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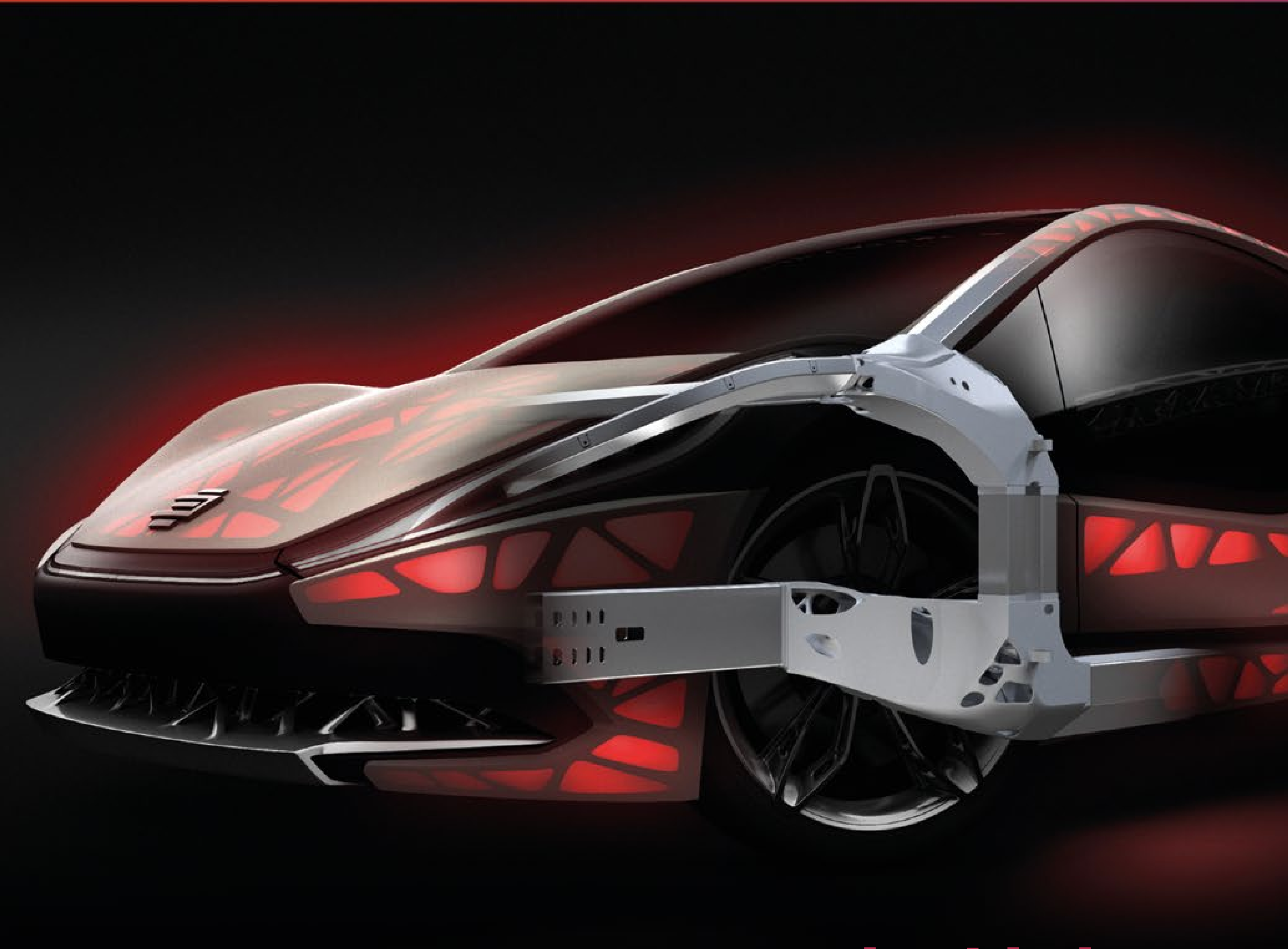
THE MAGAZINE FOR THE METAL ADDITIVE MANUFACTURING INDUSTRY

METAL AM



in this issue

STANDARDS IN METAL AM
COMPANY VISIT: GKN SINTER METALS
OPPORTUNITIES IN AUTOMOTIVE

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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

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METAL
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New opportunities for AM in the automotive sector

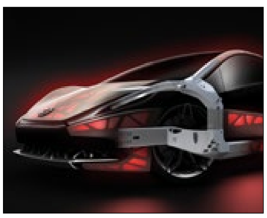
In this issue of *Metal AM* magazine we consider the opportunities for metal Additive Manufacturing in the automotive sector. Whilst the technology has become widely accepted by the automotive industry as a method for prototyping and for the manufacture of tooling, there is a growing belief that it can also be successfully used for the series production of components.

