Vol. 1 No. 4 WINTER 2015

THE MAGAZINE FOR THE METAL ADDITIVE MANUFACTURING INDUSTRY

METAL AM

in this issue

FORMNEXT 2015

HIP FOR METAL AM

CONFERENCE REPORT: EURO PM2015

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. 1. No. 4 Winter 2015

METAL ADDITIVE MANUFACTURING

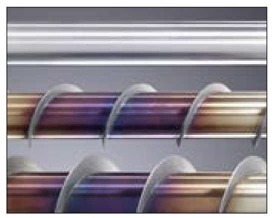
The two worlds of metal AM

Welcome to the Winter 2015 issue of *Metal AM* magazine. This issue comes on the back of a busy Autumn of exhibitions and conferences for the team at Inovar Communications. One of the most spoken about exhibitions was formnext, which took place in Frankfurt from November 17-20. As our review reveals, this inaugural event proved to be a resounding success and formnext has firmly established itself as the premier European exhibition on Additive Manufacturing (page 27).

Whilst formnext has received significant media coverage, another event that is very different in nature and scope took place in the French city of Reims from October 4-7. Euro PM2015 was the latest in the annual Euro PM conference series from the European Powder Metallurgy Association. The series, which moves to a different European destination each year, combines an industry-oriented technical conference with an exhibition and numerous networking opportunities. Although nominally a Powder Metallurgy event, there is a significant and rapidly growing volume of technical content from those active in the metal AM industry, as can be seen from our reviews on pages 51 and 65.

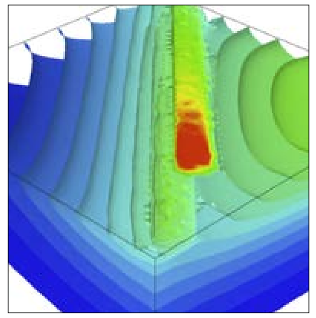
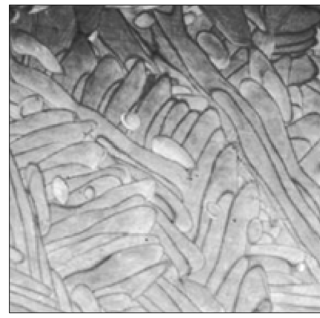
What was striking about attending these two very different events back-to-back is how one could be forgiven for imagining that they represent two quite separate industries. Formnext is to a large extent influenced by the major AM equipment suppliers, whilst the Euro PM conference comes from a background of metallurgy and the production and use of metal powders. As the metal AM industry advances, one is left with the sense that these two seemingly disparate worlds - that make up a large part of the metal AM industry - are inevitably going to have to move closer and discover the value and knowledge that each has to offer.

Nick Williams
Managing Director



Cover image
An example of a product manufactured using Trumpf's Laser Metal Deposition (LMD) technology (Image courtesy Trumpf Gmbh + Co KG)



17 28 45 59 65

Contents

industry news

Michelin and Fives join to develop industrial metal AM machines

France's Michelin Group and Fives have announced the formation of Fives Michelin Additive Solutions, a 50-50 joint venture with the aim of developing industrial metal Additive Manufacturing machines. Under the terms of the agreement the new company will benefit from a financial contribution of at least €25 million in the first three years and be located near Clermont-Ferrand, France.

Fives and Michelin plan to position Fives Michelin Additive Solutions as a key player in the growth market of metal Additive Manufacturing. The companies state that their aim is to build on the complementary expertise of the two groups to become a world leader in the segment of industrial solutions for mass production.

Michelin is reported to have been developing expertise in metal AM for several years in order to produce mould parts that are unachievable using traditional means of production such as machining or welding.

Fives operates in around thirty countries and provides both equipment and production systems for the world's leading industrial players in a variety of sectors. The company states it will use its expertise in mechanical engineering, automation and industrial process control to produce fully digitised machines and systems that meet the technological requirements of Additive Manufacturing constraints as well as those of reliability and reproducibility of controlled industrial production.

The new company will offer manufacturers in different sectors, such as automotive, aerospace, health, etc., a complete solution from the design and manufacture of machines and complete production lines to the related services.

www.michelin.com

www.fivesgroup.com

PyroGenesis to produce specialty powders for the metal AM industry

PyroGenesis Canada Inc. has announced that it plans to produce specialty powders for the Additive Manufacturing industry. The company's Plasma Atomization Process (PAP) is an enabling technology for Additive Manufacturing and Powder Metallurgy applications, having the distinction, states PyroGenesis, of producing highly flowable and very pure spherical metallic powders, all highly sought after characteristics in Additive Manufacturing applications.

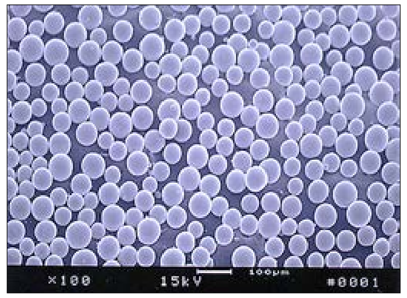
This new process enables PyroGenesis to produce metallic powders at higher production rates while, at the same time, allowing for better control of powder size distribution. The need to produce powders of a specific particle size distribution at increasingly higher production rates is driven by the growing demand created by the AM industry.

"While delivering the first of ten Plasma Atomization Systems to a client, an opportunity arose to test certain parameters which PyroGenesis identified as having the potential of improving both the production rate and purity of the powders," stated P. Peter Pascali, President and CEO of PyroGenesis. "The decision was taken, with the customer, to strategically delay delivering the first system to allow for this testing. This strategic delay not only resulted in a patent application by PyroGenesis, but paved the way for PyroGenesis to consider producing powder for 3D printing on its own."

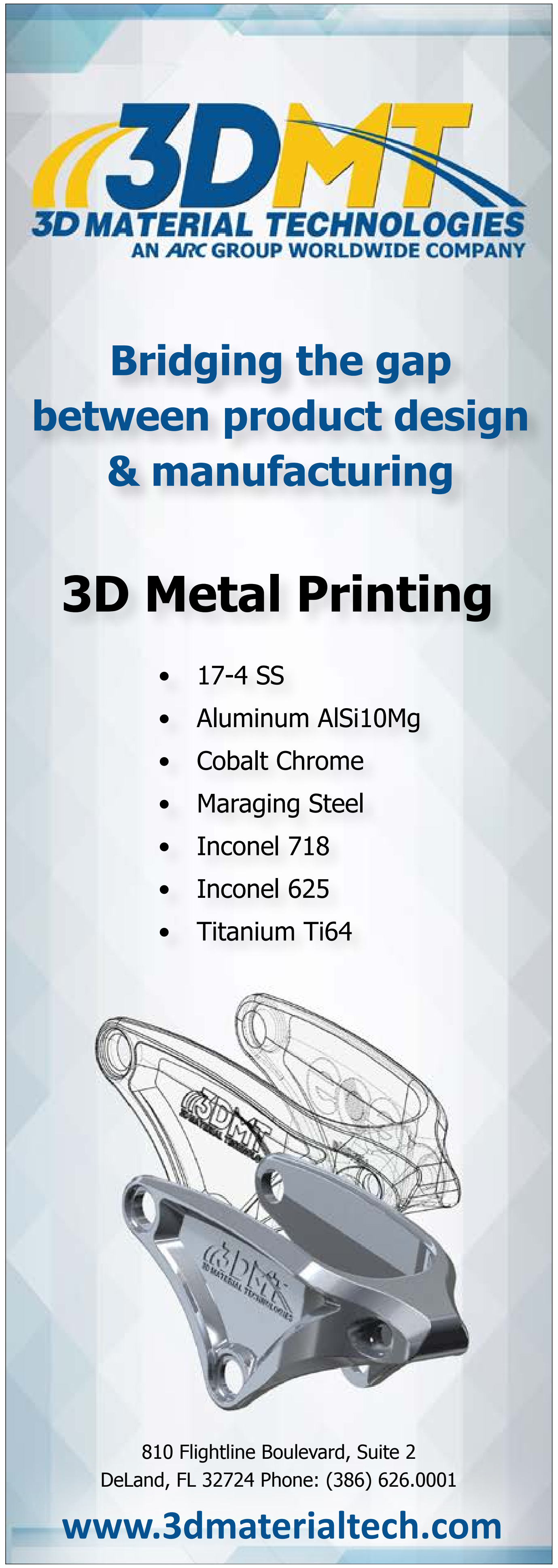
PyroGenesis stated that it has already identified customers interested in procuring its powders, though not in the quantity that would justify the purchase of a Plasma Atomization System. It is estimated that it could generate over $10M profit per year per system from powder sales alone.

The company added that it will develop next generation Plasma Atomization Systems capable of making powders from various metals being used in Additive Manufacturing, as well as from composites.

www.pyrogenesis.com



Highly flowable and pure spherical metallic powders from PyroGenesis



Avure changes its name to Quintus Technologies, supplies high speed HIP system to US

Avure Technologies AB, headquartered in Västerås, Sweden, has changed its name to Quintus Technologies AB. The US subsidiary, based in Columbus, Ohio is already named Quintus Technologies, LLC. Avure Technologies Inc. in the US will continue to focus on High Pressure Processing (HPP) food processing machines and Quintus Technologies in Sweden and the US will continue to focus on high pressure metal working and material densification equipment for the manufacturing industry.

"Quintus Technologies is the undisputed leader within high pressure technology. Stemming from the Swedish electro technical company ABB, we have over sixty years of experience of developing, building and installing systems for customers within the automotive and aerospace sectors and general industry," stated Jan Söderström, CEO of Quintus Technologies.

The Quintus press was the world's first high pressure press, a design that was used to manufacture synthetic diamonds and other products."The name Quintus Technologies underlines that we continue to focus on industrial customers requiring systems for sheet metal forming or systems for cold or hot isostatic pressing. The re-naming is a small part of a substantial effort now launched to strengthen our offer and our position on all markets, from Europe to the Americas and especially Asia. The strong history of the Quintus name will help us to release the full potential," added Söderström.

High speed Quintus Hot Isostatic Press to be installed at Oak Ridge National Laboratory

Quintus also announced it will supply a Hot Isostatic Press (HIP) to the US Department of Energy's Manufacturing Demonstration Facility (MDF) at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, USA. ORNL's new HIP will be used for research in demanding applications for aerospace, nuclear, gas turbines and other advanced-technology industries, as part of its mission to enhance the competitiveness of American manufacturing.

The model QIH-9M URQ to be installed at ORNL will hold the distinction of being the fastest and most versatile HIP in the United States, operating at a pressure of 2070 bar (30,000 psi) and a temperature up to 2000°C (3992°F). Installation is scheduled for June 2016. The press will be equipped with Quintus' patented Uniform Rapid Quenching (URQ®) technology, enabling increased productivity with optimal temperature control. URQ's advanced heat treatment of materials under pressure not only facilitates improved performance of existing alloy systems but also supports the development of novel alloy systems with unique properties.

www.ornl.gov/manufacturing
www.quintustechnologies.com

Praxair uses Ames Laboratory's advanced titanium atomisation technology for AM powders

Ames Laboratory, the US Department of Energy Office of Science national laboratory operated by Iowa State University, has announced that titanium powder created with its gas atomisation technology is now available from Praxair Inc. The fine, spherical titanium powder is suited for both Additive Manufacturing and Metal Injection Moulding applications.

"Titanium powder made with this technology has huge potential to save manufacturers materials and money," stated Iver Anderson, a senior metallurgist at Ames Laboratory. "Creating titanium powder of high quality at great volumes was what we materials scientists called the Holy Grail of gas atomisation."

Titanium's strength, light weight, biocompatibility and resistance to corrosion make it ideal for use in parts ranging from aircraft wing structures to replacement knee joints and medical instruments. Using ultra-fine, high-purity spherical titanium powder to additively manufacture or mould these parts generates around ten times less metal waste than traditional casting of parts.

"Our invention of an in-stream melt heating guide tube was critical to boost the melt temperature by at least 100°C, allowing adaptation of water-cooled 'clean' melting technologies, normally used to melt and cast strong, reliable aerospace Ti parts," stated Anderson. "This new 'hot nozzle' made possible precise feeding of highly energetic close-coupled atomisers for efficient production of fine Ti powders."

Two members of Anderson's research team, Joel Rieken and Andy Heidloff, created a spinoff company, Iowa Powder Atomization Technologies and exclusively licensed Ames Laboratory's titanium atomisation patents. IPAT worked to further optimise the titanium atomisation process and along the way won several business and technology awards for their efforts, including the Department of Energy's Next Energy Innovator competition in 2012.

In 2014, IPAT was acquired by Praxair, a Fortune 250 company and one of the world's largest producers of gases and surface coatings. Earlier this year, Praxair announced it had begun to market titanium powder.

"We talk regularly about the Department of Energy's goal of transferring research from the scientist's bench to the marketplace. This work is a strong example of how that goal can become reality. The ingenuity and continued hard work and commitment by our scientists and our licencee to get the technology to market cannot be underestimated. They make my job of transferring technology developed at Ames Laboratory into the marketplace so much easier," said Ames Laboratory Associate Director Debra Covey.

www.ameslab.gov
www.praxair.com

ARC Group Worldwide, Inc. reports first quarter results

ARC Group Worldwide, Inc., a leading global provider of advanced Additive Manufacturing and Metal Injection Moulding solutions, has reported its first quarter fiscal year 2016 results. Fiscal first quarter revenue was $24.5 million, a decrease of 14.7% compared to the prior year period. The decrease was due to lower sales to European automotive customers and delayed US product launches, as well as macro and customer attrition issues, the company stated. At the same time, 3DMT Group reported record metal Additive Manufacturing revenue during the first fiscal quarter.

EBITDA for the fiscal year first quarter was $2.6 million, a decrease of 27.1% compared to the prior year period. EBITDA margin decreased to 10.8%, from 12.6% in the prior year period, primarily related to lower plant level utilisation. The company stated that while near term headwinds remain, the management is optimistic about the medium to long term forecast for the company.

www.arcgroupworldwide.com

Höganäs boosts its Digital Metal capacity

Höganäs AB, Sweden, has announced further investment in its Digital Metal facility with the addition of a new sintering furnace to increase output of its 3D printed metal components. The additional capacity was required to meet the growing demand for 3D printed components and offer material alternatives, the company stated.

"The new furnace has significantly increased our production capacity and we are also able to sinter a wider range of metal powders," stated Ralf Carlström, General Manager for Additive Manufacturing at Höganäs.

The new high temperature furnace offers variable sintering atmosphere settings and very precise adjustment of temperature profiles, crucial to the sintering of high quality metal components.

www.hoganas.com

AP&C files two patent applications for powder manufacture process

Arcam has announced that its metal powder manufacturing subsidiary, AP&C, based in Montreal, Canada, has recently filed two strategic patent applications. The first covers high-yield production of fine powder from reactive metals with a low gas to metal ratio and low gas pressure. The second covers improved metal powder flowability.

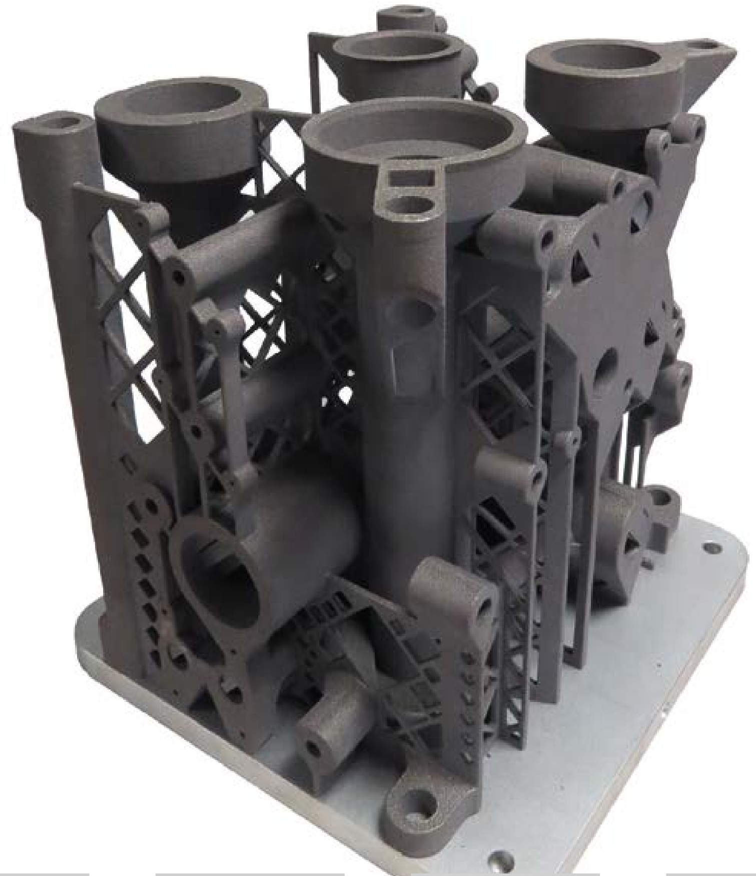
AP&C uses proprietary technology for plasma atomisation. The first strategic patent application covers the use of plasma atomisation on different heated metal sources such as wire, rod and melt. AP&C's technology allows high yield production of fine powder for all Additive Manufacturing distributions and without ceramic contamination risk.

"The production yield is one of the key drivers to produce powder at low cost. The combination of high-yield of fine powder with a low gas to metal ratio of about 10 is unique to AP&C's proprietary plasma atomisation process," stated Jacques Mallette, President of AP&C.

The company's second strategic patent application covers a method to obtain optimal flowability of fine reactive metals powder for Additive Manufacturing. The patent covers all principal reactive metals powder production methods including plasma atomisation, other gas atomisation processes, plasma spheroidisation and plasma rotating electrode. The invention allows the obtaining of the highest level of flowability for all Additive Manufacturing powder distributions.

"High and repeatable flowability is a key metal powder attribute allowing for the optimal production of quality parts using Additive Manufacturing technology," added Mallette.

www.arcam.com



Italy's CRP Meccanica and Zare Prototyping form additive technology alliance

It has been announced that an agreement has been signed between Italy's CRP Meccanica and Zare Prototyping. CRP Meccanica is recognised internationally for its high precision machine processing in motorsport, whilst Zare Prototyping is a market leader in metal Additive Manufacturing.

CRP Meccanica, with headquarters in Modena and part of CRP Group, states that it wanted to send a strong signal to the international market by implementing the service of Direct Metal Laser Sintering (DMLS) / Selective Laser Melting (SLM) through an agreement with Zare Prototyping, one of the main operators at the forefront of metal AM technology.

The union is expected to offer a complete service capable of supplying the best solutions, both in terms of production capacity and the materials processed and the technology used. High precision machine processing, for which CRP Meccanica has been known for 45 years, is now supported with the contribution of Zare Prototyping as a means to increase the production of parts and components which require both CNC technology and metal Additive Manufacturing.

"Through this alliance with Zare Prototyping, we will continue to provide an immediate and concrete response to international customers through the implementation of the DMLS / SLM service, a technology which has seen a strong growth over recent years and which we have decided to develop. Our objective is to continue to innovate, in both precision machining and in the production of DLMS / SLM components," stated Franco Cevolini, CEO and Technical Director of the CRP Group.

"The alliance with CRP Meccanica is an important strategic step in being able to compete abroad and to assert, strongly, that Italian technological excellence is also entrepreneurial excellence," stated Sauro Zanichelli, CEO of Zare Prototyping.

"Challenging yourself outside your own borders means adapting very quickly and continuously investing in facilities which allow constant technological advancement. Together, Zare and CRP Meccanica bring experience and innovation to achieve the production of metal sintered parts and components."

The alliance signed between CRP Meccanica and Zare Prototyping, it was stated, will complement not only additive and subtractive technologies, but also the experience of highly qualified and specialised personnel, becoming a point of worldwide reference for sectors such as aerospace, medicine, robotics and all those industrial areas which require reliability, high standards of quality and the ability to create complex parts and prototypes in a quick turnaround.

www.crp.eu | www.zare-prototyping.eu

Moog announces investment in Linear Mold and Engineering

Moog Inc., headquartered in East Aurora, New York, USA, has announced its investment in Additive Manufacturing with the acquisition of 70% ownership of Linear Mold and Engineering. Terms of the investment were not disclosed, but the company has an option to acquire the remaining 30%.

Linear Mold and Engineering, based in Livonia, Michigan, USA, has 120 employees and specialises in metal Additive Manufacturing. Linear provides engineering, manufacturing and production consulting services to customers across a wide range of industries including aerospace, defence, energy and industrial. Sales for the 12 months ended September 2015 were approximately $21 million.

The company was founded by John Tenbusch in 2003 as a service-focused business and began developing specialised moulds and tooling for plastic forming applications. As one of the early adopters of metal Additive Manufacturing in North America, the company was able to exploit the advantages it offered for enhanced product feature sets, rapid design cycles and high customisation.

"We see significant potential for metal additive solutions in our core markets – aerospace, defence and industrial applications – in addition to the markets and customers that Linear is already serving," stated Sean Gartland, Vice President of Strategic Growth Initiatives at Moog.

Moog's high-performance systems control military and commercial aircraft, satellites and space vehicles, launch vehicles, missiles, automated industrial machinery, wind turbines, marine and medical equipment.

www.moog.com

www.linearmold.com

Additive Manufacturing innovation centre to open in Chongqing

China's National Engineering Research Center of Rapid Manufacturing is set to open a new Additive Manufacturing innovation centre in Chongqing Municipality, southwest China. The centre will help develop technologies and products for industries including aviation, automotive and health care, according to the city's commission of economy and information technology.

The commission stated that investment deals have been signed with some 15 companies and institutions on robotics and smart equipment. The centre is scheduled to begin trial operation in January 2016.

Optomec receives investments from GE and Autodesk

Optomec, based in Albuquerque, USA, has announced that both GE Ventures and Autodesk, Inc have recently made strategic investments in the company. The investments will be used to further the development, promotion and deployment of Optomec's proprietary AM solutions for a range of industrial applications. Additionally, it was stated that the companies intend to expand on a variety of historic collaborations.

"Optomec is extremely pleased to welcome GE Ventures and Autodesk as strategic investors," stated Optomec CEO, Dave Ramahi. "Our strategic visions are well aligned on many fronts, ranging from the need for an open systems approach to drive adoption, to the role that these technologies can play in advancing key initiatives such as the Industrial Internet and IoT. We are very fortunate to be able to draw on their technical and commercial expertise."

Optomec's commercial relationship with GE dates back to 2005, when GE Global Research was one of the first customers to acquire an Aerosol Jet printed electronics system. More recently, GE has expanded its installation with systems at Power & Water, Aviation and Healthcare. One key area of collaboration is 3D Sensors that are directly printed onto high-value components. Such tightly integrated sensors provide critical input to structural health and have the potential to substantially reduce the life cycle cost of complex mechanical systems.

"It's always a great opportunity when we are able to invest in a company we've been working with as part of a customer relationship," stated Steve Taub, Senior Director, Advanced Manufacturing at GE Ventures. "We know from direct experience that Optomec's advanced manufacturing solutions are successful and look forward to its continued developments within the space."

The investment from Autodesk was made through its Spark Investment Fund. "The Spark Investment Fund aims to push the boundaries of Additive Manufacturing and we believe a connected ecosystem between hardware and software is key in spurring innovation and collaboration," stated Samir Hanna, Vice President and General Manager, Consumer and 3D Printing, Autodesk. "We're excited to have a shared vision with Optomec in enabling Additive Manufacturing technology to be seamlessly integrated into conventional production platforms to advance the overall design and fabrication process."

Optomec has previously worked with Autodesk using its software tools to generate design data that ultimately drive Optomec's AM systems. Both companies intend to work to develop software tools that leverage the Spark 3D printing platform in better connecting hardware and software for AM.

www.geventures.com
www.autodesk.com
www.optomec.com

Renishaw brings Additive Manufacturing to America's Cup sailing challenge

Renishaw has announced that it has joined the UK based Land Rover BAR Technical Innovation Group as an official supplier in its attempt to win the America's Cup sailing challenge. The company will contribute its expertise in metal Additive Manufacturing and position feedback encoding.

The America's Cup is the oldest international trophy in world sport and Britain has never won it. It is the world's premier sailboat racing contest and the 35th race will be held in Bermuda in 2017, in foiling multi-hulls. Land Rover BAR is the British challenger and Ben Ainslie, winner of four Olympic gold sailing medals, is the Team Principal and Skipper.

The Land Rover BAR Technical Innovation Group (TIG) was formed to bring together advanced technologies and develop them to give the sailing team a competitive edge. The TIG complements the existing Land Rover BAR design team and allows it to rapidly develop, test and prove these technologies. The TIG has already engaged a number of key partners and suppliers from British industry, including Land Rover, BT and BAE Systems.

"As a British engineering company with core skills in precision and performance, combined with expertise in position encoding and metal 3D printing, we are delighted to have the opportunity to make a valuable contribution to the TIG and help Land Rover BAR bring the America's Cup back to Britain," stated Robin Weston, Marketing Manager of Renishaw. Renishaw's contribution will be through its metal AM knowledge, helping to optimise the design and construction of critical metal parts of the team's race boat. It is also contributing by providing ongoing expert advice on position encoder technology.

"We don't underestimate the challenge ahead of us. We are a first time challenger for the America's Cup, and only one challenger has ever won it at the first attempt. We want to leave no stone unturned in our search for new technologies that will help us to bring the Cup home. That's why we have developed the Technical Innovation Group and are pleased to have the support of Renishaw," stated Ben Ainslie.

www.renishaw.com
www.land-rover-bar.americascup.com

Manifold for Land Rover BAR produced on Renishaw Additive Manufacturing system (Credit Renishaw)

Jonathan Wroe, EPMA Executive Director, dies age 61

The European Powder Metallurgy Association has reported that Jonathan Wroe, the association's Executive Director, has died following a short illness. Wroe, who was 61, has been the EPMA's Executive Director since 2001.

Under Wroe's leadership the EPMA has seen its membership grow to record levels, new sectorial and working groups formed and many EU funded projects established and coordinated by the trade association. As well as broadening the scope of the popular series of Euro PM Conferences, Wroe was integral to the development of PM industry road maps, launch of the Global PM Property Database and the publication of a wide variety of free PM technology guides.

Jonathan Wroe will be missed by the PM community, not least by those at the EPMA secretariat, the association's board and all who have worked with him over the years.

www.epma.com

Norsk Titanium to expand production with additional rapid plasma deposition systems

Norsk Titanium AS, a manufacturer of aerospace-grade titanium components, has ordered an additional three Rapid Plasma Deposition (RPD) Additive Manufacturing machines following higher than forecast demand from the aerospace and defence sector. The company stated that it has contracted Norway-based Tronrud Engineering AS to supply the new systems.

"We are pleased to contract with Tronrud to build our exclusive technology for the production of aerospace-grade titanium structures," stated Norsk Titanium's President and Chief Executive Officer Warren M Boley, Jr. "These 3D Additive Manufacturing machines will further boost Norsk Titanium's customer response time and expand manufacturing capacity to meet growing demand for titanium components from the global aerospace industry."

During Norsk Titanium's patented Rapid Plasma Deposition (RPD) process titanium wire is melted in a cloud of argon gas and precisely and rapidly built up in layers to a near-net-shape (up to 80% complete) that requires very little finish machining. Production cost is stated to be around 50% to 75% less than legacy forging and billet manufacturing techniques due to significantly less waste and machining energy.

www.norsktitanium.no
www.tronrud.no

Atomisation for metal powders short course returns

Atomising Systems Ltd and Perdac Ltd (now part of CPF Research Ltd) have announced that their popular two day intensive course, Atomisation for Metal Powders, is scheduled to take place in Manchester, UK, February 25-26, 2016.

The course, now in its 12th year, will consist of presentations from Andrew Yule (Emeritus Professor Manchester University), John Dunkley (Chairman, Atomising Systems Ltd) and Dirk Aderhold (Technical Director, Atomising Systems Ltd).

Sessions will cover the main methods of atomising metals, the specific requirements for different classes of metal, the design, operation and economics of plant, measurement methods and an introduction to modelling and prediction techniques. All current atomiser types are covered together with a wide range of metals and powder types.

www.atomising.co.uk
www.cpfresearch.com

Thales to establish metal AM centre in Morocco

Thales, the global aerospace and defence group headquartered in France, has announced plans to establish an industrial competence centre for metal Additive Manufacturing in Morocco. The project will begin in 2016 with the facility fully operational by 2018.

The project is stated as being fully in line with the 2014-2020 Industrial Acceleration Plan launched by the Moroccan authorities, which supports the development of an innovative network involving Thales and its local suppliers. "This competence centre will give us access to a highly capable ecosystem of industrial suppliers specialising in mechanical parts; helping us meet all our requirements in terms of material, performance and reproducibility for the aerospace and space markets," stated Pierre Prigent, Thales Country Director in Morocco.

