This material shows the expected trend, in that higher VED values lead to lower porosity levels. This type of trend is observed in most materials processed by powder bed fusion technology.

It was apparent that the introduction of nickel does not strongly influence the consolidation phenomena. In view of this and in order to have a more reliable comparison with the standard aluminium alloy, the build parameters were chosen to be the same as for the standard AlSi10Mg (*P*=195 W, *v*=800 mm/s, *hd*=0,17 mm, *S*=5 mm).

The optical micrograph of the Al-Si-Ni sample cross section, shown in Fig. 7, demonstrates that the powder bed fusion process can produce dense and crack-free parts. A few pores and some precipitates could be recognised. The XRD pattern, shown in Fig. 8, indicates that the precipitates could be Al_3Ni. From Fig. 8, it can be also noted that, for both powder types, most of the silicon is contained in solid solution in the aluminium phase.

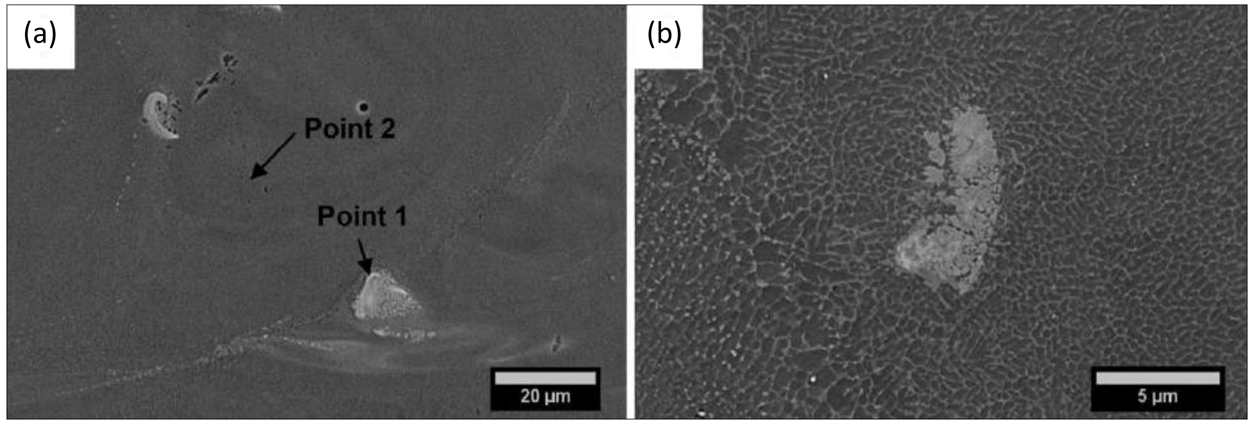


Fig. 9 FESEM micrographs of the Al-Si-Ni sample cross section [2]

The FESEM micrographs of the samples, shown in Fig. 9, highlight the fact that an extremely fine microstructure was produced. The size and the distribution of the precipitates do not follow any pattern correlated with scanning strategy, suggesting that they could be due to the mixing process rather than to a build process issue. The EDX analyses (Table 7) indicate that, even in the presence of some Al_3Ni agglomerates, the phenomena that arise in the melt pool, such as Marangoni flow and the recoil pressure effect, allow the dispersion of most of the nickel content within the aluminium alloy.

Vickers hardness tests, on the samples built with the optimised parameters, showed that the introduction of nickel into the alloy strongly increased the hardness level, from around 136 Hv to 180 Hv.

AM of magnesium alloy powders: Elektron® MAP+43 via Laser Powder Bed Fusion and Directed Energy Deposition

The final paper in this review moves from aluminium to magnesium alloys. Rajiv Tandon (Magnesium Elektron Powders, USA), Todd Palmer (Pennsylvania State University, USA) and Matthias Gieseke, Christian Noelke and Stefan Kaierle (all Laser Zentrum Hannover, Germany) reported on a study of the Additive Manufacturing, via both laser powder bed fusion and directed energy deposition, of the Magnesium Elektron powder grade, Elektron MAP+43, which was specifically developed for AM processing [3].