GKN Sinter Metals is the world's largest manufacturer of metal powder-based components for the automotive industry, producing a staggering 11 million Powder Metallurgy parts per day. Additive Manufacturing isn't new to GKN, with the company's aerospace division in particular operating a range of metal AM technologies for the production of series components. Our visit to GKN Sinter Metal's AM facility in Germany reveals how the company is approaching the development of AM for the automotive sector (page 55).

A second automotive focused article presents the concept of using metal Additive Manufacturing to produce components for the next generation of automotive spaceframes, as well as discussing in broader terms what hurdles need to be overcome to enable the greater use of AM in vehicles (page 63).

Acceptance of metal AM in sectors such as automotive relies heavily on the necessary standards being in place. We review the published standards to-date and outline the main areas of current activity (page 45).

Nick Williams
Managing Director



Cover image
The "EDAG Light Cocoon" concept car features a bionically optimised and additively manufactured vehicle structure

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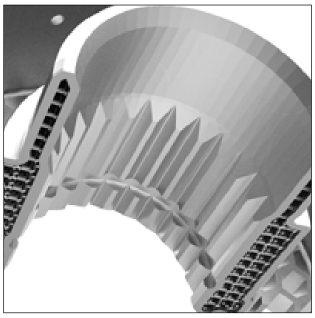

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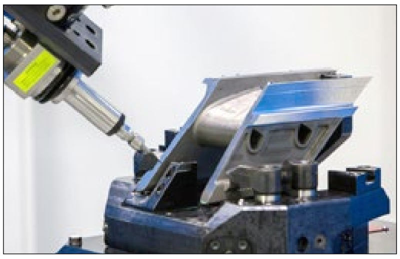
GE Oil & Gas opens new metal Additive Manufacturing production line



A robot automatically polishes a nozzle component (Courtesy GE Oil & Gas)

GE Oil & Gas has announced that a new metal Additive Manufacturing line has been established to produce high-tech end burners for gas turbine combustion chambers at its plant in Talamona, Italy. The company also announced that a completely automated production line, incorporating advanced anthropomorphic robots, has been established for the manufacture of nozzles at the facility.

After extensive validation of Additive Manufacturing during prototyping of the NovaLT16 gas turbine, GE stated that it decided to move the technology into full production, leveraging the design enhancement capabilities, cycle time reduction and improved product quality.

"The use of automated production and new techniques like Additive Manufacturing allow us to develop parts and products more efficiently, precisely and cost-effectively, accelerating the speed at which we can bring product to market," stated Davide Marrani, General Manager Manufacturing for business Turbomachinery Solutions at GE Oil & Gas.

The official unveiling of the upgraded turbine and compressor components manufacturing facility is the result of some €10 million investment over two years. The new production lines are already working and will be fully operational by the start of 2017.

"Our investment in these technologies at this site reflects our ongoing commitment to combine cutting edge technology and new manufacturing processes to lower cost and accelerate the innovation, speed and performance of industrial products," added Marrani.

GE has been investing and growing its work in Additive Manufacturing across R&D sites spanning Bangalore (India), Niskayuna (Japan), Michigan (United States), Shanghai (China) and Munich (Germany). The applications for that work span the entire GE footprint, including the use of cobalt-chromium alloys for jet engines that were originally used for joint replacements and dental implants. Talamona coming online brings years of automation and 3D printing development and investment to fruition, the company stated.

GE Oil & Gas opened an additive lab in Florence, Italy, in 2013 with the installation of its first Direct Metal Laser Melting machine. Since then, the laboratory has grown its capabilities thanks to the addition of two further machines for the development of Turbomachinery components and special alloys.

www.ge.com

Further expansion at AP&C as new powder manufacturing plant announced

Arcam AB, Sweden, has announced that its metal powder manufacturing subsidiary AP&C in Montreal, Canada, is adding further capacity by building a new powder manufacturing plant. It was stated that, when completed, total production capacity will reach at least 750 tons per year.

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

The new capacity increase follows on significant growth in 2015 and 2016 and a surge in demand for AP&C's high quality titanium powders for additive manufacturing.

"With this investment we are committing to supply our present and future customers with superior quality materials to meet the high manufacturing standards of the biomedical and aerospace industries. With the powder plant and atomising technology advancements, AP&C will add significant capacity in 2017 and onwards," started Alain Dupont, President of AP&C.

Plasma atomisation produces premium quality spherical powders of reactive and high melting point materials such as titanium. The process offers the highest purity possible, producing highly spherical particles and minimal satellite content. Plasma atomised powder exhibits exceptional flowability and packing properties.

www.arcam.com
www.advancedpowders.com

Wohlers Report states AM industry grew 25.9% in 2015

According to the Wohlers Report 2016, published by Wohlers Associates, the Additive Manufacturing industry (consisting of all AM products and services worldwide), grew 25.9% (CAGR) to $5.165 billion in 2015. The CAGR for the previous three years was 33.8%.