With its industrial processes and manufacturing capabilities, the new competence centre is a further step in the company's ongoing pre-product investment programme designed to promote the use of this innovative technology in France and other countries of operation, stated Thales.

www.thalesgroup.com

Metal Additive Manufacturing enables quick repair of marine turbochargers

A proprietary AM process is used for the repair of turbocharger nozzle rings

Erosion can result in lengthy repair times

Turbocharger specialist Tru-Marine, headquartered in Singapore, has developed a proprietary Additive Manufacturing process for the repair of turbocharger nozzle rings. The company, with operations in Singapore, China, United Arab Emirites, The Netherlands and USA, focuses on the maintenance, repair, overhaul and supply of turbochargers in marine, offshore, power plant and locomotive applications.

It has been reported that damaged nozzle rings can now be reclaimed to a 'like-new' condition as and when required, either as an intermediary option or as a reconditioned spare part, within a fraction of the time required by conventional repair methods.

According to Tru-Marine the premature erosion of nozzle rings is a commonly reported problem and in many situations spare part replacements result in long lead times and high costs. The company's AM process reconstructs worn areas directly on to the original component.

Tru-Marine stated that components can be made of multiple metal alloys or exotic materials to improve their physical properties in the areas that are necessary. Additive Manufacturing also allows simpler designs that do not incorporate fasteners or welded seams, thus enhancing performance and reducing production and delivery times.

With positive results in tensile strength and microstructure laboratory examinations, the AM nozzle rings have been tested to be suitable for turbocharger applications. Tru-Marine's breakthrough in this application has received support from government agencies and local research institutions.

www.trumarine.com

Scott Crump to feature at AMUG conference

Scott Crump will share his insights, experiences and thoughts during the Innovators Showcase

The Additive Manufacturing Users Group (AMUG) has announced that Scott Crump, co-founder of Stratasys and inventor of Fused Deposition Modelling (FDM), will share his insights, experiences and thoughts during the Innovators Showcase, taking place at its annual conference in St. Louis, Missouri, USA, April 3 – 7, 2016. Following this on-stage conversation, Crump will be presented with AMUG's Innovator Award.

The Innovators Showcase is scheduled to take place on Wednesday, April 6, 2016 and will involve a casual, relaxed interview with Crump. He will respond to questions asked by the showcase host and conference attendees with the intent of getting to know the man behind the technology and gaining guidance from his decades of experience in building and leading an innovative company in the Additive Manufacturing industry.

Mark Barfoot, AMUG president, stated, "We are very pleased that Scott Crump has agreed to participate in the Innovators Showcase. The decision to invite him was unanimous and immediate because of the impact that he has had on the industry, both through the technology he created and his personal contributions."

Scott Crump co-founded Stratasys with his wife, Lisa Crump, in 1988. He is the company's Chief Innovation Officer, a Director on its board and Chairman of the executive committee. Previously, he has held the roles of CEO, Chairman and Treasurer. Prior to creating Stratasys, Scott Crump was co-founder and Vice President of Sales of IDEA, Inc., a premier-brand manufacturer of load and pressure transducers, which was purchased by Vishay Technologies, Inc.

Designed for both novice and experienced Additive Manufacturing users, the conference agenda topics range from technology basics to advanced applications to business considerations. Although the agenda is still in development, AMUG anticipates having nearly 200 presentations, workshops and hands-on training sessions, and micro user group sessions provided by Diamond and Platinum Sponsors.

The AMUG conference will also feature its annual Technical Competition with awards for exemplary applications of Additive Manufacturing and superior part finishing. The competition provides a forum for users of additive manufacturing technologies to display their prowess with the technology.

www.additivemanufacturingusersgroup.com

Retsch introduces X-Large range

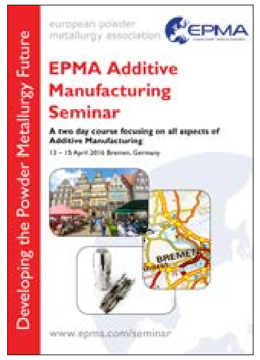
Retsch GmbH, based in Haan, Germany, has expanded its product range with a new line of instruments for applications with large feed sizes and high throughput rates. The new equipment will be integrated into the company's existing product line under the 'X-Large' brand.

The new XL models include ball mills, vibratory disc mills and sample dividers and provide a substantially higher throughput than the company's laboratory-scale models. The new range also includes testing equipment to determine Bond Grinding Indices.

The expansion of its range will give Retsch access to markets such as the coal, steel and mining industries, which until now could only be served with laboratory instruments for small sample volumes. Retsch, which celebrates its 100th anniversary this year, is now claimed to be the only supplier worldwide offering a portfolio that ranges from ball mills for nano grinding to jaw crushers with a throughput of 3500 kg per hour, thus covering the entire field of size reduction.

www.retsch.com

EPMA Additive Manufacturing seminar



The European Powder Metallurgy Association (EPMA) has announced it is organising a two-day seminar focusing on all aspects of metal Additive Manufacturing. The seminar will take place April, 13-15, 2016 in Bremen, Germany and will provide participants with an opportunity to develop their knowledge of the AM processes and applications through a series of lectures and case studies.

The seminar, which will be held in English, will be of interest to technical and managerial personnel working in the metal AM industry along with end users requiring a more comprehensive understanding of the technology. The seminar will also be beneficial to academics and researchers with an interest in AM who wish to gain an overview of trends in the field.

Topics covered will include part design, software, metal powders, machine operation and secondary operations. A selection of case studies will be presented and participants will have the opportunity to discuss the technology with leading industry experts.

Also planned are tours to the nearby Additive Manufacturing facilities of IFAM, BEGO and Materialise.

www.epma.com/seminar

VDMA reports meeting of its AM Association

The Additive Manufacturing Association within Germany's VDMA (Verband Deutscher Maschinen und Anlagenbau/ German Engineering Federation) recently held an information session at its headquarters in Frankfurt, Germany, where around 100 participants took the opportunity to hear first-hand experiences of Additive Manufacturing in the aviation and electronics sectors. Participants also heard explanations on additive practice by service providers.

The members of the association stated it was their priority not just to share information and education on AM technology but also to further technical development and standardisation. "We need to pool our strengths in order to quickly bring Additive Manufacturing to the industrial level," stated Rainer Gebhardt, Project Manager of the Additive Manufacturing Association within VDMA. Many sectors could benefit from AM's technological and economical potentials. "If we don't broaden these advantages, others will do it," cautioned Gebhardt.

www.vdma.org

Kinetic Metallisation process speeds repair of aircraft parts

Inovati, located in Santa Barbara, California, USA, will use its specialised Additive Manufacturing process, named Kinetic Metallisation, for the spot-repair of military aircraft parts. Inovati's Kinetic Metallisation system is a specialised cold spray process which accelerates particles to Mach 1 in order to coat worn out part surfaces.

The technology will allow for aircraft part replacement that would normally have taken fifteen months to become a repair that now takes just two weeks. This development, the company states, will have positive implications for the readiness of Naval aircraft fleets. Inovati has already successfully repaired a part that has logged over 3,000 hours of flight on an F/A-18.

The system utilises micron-scale powders made up of metals and ceramics in order to build up a surface, layer by layer. Any excess material is then machined off, leaving a transformed, brand new surface. Inovati has been involved in the cold spray industry for two decades and has continually streamlined the size and interface of its product. To date, Kinetic Metallisation has been applied to rocket nozzles, aircraft parts and more.

www.inovati.com

Fraunhofer and RWTH Aachen launch R&D centre for turbo manufacturing

The Fraunhofer Institutes for Production Technology IPT and Laser Technology ILT, and RWTH Aachen University's Laboratory for Machine Tools and Production Engineering (WZL) and Chair for Laser Technology (LLT) have launched the International Centre for Turbomachinery Manufacturing ICTM Aachen together with 19 industrial partners. The centre's activities will focus on research related to the repair and manufacturing of turbomachinery.

"The ICTM was founded to speed up innovation," stated Prof Fritz Klocke, Director of Fraunhofer IPT and Head of RWTH Aachen's Chair of Manufacturing Technology at the kick-off meeting. "To this end, it connects experts, joins forces and provides excellent R&D."

The industrial partners in the new network include turbine manufacturers as well as corporations and medium-sized companies covering all areas of the value chain. A variety of reasons to join the ICTM network were reported, including by a well-known turbine manufacturer who wants to introduce Additive Manufacturing methods, a machine tool manufacturer who was attracted by the unique form of cooperation, a service provider in the aviation sector looking for cooperation partners and a family-owned company interested in improving the surface quality of aerospace components made from titanium.

At the inaugural meeting, the ICTM industry partners agreed on a ten-member steering committee with representatives from the industrial companies and research institutes. The partners also selected seven collaborative research projects with a budget of around €400,000.

www.ictm-aachen.com

Wolfson Centre short courses aimed at powder handling industries

The Wolfson Centre for Bulk Solids Handling Technology, part of the School of Engineering at the University of Greenwich, UK, is running a programme of short courses throughout 2016 designed to attract those working in the area of bulk solids handling or the flow of powders.

Courses are aimed at engineers, managers, skilled operatives, maintenance crew or anyone involved in using powders. Topics include:

- Electrostatics in Powder Handling
- Powder and Dust Containment
- Industrial Control Systems
- Dust Explosions
- Caking and Lump Formation
- De-blending and Separation
- Processing of Dry Solid Materials
- Properties and Bulk Behaviour

www.bulksolids.com

Formnext 2015: Product launches take centre stage at Europe's new exhibition on Additive Manufacturing

The much anticipated inaugural "formnext powered by TCT" exhibition took place in Frankfurt from November 17-20, 2015. Squarely aimed at an industrial audience, the event succeeded in attracting almost all the major metal Additive Manufacturing technology suppliers. Whilst aglined as the international exhibition on additive technologies and tool making, there was a real sense that it was the Additive Manufacturing community that most fully embraced this new exhibition concept. As Metal AM magazine's Nick Williams reports, AM technology suppliers took the opportunity to make a number of new product launches and announcements.

Given the early support that the organisers of formnext, Messago Messe Frankfurt, received from so many leading Additive Manufacturing technology suppliers, it was almost inevitable that this new exhibition was going to be a major success. Once on-site one only had to walk into the entrance area of the impressive Hall 3 at Messe Frankfurt to appreciate the scale of the effort that the industry's leaders had made to ensure that this event was a truly impressive international showcase of what Additive Manufacturing can offer industry.

The exhibition, which featured 232 stands over an area of 14,028 m^2 of exhibition space, attracted close to 9,000 visitors from all around the world. What was immediately noticeable from the range of exhibitors is that this event was squarely aimed at those with an interest in Additive Manufacturing for industrial applications, in contrast to consumer driven systems and applications. This was further reinforced by the sense that metal Additive Manufacturing was a real driving force at the event, reflecting the fact that as the industry evolves, the series production of advanced metal components is presenting the greatest opportunity for growth.

Whilst almost all AM equipment makers were present, the exhibition

Fig. 1 Opening formnext 2015, from left to right: Johann Thoma (President, Mesago Messe Frankfurt GmbH), Uwe Behm, (Member of the Executive Board Messe Frankfurt GmbH), Tarek Al-Wazir (MdL Minister of Economics, Energy, Transport and Regional), Oliver Edelmann (Concept Laser GmbH), Wolfgang Marzin (President and CEO, Messe Frankfurt GmbH)

Fig. 2 Tarek Al-Wazir, MdL Minister of Economics, Energy, Transport and Regional at formnext 2015

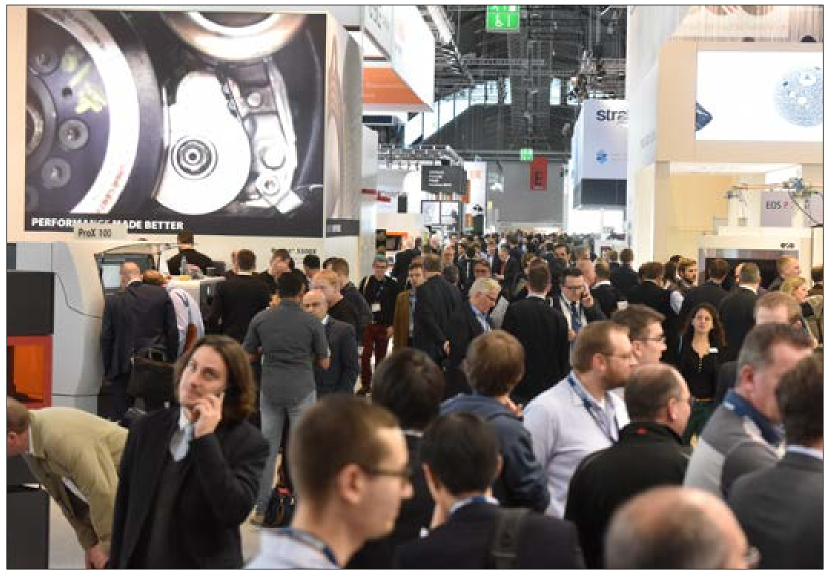


Fig. 3 The inaugural formnext exhibition attracted nearly 9000 visitors

reflected the complete global supply chain for industrial Additive Manufacturing, from metal powders and raw materials to software, production equipment and finishing systems, as well as a diverse range of AM product manufacturers. The team from *Metal Additive Manufacturing* magazine, as an exhibitor at the event, was struck by the quality of the visitors who came to our stand, including senior figures from the aerospace and other end-user industries.

"With an excellent ratio of visitors per exhibitor, the debut of formnext has really hit the ground running," stated Sascha Wenzler, Vice President at Mesago Messe Frankfurt. "Despite the tight preparation schedule, we managed to establish an excellent market position for formnext thanks to strong support from our exhibitors. At 42%, the share of international visitors at the event also sends a very positive signal."

Rainer Lotz, Managing Director of Renishaw GmbH, summarised the mood at the end of the event, stating, "The additive industry is showing off its best side here; there's nothing else like it in the world," adding that he was pleasantly surprised by the quantity and exceptional knowledge of those in attendance. "For our service department involved in contract manufacturing with additive metal components, the contacts we've gained have made formnext our best event of the year."

In parallel with the main exhibition, the formnext powered by TCT conference addressed latest developments and potential applications for Additive Manufacturing, highlighting the growing importance of the industry in product development and manufacturing. It was reported that 266 participants attended the conference, which included presentations by Audi, MTU Aero Engines, EDAG Engineering and BMW.

Over the following pages we highlight some of the major product launches and highlights from formnext.

Concept Laser outlines its AM factory of the future

Concept Laser, based in Lichtenfels, Germany, unveiled a new modular machine and plant architecture at a packed press conference in the formnext exhibition hall. Under the heading of the "AM Factory of Tomorrow", the company stated that its new, integrated machine concept promises to take Additive Manufacturing to a new level in terms of quality, flexibility and performance (Fig. 5). The company indicated that the market launch of its new system can be expected as early as the end of 2016.

Concept Laser believes that the previous solutions for metal AM machine and plant technology on the market all relied on ideas such as more laser sources, more laser power, faster build rates or an expansion of the build envelope size. Such technology, however, is based on a standalone solution without any consistent integration into the manufacturing environment, with build job preparation and build job processing proceeding sequentially. Concept Laser's new machine architecture aims to break with this convention.

Dr. Florian Bechmann, Head of R&D at Concept Laser, stated that in essence the new concept is about splitting up build job preparation, job manufacture and follow-up processing using any number of easily interchangeable modules. The intention is that this should drastically reduce the production downtimes associated with stand-alone machines. "There is plenty of potential here for improving the level of added value in the production chain. In contrast to purely quantitative approaches of previous machine concepts, we see here a fundamentally new approach for advancing industrial series production one step further."

In Concept Lasers' vision of the AM factory of tomorrow, production is decoupled, in machine terms, from the preparation and finishing processes (Fig. 6). The time window for AM production is thereby increased to a twenty four hours a day, seven days a week level, meaning that there is higher availability of all components. An automated flow of materials significantly reduces the workload for operators, and interfaces integrate the laser melting machine into traditional CNC machine technology, important for hybrid parts as well as for downstream processes such as post-processing and finishing.

The modular structure of handling stations, build and process units promises considerably greater flexibility and availability in terms of combinations and interlinking. Concept Laser suggested that this system will be able to handle a diversity of materials more effectively, and ultimately more economically, through a targeted combination of these modules.

Bechmann stated, "Build rates have increased enormously thanks to multilaser technology. The build envelope sizes have also experienced considerable growth. We now want to use an integrated machine concept to highlight the possible ways that the approaches of Industry 4.0 can change Additive Manufacturing as

Fig. 4 Concept Laser's stand at formnext

Fig. 5 The new machine architecture from Concept Laser decouples the handling unit and process unit (Courtesy Concept Laser)

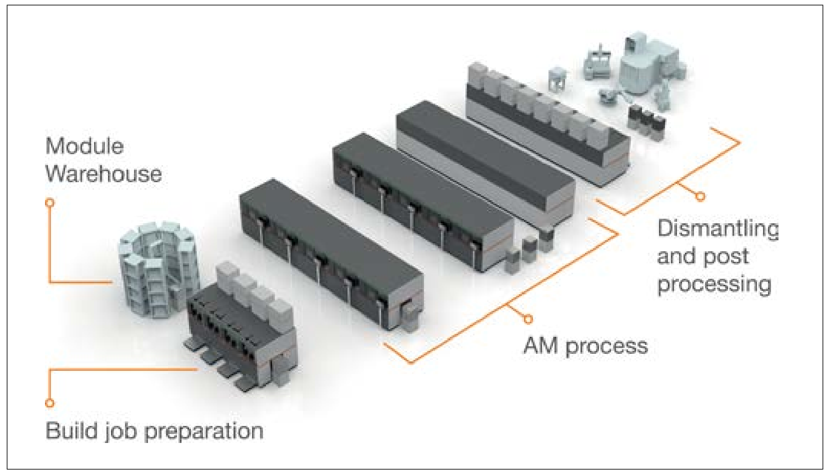


Fig. 6 Linking together the AM factory of tomorrow: Concept Laser believes that the AM Factory of Tomorrow is set to be a flexibly expandable, high-grade automated and centrally controllable metal production system which is focused fully on the production assignments in hand (Courtesy Concept Laser)

Fig. 7 The Trumpf stand at formnext 2015

Fig. 8 The new TruPrint 1000 LMF machine can produce parts measuring up to 100 mm tall and 100 mm in diameter (Courtesy Trumpf)

Fig. 9 Trumpf stated that the system technology used for LMD is already mature and available in its TruLaser Cell 3000 (Courtesy Trumpf)

the manufacturing strategy of the future. There is plenty of potential here to increase industrial added value and enhance suitability for series production."

The new process station has a build envelope of 400 x 400 x >400 mm and laser sources, process gas management and filter technology are integrated into the module. Layer thicknesses are within the usual range. In addition, the machine solution has a variable focus diameter and will be available optionally with one, two or four laser optics with laser power ranging from 400-1000 W. An available redundancy of the lasers will ensure that in multiple laser systems, if one laser fails, the remaining three lasers will still cover the entire build plate – the build job can still be completed. Bechmann commented, "More and more laser sources only increase the expected speeds to a limited extent. But ultimately they also increase the level of complexity and dependencies, which can result in vulnerability, and thus turn the desired positive effect into a negative."

Concept Laser's new machine concept has a new type of two-axis coating system which enables the return of the coater to be performed in parallel with exposure. This results in a considerable time saving during the coating process. The coater blades, made of rubber, steel and carbon, can be changed automatically during the build job as necessary. This results in several advantages according to Bechmann, "An automated tool changing system, as is the case with CNC machine technology, promises a high level of flexibility and time advantages when setting up the machine, as well as reducing the level of manual intervention by the operator. We deliberately talk here about 'robust production'."

The new modular handling station has an integrated sieving station and powder management. There is now no longer any 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.

Concept Laser states, however, that what also makes a modular handling station attractive are the possible configurations. A handling station can be linked to two process stations, for example, to create a manufacturing cell. The factory building kit also enables several handling stations to be joined together to create a material preparation facility and be physically separated from the process stations.

"In the future," stated Bechmann, "we think that AM factories will be largely automated. The transport of material or entire modules can be envisaged as being done by driverless transport systems. This could then be the next step in the development. Additive Manufacturing can be automated to the maximum extent."

Trumpf launches new machines for metal AM

Laser manufacturer Trumpf Gmbh + Co KG, based in Ditzingen, Germany, introduced new machines and equipment for the Additive Manufacturing of metal parts at formnext. With its new TruPrint 1000 LMF (Laser Metal Fusion) machine, Trumpf believes that it has created a system that appeals to both novices and those experienced in using metal AM technology (Fig. 8). The system can generate parts that are up to 100 mm in diameter and 100 mm high. The user interface, optimised for simplified touch screen control, guides the operator intuitively through the individual phases of the production process. All the components, from the laser, optics, process enclosure, filter unit and control cabinet, are integrated into the compact housing of the TruPrint 1000. In the process enclosure, the supply cylinder, construction chamber and

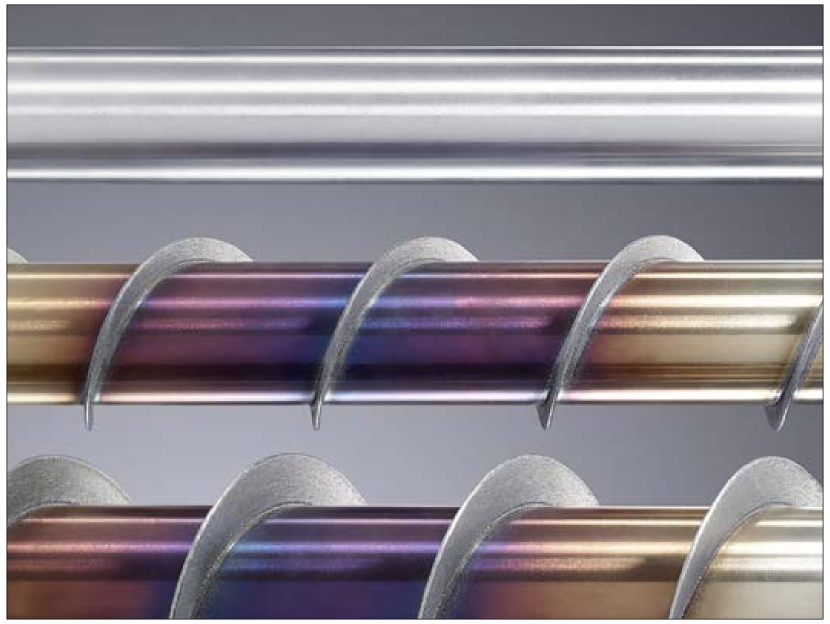


Fig. 10 In LMD the laser creates a melt pool on the surface of a part and, at the same time, melts the powder added simultaneously to create the desired shape (Courtesy Trumpf)

overflow receiver are all aligned next to each other. The supply cylinder provides capacity for up to 1.4 litres of stainless steel, tool steel, aluminium or other suitable material in powder form.

In addition to the compact 1000 model, Trumpf also unveiled a prototype of its TruPrint 3000. With this larger model, also utilising LMF technology, parts measuring up to 400 mm in height and 300 mm in diameter can be manufactured. To ensure that the process is robust and the quality of the parts remains high, the process enclosure in the 3000 model can be heated to as high as 500°C.

Trumpf has also continued the development of its Laser Metal Deposition (LMD) technology and the company presented new solutions at formnext. These systems, stated Trumpf, are suitable especially for adding volume and structures to existing parts, such as adding a bolting flange to a pipe. In LMD systems, the laser forms a melt pool on the surface of a component and fuses the powder – applied simultaneously and coaxially – so as to create the desired shape. Consequently, a layer of beads welded one to another is created. Many layers together result in a body which can expand in any direction.

An advantage of LMD technology is that the engineering required for the system is mature. Thus, depending on the specifics of the application, either the large TruLaser Cell 7040 with its five-fold design or the more compact TruLaser Cell 3000 can be equipped with the new LMD package (Fig. 9). A further advantage is the increased build speed. By adding material at rates as much as 500 cm^3 per hour, LMD can be more economical than conventional manufacturing. In addition, there is virtually no limit on the combination of materials. Almost any desired sandwich structure can be produced and the process takes place on the surface of the part in the ambient atmosphere. This reduces non-productive times and thus lowers the costs per part.

Trumpf claims that it is the world's only manufacturer to have all the laser technologies for industrial Additive Manufacturing in its programme. With this new portfolio of technologies and products, Trumpf believes that it is now offering its customers the complete package from a single source – the laser beam source, machine, powder, services and application consulting.

Fig. 11 The new entry level Additive Manufacturing system from EOS, the M 100, for direct metal laser sintering (Courtesy EOS)

Fig. 12 The M 100 can manufacture around 70 cobalt chrome dental crowns and bridges in three hours (Courtesy EOS)

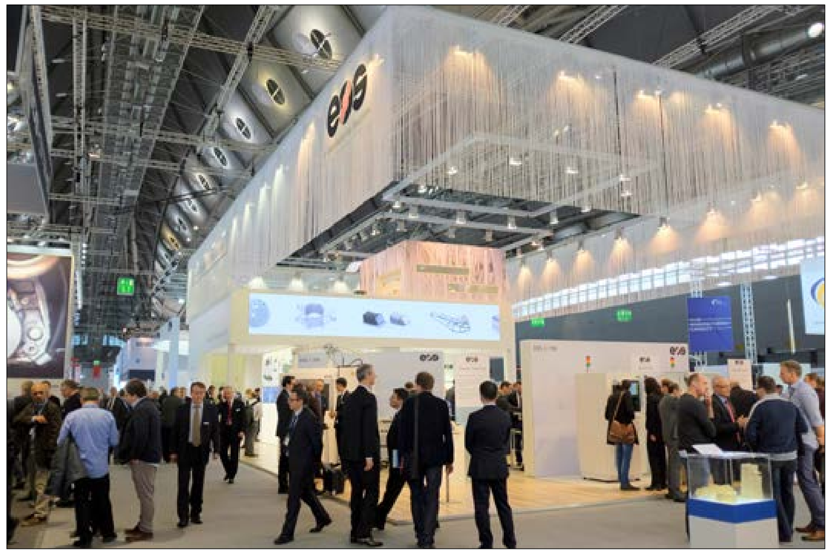


Fig. 13 The EOS exhibition stand at formnext 2015

EOS introduces the M 100, EOSTATE MeltPool Monitoring and a new stainless steel powder

Leading Additive Manufacturing systems provider EOS introduced its new EOS M 100, a compact system for Direct Metal Laser Sintering (DMLS), at formnext (Fig. 11). The company, based in Munich, Germany, also announced the EOSTATE MeltPool Monitoring system, an add-on for its larger M 290 machines, as well as a new stainless steel powder.

The EOS M 100 is based on the company's EOS M 290 in terms of process and component quality and is seen as a cost-effective entry into metal Additive Manufacturing. It features a 200 W fibre laser which, due to its beam quality and performance stability, ensures optimum and consistent processing conditions, stated the company. This feature, along with a smaller laser spot with what is claimed to be excellent detail resolution, makes it possible to produce high-quality, highly-complex and delicate components.

"The EOS M 100 system impresses with the proven DMLS quality and is also the ideal choice for those considering an entry into Additive Manufacturing. With its small build volume, which is based on a round build platform with a diameter of 100 mm, the system focuses on the cost-efficient production of small quantities. For example, the system can produce approximately seventy dental crowns and bridges in three hours," stated Dr Adrian Keppler, Chief Marketing Officer at EOS (Fig. 12).

The new system can currently process two types of materials, EOS CobaltChrome SP2 and EOS StainlessSteel 316L. EOS Titanium Ti64 is still in the development stage and will be the next material to be made available for this system.

The company's EOSTATE MeltPool Monitoring is an add-on to the EOS M 290 DMLS system and paves the way for complete part traceability as well as an automated surveillance and analysis of the melt pool during the build process. "We developed this powerful, intelligent monitoring solution jointly with Plasmo Industrietechnik GmbH, a global high-tech supplier of automated quality assurance systems. Our goal is to set a benchmark for high-end in-process monitoring for AM," stated Dr Tobias Abeln, Chief Technology Officer at EOS.

The EOSTATE MeltPool observes the light emitted by the melt pool. Its key elements are two photodiodes located on and off axis, a camera adapter, a specialised signal amplifier and according spectral filters to separate process light from reflected laser light. The software offers automatic data error correction and real-time process visualisation and evaluation.

At formnext EOS also announced it is introducing a new metal powder to the market. EOS StainlessSteel CX is targeted at mould and tool manufacture and offers an extremely corrosion-resistant stainless steel with maximum stability and excellent hardness. Following the DMLS build process, the components made with this material can be easily machined and polished, states the company. The stainless steel is resistant to most corrosive plastics and dilute acids, making it the first choice for many demanding industrial applications. Due to its corrosion resistance, EOS StainlessSteel CX also reduces tool wear and maintenance costs.