The low evaporation temperature and melting point of magnesium, coupled with its high vapour pressure, makes it challenging to process. The magnesium powder, used in both powder bed fusion and directed energy deposition processes, must be passivated during production to allow for safe handling. The resulting stable magnesium oxide layer on the surface of powder inhibits the wetting process and, therefore, influences the processing window.

Previously reported work on directed energy deposition using the rare earth containing alloy Elektron®MAP+43 has shown that it is possible to achieve a yield strength of 170 MPa, an ultimate tensile strength of 255 MPa and 7.9% elongation. These property levels compare favourably with those of a cast WE43B alloy in a T-6 heat treated condition.

The aim of the currently reported study was to present a few key aspects of the processing of rare earth containing alloy Elektron®MAP+43 using the Directed Energy Deposition (DED) and powder bed fusion processes.

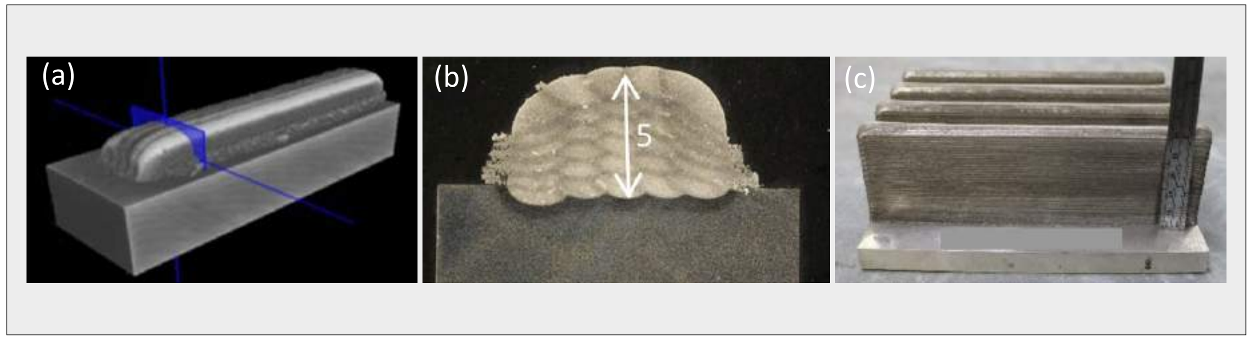


Fig. 10 Test geometry for selecting process parameters (a) and (b), final test geometry (c) [3]

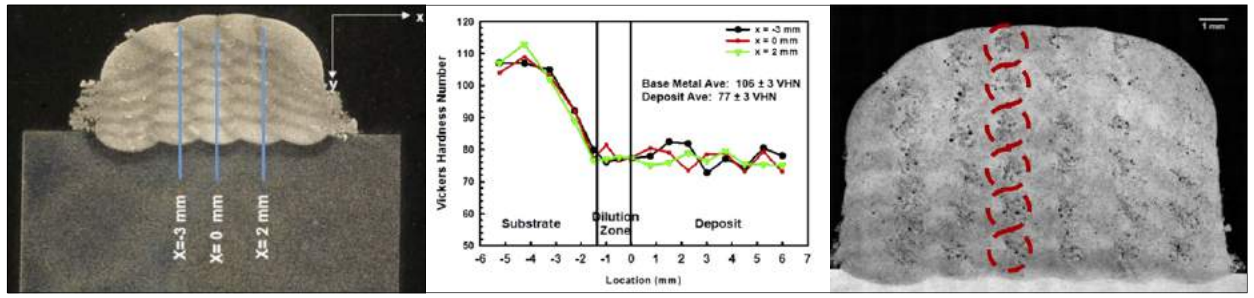


Fig. 11 Typical cross-section of an as-deposited sample showing overlapping layers, micro hardness variation along three build planes and microstructure with fine grain size and pore clusters [3]