Wohlers Associates reports that despite challenges, growth continued in many segments of the diverse industry, particularly in metal AM and the desktop 3D printer segments. In 2015, 62 manufacturers sold industrial-grade AM systems (valued at more than $5,000), compared to 49 in 2014, and twice as many as the 31 companies that sold industrial systems in 2011. All of these companies, and many others, are profiled in Wohlers Report 2016.

The 335-page Wohlers Report 2016 provides an in-depth review and analysis of the worldwide industry. It includes growth, competitive products and services and the future outlook. The report covers the technology's history, applications, processes, materials and equipment manufacturers. It documents developments in R&D, investment and collaborative activities in government, academia and industry.

www.wohlersassociates.com

Premium Aerotec begins series production of titanium components for Airbus

Premium Aerotec, headquartered in Augsburg, Germany, has announced it will begin the series production of metal additive manufactured parts for the Airbus Group at its Varel site in Friesland, Germany. The company has constructed a new production hall for the Additive Manufacturing of titanium parts in Varel and recently signed a cooperation agreement with Concept Laser as premium supplier for the machinery and plant technology.

Premium Aerotec will begin producing a double-walled pipe elbow used in the fuel system of the Airbus A400M transport aircraft. This complex part was previously produced from individual cast parts which were then welded together to form one assembly. According to Peter Sander, Head of Emerging Technologies and Concepts at Airbus, Airbus is planning to print one tonne of metal powder a month in 2018.

The new facility currently has two M2 cusing multilaser machines and one X line 1000R machine supplied by Concept Laser. "By the middle of 2016, another X line 2000R will be added. It features what is currently the world's largest build envelope (800 x 400 x 500 mm) in the field of powder-bed-based laser melting and is also equipped with 2 x 1000 W lasers," stated Gerd Weber, Site Manager of Premium Aerotec in Varel.

The cooperation agreement signed between Premium Aerotec and Concept Laser is set to promote further industrialisation of the laser melting process for applications in aviation as well the further development of plant and process technology, QA systems and the qualification of new powder alloys.

"The fact that we have been chosen as premium supplier to Premium Aerotec fills us with pride and demonstrates to us that we are on the right path," stated Frank Herzog, CEO and President of Concept Laser GmbH. "This cooperation marks an important milestone for the industrialisation of 3D metal printing in aircraft construction and undoubtedly also sends a signal to other industries."

www.concept-laser.com

Concept Laser machines in the new production hall in Varel (Image courtesy Premium Aerotec GmbH)

Metalysis and K Home partner to scale up production of titanium powder

Metalysis, based in Rotherham, UK, has announced a new partnership with K Home International, an engineering and design consultancy specialising in the primary metals industry headquartered in Stockton-on-Tees, UK. It was stated that the new partnership will pave the way for a significant scale-up in production of titanium powder developed through Metalysis' patented process, which lowers costs and produces tailored powders for AM customers.

Metalysis recently announced that it had secured £20 million of new investment, with Iluka Resources and Woodford Patient Capital Trust injecting funds into the expansion of the company's production and development capabilities. This agreement will see K Home become Metalysis' preferred engineering partner, providing additional expertise to support the drive towards commercial-scale delivery.