Keppler stated at formnext, "Our company has been pursuing an unparalleled course of growth and success for many years. By October, there were approximately 2,000 EOS systems installed around the world. We were able to double our installed base over the last three years; during the last two years, the number of metal laser sintering systems was doubled from 400 to 800 systems. During the past business year alone, the company sold 400 systems, including 220 metal systems. This underlines EOS' leadership role, particularly in the metal segment, and the growing interest in this technology, particularly in the series production segment."

During the last business year, EOS was able to increase its sales revenues by 53% over the previous year, to €263 million. All regions exceeded their targets, with North America in particular delivering a record result with more than US $100 million in sales revenues. Today, EOS has 750 employees worldwide, which represents a 38% increase in its global workforce compared to the previous year. At its Krailing headquarters EOS recently started the construction of another building, since the technology and customer centre, which opened just last year, is already reaching its capacity limits.

Fig. 14 The Renishaw exhibition stand at formnext 2015

Fig. 15 The new RenAM 500M industrial metal Additive Manufacturing system from Renishaw (Courtesy Renishaw)

Renishaw presents new systems and software

UK based Renishaw plc presented a range of new Additive Manufacturing products at formnext. These included two new metal Additive Manufacturing systems and a new build preparation software package.

The new RenAM 500M industrial metal Additive Manufacturing system was initially introduced as the EVO Project and allows the building of complex metal components directly from CAD using metal powder fusion technology (Fig. 15). Highlights of the system include a Renishaw designed and engineered optical system with dynamic focussing; automated powder sieving and recirculation, a 500 W ytterbium fibre laser and a patented high capacity dual filter SafeChange™ system.

Formnext also saw the launch of the AM400 flexible metal Additive Manufacturing system. This new model is a development of the AM250 platform. It includes all the advantages of the latest machine

Fig. 16 SLM Solutions chose an aerospace theme for its formnext booth, complete with hangar, airlines seats and cabin

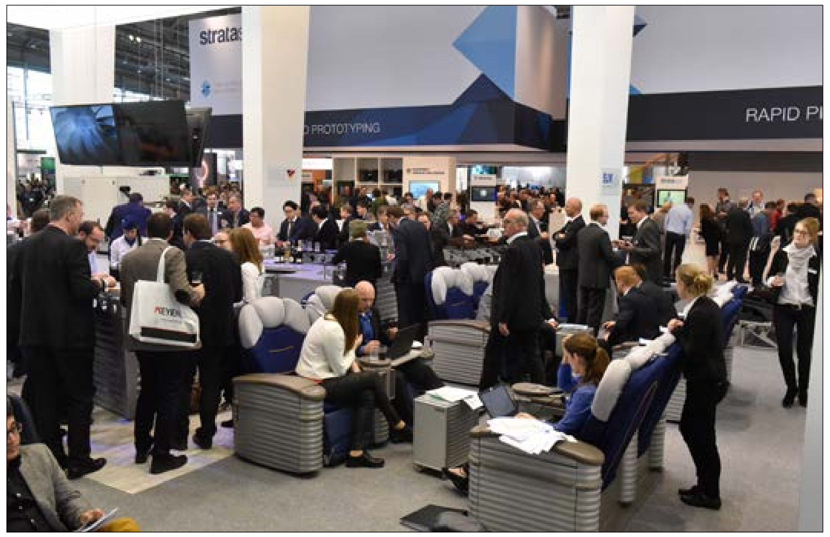


Fig. 17 Airliner-style meeting areas on the SLM Solutions stand

Fig. 18 Matsuura launched its Lumex Avance-25 hybrid metal laser sintering and milling machine to the European market at formnext

updates with larger SafeChange™ filter, improved control software, revised gas flow and window protection system and a new 400 W optical system that gives a reduced laser beam diameter of 70 micrometres.

Renishaw, which has a team of over 300 experienced software developers all working in-house, offers its QuantAM software for build file preparation. The system is designed by Renishaw specifically for the company's Additive Manufacturing systems.

Early next year, the company is opening its doors to share its expertise via Additive Manufacturing Solutions Centres. Here, manufacturers will benefit from dedicated incubator cells equipped with Renishaw AM systems. Customers can run an evaluation project to assess how AM might benefit their company with the support of Renishaw engineers. A key emphasis will be on knowledge and skills transfer, with the goal being to provide an insight into the technical and commercial benefits of AM and ultimately to provide the evidence to support investment in metal Additive Manufacturing technology.

SLM Solutions focuses on aerospace AM

SLM Solutions, Luebeck, Germany, a leading provider of metal based Additive Manufacturing technology, chose an aerospace theme for its impressive 270 m² stand at formnext. The company presented its complete product portfolio including the flagship SLM 500 HL.

SLM Solutions stated that the efficiency and performance of its systems had once again been increased over the last 12 months, with the quad laser and the patented dual-beam technology of the high-performance system SLM 500 HL increasing the volume construction rate per unit time by up to 80%. The company also presented new options with a more powerful 700 W laser for its SLM 280 HL and SLM 500 HL.

"The optimised and improved plant technology underlines our expertise and pioneering work in the Selective Laser Melting technology," stated Andreas Frahm, Director of Sales and Marketing, SLM Solutions GmbH, "In addition, further improvements are being introduced to improve the quality of our systems".

SLM Solutions' stand also served as a platform for the exchange of information on Additive Manufacturing. The Additive Manufacturing Users Group (AMUG), an independent, cross-sectoral, global association of Additive Manufacturing users, was a partner at the booth and promoted its annual conference, to be held in St. Louis, Missouri, USA, from April 3-7, 2016. This year the Federation of German Aerospace Industries Association (BDLI) was for the first time also present on SLM Solutions' stand, providing, stated the company, a space for the experts representing the interests of German aerospace industry to have conversations on the theme of Additive Manufacturing in the aerospace industry.

Matsuura offers hybrid metal laser sintering and milling machine to European market

Japan's Matsuura Machinery Corporation presented its Lumex Avance-25 hybrid metal laser sintering and milling machine at formnext (Fig. 18). The system will be available in selected European countries from January 2016. The machines, which have been sold in the Asian and Japanese market since 2003, are primarily designed for the die and mould industry.

The hybrid Lumex Avance-25 machine combines additive powder bed fusion technology and subtractive high-speed milling technology in a single seamless process. The machine is said to enable the production of complex, precise moulds and parts through a combination of powder layer manufacturing and precisely milled surfaces.

Fig. 19 Additive Industries gave visitors the chance to explore the MetalFAB1 system through virtual reality

Fig. 20 A model of the new Additive Industries MetalFAB1 system

Additive Industries promotes its MetalFAB1 system

Additive Industries' first industrial metal Additive Manufacturing system, MetalFAB1, was introduced in virtual reality form at the formnext exhibition (Fig. 19). Additive Industries claims that its new system offers substantially improved performance over typical midrange metal AM systems. The industrial grade AM machine and integrated Additive World software platform is stated to offer up to a tenfold increase in reproducibility, productivity and flexibility.

The company indicated that its improved performance is achieved by robust and thermally optimised equipment design, smart feedback control and calibration strategies, the elimination of waiting time and automation of build plate and product handling. The modular design of the MetalFAB1 system also allows for customer and application specific process configuration.

Multiple build chambers with individual integrated powder handling make this industrial 3D printer the first to combine up to four materials simultaneously in one single machine. The MetalFAB1 can be equipped with

Fig. 21 A functioning scale model of a 1936 Auto Union Type C Grand Prix sports demonstrated Audi Toolmaking's metal Additive Manufacturing capabilities

Fig. 22 A view of the Audi toolmaking stand at formnext

a maximum of four full field lasers, thereby eliminating the need for stitching when printing large objects. MetalFAB1 is also believed to be the only system to include a furnace for integrated stress relief heat treatment. The size of a single build envelope (420 x 420 x 400 mm) places the MetalFAB1 among the top three largest powder bed metal AM systems available.

It was reported that Additive Industries would be starting its Beta test programme in December 2015. It stated that four Beta machines have already been reserved by customers from demanding markets such as aerospace, high tech equipment and tooling. "We are eager to work closely together with our Beta customers. We will team up to further develop the process, new materials and applications as well as testing the performance to substantially improve the business cases of our customers," stated Daan Kersten, Co-founder and CEO of Additive Industries.

It was announced on December 1st that EOS and Additive Industries have signed a patent licence agreement in the field of industrial Additive Manufacturing of metals. The agreement initially licenses certain EOS patents to Additive Industries and may be expanded in the coming years. The parties have chosen not to disclose the details of the agreement.

"For Additive Industries, as newcomer to the industrial additive manufacturing market, this partnership is an important step on our journey to take 3D metal printing from lab to fab. Together we can expand this new production technology from the prototyping domain to the factories of the future," stated Daan Kersten, Co-founder and CEO of Additive Industries. Mike Shellabear, Director IP and Technical Support at EOS commented, "We welcome the patent licence agreement with Additive Industries as it confirms the attractiveness of the AM process for industrial use. In addition to this, the agreement is in line with EOS' strategy to license our IP to other companies in this industry."

Audi showcases the future of toolmaking and Additive Manufacturing

One of the most impressive stands at formnext was that of Audi's toolmaking division, in which the state of the art in both toolmaking and Additive Manufacturing was presented.

On a 500 m^2 stand, Audi demonstrated which aspects of toolmaking in the smart factory are already being applied today for the development and production of models in both large and small series. These include intelligent tools for shaping steel and aluminium plates that recognise process related fluctuations and optimise the material flow in the tool accordingly. Visitors could also see which additive production technologies are already applied in toolmaking today.

A highlight of Audi's stand was a functioning scale model of a 1936 Auto Union Type C Grand Prix sports car to demonstrate its metal Additive Manufacturing capabilities (Fig. 21). The company is said to be currently examining further possible applications of metal AM systems for the production of complex components.

Prof. Dr. Hubert Waltl, Audi's Board of Management Member for Production and Head of Toolmaking at the Volkswagen Group, commented at the time the scale model was announced, "We are pushing forward with new manufacturing technologies at Audi Toolmaking and at the Volkswagen Group. Together with partners in the area of research, we are constantly exploring the boundaries of new processes. One of our goals is to apply metal printers in series production."

Michael Breme, Head of Toolmaking at Audi AG, stated, "The paradigms of the smart factory are changing our work in the Toolmaking division. In the future, we will connect equipment, machinery and people even more closely with each other and will make use of new methods to develop even more flexible and precise tools."

Audi Toolmaking employs more than 2,000 people at five locations; Ingolstadt and Neckarsulm in Germany, Barcelona (Spain), Gyor (Hungary) and Beijing (China). The division designs, develops, constructs and tests tools for high and low volume production. They include sheet metal tools, equipment and apparatus, as well as mould making for aluminium die-casting and composite fibre components used in exterior and structural applications.

Sigma Labs promotes its PrintRite3D® system evaluation

Sigma Labs, Inc., based in Santa Fe, New Mexico, USA, is a leading developer of advanced, in process, non-destructive quality inspection systems for metal-based Additive Manufacturing. Following its participation at formnext Sigma Labs announced that a German company has entered into an evaluation period for its proprietary PrintRite3D products. As part of the agreement this customer, which wishes to remain anonymous at the present time, purchased a non-exclusive licence to test the PrintRite3D applications in certain of its laser-based powder bed metal machines – some of which were on display at Formnext.

Fig. 23 The formnext powered by TCT conference attracted 266 participants

Fig. 24 Delegates at the formnext powered by TCT conference

"We are delighted that this high quality organisation has decided to evaluate our PrintRite3D software in its machines to assess our patented In-Process Quality Assurance™ (IPQA®)," said Mark Cola, President and CEO of Sigma Labs. "The customer will consider adding our quality assurance and process control technology to its equipment offering starting with our INSPECT™ software, broadening the market for Additive Manufacturing. With Sigma Labs' software on site, they can easily evaluate our technology with regard to leveraging its benefits across a number of automated applications."

Materialise launches Magics^{20}

Materialise used formnext to release Magics^{20}, the latest version of its industry-leading data and build preparation software. The company stated that with Magics^{20}, the efficient use of existing and emerging AM technologies, metal AM systems in particular, has never been easier. Magics^{20}, combined with Materialise's range of software solutions for AM that include an enterprise software solution (Streamics), a range of Build Processors, an Additive Manufacturing Control Platform (AMCP) and more, is recognised as critical software for the AM industry.

Commenting on Magics[20], Materialise Founder and CEO, Fried Vancraen, stated, "When I purchased my first stereolithography machine and started Materialise 25 years ago, the industry lacked the software needed to efficiently connect a design to a 3D Printer. In order to survive and thrive as a company, we needed to develop a solution that allowed us to meet customer demand for 3D printed prototypes, on time and as ordered. The resulting software worked so well that we brought it to the market as Magics. Over the years, Magics has helped lift the AM industry as a whole to new levels by optimizing data and build preparation for an expanding range of materials and technologies."

He continued, "Now, 25 years later, we face new challenges as our customers increasingly request 3D-printed, end-use parts that meet the demanding standards of their industries - and it is a challenge we have proven able to meet. And once again, Materialise is ready to raise the AM industry as a whole to new heights by granting access to a software backbone that enables certified manufacturing: Magics[20]."

Powder manufacturers make their mark

A number of specialist metal powder manufacturers and distributors also exhibited at formnext, recognising the increasingly interesting shipment volumes as the metal AM industry moves from prototyping to volume production. Whilst all the powder-based metal AM machine suppliers also sell their own branded powder to customers, with the associated guarantee of quality and machine compatibility, there is a recognition that when a producer's metal AM volume reaches a certain level of production there is a strong economic case for dealing directly with metal powder producers. Many powder producers that serve the Metal Injection Moulding (MIM), Hot Isostatic Pressing (HIP) and Spray Forming industries are well used to supplying critical sectors such as the aerospace industry. Key powder producers at formnext included AP&C, Erasteel, HC Starck, Höganäs, Materials Technology Innovations Co Ltd, Praxair and Sandvik Opsrey.

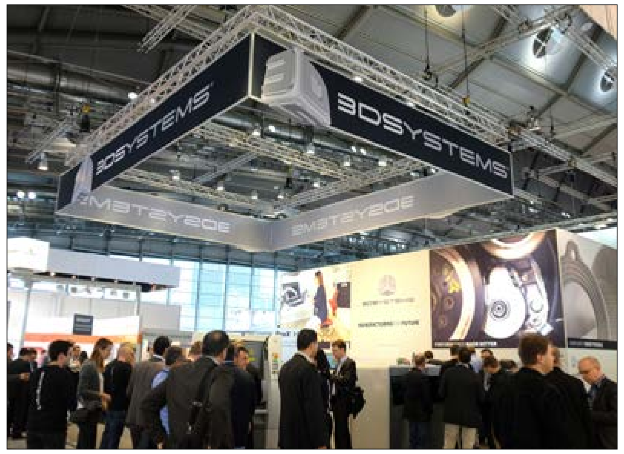
Formnext 2016

Formnext 2016 is scheduled to return to Frankfurt am Main from 15–18 November, 2016. For more information visit www.formnext.com

Author

Nick Williams
Metal Additive Manufacturing
nick@inovar-communications.com
www.metal-am.com

| contents page | news | events | advertisers' index | contact |
Formnext 2015



Hot Isostatic Pressing: Improving quality and performance in AM parts production

Hot Isostatic Pressing (HIP) has been used for a number of decades as a method to consolidate metal powders and metal matrix composites to produce fully dense components, to eliminate porosity in sintered parts, to produce metal clad parts through diffusion bonding, and to eliminate defects in castings. HIP is now also playing an important role in assuring and increasing the quality of critical components produced by powder-based Additive Manufacturing. In the following article Magnus Ahlfors and Johan Hjärne describe the HIP process and its influence on the microstructure and properties of AM Ti-6Al-4V alloys.

Hot Isostatic Pressing is a process which is used to consolidate metal powder or to eliminate defects in solids such as pores, voids and internal cracks, thus densifying the material to 100% of the theoretical density. When loose metal powders are consolidated by HIP, or when previously densified parts having surface connected porosity need to be fully densified, the HIP cycle must be done in gas tight capsules made from sheet metal or glass. Previously densified parts not having surface connected porosity, such as products with a gas tight surface, can be HIPed without the need for encapsulation. The process includes high temperature and a high isostatic gas pressure, meaning that the pressure acts on all surfaces of the component in all directions leading to densification. The mechanisms for densification during HIP are plastic deformation, creep and diffusion. Initially, plastic deformation is the dominant driving mechanism since the applied external pressure is higher than the yield strength of the material at the HIP temperature, thus making the voids in the material collapse. After the initial plastic deformation, creep and diffusion contributes to densification. These mechanisms not only collapse and close the pores, but totally eliminate them to create a material free of defects. The process has been successfully used for a number of decades to both manufacture and

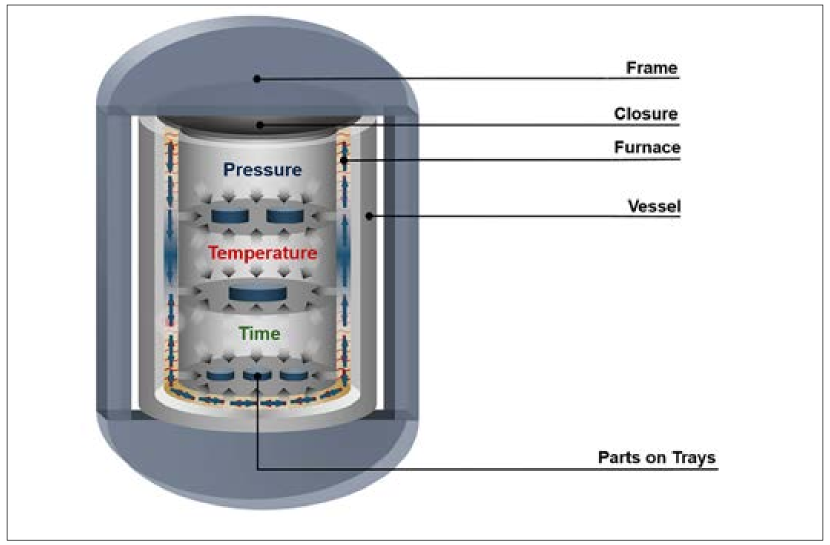


Fig. 1 A simplified schematic picture of the HIP equipment and process

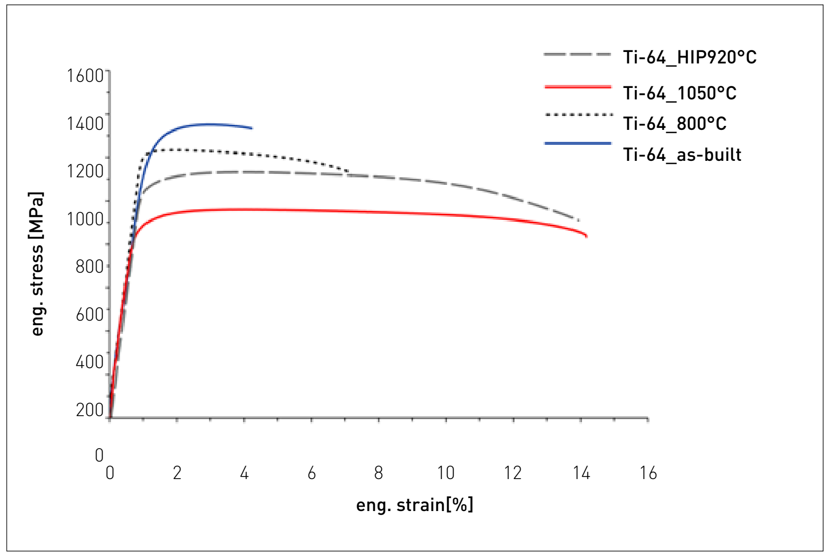


Fig. 2 Tensile curves for SLM Ti-6AL-4V (data curtesy of Leuders [1])

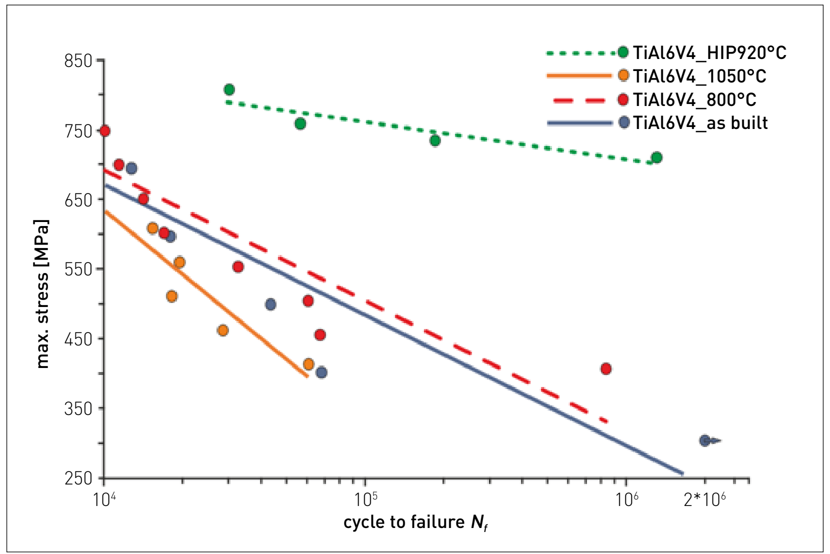


Fig. 3 Fatigue data for SLM Ti-6AL-4V (data curtesy of Leuders [1])

densify critical components for sectors such as aerospace, medical implants, power generation and oil and gas exploration. In Fig. 1 a schematic picture of a HIP process is presented.

There are three main parameters in a HIP cycle which determine the densification. These are temperature, pressure and hold time. HIP temperatures are often in the range of 70 to 90% of the solidus temperature of the material being processed and the pressure used is usually in the range of 100-200 MPa, mostly with argon as the pressure medium. The hold time is somewhat dependent on the thickness of the components being processed since there is a longer temperature delay in the core of large parts depending on the thermal conductivity of the material. For a specific material, there can be several different HIP cycles which will generate 100% density but in different ways, since all three parameters affect the densification process. For example, a cycle with relatively low temperature, low pressure, but long hold time can generate the same results as a cycle with relatively high temperature, high pressure and short hold time in terms of densification. Heating rate and cooling rate, the latter in particular, are other parameters that need to be defined for the HIP cycle. Heating and cooling rate will not affect the densification of the material, but can be very important for the final microstructure and thus the mechanical properties of the material being processed.

HIP for metal Additive Manufacturing

Even though the relative density of powder based AM material often is very high, there can be no guarantee against defects in the material such as pores and internal cracks. The defect types, size and occurrence are determined by the powder and printing parameters. These defects influence the mechanical properties of the material in a negative way, especially the fatigue behaviour. By the use of HIP for AM materials, these defects can be eliminated and the material will have a 100% relative density. The most pronounced benefit of removing printing defects by HIP is that the fatigue properties can be improved since the stress concentrations from the defects are eliminated. As reported by Stefan Leuders [1], the fatigue properties of SLM Ti-6Al-4V were shown to be improved compared to as-printed material and solution annealed material with a large increase in fatigue life and also a decrease in the fatigue slope, see Fig. 2. This is an important factor for components in highly demanding applications such as aerospace components and medical implants. One thing to note from the investigation performed by Leuders is that the yield strength actually decreases for the annealed and HIP processed SLM Ti-6Al-4V compared with the as-printed material, but instead a much improved ductility is generated, see Fig. 3. This change in properties is explained by the fine microstructure in the as-printed SLM material, which is generated by the very high cooling rates in the printing process of several thousand degrees per second and delivers a high yield strength in the as-printed condition. When post heat treatments with more

conventional cooling rates such as HIP and annealing are added, the microstructure is coarsened resulting in a lower yield strength, but ductility is improved as a result of the removal of any porosity.

As previously mentioned, a prerequisite for AM parts to be HIPed without encapsulation is for the parts to have a gas tight surface so that the pressure medium will not penetrate the material. For some powder processes, this is a challenge. Conventional press and sinter Powder Metallurgy parts, for example, have to be sintered to a very high density to enable capsule-free HIP processing. However, for AM processes, the surface will always be gas tight due to the relatively high density achieved during manufacturing, which enables capsule-free HIP processing of AM parts as-printed.

The HIP treatment of AM material will eliminate all defects, independent of the number of defects in the material prior to HIP, as long as the requirement of a gas tight surface is fulfilled. This means that it does not matter whether the material includes 0.2% or 2% porosity as-printed, since the HIP process will eliminate all the defects. This makes it possible to speed up the printing process by printing "lower quality" material with more defects since the as-HIPed material will be the same independent of the as-printed porosity levels. This enables time and cost savings in the printing process by printing the components faster.

Since the pores in as-printed powder based AM material are homogeneously distributed throughout the material, the shrinkage generated during HIP will be homogeneous in all directions over the volume, and corresponding to the amount of porosity removed. Thus, no distortion of the net shape AM parts is to be expected during HIP, however a relief of the residual stresses in the material introduced during the AM process will occur.

HIP equipment suitable for Additive Manufacturing

Quintus Technologies is the world's largest manufacturer of HIP systems and has delivered state of the art HIP systems worldwide for the last fifty years. During recent years, Quintus has developed a series of HIP systems perfectly matched to the requirements of the Additive Manufacturing industry (Fig. 4). This small HIP series has a varying furnace diameters of 0.186 to 0.375 m and furnace height of 0.5 m to 1.2 m. These presses are modularised, meaning that customers can choose what pressure level, temperature range and cooling rate they want for their specific process. All units are delivered fully tested as plug and play units.

This series of small HIP systems, with Quintus Technologies' patented Uniform Rapid Cooling (URC®) or Uniform Rapid Quenching (URQ®) furnaces, can provide extremely fast cooling rates of up to 3000°C/min,

high productivity and robustness, and even combine HIP and heat treatment in the same cycle. The required cooling rates for heat treating Ti, TiAl and CoCr alloys can almost always be achieved with the URC® furnace, which is standard for all Quintus Technologies' HIP systems. These systems can easily cool the full workload in a small HIP with cooling rates up to 200°C/min (Table 1) and, in addition, the URC® technology ensures that all areas of the workload are cooled uniformly, minimising thermal distortion and non-uniform grain growth. For additively manufactured medical implants and aerospace components, HIP is now standard practice and, for these applications, it is becoming more and more common to include the heat treatment directly in the HIP cycle. Should even higher cooling rates be needed, URQ® furnaces could also be offered to achieve cooling rates as high as 3000°C/min.

Most often it is advantageous to in-source HIPing, not only to reduce cost but also to control and optimise the HIP parameters for best results. Other benefits would be reduced stock levels and shortened delivery times. Table 1 shows what the approximate operational cost will be per cycle for the different sizes in the Quintus technologies' small HIP series.

Fig. 4 Quintus Technologies small HIP series

Product name	HZ size (DxH) [m]	Cooling rate [C/min]	Operating cost/cycle [€]*	Number of cycles / day*
QIH9	0.087 x 0.160	URQ® Up to 3000 URC® Up to 200	50	7
QIH15	0.186 x 0.500		92	5
QIH21	0.228 x 0.700		103	5
QIH32	0.300 x 0.890		115	4
QIH48	0.375 x 1.200		130	3.6

*Operating cost and number of cycles per day are based on the following cycle; P=150 MPa, T=1200°C, Hold time = 120min); and includes power, gas, personnel and spare and wears for a Quintus Technologies' small HIP.

Table 1 Product data and operational cost for the Quintus small HIP series

New HIP process developments for AM

Powder bed, layer by layer, manufacturing processes have directional solidification and cooling in the build direction due to the nature of printing. The directional solidification and cooling make the grains grow in the building direction through the layers resulting in a columnar microstructure. This columnar microstructure gives the as-printed material anisotropic mechanical properties, where the properties in the building direction (z) can be quite different from the properties in the plane perpendicular to the building direction (x, y). A typical as-printed microstructure of EBM Ti-6Al-4V is shown in Fig. 5 where the build direction is indicated with an arrow and the columnar grain structure is evident [2].

The columnar microstructure and anisotropic properties of as-printed powder bed deposition material can be a great drawback in many applications. In order to increase the potential applications that can benefit from the complex geometries made possible by powder bed deposition, it is of interest to develop a post printing treatment that can break down the coarse columnar microstructure of as-printed material into a more refined and equiaxed microstructure. A study of potential post treatments for generating equiaxed microstructures of AM material has been performed by Oak Ridge National laboratory in Oak Ridge, Tennessee, USA, and Quintus Technologies in Västerås, Sweden [3].