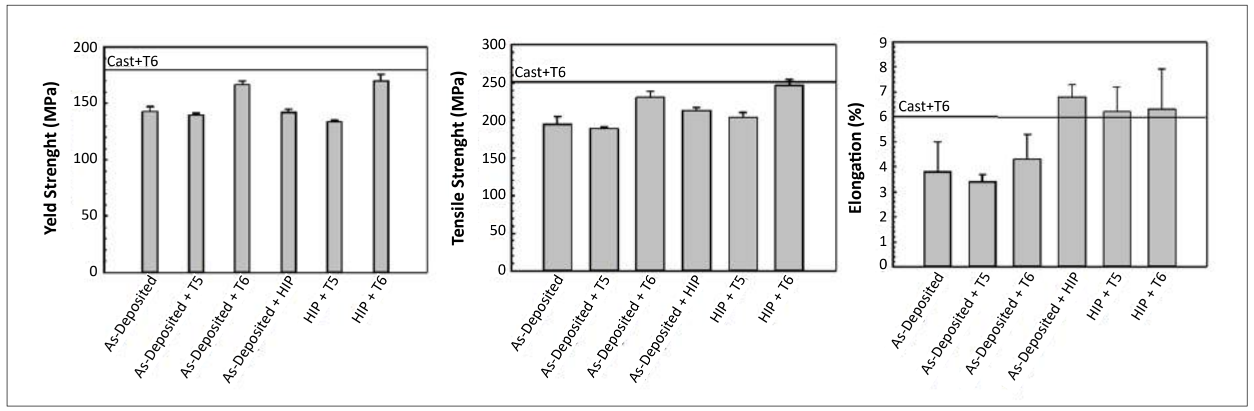


Fig. 12 Mechanical properties of Elektron®MAP+43 produced via directed energy deposition [3]

Directed Energy Deposition

Directed Energy Deposition studies used a gas atomised spherical Elektron® MAP+43 powder (D_{10} = 50 µm, D_{50} =83 µm, D_{90} =133 µm). The deposition experiments were performed on a custom fabricated deposition system with build dimensions of up to 1000 mm L x 300 mm W x 450 mm H. The power source was an ytterbium fibre laser with a wavelength ranging from 1070 to 1100 nm. Powder was delivered using a custom designed four nozzle system. The substrate was placed approximately 10 mm from the nozzles. At this location, the laser beam was in a defocused position and had a measured beam diameter of approximately 4 mm. The process parameters investigated included varying the laser power between 1750 and 2250 W, travel speed between 0.85 and 1.27 cm/s, nozzle gas flow between 100 and 200 l/min and layer height step between 0.038 and 0.1 cm. The powder flow rate was set at 5 g/min and the chamber oxygen level was between 80 and 110 ppm.

In this initial development work, five-pass wide and six-layer high deposits were fabricated as shown in Figs. 10a and b. The substrate used was wrought Elektron® 43. These builds were assessed in terms of microhardness, microstructure, grain size and porosity. The test results were ultimately used to select the processing parameters for building the final test geometry, which was 15.24 cm long, 5.08 cm high and 1.27 cm thick, as shown in Fig. 10c. The selected parameters used a laser power of 2250 W, travel speed of 1.06 cm/s and a step height of 0.062 cm. Some of the samples shown in Fig. 10c were Hot Isostatically Pressed following deposition. Tensile test specimens were machined in both the horizontal and vertical orientations and were in various conditions, including as-deposited, as-deposited + T5 (artificial aging at 250°C for 16 h), and as-deposited + T6 (a solutionising treatment at 525°C for 2 h followed by aging at 250°C for 16 h).