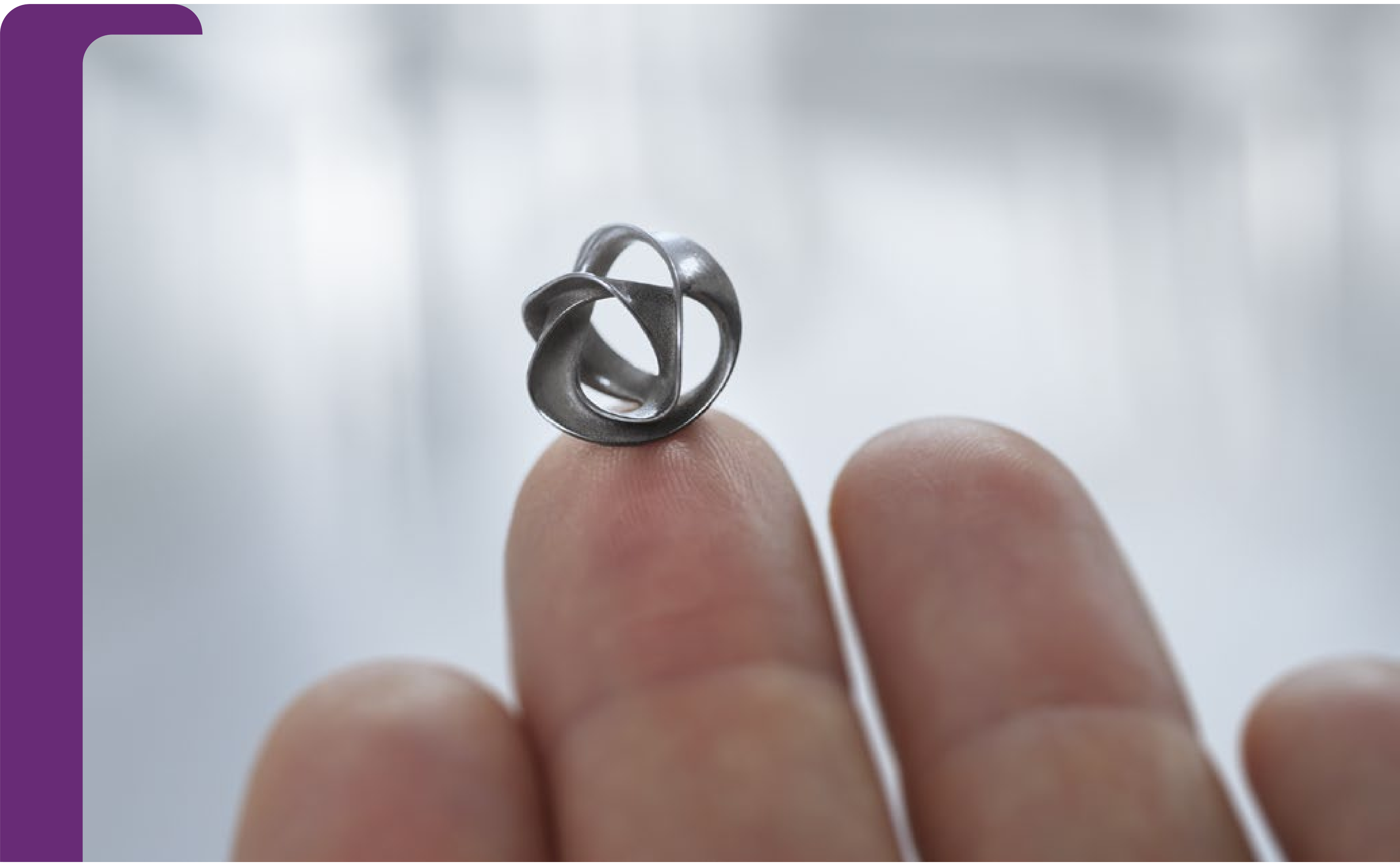
Drawing on the experience of partnering on a number of assignments during recent years, K Home will help to expand the commercial implementation of Metalysis' current technologies, bringing skills and resources to enhance the design, building and operation of commercial production facilities.

Metalysis' technology transforms ores directly into metal powders using electrolysis. This technique can be used to lower the cost of producing high value metal powders such as titanium and tantalum. High grade and uniform, the lower-cost powders suit a wide variety of industrial AM processes, which are currently being trialed and implemented across the aerospace, automotive and biomedical engineering industries.

"This partnership represents a very exciting opportunity to bring together such immense, complementary expertise to expand and strengthen our production capacity," stated Dion Vaughan, CEO of Metalysis. "This combined experience, underpinned by a recent injection of investment, represents a powerful platform for growth, which will enable us to deliver greater volumes of product for our customers and support further innovation in new sectors going forward."

Andrew Home, CEO of K Home International, added, "Bringing together our team with our partners at Metalysis represents a fantastic opportunity to build on the success of numerous projects that we have collectively delivered over the past few years. We hope that by working together we can drive Metalysis' patented techniques of metal production into new sectors and draw on our collective experience to expand our reach into new and broader international markets."

www.metalysis.com | www.khe.co.uk




Alcoa to supply metal AM fuselage and engine parts to Airbus

Alcoa has entered into an agreement with Airbus to supply additive manufactured titanium fuselage and engine pylon components for Airbus commercial aircraft.

"We are proud to partner with Airbus to help pave the way to the future of aerospace development and manufacturing," stated Alcoa Chairman and Chief Executive Officer Klaus Kleinfeld. "The unique combination of our multi-material alloy development expertise, powder production capabilities, aerospace manufacturing strength and product qualification know-how position us to lead in this exciting, emerging space."

The agreement will draw on Alcoa's aerospace experience and new technologies gained through the recent acquisition of RTI International Metals. Alcoa also recently invested in Additive Manufacturing and metallic powder production capabilities at its technical centre outside Pittsburgh, Pennsylvania, USA.

Alcoa stated it will employ advanced CT scan and Hot Isostatic Pressing capabilities at its advanced aerospace facility in Whitehall, Michigan. Alcoa today owns and operates one of the largest aerospace HIP technology complexes in the world.

www.alcoa.com

Renishaw opens new AM Solutions Centre in India

Renishaw has announced the opening of a new Additive Manufacturing Solutions Centre in Pune, India. The facility will be equipped with its latest AM systems and provide an environment in which customers can expand their knowledge and confidence in using AM technology.