In this study, three different post printing treatments for EBM Ti-6Al-4V were investigated to see if the columnar grain structure of as-printed material can be broken down into a more equiaxed grain structure. The first post treatment

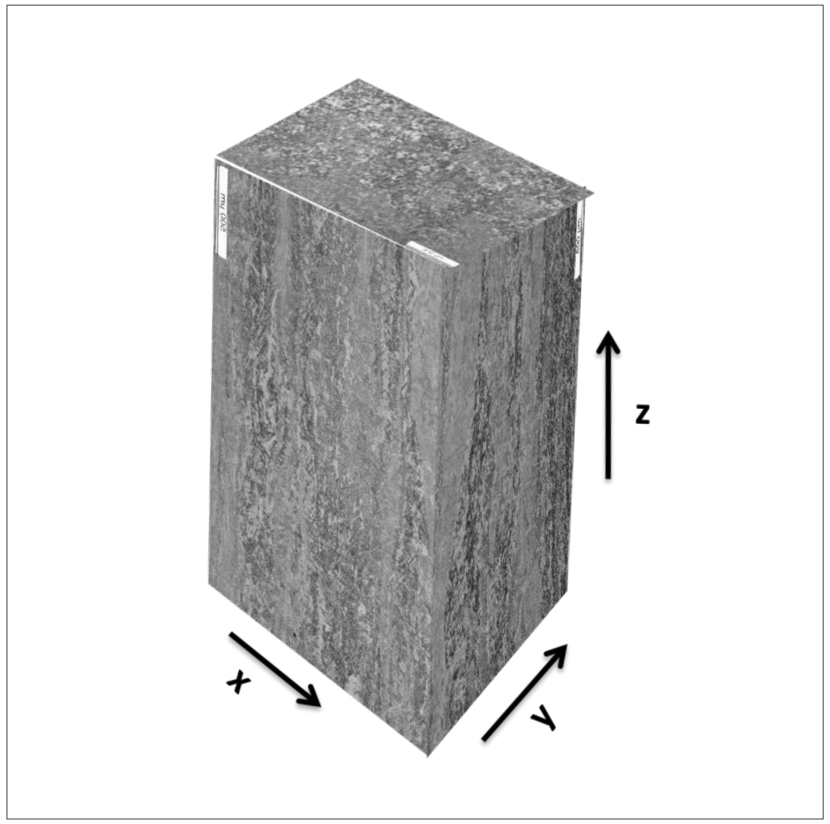


Fig. 5 Typical columnar grain structure of EBM Ti-6Al-4V [2]

investigated was the standard HIP cycle for EBM Ti-6Al-4V, recommended by Arcam AB, with a temperature of 920°C, a pressure of 100 MPa, a two hour hold time and rapid cooling. The second post treatment was a similar HIP cycle, but with a HIP temperature above the β-transus temperature and with slow natural cooling. The third post treatment was a HIP cycle with a temperature far above the β-transus, relatively short hold time and rapid quenching. In Table 2 and Fig. 6, the thermal and pressure profiles of the post treatments are presented.

PT1 and PT3 were performed in the QIH9 URQ® (Uniform Rapid Quenching) system at Quintus Technologies in Västerås, Sweden and PT2 was performed in a QIH9 URC® at Quintus Technologies in Columbus, Ohio, USA.

The material used in this study was alloy Ti-6Al-4V fabricated with an Arcam Q10 Electron

Beam Melting system at the ORNL Manufacturing Demonstration Facility. Standard EBM Ti-6Al-4V printing parameters were used, with the powder layers deposited at 50 µm. The samples used in the study were cylinders and prismatic bars.

The resulting microstructures of the study are shown in Fig. 7 where (b) shows the as-printed material, (c) shows the PT1 standard HIP treated material, (d) shows the PT2 HIP treated material above the β-transus followed by slow cooling, and (e) shows the PT3 HIP treated material above the β-transus followed by rapid cooling. Fig. 7 (a) shows the build direction and the position in the sample where the micrographs were taken from. The black dots in Fig. 7 (b) are pores from the printing process and, in (c), (d) and (e), there are no black dots since the HIP process has eliminated the porosity.

The material treated with PT1 still shows a columnar grain structure similar to the as printed microstructure, showing no improvement for the aim of the study. On the other hand, the materials treated with PT2 and PT3 show a significant difference from the as-printed material resulting in a homogeneous microstructure with fully equiaxed grains. However, the slow cooling rate involved in the PT2 treatment (approx. 85°C/min) resulted in large α colonies. Such a colony microstructure has a negative impact on fatigue behaviour. For PT3, which had the same HIP temperature and pressure as PT2 but a much faster cooling rate after the hold time, the material shows the same equiaxed grain structure but with very fine α precipitates that are distributed more as a basket-weave microstructure rather than a large colony microstructure.

The observation that the microstructure can be changed from columnar to equiaxed beta grains via Hot Isostatic Pressing above the β-transus temperature of the alloy indicates a potential internal stress in the as-fabricated samples that is large enough to possibly cause recrystallization and

Cycle	Thermal profile	Pressure	Cooling type
PT1	25°C → 920°C @120min → 25°C	100 MPa	Rapid quench
PT2	25°C → 1120°C @120min → 25°C	100 MPa	Natural cooling
PT3	25°C → 1120°C @30min → 25°C	100 MPa	Rapid quench

Table 2 Overview of the post treatment cycles

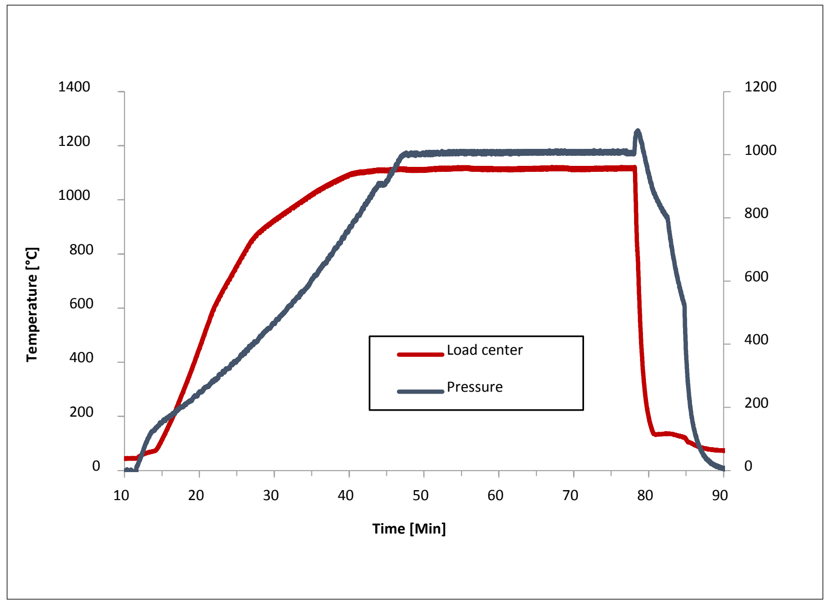


Fig. 6 PT3 HIP cycle logged data

grain growth of the beta grains. Other potential mechanisms could be that, on heating above the β-transus, the entire existing grain boundary α dissolves, allowing for free migration of the β grains and this may result in abnormal grain growth. Studies are currently underway to understand the mechanism of this transformation and fine-tune the HIP parameters to attain the equiaxed microstructure. In-depth EBSD analysis will be carried out to understand the origin of the equiaxed microstructure on HIPing of samples above the β-transus compared to a normal HIP cycle.

Conclusions and outlook

Hot Isostatic pressing is an effective process to eliminate defects in powder based additively manufactured parts, generating 100% dense material with improved fatigue properties and ductility. The fast cooling possibilities with URC® and URQ®, provided by Quintus Technologies' HIP units opens up new possibilities of thermal treatment of AM material under pressure. One example of new post treatments, made possible with URQ® HIP, is the above β-transus HIP cycle under high pressure of EBM Ti-6Al-4V followed by rapid quenching, which was shown to completely break down the columnar grain structure in the material to a homogeneous and equiaxed grain structure. The URC® and URQ® HIP units are capable of generating varying cooling rates that allow the tailoring of the microstructure according to the property requirements. Research between Quintus Technologies and Oak Ridge National Laboratory is aiming towards fine-tuning the HIP parameters for optimum properties and understanding the mechanism of the involved phase transformations.

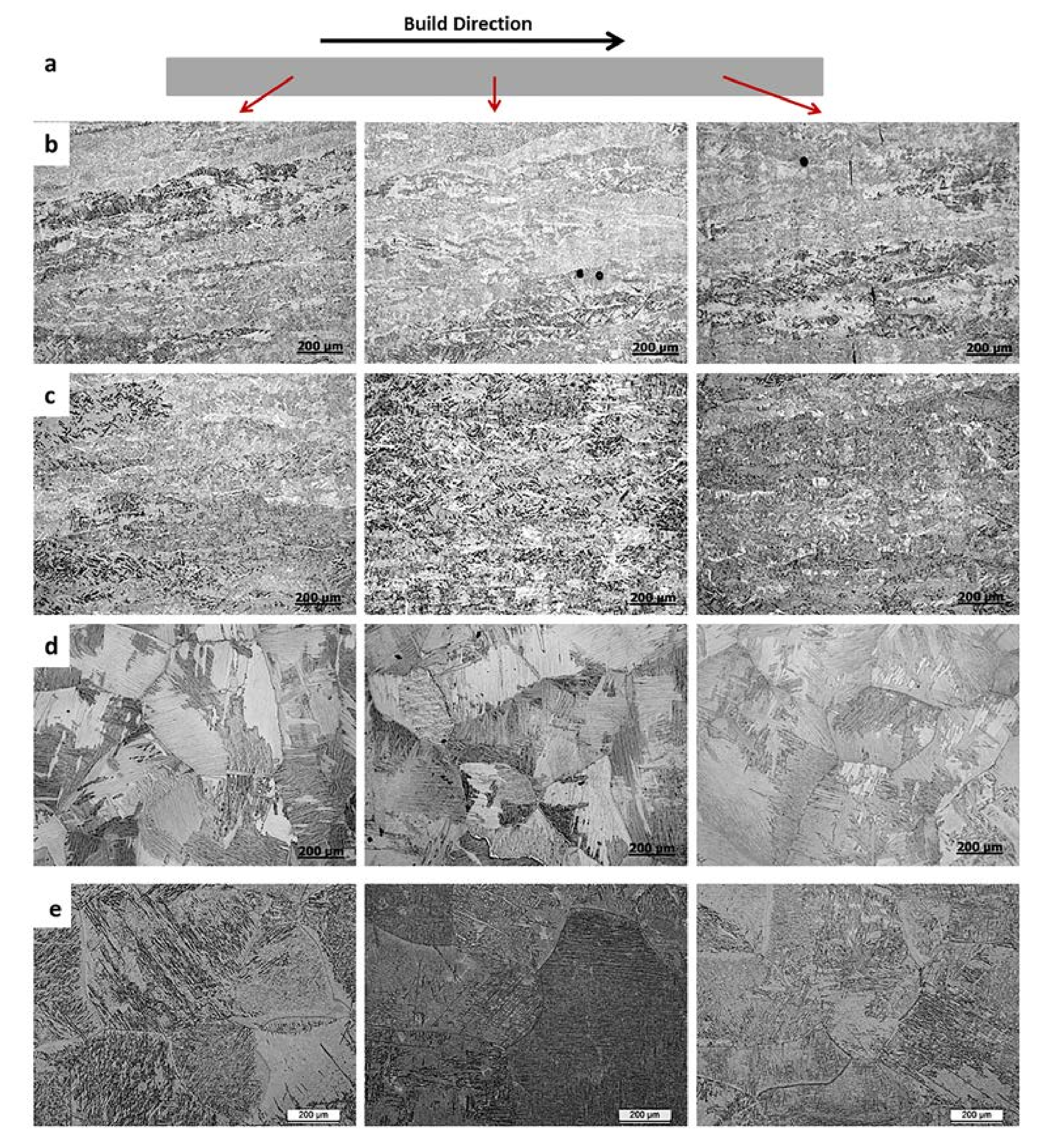


Fig. 7 (a) Build direction and micrograph position, (b) as-built samples, (c) PT1 standard HIP cycle with rapid cooling, (d) PT2 above β-transus HIP cycle with slow cooling (e) PT3 above β-transus HIP cycle with rapid quench

Contact

Quintus Technologies AB
Quintusvägen 2, B343
SE 721 66 Västerås, Sweden
Tel: +46 (0)21 32 70 00
Email: info@avure.se

Oak Ridge National Laboratory
Oak Ridge, TN 37831
Tel: +1 865-576-8401
E-mail: reports@osti.gov

References

[1] On the mechanical performance of structures manufactured by Selective Laser Melting: Damage initiation and propagation, Stefan Leuders, University of Paderborn, Germany, as presented at AMPM2014, MPIF, USA
[2] H. Galaragga, D. Lados, R.Dehoff, M. Kirka, Unpublished ongoing research.
[3] Understanding the Role of Hot Isostatic Pressing Parameters on the Microstructural Evolution of Ti-6Al-4V and Inconel 718 Fabricated by Electron Beam Melting, William H. Peter et al

Metal AM at Euro PM2015: EBM for aerospace and automotive, powder recycling, and advances in SLM

For readers who have not yet discovered the annual conference of the European Powder Metallurgy Association (EPMA), the Euro PM conference series has grown to become a rich source of technical information on the latest advances in powder-based metal AM. The Euro PM2015 Congress, held in Reims, France, 4-7 October 2015, was no exception and Dr David Whittaker reports on a number of key technical presentations made during the first two Additive Manufacturing sessions at the congress.

Mechanical properties of Ti-6Al-4V manufactured via Electron Beam Melting

The Electron Beam Melting session was opened with one of the six nominated keynote papers in the conference, presented by Thays Machry (Airbus Group, UK) and co-authored by David Eatock and Jonathan Meyer (also Airbus Group), Alphons Antonysamy (GKN Aerospace, UK) and Alistair Ho and Phil Prangnell (The Manchester University, UK). This paper considered the effect of part geometry on the microstructure and consequent mechanical properties of Ti-6Al-4V specimens manufactured by Electron Beam Melting (EBM).

The Additive Manufacturing research team at Airbus Group is evaluating the manufacture of Ti-6Al-4V parts via EBM technology with a view to production of flight hardware. Compared with other metal AM processes, EBM offers a high building speed and higher level of geometric freedom. The higher level of geometric freedom is obtained due to pre-heating (to around 730°C) the loose powder deposited after each layer, thus creating an annealing effect and eliminating the residual stresses generated during the process.

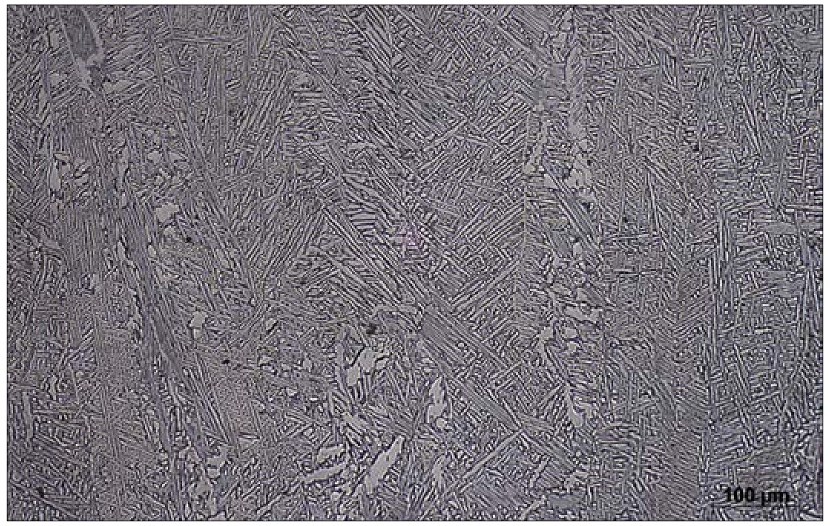


Fig. 1 Typical microstructure of EBM produced Ti-6Al-4V component with 35 mm diameter (image from centre point) [1]

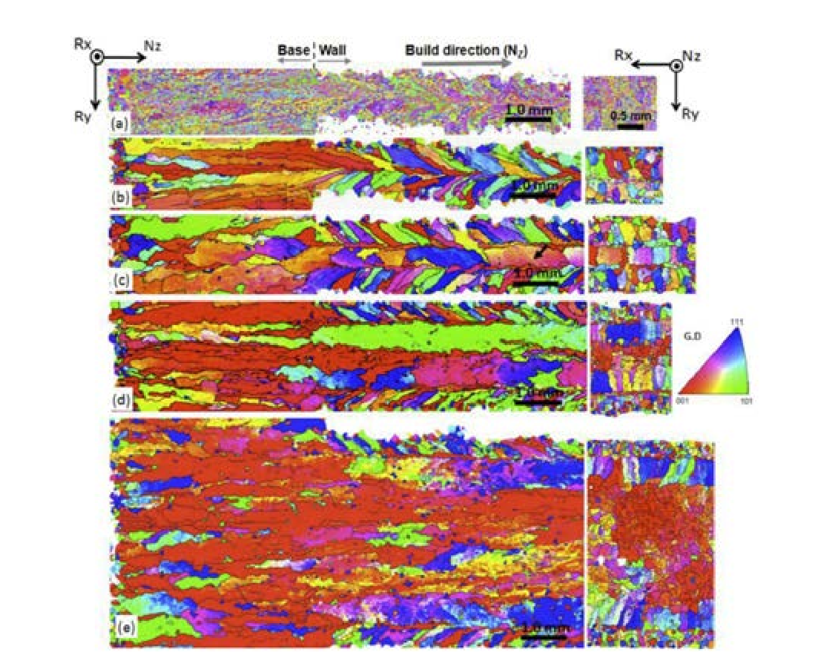


Fig. 2 EBSM maps of vertical cross sections from samples with different wall thicknesses (made with Ti-6Al-4V EBM), (a) shows an original α phase map and (b) to (e) shows reconstructed ß grain structures for 1 mm, 1.5 mm, 2 mm and 5 mm wall [1]

Specimen diameter (mm)	Height (mm)	No. of samples
6	80	3
10	80	3
14	80	3
18	80	3
22	80	3
26	80	3
30	80	3
35	80	3
40	80	3

Table 1 Experimental Ti-6A-l4V specimens manufactured for tensile and microstructural analyses [1]

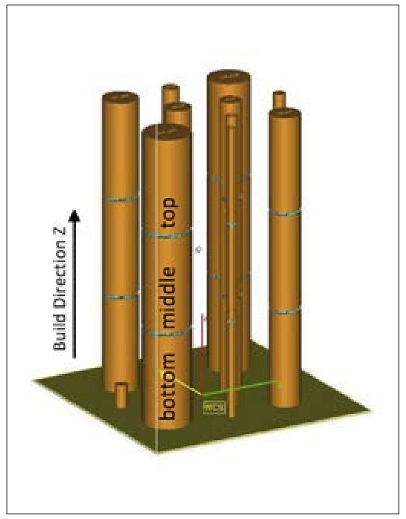


Fig. 3 Arrangement of specimens in build platform from Arcam A2 machine [1]

During the EBM process, the material microstructure can be influenced by several process parameters, such as heat in the chamber, height of the build (Z-height), build packing density and beam scanning velocity. Additionally, the heat dissipation during the build is another important factor that influences the material microstructure. In this case, the microstructures of thick and thin components would be different, as well as the microstructures from short and taller components. Therefore, this study has investigated the influence of component size on the mechanical performance and microstructure of Ti-6Al-4V cylinders, as well as the influence of build height on component tensile strength.

Pure titanium is an allotropic element, which adopts more than one crystal structure with a change in temperature. At room temperature, pure Ti transforms into a hexagonal closed packed (HCP) form, known as α-phase. At high temperatures above 882°C, Ti exists in a body centre cubic (BCC) form, known as β-phase until reaching the melting temperature of about 1670°C, which is also known as the ß transus temperature. Titanium can be alloyed with elements categorised as stabilisers, known as α or ß stabilisers. These stabilisers influence certain characteristics of the material such as altering the α → ß transition temperature of titanium (882°C). Ti-6Al-4V is a type of α + ß stabiliser containing a combination of α and ß stabilising phases at room temperature.

The bulk microstructure of Ti-6Al-4V produced in EBM is made up of columnar prior ß grains delineated by grain boundary α. In addition, within the prior ß grains, a transformed α + ß microstructure with both α-colony and Widmanstätten morphology is apparent. Fig. 1 shows an image taken with an optical microscope of one of the specimens from this study. The grain growth on solidification is controlled by what happens at the melt pool surface. Grains generally grow normal to the melt pool surface. Columnar growth in the build direction is due to the effect of adding many layers and orthogonal rastering.

Existing literature shows a variation of microstructure depending on specimen thickness. In this reported study, samples were produced with a thick base on which thinner section walls were built using the EBM process. Fig. 2 shows the cross sections parallel to the build direction of reconstructed ß grain structures through the transition from a wide base to vertical walls measuring 1 to 5 mm in thickness. Fig. 2(a) shows an original α phase map and (b) to (e) show reconstructed ß grain structures for 1 mm, 1.5 mm, 2 mm and 5 mm walls. On the right side of each is a plan view taken half-way up the vertical walls. It is clear that the geometry of the component influences the grain size formation during build lay-up.

In the study, specimens were manufactured by EBM using an Arcam A2 machine. Plasma atomised Ti-6Al-4V powder was used to manufacture all specimens. A total of 27 round specimens with nine different component thicknesses were produced. The cylinders were built with 80 mm height. Table 1 summarises the specimens and Fig. 3 shows how the specimens were arranged and built. Three specimens of each diameter were built on the top of one another. These specimens were referred to throughout the work as bottom (closer to build plate), middle and top. All specimens subsequently went through the same cycle of Hot Isostatic Pressing (HIP) at 920°C for two hours at 102 MPa pressure.

As a first step in the study, the influence of different specimen diameters was investigated. Table 2 shows the average of the results from the samples in the bottom, middle and top of the build in terms of Z-height.

A considerable variation in the proof stress and ultimate tensile strength (UTS) was present. It appeared that, as the component thickness increased, the tensile strength was greater (Fig. 4). The error bars refer to the standard deviation of the results and the trend line plotted shows a R^2 value of approximately 0.94 for 0.2%PS and 0.93 for UTS. The component with 40 mm diameter shows an increase of 5% in proof stress and UTS in comparison with the component with 6 mm. The remaining properties (elongation, reduction of area and Young Modulus) were found not to be significantly influenced by component thickness.

The influence of build height on the strength of the samples was analysed. Figs. 5 and 6 show the 0.2% PS and UTS plotted for the samples at bottom (1), middle (2) and top (3) of the build plate. It can be observed that, close to the build plate, there is a small variation of strength, independent of component

Diameter (mm)	0.2% PS (MPa)	UTS (MPa)	Elongation (%)	Reduction of Area (%)	Young Modulus (MPa)
6	830	900	15	40	1214
10	838	906	19	39	1185
14[*]	833	901	18	37	1196
18	848	919	15	33	1163
22	852	929	16	34	1190
26[**]	855	935	20	34	1194
30	860	938	19	33	1223
35	862	940	17	34	1236
40[**]	873	950	20	36	1223

[*] One specimen failed prematurely and had to be discarded for the analysis
[**] One result was identified as anomaly and was not included in the analysis

Table 2 Results from tensile test performed on Ti-6Al-4V specimens [1]

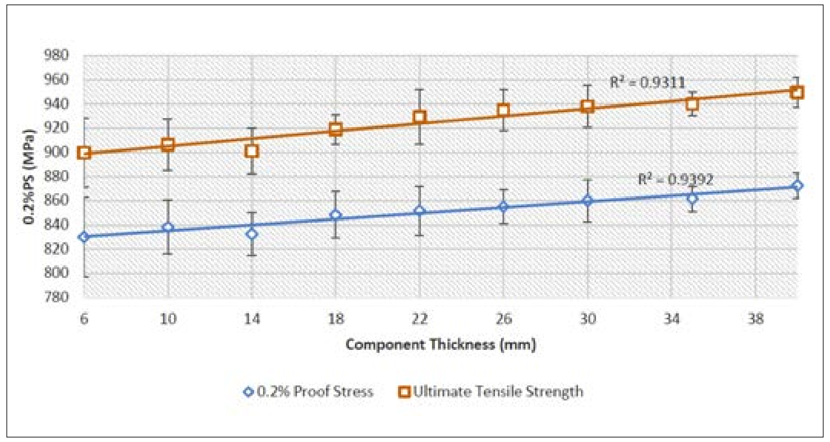


Fig. 4 Proof stress and ultimate tensile strength plotted against component thickness [1]

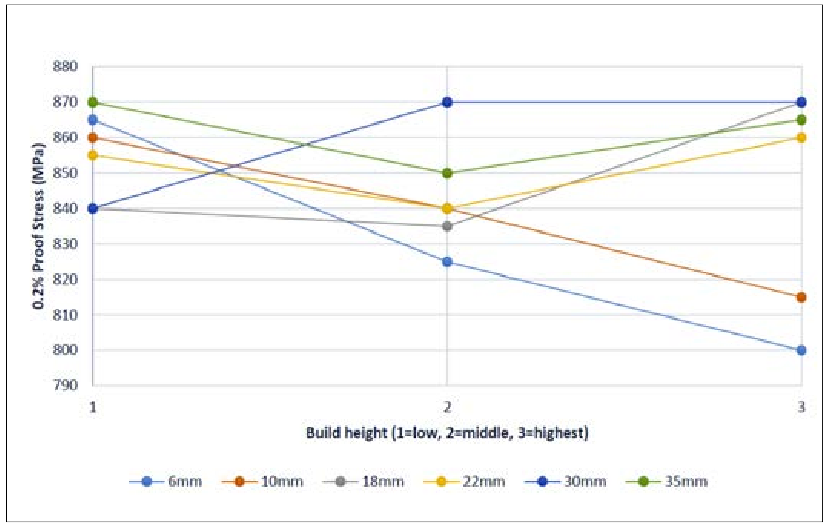


Fig. 5 Proof stress plotted versus the build height for Ti-6Al-4V component thickness [1]

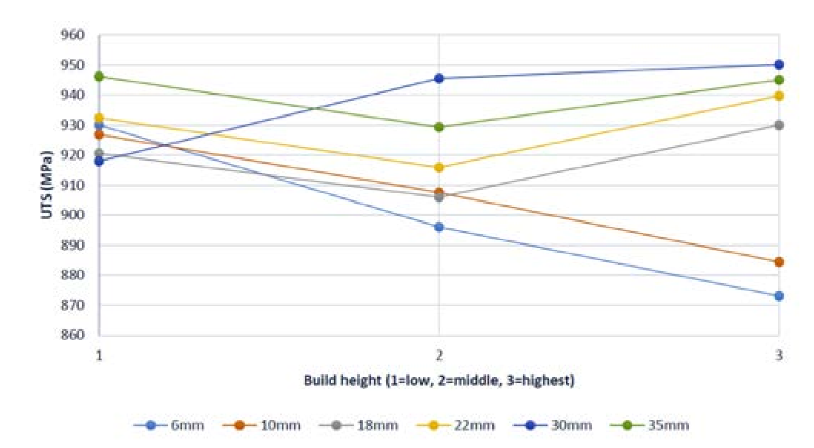


Fig. 6 Ultimate tensile strength plotted versus the build height for Ti-6Al-4V components [1]

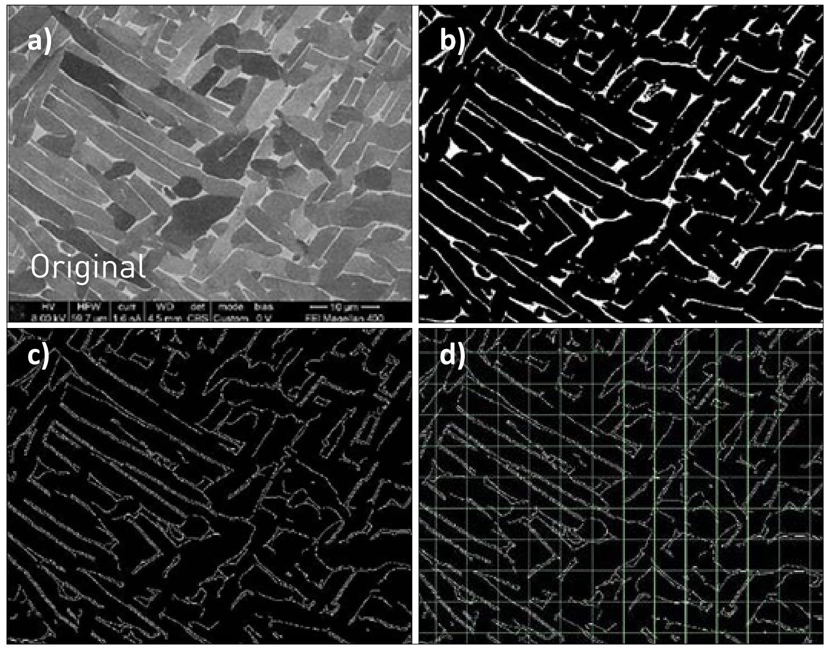


Fig. 7 Process of measuring the α-plate spacing from an original SEM image (a), to threshold image distinguishing α and β phases (b), edged image to outline phase boundaries (c) and use of linear intercept method to determine α-plate spacing (d) [1]

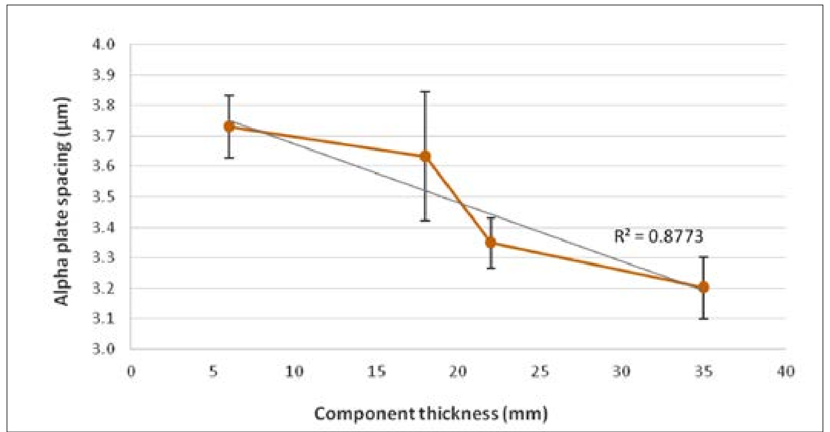


Fig. 8 Alpha plate spacing plotted versus component thickness [1]

thickness. As the build in Z-height grows, the difference in strength diverges and, at the top of the build, it is possible to identify a decrease in strength in the smaller (6 and 10 mm) diameter components. In contrast, components with 18, 22, 30 and 35 mm diameter show a slight increase in the strength along the build Z-height.