"The overall mechanical properties obtained in the study compared favourably with those typical of a cast WE43B alloy"

A high as-deposited relative density of >99% of theoretical was achieved by optimisation of the deposition parameters. As compared to the starting powder grain size of approximately 2 µm, the average grain size in the deposited samples ranged from 8 µm to 9.6 µm. The micro hardness of the deposited layers ranged from 76 HVN (Hardness Vickers Number) to 81 HVN (versus a micro hardness of 96 HVN for the

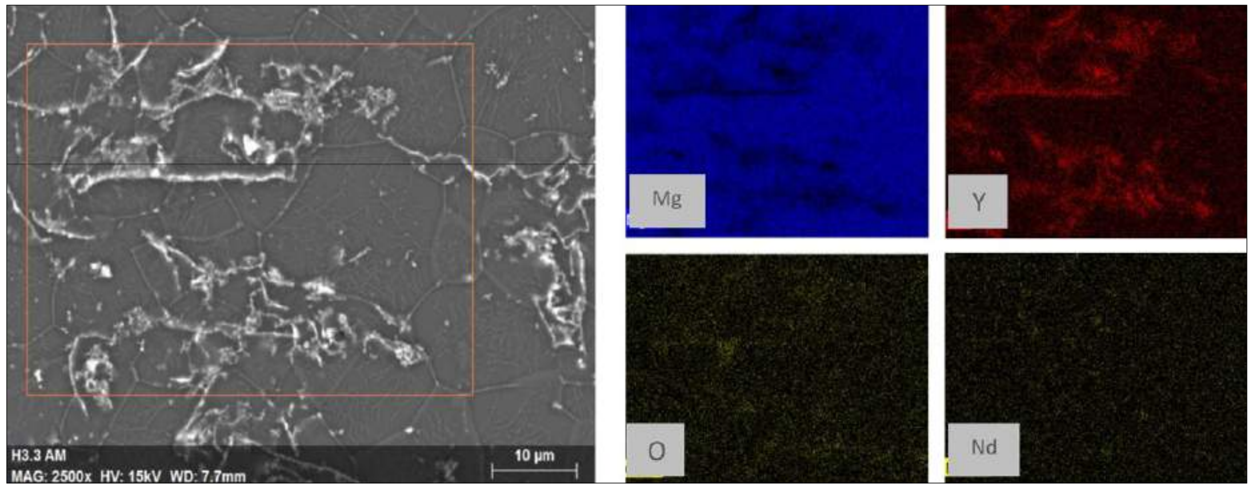


Fig. 13 Microstructure and elemental scan maps of a Hot Isostatically Pressed and heat-treated sample [3]

starting powder). There was no gradient in the micro hardness in the vertical build direction and the microstructure consisted of small repeating isolated clusters of pores, as shown in Fig. 11. These pores were present mainly in the overlap zones between successive passes. The best results were obtained using a laser power of 2250 W with a scan speed of 1.06 cm/s and an overlap of 0.20 cm. Under these conditions, an optimum combination of small grain size (8 µm), small pore volume (0.70%) and high as-deposited micro hardness (81 HVN) was obtained.

The mechanical properties of the as-deposited, HIPed and heat treated samples are shown in Fig. 12. HIPing increased the overall ductility together with a slight improvement in UTS. The artificial age T-5 cycle did not result in any significant change to the as-deposited properties. In comparison, the T-6 treatment restored the aging response and improved yield, UTS and elongation. The overall mechanical properties obtained in the study compared favourably with those typical of a cast WE43B alloy.

The HIPed + T6 heat treated microstructure is shown in Fig.13. No pores were observed in the HIPed samples. The elemental scan maps show the presence of Y, O and Nd. The yttrium rich phase did not completely dissolve in the 525°C/2 h solutionising cycle. It should be