Renishaw sees the new Indian centre as a cornerstone in its ambition to be a major contributor to the adoption of AM in the Indian manufacturing sector. "We are delighted to be opening the first Solutions Centre in India. The thrust of the Additive Manufacturing centres is to create a platform on which to work in close partnership with our customers to help them realise the benefits of AM in their products and manufacturing processes," stated Rhydian Pountney, Renishaw's Director responsible for Indian Sales and Marketing Operations.

"Renishaw's vision is to make AM a mainstream manufacturing technology, used in series production of high performance parts for aerospace, medical, automotive, oil & gas, mould & die and consumer products. The technology will enable companies to design and make innovative products with spectacular gains in performance and efficiency," added Clive Martell, Head of Global Additive Manufacturing.

www.renishaw.com

New $39M Additive Manufacturing centre at GE


After printing the metal parts are placed inside curing ovens filled with argon or nitrogen (Image: GE Reports/Chris New)

GE has opened a new manufacturing facility with the aim to drive innovation and the implementation of Additive Manufacturing across the company. The Centre for Additive Technology Advancement (CATA), located near Pittsburgh in Findlay Township, Pennsylvania, USA, will focus on developing and implementing industrial Additive Manufacturing applications from which all GE businesses and customers will benefit.

The new facility represents a $39 million investment over three years and will result in the creation of 50 engineering jobs initially, in disciplines ranging from mechanical and electrical to systems and software engineering. The site is designed as an innovation hub, offering training and development in both design and applications.

"Today's opening is strong evidence that GE is leading the digital transformation of industry, starting with a hub for the advancement of Additive Manufacturing techniques," stated GE Chief Productivity Officer Philippe Cochet. "The application of insights from digital connectivity in collaboration with intelligent devices will elevate the skills of our workforce, streamline productivity and enhance product development overall. This represents a new era of manufacturing."

GE is organised around a global exchange of knowledge known as the GE Store, through which each business shares and accesses the same technology, markets, structure and intellect. It is stated that each invention further fuels innovation and application across the company's industrial sectors.

www.ge.com

H C Starck invests in processing technology for specialised refractory metal AM powders

H C Starck has announced it has invested in state-of-the-art processing capabilities to manufacture specialised refractory metal powders for Additive Manufacturing. The company's Fabricated Products Division (FPD) now offers spheroidised refractory metal powders with tailored chemistry and particle size distribution.

H.C. Starck offers molybdenum and tungsten spherical powders optimised for Additive Manufacturing as well as adapted for specific applications based on customer requirements.

"H C Starck is excited to offer its refractory metal powders to the rapidly growing Additive Manufacturing industry. This presents an opportunity for us to expand our core competencies in refractory metals and alloys beyond traditional manufacturing operations used in the fabrication of our products," stated Dmitry Shashkov, Member of H C Starck's Executive Board and Head of the Fabricated Products Division.

"As a leading global supplier of high performance technology metals, H C Starck now offers spherical powders as a natural extension of our vertically integrated fabricated products business. Investment in new processing technology enables us to help our customers meet their unique and demanding challenges in Additive Manufacturing. We are working with customers in several industries, including medical and industrial imaging, nuclear and thermo-nuclear energy and various aerospace related components, where we are global players."

H C Starck's new powder products are engineered for enhanced processability and product performance when utilised with popular Additive Manufacturing techniques such as binder jet, directed energy deposition and powder bed fusion. It is claimed that the inherent spherical shape of H C Starck's powders results in improved flowability and high apparent density, while meeting the stringent purity level demanded by customer and application needs.

The H C Starck Group is a leading global supplier of technology metals and technical ceramics with facilities in Europe, North America and Asia, supplying key sectors in electronics, chemical processing, automotive, medical technology, aerospace, defence, energy and environmental technology, mechanical engineering and tool making.

www.hcstarck.com

Ultrafine gas atomised powders available from Atomising Systems

Atomising Systems Limited, Sheffield, UK, has announced that significant research and development work has been undertaken on its gas atomiser systems to address the increasing market for ultrafine gas atomised powders. Following work to improve the tundish system, the 200 kg batch capacity gas atomiser has now been upgraded with a high power gas heater allowing much higher atomising gas temperatures to be achieved.

Coupled with extensive work on ASL's gas atomising nozzle system, the upgrades enables the production of stainless steels with a median particle size of less than 20 microns. Further investment in uprated sieving and classification systems also allows ASL to undertake powder separations from over 100 microns down to less than 5 microns. With these upgrades ASL states that it has more than doubled its production capacity for the finest grades.

It was announced that the company's quality control laboratory has also received a significant boost with a new Malvern Mastersizer, a total oxygen determination instrument, a compaction press and tensometer for green determination of water atomised powders and an XRF chemical analyser. All are now in operation, assuring the quality and consistency of the ultrafine gas atomised powders.