Typically there are two factors that influence the alpha-beta transformation and, consequently, mechanical properties of specimens built using EBM. These are the thermal conductivity (or cooling rate) and the accumulated heating (time at temperature). Based on several pieces of experimental research on EBM, it is believed that the lower scatter in the strength of the specimens in contact with the build plate might be an influence of the effectiveness of the heat dissipation throughout the metal start plate. This causes the component to thermally conduct the heat away predominantly into the plate and, consequently, affects the microstructure and mechanical properties. As the build grows in the Z-height, the heat flux and accumulated heating changes, depending on the specimen geometry.

In the thinner samples, where a decrease in strength is seen, the conduction of the heat deposited along the build is less as a smaller area is in contact with the plate. In the thicker samples, heat is conducted downwards in the direction of the build plate more efficiently due to the higher contact area with the build plate. As the melted area in a layer increases, a radial thermal conductivity from core to surface also exists. This also influences the formation of the alpha plates and spheroidisation of beta phase, leading to an increase in strength and decrease in standard deviation as observed in Fig. 4. Interestingly, the samples in the middle showed a slight decrease in strength (Figs. 5 and 6). The samples on the top, when completed, start dissipating heat not only through the melted material, but also through

radiation at the top surface. In this case, the middle sample will stay longer at high temperatures and cool down more slowly than the top and bottom specimens. Hence, coarse grains will be formed and a slight decrease in strength observed.

In terms of microstructure, the α-colony size is important in determining the mechanical properties of Ti-6Al-4V alloys. Decreasing the α-colony size improves the performance of the titanium alloy, such as ultimate strength, yield strength, ductility and crack propagation resistance. In the metallographic analyses reported in this study, the α-plate spacing was measured for each component because it is a suitable representation of the α-colony size. For the α-plate spacing measurements, SEM images were taken at random locations on each specimen and image correlation was used. The technique used to measure the α-plate spacing was developed at the University of Manchester. Fig. 7a shows a typical SEM image taken from a 6 mm component. The shades of grey/ black areas are the α-phase plates, whilst areas surrounding the α-phase are the discontinuous β-phase. The image is then enhanced using dynamic background correction so that α and β-phases can be distinguished (Fig. 7b). The image is then differentiated to detect greyscale gradient peaks in the images and thus effectively detect the phase boundaries between α and β phases to outline the boundaries of the phases (Fig. 7c). The linear intercept method was then used to determine the alpha plate spacing from the digitised phase boundary image (Fig. 7d).

The values measured on the components are graphically shown in Fig. 8. A decrease in α-plate spacing was observed with the increase in component thickness. The presence of finer α-plates in thicker components can be attributed to a more efficient cooling of the component during the build, where higher cooling rates will result in better mechanical performance.

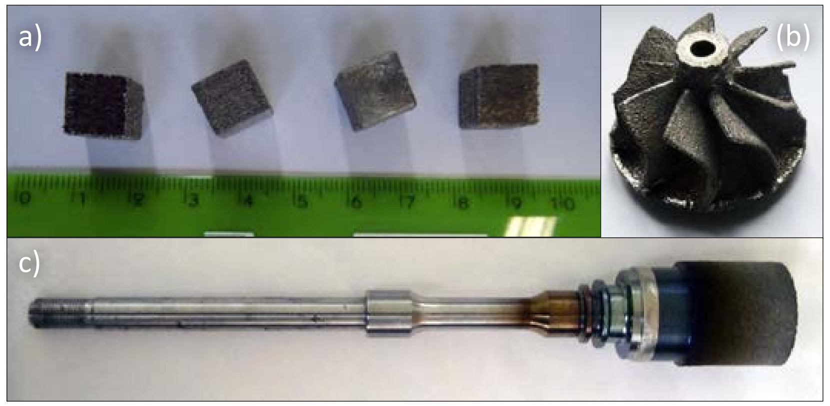


Fig. 9 (a) RNT650 EBM test samples, (b) EBM turbocharger wheel, (c) Joining trial [2]

Titanium aluminides for automotive applications

A paper in the EBM session from Giorgio Baudana, Sara Biamino, Paolo Fino and Claudio Badini (Politecnico di Torino, Italy), Burghart Kloden (Fraunhofer IFAM, Dresden, Germany) and Anita Buxton (TWI Ltd., UK) addressed the processing by EBM of titanium aluminides for automotive applications.

> *"γ-TiAl is an important class of structural materials, which, because of the excellent physical and mechanical properties, plays an important role in the aerospace and automotive industries"*

γ-TiAl is an important class of structural materials, which, because of the excellent physical and mechanical properties, plays an important role in the aerospace and automotive industries. In particular, these aluminides are considered an attractive alternative to nickel-based superalloys due to a lower density (around 4 g/cm^3 for γ-TiAl alloys and 8 g/cm^3 for Ni-based superalloys). In this reported work, carried under the aegis of a European project TIALCHARGER, TiAl-based powders, Ti-48Al-2Cr-2Nb (48-2-2) and Ti-48Al-2Nb-0.7Cr-0.3Si (RNT650), were used to fabricate specimens and prototypes of hollow turbocharger turbines by Electron Beam Melting (EBM).

The TiAl powders were produced by gas atomisation and had particle sizes between 45 and 150 µm. Test samples (Fig. 9a) and test turbocharger wheels (Fig. 9b) were produced using an Arcam A2X EBM machine, with a layer thickness of 70 µm. Fig. 9c shows a sample used for the evaluation of joining by brazing. The test samples made from alloy Ti-48Al-2Cr-2Nb (48-2-2) were found to be fully densified with only a minor amount of build flaws.

The chemical composition of the specimens was analysed and compared with the chemical composition of the starting powder. The results are shown in Table 3. The observed loss of Al was in the range of 1.4 wt% (comparable with data from the literature), while the impurity contents are comparable between the powder and the part (indicating the cleanliness of the process).

	Al [wt%]	Cr [wt%]	Nb [wt%]	Fe [wt%]	O [wt%]	N [wt%]	C [wt%]	S [wt%]	Ti [wt%]
48-2-2 Powder	34.10	2.37	4.78	0.03	0.084	0.004	0.006	<0.001	Bal.
48-2-2 Specimen	32.70	2.30	4.86	0.05	0.079	0.006	0.014	<0.001	Bal.

Table 3 Chemical composition of powder and specimens [2]

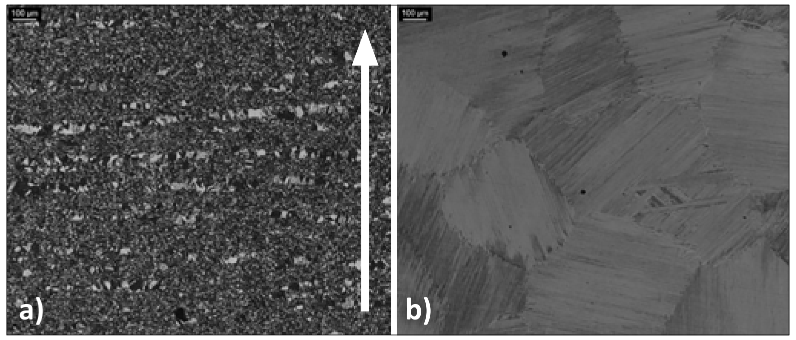


Fig. 10 (a) Microstructure of the specimen post EBM, (b) microstructure post heat treatment [2]

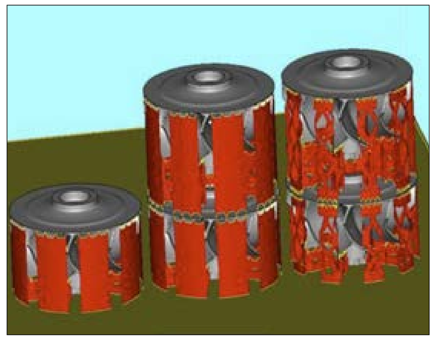


Fig. 11 Turbocharger prototypes: sample placement within build chamber with different support structures [2]

The microstructures in the as-EBM and heat-treated states were examined. Directly after EBM, the microstructure consisted of equiaxed coarse and fine grains (Fig. 10a). An additional heat treatment (1350°C for 2 hours) homogenised the microstructure to a fully lamellar type (Fig. 10b).

Test samples of alloy Ti-48Al-2Nb-0.7Cr-0.3Si (RNT650) and hollow turbocharger wheel prototypes (Fig. 11) were produced. These samples were fully densified. The chemical composition of the specimens was analysed and compared with powder chemical composition and a reference RNT650 material produced by casting. The results are shown in Table 4. A 2-3% aluminium loss was detected from powder to specimen during EBM, giving a specimen with a chemical composition that matches extremely well with the reference casting part.

Similarly to alloy Ti-48Al-2Cr-2Nb, the microstructure after EBM consisted of equiaxed coarse and fine grains (Fig. 12a). After a heat treatment at 1355°C for 1 hour, a near lamellar microstructure was obtained. The RNT650 material produced by EBM was subjected to X-ray diffraction analysis and the identified phases were the main γ-TiAl phase and traces of α_2-Ti_3Al phase as for the 48-2-2 alloy (Fig. 12b).

The scheme for the reported joining (brazing) trials is shown in Fig. 13a. Figs. 13b and 13c to 13h show SEM and elemental distribution maps at the triple joint TiAl-Ni-steel. The characterisation highlights a good adhesion between TiAl, the Ni alloy and the steel. As regards element distribution, it was possible to observe that iron from the steel diffuses into the Ni layer and, in a similar way (but at a lower level), titanium from the TiAl also diffuses into the Ni layer.

The level of adhesion shown in these joining trials is regarded as very promising for the application.

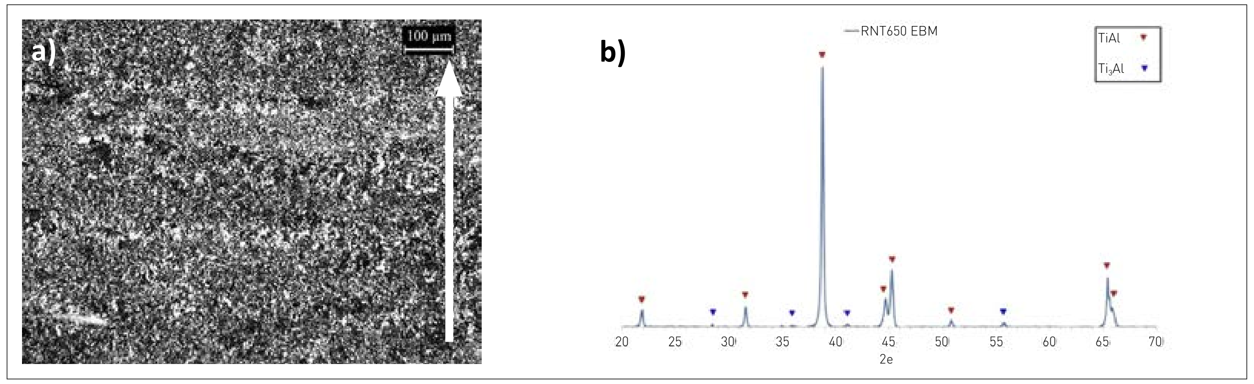


Fig. 12 (a) microstructure as-EBM of the RNT650 alloy, (b) X-Ray spectrum of the RNT650 alloy as-EBM [2]

Recycling of metal powders in the Additive Manufacturing process

In the session on Properties and Failure Analysis a paper by D Novotnak and L Lherbier (Carpenter Powder Products, USA) addressed the important issue of the impact of recycling AM powders. Most iron, nickel and cobalt based AM alloys are argon or nitrogen atomised. The gas atomisation process, whether using freefall or close coupled technology, produces a wide range of powder particle sizes. The restrictive nature of powder bed AM processes requires screening of atomised powder to a narrow particle size distribution (PSD). Resultant yields can be low, depending on the alloy, and consequent pricing high. Since powder bed processes require substantial amounts of powder not used to manufacture components, many end-users are recycling the powder. The overall effect of recycling powder on quality is not well known. However, recent studies on recycled powder have shown effects on PSDs and oxygen levels in the powder.

The purpose of this paper was to discuss the effect of recycling these powders many times, both on the powder itself and the ultimate quality of the component. The nominal compositions of the powders studied in this work are given in Table 5.

To produce satisfactory AM components, basic powder requirements, as illustrated in Fig. 14, include chemistry, particle size distribution, morphology and flow properties and cleanliness. Among all the realities of manufacturing a quality powder, cleanliness may be the most critical in determining final part quality. The powder user, independent of which machine is being used to manufacture the AM component, must maintain clean powder containers, limit airborne contaminants and avoid cross contamination with other alloys. While the factors listed above for manufacturing quality components are necessary and required, the focus of this reported work was to point out potential issues associated with the

	Al [wt%]	Cr [wt%]	Nb [wt%]	Si [wt%]	Ti [wt%]
RNT650 Powder	34.52	1.09	4.96	0.24	Bal.
RNT650 Specimen	32.50	1.00	5.38	0.26	Bal.
RNT650 Hollow Wheels	31.65	1.07	5.20	0.28	Bal.
RNT650 Casting Reference Specimen	32.63	1.07	5.55	0.22	Bal.

Table 4 Chemical compositions of RNT650 powder, samples produced by EBM and casting reference sample [2]

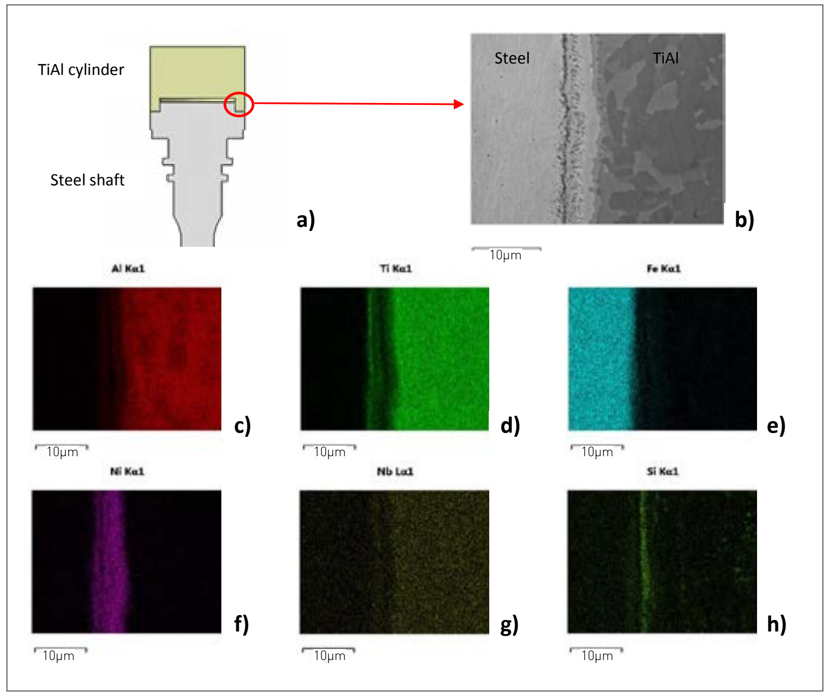


Fig. 13 (a) Joining trial scheme (section), (b) FE-SEM image at 5000 x magnification of the EDS elemental mapping area, from (c) to (H) EDS elemental maps [2]

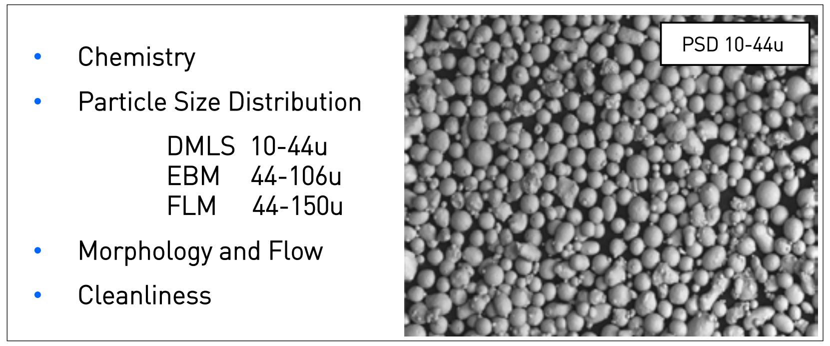


Fig. 14 Basic powder requirements for Additive Manufacturing [3]

Type	Alloy	C	Mn	Si	Cr	Ni	Co	Fe	Al	Ti	Nb	Mo
Stainless	15-5PH	0.05	0.50	0.50	14.5	4.5	-	Bal	-	-	-	-
Nickel	718	0.05	0.20	0.20	19.0	53	-	Bal	0.50		5.0	-
Cobalt	F75	0.20	0.50	0.50	28	-	Bal	-	-	-	-	6.0

Table 5 Nominal compositions of the AM grades in the study [3]

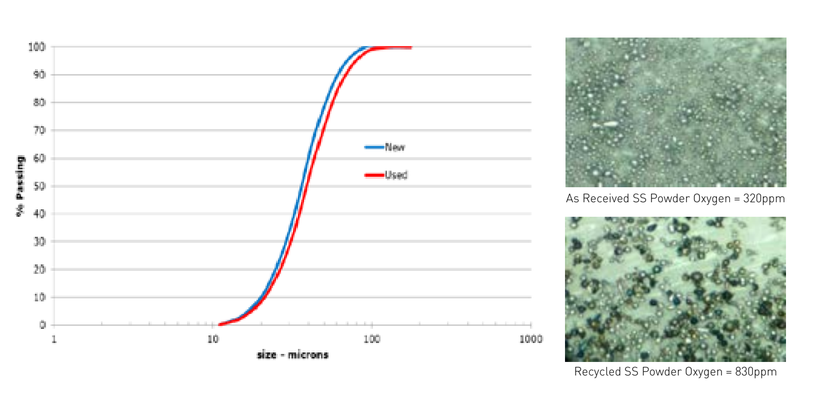


Fig. 15 PSD and visual changes from powder cycling [3]

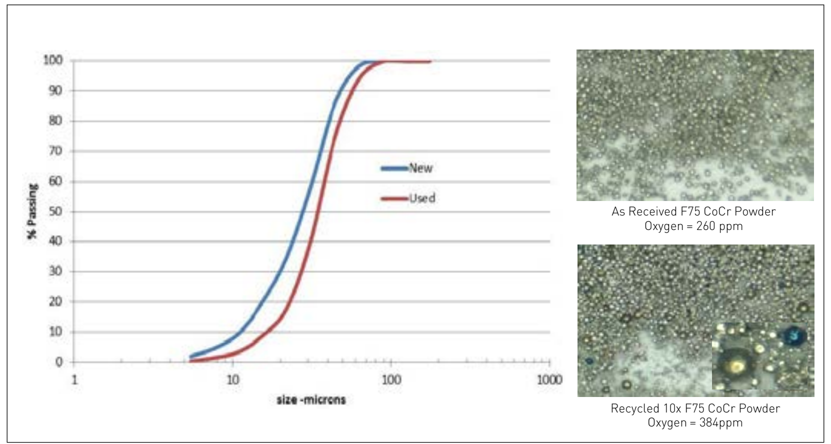


Fig. 16 PSD and visual changes from powder recycling [3]

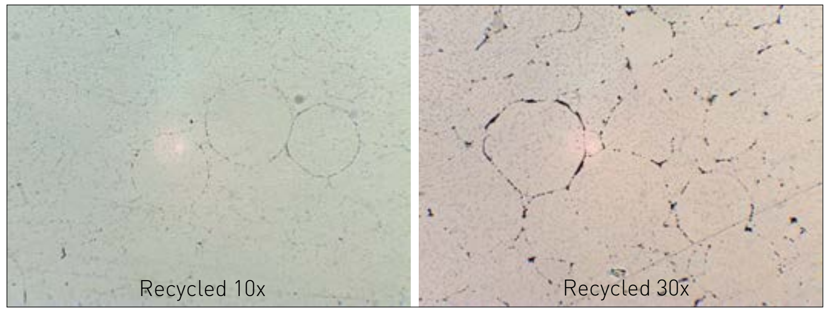


Fig. 17 Metallographic comparison of F75 at 10x and 30x recycled powder [3]

use of recycled powders for the AM bed processes.

Examination of recycled stainless steel powder (Fig. 15) shows a reduction in the number of fine particles in the powder. A more important issue, however, may be the number of oxidised particles observed in powders that were recycled many times. Oxygen analyses of the two powders showed an increase from 320 ppm in the virgin material to 830 ppm in the recycled powder.

A similar analysis was conducted on the F75 CoCr alloy. Again, as shown in Fig. 16, a loss of fines was observed after recycling ten times. The oxygen level increased from 260 ppm to 384 ppm. Oxidised particles were clearly visible in the recycled powder. Evaluation of the same powder recycled 30 times showed an increase in oxygen level to 568 ppm. Consolidation of the powders recycled 10 times and 30 times, as illustrated in Fig. 17, shows an increased amount of oxidised particles in the microstructure with increased recycling.

Additional work remains to be done on the effect of the oxidised particles on mechanical properties and to determine the number of times a powder can be safely recycled. Initial results indicate that oxygen pick-up is affected by the chemical composition of AM alloy powder types. The latest study has focussed on the use of recycled powders in making a DMLS test bar with different sections from recycled powder, virgin powder and a blended powder of recycled and virgin powder. A comparison of the test bar sections is shown in Fig. 18. Although

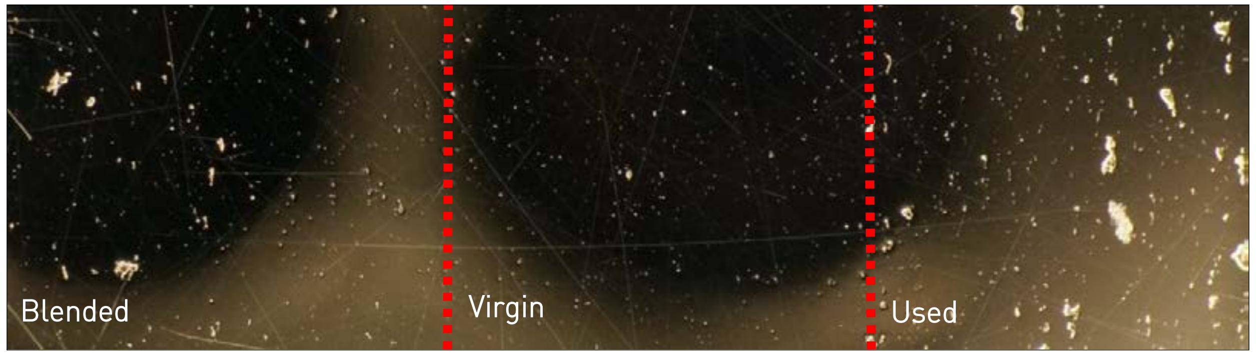


Fig. 18 Influence of recycled powder on porosity [3]

the expected oxidised particles were present in the test bars, an unexpected porosity difference was also observed in the microstructures. The virgin powder section showed the least porosity followed by the blended powder (virgin plus recycled) and then by the recycled. The results would indicate the need for subsequent consolidation by hot isostatic pressing in order to produce the highest quality component.

Modelling of short crack initiation in Selective Laser Melting

The next paper came from Tom Andersson, Anssi Laukkanen, Tatu Pinomaa, Antero Jokinen, Antii Vaajoki and Tarja Laitinen (VTT Technical Centre of Finland Ltd, Finland) and addressed the mesoscale modelling of short crack initiation in metallic microstructures created by Selective Laser Melting (SLM).

Selective Laser Melting is a versatile AM manufacturing method that has found extensive use in rapid prototyping. A significant issue for the increased use of SLM is the technology's utilisation in key components with high performance requirements. For example, in the aerospace sector, the use of SLM in rotating components operating at elevated temperatures imposes an essential requirement for the parts to be defect free. However, in practice, such material microstructures have proven to be difficult to achieve and issues with process consistency in complex part designs make such efforts ever more challenging.

In order to address this issue, this paper presented a material defect structure based modelling methodology for the evaluation of the significance of individual microstructure-scale defects in influencing the operating time required for the initiation of short fatigue cracks. The first step in this analytical method was the capture, from scanning electron micrographs (SEM), of information on manufacturing defects in AM specimens, such as pores, cracks, various clusters and interface defects between laser melted layers.

Input information on residual stresses is also significant in material lifetime prediction. Generally, it is almost impossible to determine residual stresses without destroying the component. To determine residual stress level, whilst still keeping the component intact, it is necessary to model the SLM process. A simplified process model for SLM to predict the residual stress-strain state of the component has been used. A thermomechanical process model for SLM is presented in Fig. 19. This process model has been combined with an image-based microstructural model of the defect structure, in order to establish the link between microstructural defects and fatigue performance. The various identified defect shapes and types in the microstructure have been modelled using image-based FEM under uniaxial tension. The method makes the evaluation of the significance of different defect types and sizes possible. Their significance, with respect to Fatigue Performance Indicators (FPIs), can be extracted.