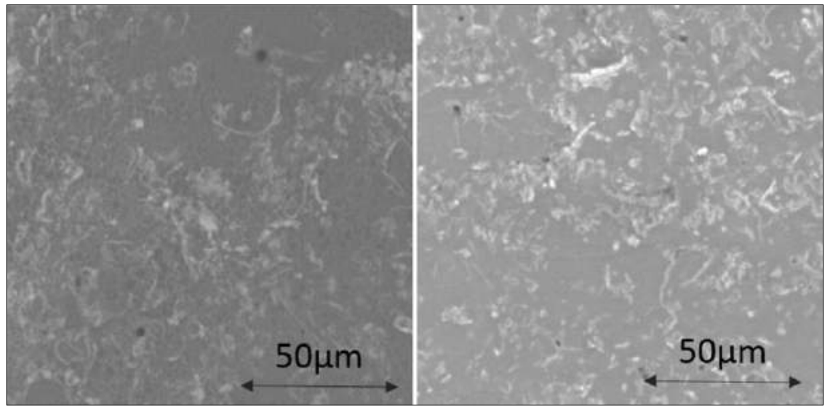


Fig. 14 As-deposited micrographs of the sample using a normal scan strategy (left), and using additional volume exposure (right) showing rare-earth enriched phases [3]

noted that the starting powder used in this investigation was passivated for safe handling and, therefore, the presence of Y_2O_3 was expected. In addition, yttrium has a greater affinity for oxygen than magnesium and it is possible that some yttrium oxide may have formed during the melting process through the reduction of MgO.

During the investigation, magnesium vaporisation and powder dust was created inside the deposition chamber. The low density of magnesium powder could be a factor in dust creation and on-going efforts are being aimed at mitigating this effect, including studying the effects of optimised particle size distributions. Another on-going area of investigation is to reduce the occurrence of pore clusters, as shown in Fig. 11. Early results indicate that, by employing secondary re-melting techniques at lower power settings ranging from 500 W to 1500 W (between successive passes), it is possible to minimise as-deposited microporosity.

Although a relatively simple rectangular geometry with an overall volume of about 400 cm^3 was deposited in these studies, the resulting properties have given the authors confidence that it should be possible to scale the DED process to more complex shapes.

Laser Powder Bed Fusion

Laser Powder Bed Fusion investigations were performed on an SLM 125HL machine with a 100 W fibre laser and a focus diameter of 70 µm, using gas-atomised Elektron®MAP+43 powder with a particle size distribution D_{10}= 22.5 µm, D_{50}=31 µm and D_{90}=45 µm.

A 50 x 50 x 50 mm³ build volume was used along with high purity Ar as shielding gas. Parameter studies on varying laser power, scan speed and hatch distance were performed with the goal of obtaining high as-deposited density (>99%). The laser power was varied between 20 W and 100 W, the scan speed between 200 and 10,000 mm/s and the hatch distance between 15 µm and 120 µm. A layer thickness of 50 µm was used with a focal position of 0 mm. The initial builds used a cylindrical geometry of 6.5 mm dia. x 6.5 mm height. Once the processing window was selected, 6.5 mm dia. x 43 mm tall cylindrical specimens were fabricated, from which tensile specimens were machined.

The scan strategy played a significant role in the powder bed fusion process. A baseline or normal build strategy was developed, which resulted in a high build density of >99%. A slightly modified build strategy, called additional volume exposure, was investigated, in which a second powder deposition is incorporated after the first exposure without lowering the build platform. This process was performed at a significantly higher scan speed than the normal build strategy, but resulted in parts with better surface finish and finer grain size. Samples were HIPed and heat treated to a T-6 condition before machining. During tensile testing, some of the samples exhibited premature failure due to the presence of an inhomogeneous distribution of pores that acted as defect sites. Pore-free samples achieved a yield strength of 194 MPa, ultimate strength of 312 MPa and elongation of up to 14%. These values are superior to the Elektron®MAP+43 strength obtained via directed energy deposition and better than typical values for cast WE43.

The as-deposited microstructures using a normal scan strategy (P_L =100 W, V_S =75 mm/s, and S_h =95 µm) and using additional volume exposure (P_L =90 W, V_S =800 mm/s, and S_h =45 µm) are shown in Fig. 14. The lighter phases are the Y and Nd-rich phases that are very similar to those observed in the microstructures of the directed energy deposited samples.

The authors concluded that, although the powder bed fusion process can be optimised to give a high deposited density of >99%, further process parameter development is necessary to achieve a high reliability of build without internal defects, especially in other tilt orientations. The mechanical properties using powder bed fusion were superior to those obtained via directed energy deposition.