"While a massive increase in orders for water atomised powders has kept us very busy, we have not neglected to develop our capability to serve our gas atomised powder clients with new grades for Metal Injection Moulding, Additive Manufacturing, Hot Isostatic Pressing and thermal spray processes amongst others. These investments are already proving to be extremely beneficial," stated Simon Dunkley, ASL's Managing Director.

"This QC laboratory investment of well over £200,000, coupled with the recruitment of extra laboratory staff, ensures ASL can provide a QC service exceeding that expected of our demanding clients."

www.atomising.co.uk

Gas atomising at Atomising Systems Limited

AMUG 2016 Conference: Record delegate numbers in St Louis

The annual conference of the Additive Manufacturing Users Group (AMUG) took place in St Louis, Missouri, USA, from April 3-7, 2016. The event has grown over many years into a highly respected technical conference and exhibition with a strong focus on encouraging networking between users of AM technology.

This year's event attracted 1,061 attendees, a 36% increase on 2015. The continued growth of the event is, in part, a reflection of the continuing growth of the AM industry as a whole, however the event's unique style and its focus on AM users has both ensured a loyal following whilst drawing new faces into the group. Notably there was a strong metals focus at this year's event, reflected in the both the technical sessions and exhibition.

AMUG's origins date back to the early 1990s when the founding group was called 3D Systems North American Stereolithography Users Group. This group focused solely on the advancement of stereolithography for the owners and operators of 3D Systems' equipment. Today, AMUG's mission is to educate and support users of all Additive Manufacturing technologies. The primary charter of the group remains the same, but its members are much more diversified, global and focused in advancing Additive Manufacturing technology for series production as well as prototyping.

For readers unfamiliar with the AMUG conference, two aspects stand out. Firstly, the event is organised by volunteers whose careers are closely associated with the AM industry. The passion and enthusiasm of the volunteers, however, is never at the expense of professional organisation and an appreciation that participants are there to learn and do business is never far from the surface.

The second aspect of the event that will come as a surprise to many newcomers is the hospitality. Such an abundance of food and drink is of course only made possible through support of 'diamond' sponsors that included 3D Systems, Carbon, Concept Laser, ExOne, GE, HP, Renishaw, SLM Solutions, Somos and Stratasys. The aim and the result of this is that over nearly a week you are regularly placed in a position to network informally with peers and industry leaders.

Mark Barfoot, the outgoing President of AMUG, stated, "On behalf of the board, I want to thank everyone that helped make that event such a great success. We want to thank our exhibitors and sponsors that help fund the event, but more importantly, provide top-notch training sessions specific to their products."

"We also couldn't be a success without the work of the board, global ambassadors, liaisons, track leaders, keynotes, presenters, moderators and everyone else that participated in various ways. You are what really makes the AMUG event unique with your passion and support of the industry and our group. I want to stress what I said in my opening and closing remarks at the conference: our efforts go beyond the once-a-year conference. The conference educates, energises, excites so that each of you can be AM champions within your companies and throughout industry."

More than 1000 participants attended AMUG 2016 (Photo AMUG)

Panel discussions with industry leaders

The team from *Metal Additive Manufacturing* magazine was delighted to be able to attend AMUG as a Gold Sponsor and look forward to the event's continued success in 2017.

AMUG's President and board members

AMUG has announced that Steve Deak (GE Aviation) has been selected to replace Mark Barfoot as President, following Barfoot's two terms in the role. Paul Bates, who served as Deputy Vice President will replace Deak as Vice President. The user group also announced its 2016 - 2017 board, elected by AMUG members during the 2016 AMUG conference.

Deak served as president of 3DSUG, the predecessor of AMUG, in 2000, 2004 and 2005. "I am honoured to serve once again as president of AMUG, following my two terms as vice president," stated Deak. "Our board has great experience coupled with strong sense of purpose for the organisation and passion for our members. I look forward to leading AMUG and engaging more of our members in preparation for the 2017 conference."

The AMUG board's primary responsibility is to oversee the April 2017 conference. In a vote of confidence, the members accepted the standing board's recommendations, which leave the board relatively unchanged. The elected board accepted the appointments recommended by the outgoing board for the positions of Chairman, Treasurer, Deputy Vice Presidents and AM Industry Advisor. The 2016- 2017 AMUG Board members are:

- President: Steve Deak, GE Aviation
- Past President: Mark Barfoot, Hyphen
- Chairman: Gary Rabinovitz, Reebok
- Vice President: Dana McCallum, Carbon
- Vice President: Paul Pates, UL
- Deputy Vice President: Derek Ellis, Computer Aided Technology, Inc.

Av networking lunch at AMUG 2016

One section of the AMUG 2016 expo

- Deputy Vice President: Mark Wynn, Yazaki North America
- Treasurer: Vince Anewenter, Milwaukee School of Engineering
- Event Manager: Tom Sorovetz, Fiat Chrysler Automobiles
- Secretary: Kim Killoran, Stratasys
- AM Industry Advisor: Todd Grimm, T. A. Grimm & Assocs.
- Advisor: Mark Abshire, Computer Aided Technology, Inc.