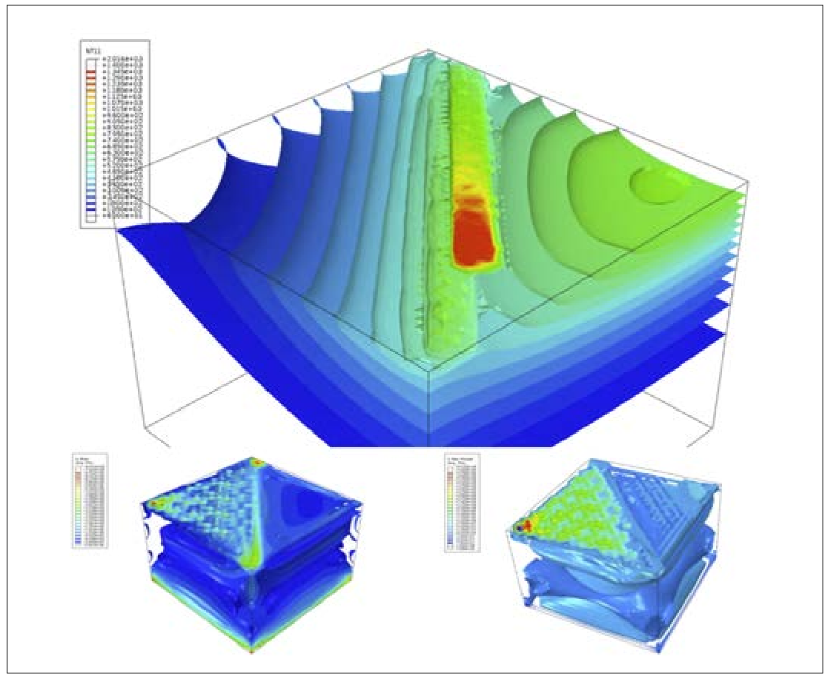


Fig. 19 Temperature isosurfaces during the simulation of the final layer and 1st principal and equivalent stresses [4]

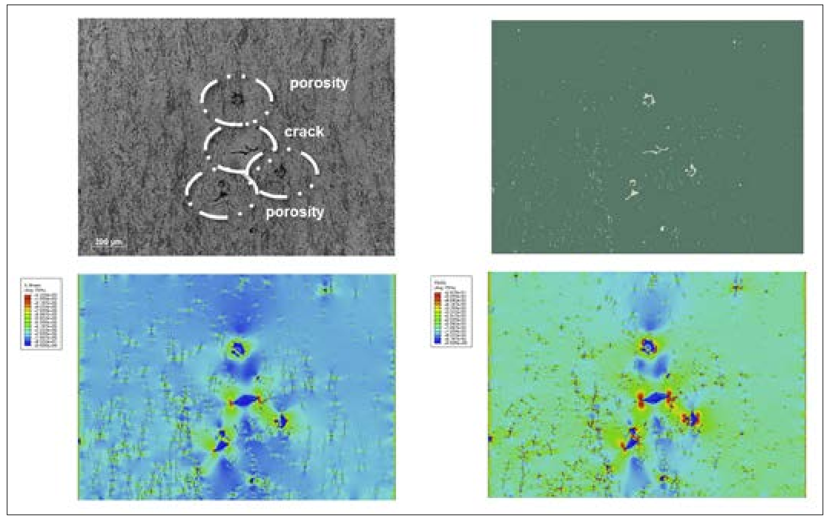


Fig. 20 Modelling procedure from upper left to lower right: microstructure, defect structure, equivalent stress and strain contours [4]

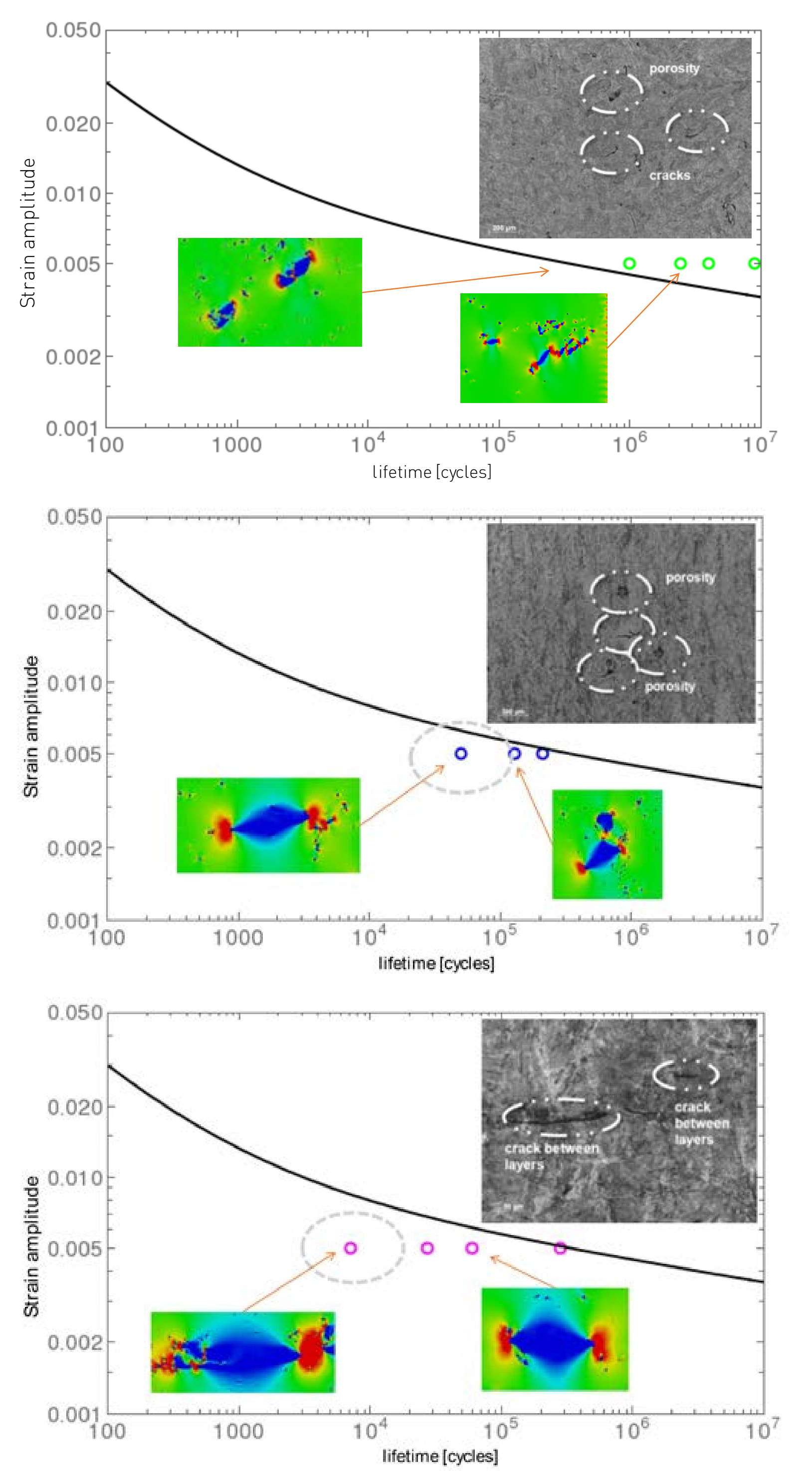


Fig. 21 The effect of defect type on lifetime prediction [4]

The procedure for image-based microstructure modelling is presented in Fig. 20. The Fatemi-Socie (F-S) parameter was used in the subsequent evaluations. FPIs provide a quantitative estimate of the relation between microstructural stress-strain states and fatigue initiation life and therefore assess the criticality of specific microstructural features with respect to defect initiation. FPIs enable the linking of individual micro-structural defects and the respective fatigue initiation lifetime estimates, thus quantifying the significance of microstructural defects and their interactions throughout the micro-structure. The effects of defect type in three analysed microstructures are presented in the Coffin-Manson curves in Fig. 21.

The effect of residual stress in a selected case is presented in Fig. 22. Three different residual stress levels have been introduced. The analysis of the worst case (circled in upper image) is shown in the lower image of Fig. 22.

Processing parameters and chemical composition of tool steels

The final contribution to this session remained with the SLM process. This paper, from J Lemke, R Casati, A Demir, B Previtali and M Vedani (Politecnico di Milano, Italy) and C Andrianopoli and M Massazza (Cogne Acciai Speciali SpA, Italy), considered the effects of processing parameters and chemical composition of tool steels on the integrity and properties of low-thickness parts.

The aim of the reported research work was to present the first step in the development of new hyper-eutectic tool steels available for SLM processes. A modified stainless steel of the 304 series, featuring the addition of large amounts of C and B and designated as 304CS, was considered to create a hypereutectic hard and corrosion resistant alloy with an expected strong performance under severe service conditions. It was thought that processing of such alloys might bring difficulties related to the brittleness of the primary hard phases and to the risk of oxidation of the alloying elements.

To compare the alloy properties after SLM with those achieved after conventional production methods, samples of the same feedstock alloy have been cast in an alumina crucible and changes in microstructure and hardness were evaluated. As a final step, a 316L stainless steel was processed by the same methods to add further comparison issues to the research results. 316L stainless steel is one of the most widely studied materials with the SLM process and therefore provides a good benchmark.

The compositions of the two stainless steels were as quoted in Table 6. Reference samples of the two alloys were cast in alumina crucibles under argon atmosphere and transverse cross sections of these castings were cut and prepared for microstructural investigations. A prototype powder bed device was employed for the laboratory-based selective laser melting tests on the two powders. This device was composed of a multimode continuous wave active fibre laser, coupled to a scanner head.

A parametric study of the selective laser melting of 304CS was conducted. After preliminary tests, three power levels between 120 W and 200 W and four levels of scan speeds between 70 and 170 mm/s were adopted. On the other hand, hatch spacing, layer thickness and focus were kept fixed. The details of the processing parameters are shown in Table 7.

Representative micrographs of 304CS in the cast form are shown in Fig. 23. The hypereutectic microstructure consisted of many primary hard carbides/borides, which could reach sizes as large as the mm range, as shown in Fig. 23a. At higher magnification (Fig. 23b), smaller carbides/borides and the eutectic constituents could be clearly identified. Black graphite flakes were also present in the alloy, owing to relatively slow solidification and cooling rates experienced by the cast samples.

Accurate SEM and EDX analyses were used to identify the amounts of the different phases found. Local elemental concentrations are reported in Table 8. Carbides and borides of different shapes and compositions were identified. The highest fraction consisted of coarse Cr-rich carbides/borides with a rectangular shape and a size ranging from a few microns up to the millimetre scale. The eutectic constituent, which formed between the primary carbides/borides, was rich in Ni and Si. Also, at the boundaries of the coarse primary phases, small carbides/borides were

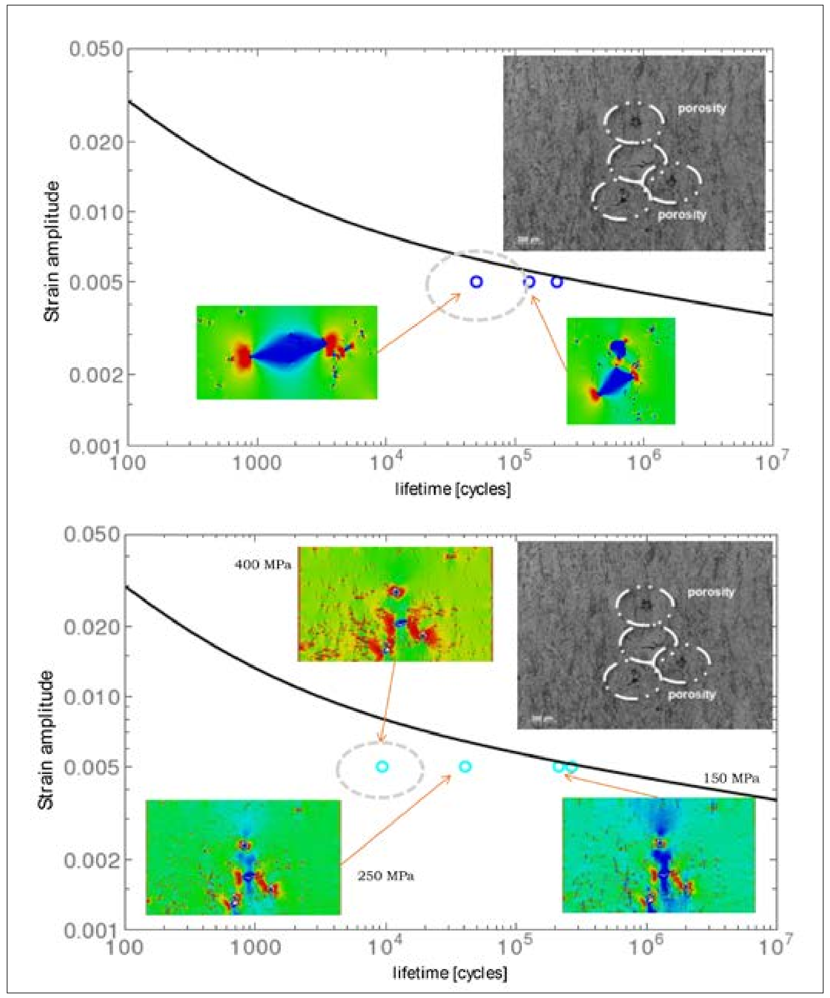


Fig. 22 Effect of residual stress (upper without, lower with residual stress) [4]

	C	Si	Cr	Ni	B	Mn	Mo	Fe
304 CS	1.96	2.94	13.32	10.89	3.68	-	-	Bal.
316L	<0.03	0.5	17	12	-	1.5	2.5	Bal.

Table 6 The main alloying elements in 304 CS and 316L steel (mass%) [5]

Varied parameters		
Power	P [W]	120, 150, 200
Scan speed	v [mm/s]	70, 120, 150, 170
Fixed parameters		
Focal position	Δz [mm]	0
Ar flow rate	[Nl/min]	20
Hatch spacing	h [μm]	100
Layer thickness	t [μm]	50

Table 7 Details of the experimental plan applied in the study of Selective Laser Melting of 304 CS powder [5]

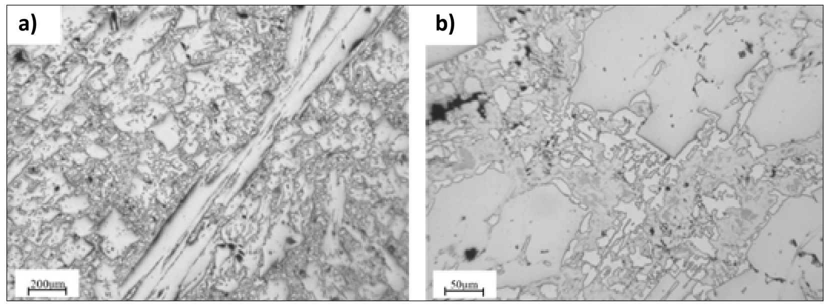


Fig. 23 Microstructure of 304 CS cast in alumina crucible [5]

	Si	Ti	V	Cr	Mn	Fe	Ni	Nb
position A		5.21	0.93	5.56	0.22	1.14	0.15	86.80
position B	0.08			34.31	1.46	61.67	2.48	
position C	12.93			6.37	0.77	59.62	20.31	
position D	0.22			25.55	1.18	69.95	3.10	
position E	7.82			1.57	0.87	67.31	22.43	
position F	1.63			6.10	1.64	84.20	6.43	

Table 8 Chemical compositions of phases identified

	V1=70 mm/s	V2=120 mm/s	V3=150 mm/s	V4=170 mm/s
P=120 W	2	2	1	1
P=150 W	3	3	2	2
P=200 W	3	4	2	2

Table 9 Laser scan parameters vs. achieved quality of build volume. Darker shades of colour indicate higher quality levels regarding the number and size of defects [5]

found with high amounts of Nb, Ti or Ni.

Low thickness parts of 304 CS were processed next by SLM, with a power of 150 W or 120 W at different scan rates. The samples were found to be well bonded to the substrate. However, particularly for the highest scan rates, large surface cracks were observed. The microstructures of the samples were examined and classified, on the basis of the amounts of defects, namely porosity and cracks, into four levels (4 being the best level and 1 the worst). Level 4 is characterised by large defect-free areas, some macroscopic surface cracks and a few zones of small pores in the low micron range. In level 3, a few micro cracks and also some large voids with dimensions over 100 µm were present, while large areas were dense without defects. The microstructures of samples classified as level 2 were full of pores and also macroscopic and microscopic cracks, but some defect free areas could also be found. Level 1 is characterised by a consistently imperfect microstructure. An analysis, relating the achieved quality to the selected scan parameters, is shown in Table 9. At low power levels and high scanning rates, the samples showed many defects.

In comparison to the microstructure of the cast sample, the 304CS, processed by SLM, featured a much finer microstructure. Representative optical and SEM micrographs are shown in Fig. 24. The microstructure consisted of small, sharp carbides in the 2 - 3 µm size range in a eutectic matrix. No substantial difference in microstructure was noted between the feeding and transverse directions. The cast microstructure of the 316L stainless steel was characterised by austenitic grains (Fig. 25a) and a few pores. On the other hand, the 316L structure generated by SLM processing consisted of austenite cellular colonies, with a size smaller by a factor of 100 than the cast grain structure. Compared to 304CS, the microstructure was more homogenous due to the absence of hard and brittle carbides, making it also less prone to cracking. Again, no substantial difference in microstructure was noted between the feeding and transverse directions.

Hardness and microhardness measurements were performed on the investigated alloys. The results are shown in Table 10. While the hardness of the austenitic 316L steel increased slightly when moving from cast to SLM processed samples due to grain refinement, the increase in hardness of the SLM 304CS alloy was very high. The size reduction of carbides/borides from the millimetre scale to the micron size induces a dramatic increase in hardness.

The authors concluded by stating that further investigations are still required to find the optimum build parameters to reduce the number of pores and cracks, but that the results to date strongly suggest that the alloy could be used with further optimisation for AM.

Author

David Whittaker
DW Associates
231 Coalway Road, Wolverhampton
WV3 7NG, United Kingdom
Tel: +44 (0)1902 338498
Email: whittakerd4@gmail.com

References

[1] T Machry, D Eatock, J Meyer, A Antonysamy, A Ho and P Prangnell, Effect of Microstructure on the Tensile Strength of Ti6Al4V Specimens Manufactured using Additive Manufacturing Electron Beam Process, , as presented at Euro PM2015, Reims, France, October 4-7 2015.

[2] G Baudana, S Biamino, P Fino, C Badini, B Kloden, A Buxton, Titanium aluminides for automotive applications processed by Electron Beam Melting, as presented at Euro PM2015, Reims, France, October 4-7 2015.

[3] D Novotnak and L Lherbier, The Impact of Recycling AM Powders, as presented at Euro PM2015, Reims, France, October 4-7 2015.

[4] T Andersson, A Laukkanen, T Pinomaa, A Jokinen, A Vaajoki and T Laitinen, Mesoscale Modelling of Short Crack Initiation in Metallic Selective Laser Melting Microstructures, as presented at Euro PM2015, Reims, France, October 4-7 2015.

[5] J Lemke, R Casati, A Demir, B Prevital, M Vedani, C Andrianopoli and M Massa, Effect of Processing Parameters and Chemical Composition of Tool Steels on Integrity and Properties of Low-Thickness Part Produced by Selective Laser Melting, as presented at Euro PM2015, Reims, France, October 4-7 2015.

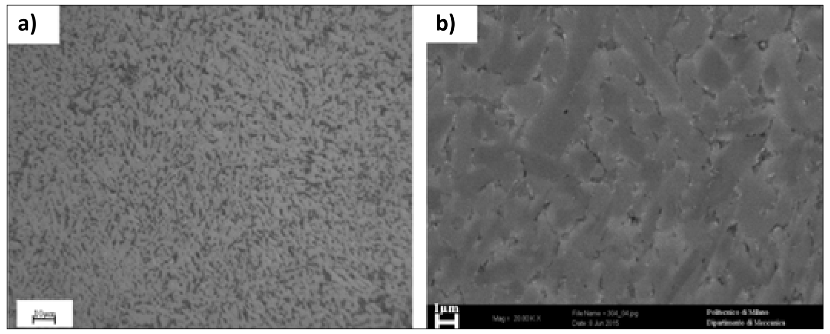


Fig. 24 Representative microstructure of 304 CS produced by SLM shown along the feeding direction (a) optical micrograph; (b) SEM micrograph [5]

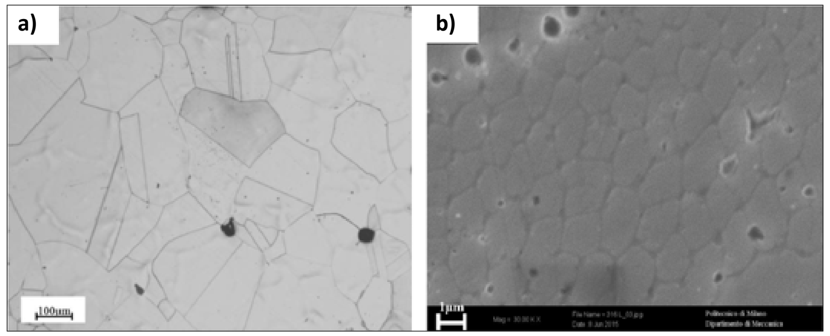


Fig. 25 Representative microstructures of austenitic 316L; (a) optical micrograph of cast 316L; (b) SEM micrograph of 316L steel along the feeding direction produced by SLM [5]

	Cast hardness [HV]	SLM hardness [HV]
304 CS	581 +/- 94	1050 +/- 36
316L	189 +/- 15	202 +/- 10

Table 10 Hardness of 304 CS and 316L samples, cast and SLM processed [5]

Metal AM at Euro PM2015: Superalloys, powder atomisation and advances in inkjet and LMD processes

In part two of our report on technical advances in metal AM at the Euro PM2015 Congress, Reims, France, October 4-7 2015, Dr David Whittaker reports on six further papers presented at the conference's very well attended metal AM sessions. These papers cover the heat treatment of IN939 superalloy parts, the production of Ni718 superalloy powder, advances in inkjet-based metal AM and the production of gears by Laser Metal Deposition (LMD).

EURO PM2015 congress & exhibition

Heat treatment and mechanical testing of IN-939 superalloy

The session on superalloys was opened with a contribution from Hakan Brodin (Siemens Industrial Turbomachinery AB, Sweden) on the heat treatment and mechanical testing of a selective laser melted superalloy, IN-939.

Alloy IN-939 is a corrosion resistant nickel-based superalloy, where components are typically manufactured by precision casting and currently mainly used as blade and vane material in industrial gas turbines. Using standard manufacturing routes, the alloy is never used in the as-manufactured condition because of the heavy segregation that would appear after casting. Therefore, a solution heat treatment is always necessary, followed by an aging procedure to achieve the appropriate strength and ductility levels. The nominal material composition for castings is given in Table 1.

The reported study focussed on mechanical testing experiments after heat treatment of IN-939 manufactured by Selective Laser

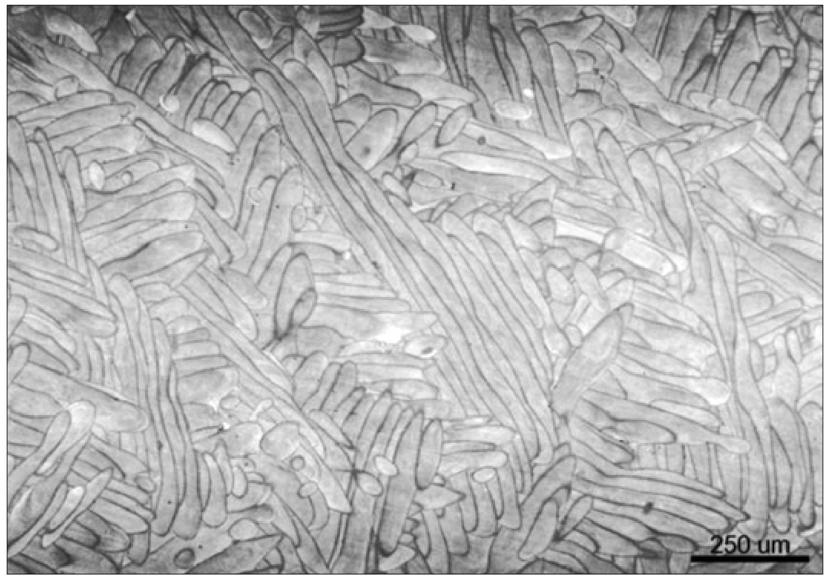


Fig. 1 As-manufactured microstructure, IN-939. Build direction is perpendicular (out of the plane) compared to the picture [1]

Melting AM technology. A typical as-manufactured IN-939 microstructure is shown in Fig. 1. In this figure, the build direction was perpendicular to the image plane, i.e. out of the plane. The powder used was argon gas atomised and consolidation was carried out using an EOS M270 DM machine, with 195 W laser power and 20 µm layer thickness.

Anisotropy can be a problem in AM materials and, therefore, two test specimen orientations were evaluated, 0° (parallel to the build platform / perpendicular to the build direction) and 90° (parallel to the build direction). The initial heat treatment used during the material development of IN-939 was a two stage heat treatment. Due to the very low tensile and creep ductility achieved, the heat treatment was later modified to improve ductility at the expense of reduced tensile strength. The proposed heat treatment route was then a four stage heat treatment. Heat treatment procedures are shown in Table 2. In the current work, attention was on the heat treatments according to procedures 1 and 2. For products with high performance demands, a HIP procedure was proposed prior to step 1.

"By using a proper solution heat treatment and aging procedure, the tensile strength of SLM processed material will be superior to a casting"

Tensile testing at ambient and elevated temperature was performed on a) as-manufactured, b) HIPed and heat treated material. The measured values of yield stress, ultimate tensile stress, elongation at fracture and energy at fracture for as-manufactured IN-939 are shown in Fig. 2. These results display anisotropy and a material with high elongation at fracture compared to the typical values of 2-8% for heat treated precision cast IN-939. The main reason for the good elongation and ductility is the absence of heat treatment, where a γ-γ' microstructure has not developed due to the fast cooling during SLM processing. In order to allow a comparison of different heat treatments, Fig. 3 shows yield stress and ultimate tensile stress for the 0° direction after different heat-treatments, compared to precision casting data. The initial (as-manufactured) strength of an SLM material is as strong as the corresponding cast material after a solution heat treatment and aging. By using a proper solution heat treatment and aging procedure, the tensile strength of SLM processed material will be superior to a casting.

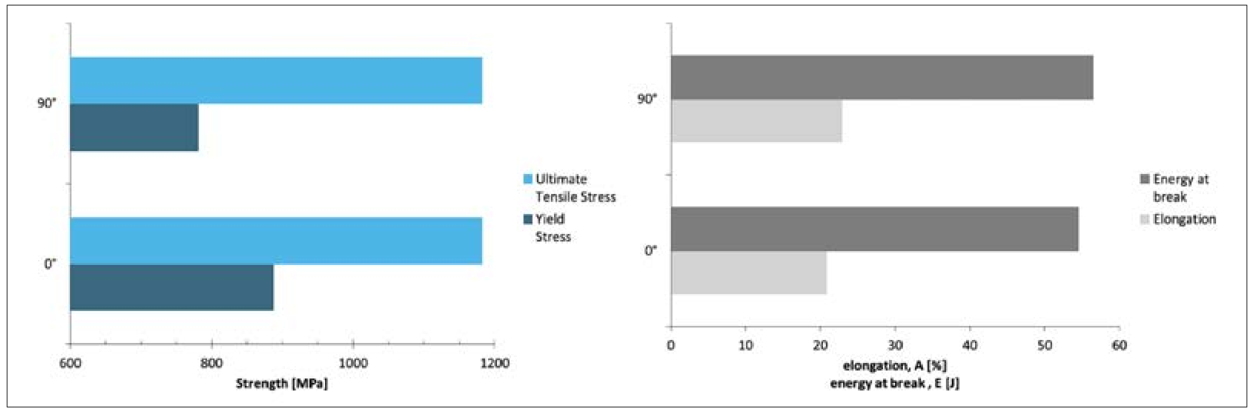


Fig. 2 Left: UTS and Yield stress for 0° and 90°, Right: Elongation and energy at fracture. As-manufactured condition [1]

C	Cr	Co	Mo	W	Ta	Nb	Al	Ti	Zr	B	N	O	P	S	Ni
0.15	22.4	19.0	<0.01	2.0	1.45	1.0	2.0	3.7	<0.003	0.004	<0.005	<0.002	<0.005	<0.001	Bal.