Finally, further investigations are planned to compare the differences in microstructure between the DED and powder bed fusion processes.

References

[1] 'Investigations on Aging Behaviour of Aluminum Powders During a Lifetime Simulation for the LBM Process', D Bauer *et al*, as presented at the World PM2016 Congress, Hamburg, October 11-14, and published in the Proceedings by EPMA, Shrewsbury, UK.

[2] 'Microstructural and Mechanical Properties of Al-Si-Ni alloy Produced by Direct Metal Laser Sintering'. A Aversa *et al*, as presented at the World PM2016 Congress, Hamburg, October 11-14, and published in the Proceedings by EPMA, Shrewsbury, UK.

[3] 'Additive Manufacturing of Magnesium Alloy Powders: Investigations Into Process Development Using Elektron®MAP+43 Via Laser Powder Bed Fusion and Directed Energy Deposition', R Tandon *et al*, as presented at the World PM2016 Congress, Hamburg, October 11-14, and published in the Proceedings by EPMA, Shrewsbury, UK.

Author

Dr David Whittaker is a consultant to the Powder Metallurgy industry.
Tel: +44 (0)1902 338498
Email: whittakerd4@gmail.com

Proceedings

The proceedings of the World PM2016 technical sessions and poster program are published in digital format by the European Powder Metallurgy Association. For more information visit www.epma.com

industry events

2017

ADDITIVE MANUFACTURING FORUM 2017
March 1-2, Berlin, Germany
www.additivemanufacturingforum.de

AERODEF Manufacturing by SME
March 7-8, Fort Worth, USA
www.aerodefevent.com

TCT Asia 2017
March 8-10, Shanghai, China
www.tctasia.com.cn/en

AMUG CONFERENCE 2017
March 19-23, Chicago, USA
www.additivemanufacturingusersgroup.com

PM CHINA 2017
April 26-28, Shanghai, China
www.cn-pmexpo.com/en/

Rapid + TCT 2017
May 8-11, Pittsburgh, USA
www.rapid3devent.com

19th Plansee Seminar
29 May – 2 June, Reutte, Austria
www.plansee-seminar.com

6th National Congress on Powder Metallurgy 1st Ibero-American Powder Metallurgy Congress
June 7-9, Ciudad Real, Spain
www.vicnp.es

AMPM2017 - Additive Manufacturing with Powder Metallurgy Conference
June 13-15, Las Vegas, USA
www.ampm2017.org

POWDERMET 2017
June 13-15, Las Vegas, USA
www.powdermet2017.org

3D Print Event
June 13-16, Lyon, France
www.3dprint-exhibition.com

Additive Manufacturing Europe 2017
June 27-29, Amsterdam, The Netherlands
www.amshow-europe.com

EURO PM2017 - Congress & Exhibition
October 1-4, Milan, Italy
www.europm2017.com

formnext powered by TCT
November 14-17, Frankfurt, Germany
www.formnext.com

Pick up your free copy!
Metal AM magazine is exhibiting at and/or being distributed at events highlighted with the Metal AM cover image

Event listings and Media Partners

If you would like to see your metal Additive Manufacturing related event listed on this magazine and on our websites, please contact Paul Whittaker:
email: paul@inovar-communications.com

We welcome enquiries regarding media partnerships and are always interested to discuss opportunities to cooperate with event organisers and associations worldwide.

advertisers' index

Advertising opportunities

***Metal Additive Manufacturing* is the magazine for the metal Additive Manufacturing industry**

Metal Additive Manufacturing is the business-to-business magazine that focuses on commercial and technical developments in the metal AM industry.

As well as featuring the latest business and applications news, technical developments in the industry will also be highlighted, making the magazine the essential resource for part manufacturers and end-users, along with equipment and material suppliers.

For more information contact Jon Craxford Advertising Sales Director, Tel: +44 207 1939 749 Email: jon@inovar-communications.com

EURO PM2017 CONGRESS & EXHIBITION