The incoming board also re-appointed three AMUG global ambassadors:

- Ambassador: Graham Tromans, GP Tromans Associates
- Ambassador: Stefan Ritt, SLM Solutions
- Ambassador: Nora Cibula, Concept Laser

The board's responsibilities will involve building the program for the 2017 conference, soliciting support from businesses in the Additive Manufacturing industry and overseeing the event's day-to-day activities. The five-day event will include a two-night expo, hands-on workshops, instructional sessions, technical presentations and an Awards Banquet gala. The venue for the 2017 users group conference, which will be held April 2 – 6, will be announced at a later date.

www.am-ug.com

GKN Aerospace enhances its global position as Tier 1 supplier and leverages its AM expertise

GKN Aerospace is one of four divisions within UK-based GKN plc, providing around one third of total group sales of £8 billion in 2015. The other divisions include Driveline (automotive) at 46%, Powder Metallurgy at 12% and Land Systems at 9% (Fig. 1).

The increase in GKN Aerospace's sales from £700 million in 2006 to over £2.5 billion at the end of 2015 has seen the business consolidate its position as one of the most comprehensive global Tier 1 suppliers to the aerospace industry. Today the business specialises in airframe structures, engine systems, electrical wiring and window transparencies, whilst also offering landing gear and MRO services.

Kevin Cummings, Chief Executive Officer of the aerospace division said at a recent media briefing in London that the remarkable growth of 8-10% per year achieved over the last ten years had been through a combination of organic growth and acquisitions. "Future growth is assured through $3.5 billion of new business having been acquired in 2015," stated Cummings.

In October 2015 GKN Aerospace completed the acquisition of Fokker Technologies of the Netherlands, which strengthened GKN Aerospace's aerostructures capabilities and added electrical wiring systems, landing gear and associated services. Cummings stated that the Fokker acquisition was an excellent fit for both companies, making GKN Aerospace the second largest global Tier 1 supplier to the aerostructures and engine systems sectors, whilst

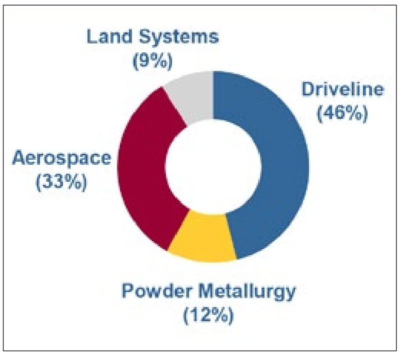


Fig. 1 GKN Aerospace is the second largest division within GKN after Driveline.

being the third largest supplier of electrical wiring systems.

The company puts itself as the leading global Tier 1 supplier of special products such as window transparencies for flight deck and passenger cabin windows, ice protection systems and lightweight missile canisters. It counts among its customers most of the major aircraft and aero engine producers including Airbus, Boeing, General

Electric, UTC, Lockheed Martin, SNECMA, Rolls Royce, etc. The commercial to military aerospace customer balance was reported to be 75% to 25%.

Additive Manufacturing seen as prime focus for future growth

Chris Gear, Chief Technology Officer, also speaking at the media briefing said that key to sustaining above average market growth is for GKN Aerospace to continue to expand its technology and product capabilities. In this regard the company sees Additive Manufacturing (AM) as one of the prime focuses for future growth especially for advanced metallic structures which can achieve both weight and cost savings for the user.

Gear said that GKN Aerospace has established global centres of excellence for AM in the USA, Sweden and the UK using a variety of AM processes including Electron Beam Melting (EBM), Laser Powder Bed (LPB) and Stereolithography (SLA). He stated that a key objective was to develop large scale deposition systems which can produce large near-net AM preforms for engine and airframe structures, as well as optimised structures such as large bulk heads, wing ribs and spars which would be too large for powder bed AM processes.

AM requires much less machining than traditional forgings or castings by only adding material where needed. It can offer weight savings of 15-30% over traditional processes, stated Gear. Titanium AM parts produced for ULA's Vulcan rocket engine in the USA are just one example of a large AM part produced by GKN Aerospace already in use. Fig. 2 shows the Vulcan rocket application where the individual large Ti alloy AM parts have been welded together to form the casings.

GKN Aerospace is also using small-scale deposition processes such as laser powder bed to produce smaller near-net higher detailed shapes. AM can also be used to directly deposit additions such as bosses onto larger structures, or be used for the modification of and repair of high value engine and airframe components. GKN Aerospace states that it already has metal AM bosses flying on civil aircraft engines.