Table 1 Nominal composition of IN-939 for precision castings [1]

Procedure	Step 1	Step 2	Step 3	Step 4	Note
1	Solutioning 1150°C / 4 h	Ageing 850°C / 16 h	n/a	n/a	Gas quench after 1
2	Solutioning 1160°C / 4 h	Ageing 1000°C / 6 h	Ageing 900°C / 24h	Ageing 700°C / 16 h	Gas quench after 1,2,3
3	Solutioning 1160°C / 4 h	Ageing 1000°C / 6 h	n/a	n/a	Gas quench after 1

Table 2 Heat treatments proposed for IN-939 [1]

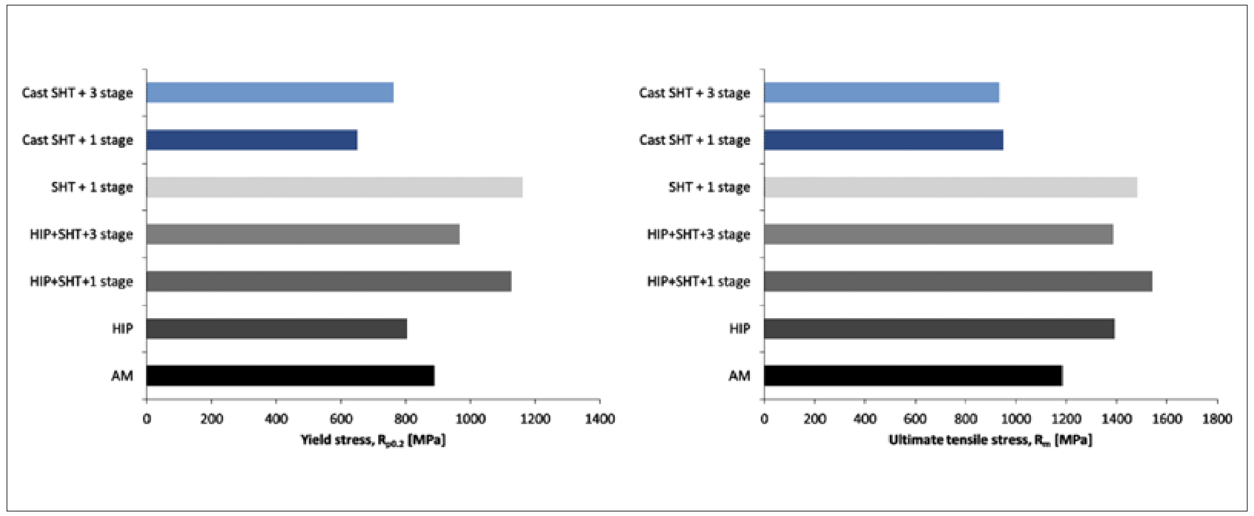


Fig. 3 Yield and ultimate tensile stress for different material conditions, direction 0°. Reference precision casting levels are also indicated [1]

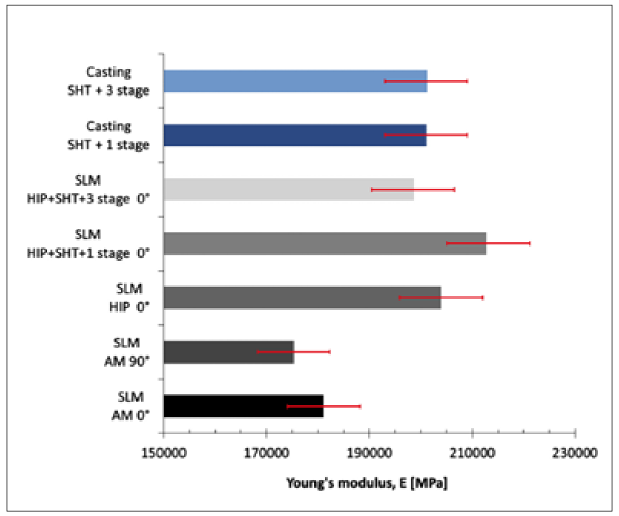


Fig. 4 Stiffness of as-manufactured and HIPed material. Data reported for AM material in the 0° direction. Typical (in-house generated) precision casting level indicated as reference [1]

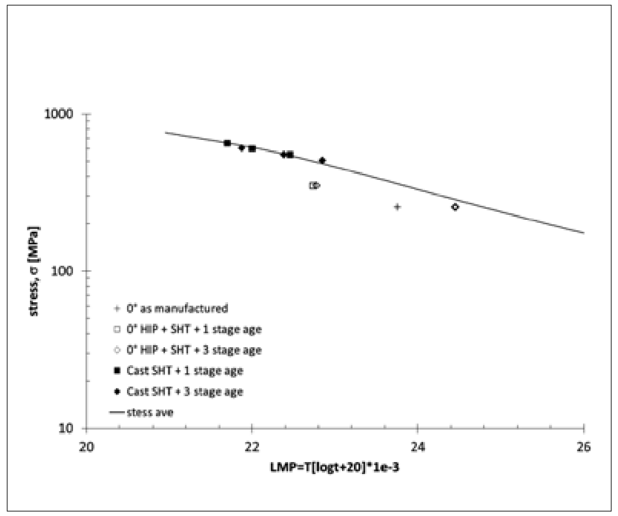


Fig. 5 Creep test results for AM IN-939 in 0° direction and cast IN-939 [1]

Stiffness in the different test directions 0° and 90° versus material condition is shown in Fig. 4. Reference in-house data for cast material is also included in this figure. It is clear that hot isostatic pressing is beneficial for material behaviour. Even though the material is already homogeneous before HIP, containing low porosity and being crack free, the results indicate a significant change in stiffness. Creep testing has been performed for a solution strengthened superalloy as rupture tests in the 0° and 90° directions (Figs. 5 and 6). Creep tests have been reported as stress as a function of the Larson-Miller

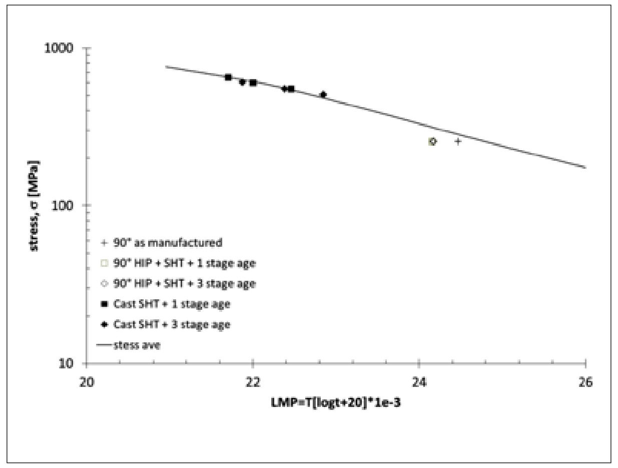


Fig. 6 Creep test results for AM IN-939 in 90° and cast IN-939 [1]

Parameter (LMP). The Larson-Miller parameter is defined as:

$$LMP = T.[\log(t) + C]. 10^{-2}$$

where T = temperature (K),t = time (h) and C is the Larson-Miller constant, typically set at 20.

The 0° direction is known to be inferior with regard to creep performance (rupture time, elongation at rupture) than the 90° direction. The performance of the 90° direction in the as-manufactured condition can be compared to cast material.

The tensile testing of SLM-processed IN-939 has indicated that the material is anisotropic with regard to strength in the as-manufactured condition. This can be seen in the tensile test results (both yield stress and ultimate tensile stress). Elongation and energy at fracture do not seem to be as significantly influenced by the anisotropy. Material stiffness is lower in the as-manufactured condition compared to what can be expected in a material manufactured by precision casting. A HIP process seems to be able to improve the poor stiffness observed in the as-manufactured material.

The anisotropic behaviour of IN-939 can also be observed in the creep behaviour of the alloy. In the as-manufactured condition, the material creep behaviour is significantly inferior in the 0° direction compared to a casting. On the other hand, in the 90° direction, the creep resistance is on a par with precision cast material. A heat treatment can improve the creep properties in the 0° direction with the consequence that the better performing (90°) direction reduces the resistance against creep damage.

Results in the reported study indicate that a further refinement of the heat treatment could have the potential to remove the creep life anisotropy. Further work is needed to optimise the heat treatment in this respect.

"A HIP process seems to be able to improve the poor stiffness observed in the as-manufactured material"

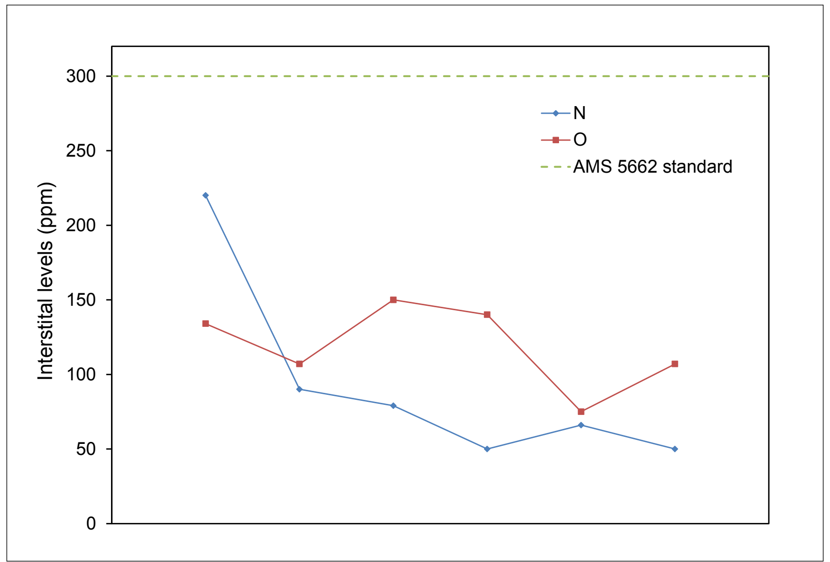


Fig. 7 Evolution of the N and O levels over the past year in Ni718 powder for laser melting powder bed application [2]

Improving quality and production capacity for Ni based powders

The next paper in this session was from P Vikner, R Giraud and C Mayer (Erasteel, France) and M Sarasola (Metallied Powder Solutions, Spain) and presented the process improvements made by Erasteel to produce quality Ni- and Co-based superalloy powders for AM in terms of interstitial cleanliness, particle size and morphology.

In order to improve the nitrogen and oxygen content in the powders, it important to exercise good control over the vacuum induction melting and the atomisation processes and to limit the contact between air and hot powder. It is also important to prevent moisture and foreign particles from entering the powder. Moisture would have a negative impact on flowability and foreign particles can degrade the performance of the final product. In the production line at Metallied, the powder is constantly under a protective atmosphere with a view to avoiding any pick-up of oxygen, nitrogen, moisture or foreign particles. In order to further improve the cleanliness, all powder handling is done in a new dedicated facility that is separated from the upstream production. An inert gas blender and inert gas packing ensure a clean homogenous powder.

By addressing the sources of nitrogen pick-up at all the stages of powder fabrication, the nitrogen level in the final alloys has been reduced, as shown in Fig. 7 for Ni718 for laser melting powder bed applications, requiring powder particle sizes between 10 and 53 µm. This improvement in Ni718 superalloys will decrease the risk of TiN stringers formation in the powder (or subsequently in the built part). Such stringers, due to their low ductility, would become initiation sites for cracks. With a similar objective of reducing the risk of the formation of detrimental oxides, the oxygen level in Ni718 can also be kept well below the maximum level as shown in Fig. 7 for fine powders between 10 and 53 µm.

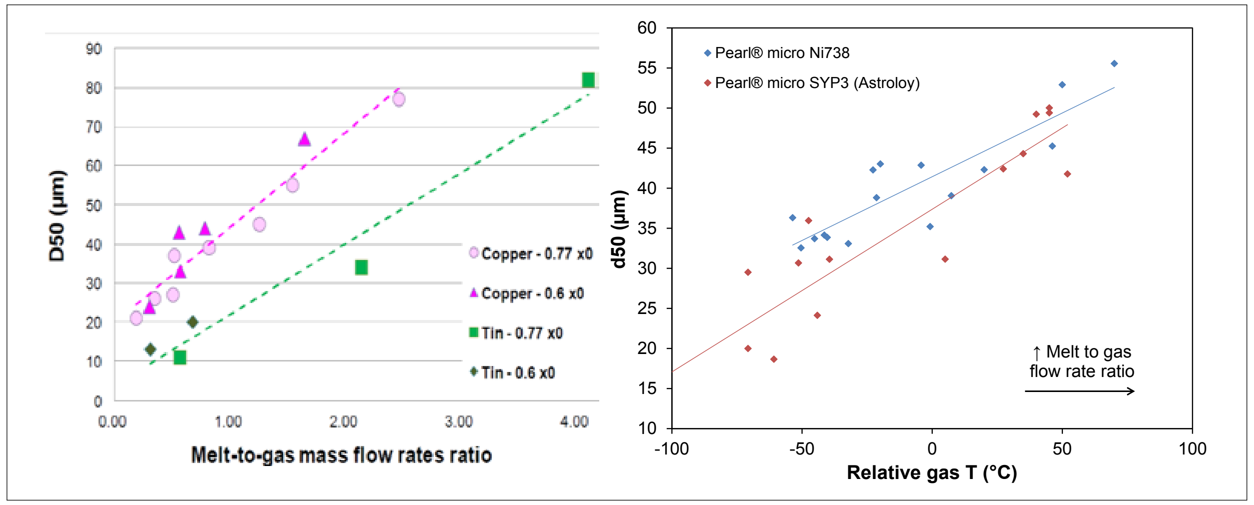


Fig. 8 Evolution of the d50 with metal-to-gas mass flow rate ratio for Sn and Cu powders(left) and evolution of d50 of two Ni base superalloys with the relative temperature at the bottom of the tower (right) [2]

In order to exercise control over powder size and morphology, it is necessary to adjust atomisation parameters. It is also desirable to be able to monitor atomisation parameters to ensure that the process is under control. In water and gas atomisation, most of the relevant process parameters can be covered by the "melt-to-gas flow rates ratio". Increasing this ratio leads to an increase of the median value of the particle size distribution (d50) as shown in the left hand side of Fig. 8 for tin and copper powder.

In the Erasteel process, this ratio is monitored through the in-line measurement of powder temperature at the bottom of the atomiser. For a given gas nozzle configuration, the metal feed rate was varied, leading to a variation in the melt-to-gas flow rates ratio. If the gas feed is kept constant, the particle size will vary as a function of gas temperature. On the right side of Fig. 8, a plot of the d50 against the relative gas temperature for two Ni based alloys, Ni738 and SYP3 (Astroloy), confirms this trend.

For Additive Manufacturing applications, the size and size distribution of the powder are critical, but it is also necessary to control the shape of the powder.

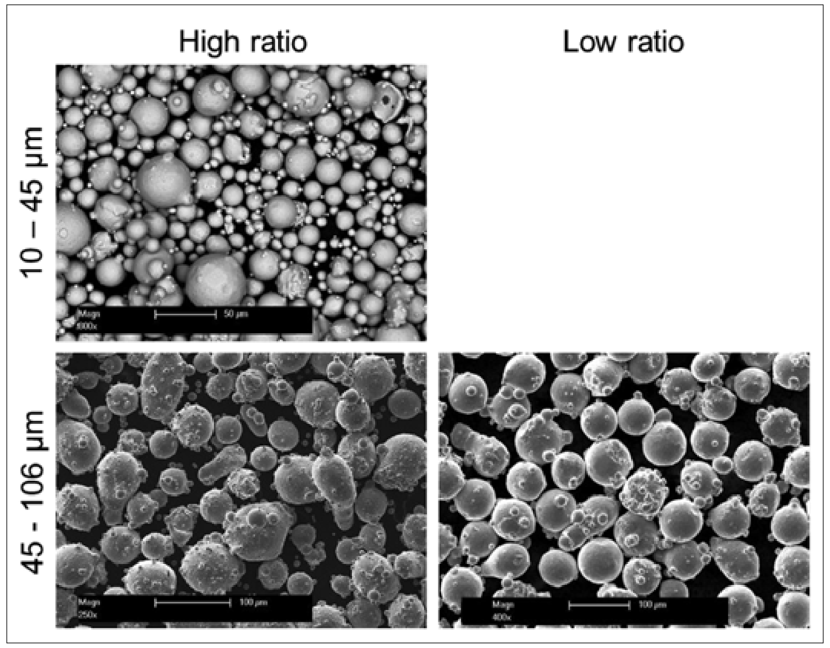


Fig. 9 SEM image of Pearl® Micro Ni718 powder for two particle size distributions (10 – 45 µm for powder bed application and 45 – 106 µm for deposition application) and two melt-to-gas mass flow rates ratios [2]

The powder must be able to flow well in the Additive Manufacturing devices, to spread well in the case of powder bed applications and to limit the risks of induced porosity. It is therefore important to be able to produce rather regular spherical powder and to limit the presence of satellite particles.

By tuning the gas to melt flow ratio, it is possible to adapt the morphology of powders to targeted Additive Manufacturing applications, as shown in Fig. 9. With a high gas to melt flow ratio, the morphology of particles smaller than 45 µm with spherical, regular particles is adapted to laser melting powder bed technology, but the higher fraction of powders, between 45 and 106 µm, shows very irregular particles. It was thus necessary to tune the gas to melt ratio to improve the morphology of particles between 45 and 106 µm. This regularity of morphology is mandatory for depo-

C	O	Co	Cr	Cu	Fe	Mo	P	Si	V	W	Ni
0.056	0.008	1.82	21.7	<0.01	18.6	9.20	0.008	0.36	<0.01	0.90	Bal
LECO	LECO	ICP	ICP	ICP	ICP	ICP	ICP	ICP	ICP	ICP	ICP

Table 3 Chemical composition in wt% of the Hastelloy X powders as determined by ICP and LECO test [3]

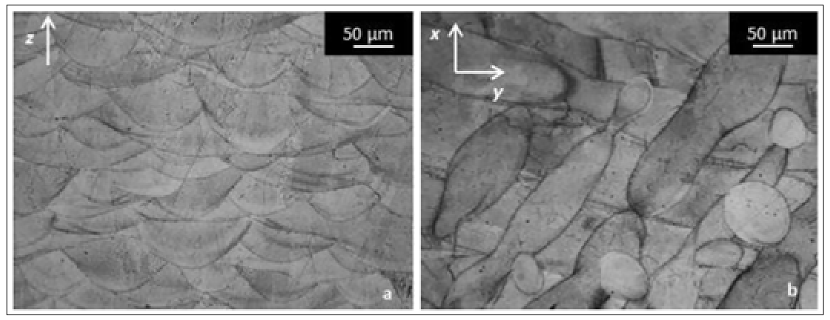


Fig. 10 Optical images of etched as-built samples: yz plane, showing the growth direction z (a) and cross-section xy plane (b) [3]

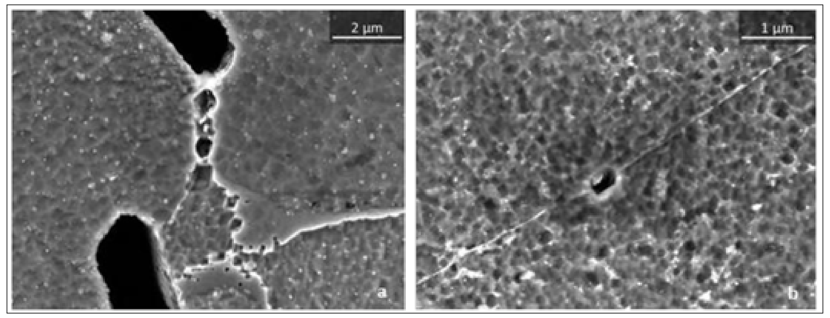


Fig. 11 FESEM images of Hastelloy X solution treated at 1175°C for 1 h followed by water quenching, after etching [3]

Solution Treatment	HBW 2.5/62.5	$HV_{0.3}$	ASTM Grain size number
as-built	235 ±5	277 ±4	-
1175°C 15 min, water quenched	185 ±11	220 ±3	6.5
1175°C 30 min, water quenched	159 ±4	204 ±4	6.0
1175°C 60 min, water quenched	148 ±3	197 ±5	5.5
1175°C 120 min, water quenched	151 ±2	193 ±8	5.5
1066°C 60 min, water quenched	210 ±5	266 ±17	-

Table 4 Hardness values and grain size of Hastelloy X samples before and after solution treatment [3]

sition or cladding type technologies (targeted size of particles between 45 and 125 µm depending on the type of machine), with flowability being a determining factor.

In this first stage of process optimisation, Erasteel has focussed effort on the process-related issues of reduced interstitial levels and control over the size distribution and morphology of the powders. This effort is being continued with the view of reaching a complete understanding.

Heat treatment optimisation of Hastelloy X superalloy

The final paper reviewed in this session came from Giulio Marchese, Sara Biamino, Matteo Pavese, Daniele Urgues, Mariangela Lombardi and Paolo Fino (Politecnico di Torino, Italy) and Giangranco Vallillo (GE AVIO s.r.l., Italy) and addressed the optimisation of heat treatment of Hastelloy X superalloy, processed by Direct Metal Laser Sintering (or Selective Laser Melting).

Hastelloy X is a widely used superalloy. It is a nickel-chromium-iron-molybdenum alloy with outstanding high temperature strength and oxidation resistance. Given these properties, it is ideal for gas turbine engines, aircraft, industrial furnaces and chemical processing applications, such as pyrolysis tubes and muffles. The microstructure and hardness of Hastelloy X, processed by DMLS, are very different from those achieved in traditional manufacturing and, therefore, the authors considered it to be necessary to specifically study the response to heat treatment.

The reported work has studied the effect of heat treatment on the microstructure and hardness of a Hastelloy X alloy (composition as in Table 3 and particle size distribution between 15 µm and 53 µm) processed by DMLS, using a EOSINT M280 machine, by GE AVIO s.r.l. According to the literature, performing heat treatment can increase grain size and make it possible to control $M_{23}C_6$ carbide precipitation along grain boundaries, which is thought to increase creep resistance. For these reasons, it was considered crucial to study the solution treatment before the investigation of aging treatment, in order to optimise heat treatment parameters.

The as-built samples, provided by AVIO, had a low level of total porosity of about 0.4% ± 0.1%, as measured by optical microscopy. Metallographic assessment of these samples showed that the rapid and localised melting and cooling in the DMLS process created a very fine microstructure, as illustrated in Fig. 10. Along the plane *yz* it is possible to observe the shape of melt pools with their contours.

Solution treatments were then carried out at 1175°C and 1066°C. The influences of the various solution treatments on grain size and hardness are summarised in Table 4. For solution treatments at 1175°C, a reduction of hardness and grain growth can be observed (Table 4). Also, the grain growth reaches a limit after a solution time of one hour. The grains do not grow further with increasing treatment time and the hardness remains constant at its lowest value. By contrast, the heat treatment at 1066°C was insufficient to ensure an effective solution response. In fact, the microstructure remained similar to that of the as-built samples (shown in Fig. 10), as confirmed by the small reduction in hardness observed. Therefore, the chosen treatment for the further aging trials was a solution treatment at 1175°C for 60 minutes.

After this solution treatment, the microstructure is composed of equiaxed grains of gamma phase, twins and dark points that could indicate carbides precipitates in the grains and on the grain boundaries. XRD analysis indicates the presence of gamma phase only with a 3.60 Å lattice parameter, while the carbides have not been identified probably because the levels present are below the sensitivity threshold of the instrument. Even if they are present in small quantities, however, FESEM analysis shows some possible residual carbides in the gamma phase matrix, with an extremely fine size lower than 1 µm (Fig. 11). These microstructures are ideal as a starting point for the aging treatments, since no coarse or large carbides are observed. So, appropriate aging treatments can be determined with the aim of controlling the type and shape of carbide precipitates.

Heat Treatment	HBW 2.5/62.5	$HV_{0.3}$	ASTM Grain size number
as-built	235 ±5	277 ±4	-
solution treated (1175°C, 1 h, water quenched)	148 ±3	197 ±5	5.5
aged 745°C 3 h, air cooled	177 ±6	234 ±7	5.5
aged 745°C 6 h, air cooled	185 ±2	243 ±6	5.5
aged 788°C 3 h, air cooled	171 ±2	229 ±5	5.5
aged 788°C 6 h, air cooled	182 ±2	234±10	5.5

Table 5 Summary of hardness values and grain size obtained with different aging treatments [3]

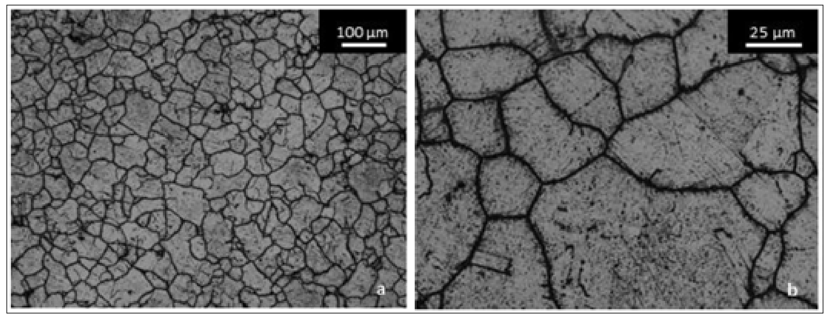


Fig. 12 Optical microscope images of Hastelloy X aged at 745°C for 3 h, after etching [3]

Different aging treatments were performed at 745°C and 788°C for 3 h and 6 h. After the aging treatments, the grain size remains the same, while the hardness increases due to precipitation of carbides, as reported in Table 5. Precipitation of the carbides occurs predominantly along the grain boundaries, but they can also be found within the grains, as shown in Fig. 12. The hardness of the Hastelloy X is seen to increase substantially after an aging treatment of 3 h at 745°C or at 788°C, due to a very homogeneous precipitation of carbides. The hardness obtained is similar to that cited in the literature or in technical sheets for commercial alloys.

An important objective of further work by this group will be the determination of the precipitated carbide type, both by XRD and TEM. This knowledge will allow the tailoring of the heat treatment to obtain an appropriate precipitation of $M_{23}C_6$. The differences between the traditional aging treatment and the one optimised for the DMLS-produced Hastelloy X, and the consequent effect on the mechanical properties at both room and high temperature, will allow DMLS to become a versatile and efficient technique to produce components with this superalloy.

Precision ink jet printing on a powder bed

The first contribution to the Special Processes and Materials session came from Robert Frykholm, Bo-Goran Andersson and Ralf Carlstrom (Höganäs AB) and reported on progress with the company's Digital Metal® technology.

This technology is based on precision ink-jet printing of an organic binder on a powder bed, followed by a separate sintering treatment to obtain final strength of the component. This approach offers a number of benefits over the powder bed AM technologies, which involve melting of powders.

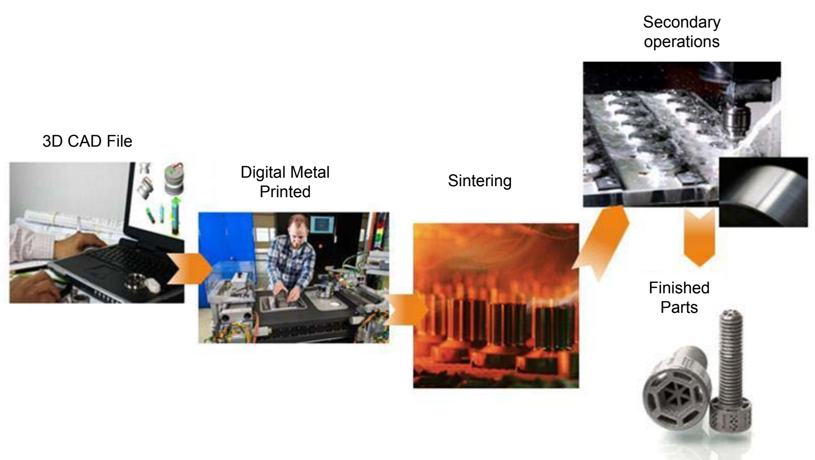


Fig. 13 Overview of the complete Digital Metal process [4]

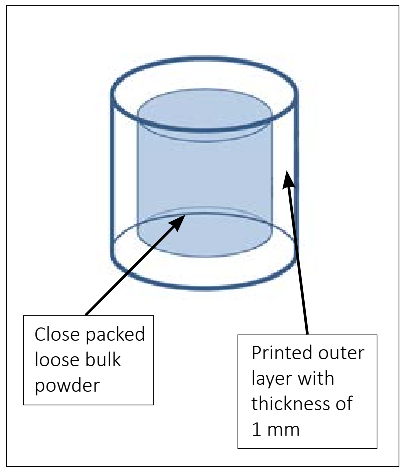


Fig. 14 Principle of shell printing [4]

The whole volume of the build box can be maximised as the components can be packed tightly because no account of thermal conductivity needs to be taken. Also, there is no need, in principle, for building support structures during printing because the components are supported by the powder bed in the build box. As printing of the metal powders occurs at room temperature followed by a separate sintering, there is no heat involved during building and printing can be performed without protective gas. Since no melting takes place during building, green components can be produced with very high detail levels and tolerances. Also, since forming and heat treatment are separated, this allows for a wide materials selection range. The complete Digital Metal process is shown in Fig. 13.

With standard processing of 316L stainless steel in the Digital Metal process, a density level of approximately 96% of theoretical can be achieved. If higher density is desired it is possible to apply Hot Isostatic Pressing (HIP). With this technique, almost full density can be reached. However, there is also an alternative route to obtaining high density and that is by reducing the printed volume of the component. The principle in this case is to print only the surface layer of the component and to allow the bulk of the component to be dense packed loose powder contained by the printed shell. This technique is referred to as shell-printing. Even though the powder in the bulk is loose, the powder particles are close packed and not able to move. The principle of shell-printing is shown in Fig. 14.

As well as the positive effect on density, there are additional benefits with this technique. Since the total printed volume is reduced, both time and the amount of organic additive can be reduced. The fact that the amount of organic additive can be reduced is important when processing elements sensitive to carbon, e.g. Ti-alloys. This makes debinding of components easier and faster, both because the total amount of C needed to be removed is reduced, but also because all C is present in the component surface at the start of the process and does not need to migrate from the bulk.

The reported experimental study was performed with 316L stainless steel powder. Conventional printing and shell-printing were both applied. Sintering of the steel was performed in vacuum or hydrogen at 1360-1380°C for 2 h. Hot Isostatic Pressing was performed at 1150°C for 1.5 h with a pressure of 1000 bar. To investigate the mechanical performance of

"To date, the stainless steel 316L has proved to be the workhorse material in the Digital Metal process"

	Density g/cm³	Tensile strength MPa	stdv	Yield strength MPa	stdv	Elongation (%)	stdv	HRB
316L Standard print	7.67	511	2.3	170	1.2	58	0.74	60
316L Shell print	7.84	528	1.7	175	0.6	57	1.5	62
MPIF 35, MIM, Minimum		450		140		40		
MPIF 35, MIM, Typical	7.6	520		175		50		67

Table 6 Mechanical performance of 316L, processed by Digital Metal technology [4]

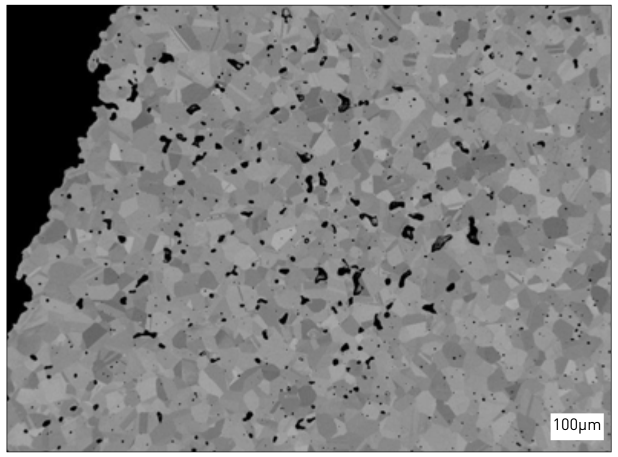


Fig. 15 Pore-and microstructure of surface zone after shell-printing and sintering [4]

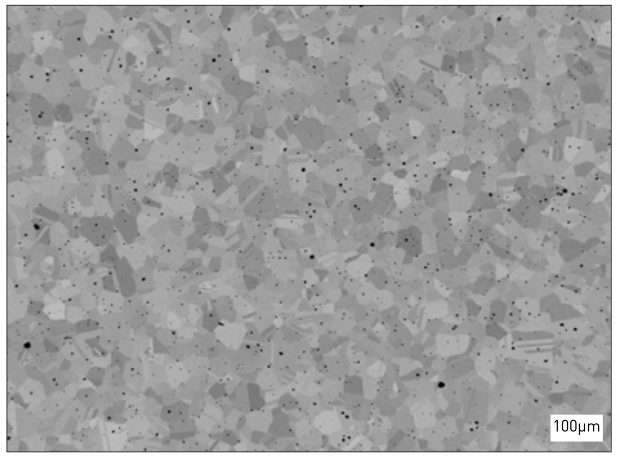


Fig. 16 Pore-and microstructure of bulk after shell-printing and sintering [4]

316L, tensile test bars were produced. To date, the stainless steel 316L has proved to be the workhorse material in the Digital Metal process. It can be processed to close to full density with correct sintering settings. The material is sintered at high temperature, close to the solidus temperature. When sintered in vacuum, a partial pressure of Ar is applied. This is done to reduce the loss of Cr from the surface, which otherwise might occur due to the vapour pressure of Cr. Loss of Cr has to be prevented in order to maintain the corrosion resistance of the steel.

Using the standard process, 316L can be printed and sintered to around 7.7 g/cm³ density (96-97% of theoretical density) (Table 6). To reach higher densities, the sintering temperature could be increased, but this is normally not done since the higher temperature would have a negative effect on achievable tolerances. If higher densities are required, HIP can be performed. A prerequisite for this treatment is that the density of the sintered specimen must be high enough not to have a structure with interconnected porosity. With closed porosity, pressure will be applied uniformly on the outer component surfaces and therefore induce densification. For a standard Digital Metal processed 316L component, the porosity is low enough to allow effective HIP.

To obtain high densification directly in the sintering stage, the shell-printing technique can be applied. The result of applying this process can be seen in Fig. 15. In this case, a cylinder with height 24 mm and diameter 24 mm was produced by printing only a 1 mm thick surface shell. The image shows pore and microstructure after sintering, with the surface shell to the left. As can be seen, the addition of organic constituent has an effect on densification. The surface zone has porosity on the same level as for a standard printed specimen, while the bulk has significantly reduced porosity. This is visualised more effectively in Fig. 16, which displays the structure of the bulk. Only small and evenly distributed pores are present and the densification is almost on the same level as for HIP.

Data from the mechanical testing are given in Table 6 together with MPIF 35 standard data for MIM components. It can be seen that the material is well above the minimum levels and that performance, in fact, matches typical values. There is no large difference between standard and shell printed specimens, although shell-printing offers somewhat higher strength and hardness.

Carbon contents after sintering are shown in Table 7. This table displays a clear effect of the reduced amount of organic constituent in the shell-printing process, with reduction of final C-level from 0.013 wt% down to 0.003 wt%. Comparing with the MPIF 35 standard, it can also be seen that both materials are within the limit for C-content.

	C-level wt.%
316L Standard print	0.013
316L Shell print	0.003
MPIF 35, MIM	0.03 max

Table 7 C-level after sintering [4]

Alternative approaches to densifying printed green parts

The next paper remained with ink-jet printing technology and was presented by Juan Isaza, Claus Aumund-Kopp, Sandra Wieland, Frank Petzoldt, Mathis Bauschulte and Dirk Godlinski (Fraunhofer IFAM, Bremen, Germany). The authors highlighted two alternative approaches to densifying the printed green parts; super-solidus liquid phase sintering to high density or partial sintering without shrinkage followed by infiltration.

The paper reported on case studies aimed at developing innovative applications based on each of these approaches. The first case study addressed the potential for producing complex tools (with conformal cooling channels) by liquid phase sintering of printed parts made from either X190CrVMo20 (M390) or HS 6-5-2 (M2) tool steel. X190VrVMo20's eutectic reaction requires extremely careful control of sintering temperature. At sintering temperatures above 1265°C, the surface of the samples becomes

Specimen	67A and 67B		75A and 75B		79A and 79B	
Debinding	700°C/ 1h and 855°C/ 45min					
Sintering	1100°C / 1h		1200°C / 2 h		1200°C / 3 h	
relative Density of Ti6Al4V	67%		75%		79%	
Soaking time [min]	30	20	30	20	30	20

Table 8 Density of the 3D-printed samples and processing parameters [5]

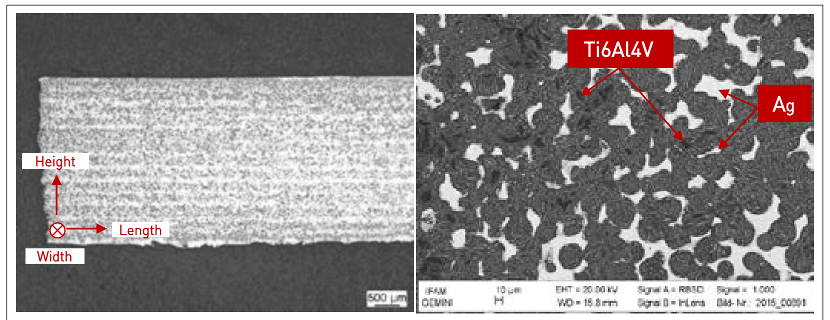


Fig. 17 Microstructure of infiltrated sample 75B [5]

smoother, but the shape begins to deteriorate, because of the high amount of liquid phase. At temperatures below 1260°C, the density and the surface quality decrease because nearly no liquid phase is present. At temperatures around 1263°C, there seems to be an optimum balance between shape retention, surface quality and density.

With additional dwelling steps at different temperatures below the maximum sintering temperature and low heating ramps to ensure shape retention, 99% of theoretical density can be achieved. Another approach to improving the density is to lower the layer thickness of the printing process, reaching slightly higher sintered densities of an additional 0.5%. The hardness after sintering and cooling down is typically between 50 and 55 HRC and can be further improved by heat treatment.

The high speed steel HS 6-5-2 shows two equilibria between melt and solid in its phase diagram. Sintering temperatures in the lower range between 1230°C and 1290°C do not lead to full density in reasonable sintering times. In contrast, a sintering programme in the range of the second equilibrium with a long dwelling time of 90 min at 1320°C followed by a short dwelling time of 15 min at 1330°C leads to a density of 98 to 99% of theoretical density combined with good shape retention and a smooth surface. Lowering the layer thickness to 150 µm compared with 177 µm leads to the same slightly higher sintered densities of an additional 0.5% as observed with the X190CrVMo20 powder.

> *"Another approach to improving the density is to lower the layer thickness of the printing process"*

The surface quality of the parts, which is determined by powder particle size and the surface tension of the liquid phase in sintering, makes secondary finishing operations, at least on functional surfaces, necessary. Nevertheless, large volume machining can at least be avoided and more complex parts, for example with internal opened cavities, can be produced. Hence, applying this AM technology to tool steels could lead to cost savings and shorter production times for tools.

The innovative application, targeted by the infiltration approach, was the manufacture of MRI-compatible medical implants. The aim of the second study was, therefore, to reduce the magnetic susceptibility of titanium while retaining its outstanding material properties. For this, a titanium-silver material was manufactured and tested for MRI compatibility. By combining the paramagnetic titanium (matrix) with the strong diamagnetic silver, the formation of artefacts in MRI should be minimised. Porous samples of alloyed titanium powder (Ti-6Al-4V) were produced by ink-jet printing and were then sintered and infiltrated with silver.

Ti-6Al-4V rods were prepared by means of inkjet-based 3D printing and were subsequently debound and sintered. Titanium gas atomised powder with a median particle size D50 of 38 µm was used. This material had a bulk density of 2.44 g/cm³ and a tap density of 2.71 g/cm³. The binder used during the process is sold under the trade name Ex1-Lab-Binder-02. Due to the shrinkage behaviour during sintering, two different geometries were designed for printing: Ø 4 x 50 mm³ for density levels of 75% and 67% and Ø 4.3 x 56 mm³ for a density level of 79%. Table 8 shows the debinding and sintering basic data for the different samples.

In total, six samples were infiltrated (two samples for each density level) at 980°C with two different soaking times (30 min and 20 min) in the furnace. Silver powder (99.9 %) with a particle size distribution of -10+20 µm was used for the infiltration. Due to the variations in shrinkage behaviour in the set of samples, they were manually post-processed after infiltration to achieve a uniform geometry for subsequent characterisation. The microstructural analyses on all of the samples showed that, after the infiltration, no porosity was left. In the image taken by optical microscope at low magnification (Fig. 17, left), the layered structure originating from the printing process is clearly visible. The higher magnification in REM (Fig. 17, right) reveals that, during the infiltration process, diffusion also takes place and additional phases are formed from the original Ti-6Al-4V and silver. According to XRD assessments, this is mainly TiAg. The amount and distribution of the phases present varies depending on the density of the titanium and the soaking time.

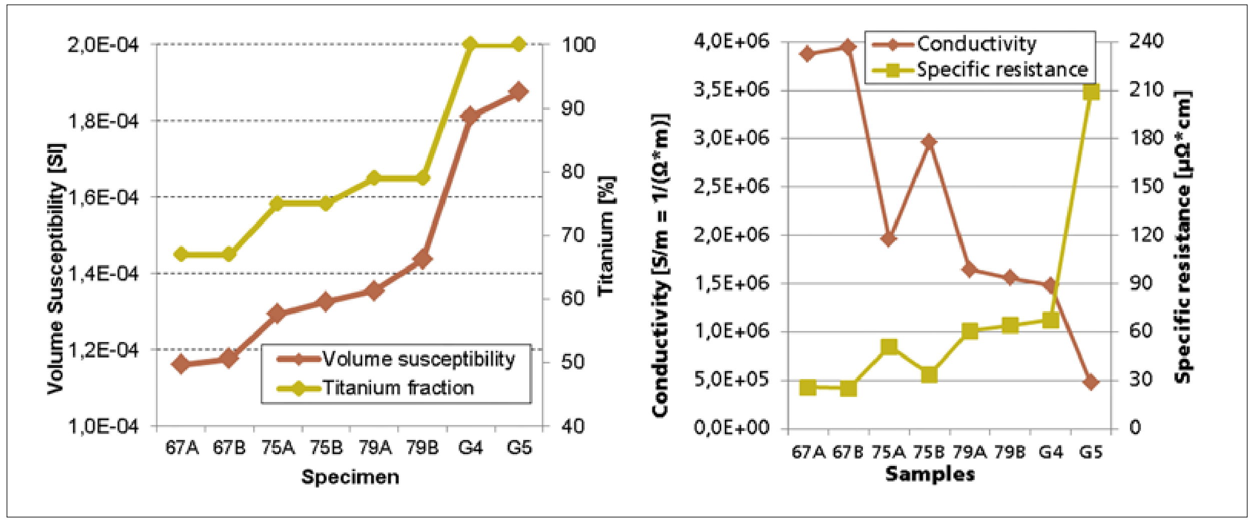


Fig. 18 left) Correlation between titanium content and susceptibility; right) electrical conductivity of the test samples [5]

The susceptibility of the samples was determined after post-processing. For each sample, three values were measured and then averaged. The resulting mass susceptibility was calculated from the predetermined density for the samples and the measured volume susceptibility. By combining the original titanium with the diamagnetic silver, it was possible to reduce the magnetic susceptibility of the material. A silver content of 33 vol. % (53 wt.%) leads to a reduction of volume susceptibility of approximately 38%. At a lower silver percentage 25 vol.% (45 wt.%), the reduction of volume susceptibility was up to 29%. The correlation between the titanium content and susceptibility can be seen in Fig. 18 (left). It was also noted that the susceptibility is higher with shorter soaking times.

The electrical conductivity of the samples was determined by four-point measurement. With increasing silver content, it is possible to trace a significant increase in the conductivity compared to solid material (Grade 5) (Fig. 18 right).

To determine the artefact behaviour of the samples in the MRI, scans of the samples were made in a water phantom. The samples were then aligned perpendicular to the static field of the tomograph. To visualise the distortion field caused by

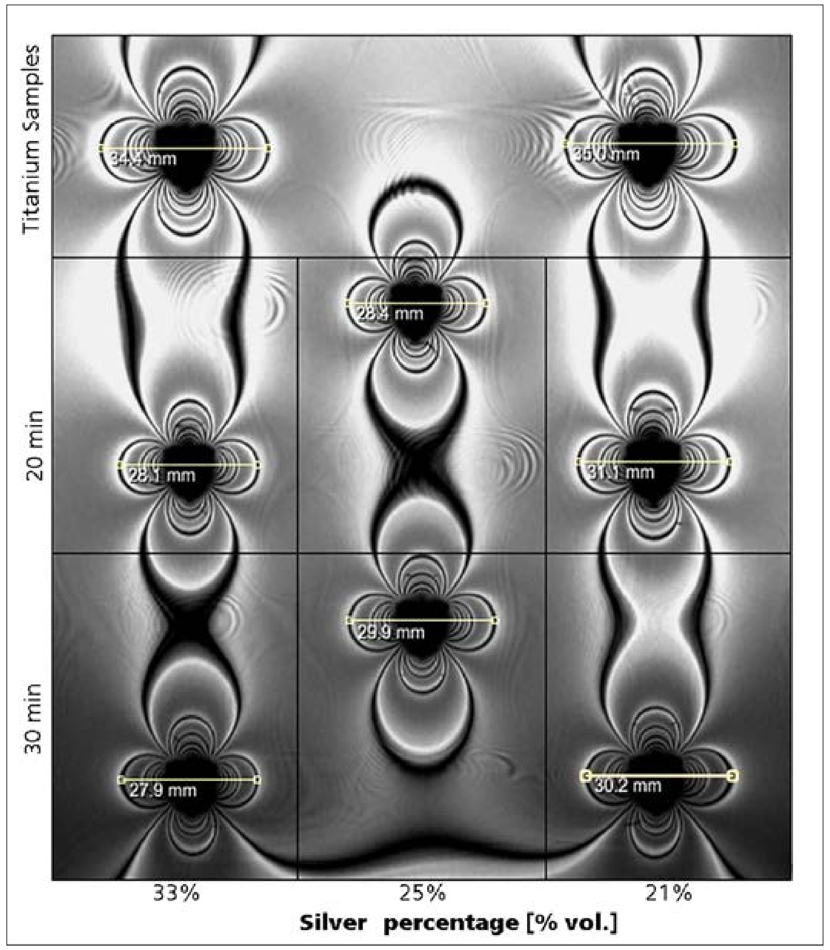
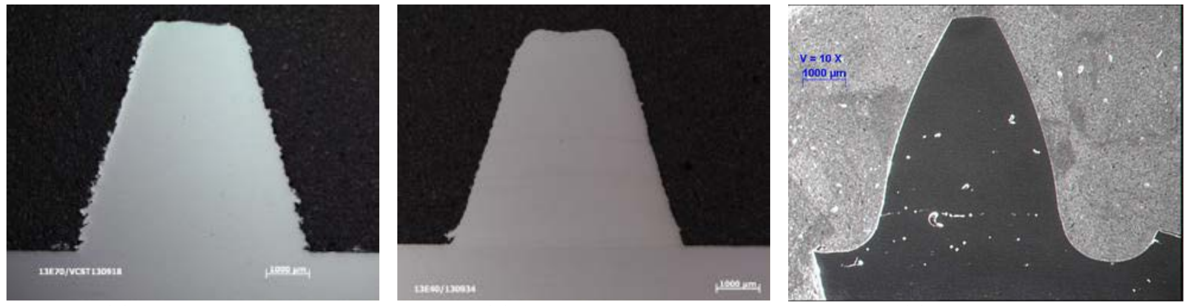


Fig. 19 Distortion fields caused by the samples [5]



(a) Parameter set 2
low alloy steel; as-built

(b) Parameter set 2
X42Cr13 steel; as-built

(c) Parameter set 1
Low alloy steel; machined

Fig. 20 Cross sections of teeth after Laser Metal Deposition [6]

the samples, a TRUFI sequence (True Fast Imaging With steady precession) was used.

All samples show strong field distortions during measurement. In order to distinguish between the samples, the diameter of the artefact rings perpendicular to the field direction was measured. The evaluation of all image files was carried out using image processing software. In order to consider the geometry of the samples, the distance of the artefact boundary was calculated to the sample contour being perpendicular to the field direction. The diameter of the distortion is highest in the solid material samples (see Fig 19, upper left for Grade 5 and Fig. 19, upper right for Grade 4) and decreases in the infiltrated samples with increasing silver content from right to left.

It has been demonstrated that, by combining Ti-6Al-4V, with its excellent mechanical properties, with diamagnetic silver, the magnetic susceptibility can be reduced as well as the artefact distortion, opening a new dimension in the production of special medical devices made from titanium. Although images free from artefacts have not been achieved with the presented combination, the significance of the artefact reduction will need to be studied for specific applications.

Process development of gears manufactured by Laser Metal Deposition

Finally, Marleen Rombouts and Gert Maes (Vito, Belgium), Freddy Varspringer (VCST, Belgium) and Scott Wilson (Oerlikon Metco, Switzerland) turned the attention to the Laser Metal Deposition (LMD) process in considering this process's use for fast production of prototype automotive gears. The drawback of the currently applied production method for such parts is the long delivery time (minimum 6-8 weeks) of the hard metal tooling required to hob the shape of the teeth. Typical failure modes for gears are tooth root fatigue fracture and pitting wear on the tooth flanks (surface contact fatigue).

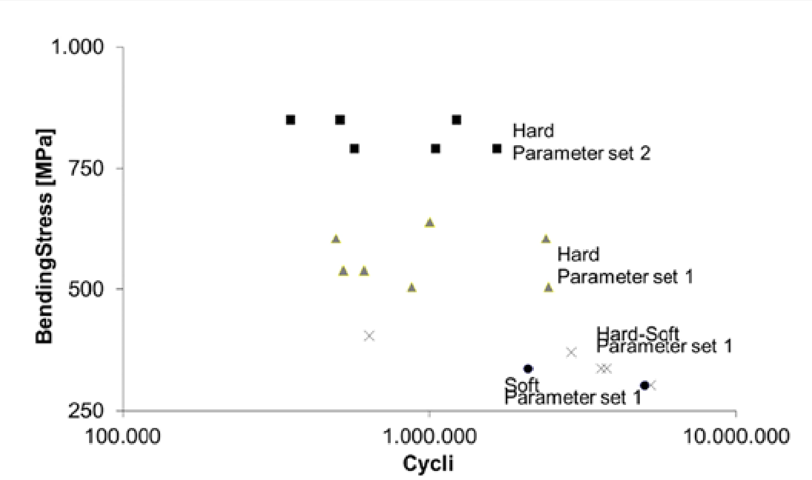


Fig. 21 Tooth bending fatigue test results [6]

Laser metal deposition has been performed at Vito on a CNC machine with rotational axis, 1kW fibre laser, processing optics, powder feeder and coaxial cladding nozzle. Two different parameter sets have been used for production; only set 2 resulted in nearly 100% dense teeth, while the material deposited using set 1 contained a significant amount of porosity (the details of these parameter sets were not, however, divulged in the paper). The individual teeth have been built up by laser metal deposition on a S355 steel shaft with diameter of about 60 mm. The dimensions of the teeth are in the range of 5-10 mm high, 2-10 mm wide and 20 mm along the cylindrical axis.

As feedstock, different powders from Oerlikon Metco, including low alloy steel (designated as 'soft') and X42Cr13 steel (designated as 'hard'), have been processed. Gears combining both materials have also been manufactured ('hard-soft'). The LMD gears have all been tested in the as-built condition.

Using parameter set 1, lack-of fusion defects could be observed on the cross sections, while parameter set 2 resulted in almost 100% dense deposits (Fig. 20). The deposits at optimum processing conditions were characterised by good bonding, low dilution and were almost defect-free (occasionally a small spherical pore). The roughness of the side surface was significantly higher for the low alloy steel deposit.

The average hardness of the low alloy steel after LMD was around 280 HV, while the X42Cr13 ('hard') steel resulted in a deposit with average hardness of 550-600 HV. As a reference, typical hardness values for conventionally manufactured 16MnCr5 gears are 350 HV in the core and 700 HV in the carburised surface layer.

The results for tooth bending fatigue of the LMD gears are presented in Fig. 21. For parameter set 1, a higher bending strength during cyclic loading was obtained for the 'hard' steel than for the 'soft' low alloy steel. A slight improvement in bending strength was obtained for the gear consisting of the 'soft' steel in the core region and the 'hard' steel at the edges compared to the fully 'soft' steel gear. A significant improvement in bending strength was obtained by altering the processing conditions from parameter set 1 to parameter set 2, as a result of the absence of pores in the latter case. At optimum processing conditions, a fatigue bending strength of 800-850 MPa has been reached with the gear consisting completely of 'hard' steel. As a reference, case hardened 16MnCr5 steel has a bending stress of around 860 MPa.

Gears, produced using parameter sets 1 and 2 and the hard steel powder, have been subjected to surface contact fatigue tests (see Fig. 22). All tests were stopped before failure occurred and before the normal ending of the test, in order to enable an intermediate evaluation of the gears. These tests indicate an allowable contact stress of around 1100 MPa. As a reference, an allowable contact of 1500 MPa can be expected from case hardened 16MnCr5 steel. The authors reached the final conclusions that the fatigue strengths, under bending and contact stress, already achieved have satisfied

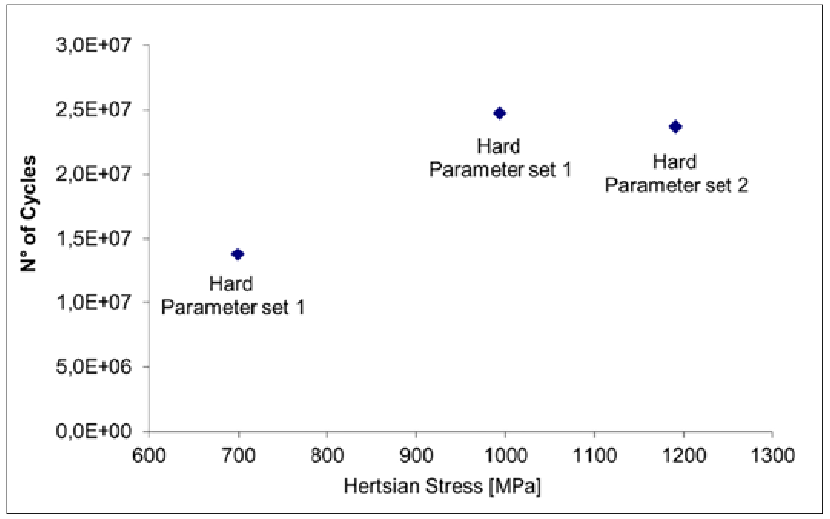


Fig. 22 Surface contact fatigue test results [6]

the requirement for prototype gears, but that further analysis of the dynamic mechanical behaviour of gears, built using other powders and with additional heat treatments, is on-going.

Author

David Whittaker
DW Associates
231 Coalway Road, Wolverhampton
WV3 7NG, United Kingdom
Tel: +44 (0)1902 338498
Email: whittakerd4@gmail.com

References

[1] H Brodin, Heat Treatment and Mechanical Testing of a Selective Melted Superalloy, as presented at Euro PM2015, Reims, France, October 4-7 2015.

[2] P Vikner, R Giraud, C Mayer and M Sarasola, Towards Improved Quality and Production Capacity for Ni based Powders for Additive Manufacturing, , as presented at Euro PM2015, Reims, France, October 4-7 2015.

[3] G Marchese, S Biamino, M Pavese, D Urgues, M Lombardi, P Fino and G Vallillo, Heat Treatment Optimization of Hastelloy X Superalloy Produced by Direct Metal Laser Sintering, , as presented at Euro PM2015, Reims, France, October 4-7 2015.

[4] R Frykholm, B-G Andersson and R Carlstrom, Progress of precision ink jet printing on a powder bed, , as presented at Euro PM2015, Reims, France, October 4-7 2015.

[5] J Isaza, C Aumund-Kopp, S Wieland, F Petzoldt, M Bauschulte and D Godlinski, New Materials and Applications by 3D-Printing for Innovative Approaches, , as presented at Euro PM2015, Reims, France, October 4-7 2015.

[6] M Rombouts, G Maes, F Varspringer and S Wilson, Process Development and Material Properties of Gears Manufactured by Laser Metal Deposition, as presented at Euro PM2015, Reims, France, October 4-7 2015.

World PM2016

In 2016, the Euro PM conference becomes the PM2016 Powder Metallurgy World Congress and Exhibition, taking place in Hamburg, Germany, October 9-13, 2016. The event will include a number of technical sessions focussed exclusively on metal AM. The PM world congress takes place every two years and rotates between Europe, Asia and North America. To find out more visit www.worldpm2016.com

industry events

2016

3D Printing Electronics Conference
January 19, Eindhoven, The Netherlands
www.3dprintingelectronicsconference.com

3D Medtech Printing Conference
January 27, Maastricht, The Netherlands
www.3dmedtechprintingconference.com

APS Meetings
February 3-4, Lyon, France
www.apsmeetings.com

PM 16 International Conference
February 18-20, Pune, India
www.pmai.in/pm16

METAV 2016
February 23-27, Dusseldorf, Germany
www.metav.com

MIM2016 International Conference on Injection Moulding of Metals, Ceramics and Carbides
March 7-9, Irvine, USA
www.mpif.org/Meetings/2016/MIM2016

TCT Asia + Personalize
March 10–12, Shanghai, China
www.tctasia.com.cn/en/

Additive Manufacturing Users Group Conference
April 3-7, St. Louis, Missouri, USA
www.additivemanufacturingusersgroup.com

PM China 2016
April 27-29, Shanghai, China
www.cn-pmexpo.com

Rapid 2016
May 16-19, Orlando, USA
www.rapid3devent.com

POWDERMET2016 Conference on Powder Metallurgy & Particulate Materials
June 5–8, Boston, USA
www.mpif.org

AMPM2016 Additive Manufacturing with Powder Metallurgy
June 5–7, Boston, USA
www.mpif.org

Additive Manufacturing and 3D Printing International Conference
July 12–14, Nottingham, UK
www.am-conference.com

AM3D Additive Manufacturing + 3D Printing Conference & Expo
August 21–24, Charlotte, USA
www.asme.org/events/am3d

TCT Show + Personalize
September 28-29, Birmingham, UK
www.tctshow.com

3D Print
October 4-5, Lyon,France
www.3dprint-exhibition.com

6th International Conference on Additive Manufacturing Technologies AM 2016
October 6–7, Bangalore, India
www.amsi.org.in

PM2016 Powder Metallurgy World Congress & Exhibition
October 9-13, Hamburg, Germany
www.epma.com/world-pm2016

MS&T 2016 - Additive Manufacturing of Composites and Complex Materials
October 23–27, Salt Lake City, USA
www.matscitech.org

Formnext 2016
November 15-18, Frankfurt, Germany
www.formnext.com

Euromold 2016
December 6-9, Düsseldorf, Germany
euromold.com

Additive Manufacturing Americas 2016
7-9 December 2016, Pasadena, USA
www.amshow-americas.com

Event listings If you would like to see your metal AM related event listed please contact Paul Whittaker:
email: paul@inovar-communications.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

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