EBM can also produce very near net shape and structurally optimised, small to medium sized engine and airframe components and the company has teamed up with AM specialist Arcam AB in Sweden to optimise the EBM process for aerospace applications.

GKN Aerospace firmly believes that AM processes will revolutionise the manufacturing of aerospace components by enabling new, efficient, lightweight designs to be created and new, specially tailored higher performing materials to be adopted. GKN has established a titanium and Ti alloy powder manufacturing facility at Hoeganaes Corp., a leading global metal powder producer, based in Riverton, New Jersey, USA, and part of the GKN Powder Metallurgy division.

GKN Aerospace will also draw on the know-how of the Powder Metallurgy division for the production of precision engineered products and both divisions will share

Fig. 2 Vulcan rocket engine casing produced by GKN Aerospace using fine scale wire Additive Manufacturing

the knowledge gained from their growing involvement and expertise in the use of Additive Manufacturing.

Gear stated that static and dynamic property data has been established for a range of titanium and titanium alloy powders used in AM which showed good results compared with equivalent cast alloys. The company is presently not prepared to share the obtained property data except through collaboration with end users. It will, however, share some of its achievements in metal AM at the forthcoming Farnborough Air Show, which takes place in the UK, 11-17 July, 2016.

www.gkn.com/aerospace

Report discussing markets and technology for AM jewellery available for free download

A report published by Andrew Nyce Associates, Florida, USA, discusses the Additive Manufacturing of precious metal jewellery, forecasts US retail sales up to 2026 and assesses the technological and economic obstacles that must be overcome in order for these forecasted sales to be achieved. The report is now available to download free of charge.

Based upon a market penetration analysis assessing the "Optimistic", "Pessimistic", and "Most Likely" US retail sales of 3D-Precious Metal Printing (3D-PMP) jewellery in 2026, Andrew Nyce Associates arrived at the "Most Likely" market forecasts for 3D-PMP platinum, gold and palladium jewellery.

The US retail sales of platinum, gold and palladium jewellery manufactured by Additive Manufacturing are forecast to reach $234, $35, and $1 million respectively by 2026. However, significant technical barriers remain to be addressed before these sales levels can be attained, the report states.

Both from the interviews and SWOT analysis results, the technical barriers to achieve the 2026 sales levels were identified along with potential ways to overcome these barriers. The study was carried out under the direction of Andrew Nyce, President of Andrew Nyce Associates. Nyce has over 50 years of experience as a research scientist and engineer, entrepreneur/business owner in advanced and engineering materials based businesses as well as 10 years of experience as a jewellery designer fabricating handmade gold, platinum, palladium and silver jewellery.

18K gold ring (Courtesy Cooksongold)

The report, 'An Assessment of the 2026 U.S. Markets and Technology for Jewellery Manufactured by 3D-Precious Metal Printing (3D-PMP) of Gold, Platinum and Palladium Powders' can be downloaded free of charge from the *Metal AM* website by contacting Andrew Nyce.

Email: andrewnyce73@gmail.com

www.metal-am.com

Kegelmann Technik teams with Concept Laser for series production of metal AM components

For over 25 years Kegelmann Technik, located in Rodgau, Germany, has produced models, prototypes, tools and finished products utilising Additive Manufacturing technologies. In May 2016, Kegelmann Manufacturing GmbH & Co.KG was formed to build on this experience and focus on the series production of metal Additive Manufacturing components.

The Group has just announced a comprehensive framework agreement with Concept Laser that will see the installation of several laser-melting machines and a strategic partnership in mutual knowledge exchange, particularly on the reproduction and optimisation of series-production quality in Additive Manufacturing.

"Our customers expect us to deliver process quality, flexibility and speed. Excellent quality control and verifiable results in real time during the actual laser melting convinced us to partner with Concept Laser," stated Stephan Kegelmann, CEO of Kegelmann Technik GmbH.

Kegelmann Technik offers an extensive range of innovative manufacturing processes under one roof and decades of knowledge in establishing and maintaining reproducible quality in Additive Manufacturing. In doing so, Kegelmann Technik has become fully integrated into numerous customers` value chains and plays a key role in developing and designing new products successfully.

"We are very pleased to be able to bring aboard such an innovative and experienced customer in Kegelmann Technik. We will most certainly learn from their wealth of experience in the future," added Oliver Edelmann, Vice President Global Sales & Marketing at Concept Laser.


Equipment handover in the show room of Concept Laser (Courtesy Concept Laser GmbH)

Kai Kegelmann, CTO of Kegelmann Manufacturing GmbH & Co.KG, expressed his excitement over the technology found in the M2 cusing Multilaser that boasts two 400 watt fibre lasers by adding, "I am fascinated by lightweight and bionics ability to improve component performance. By investing in high-power lasers and additional QM accessories we underscore our values of speed, flexibility and process quality."

www.ktechnik.de
www.concept-laser.de

Granta and Senvol collaborate on AM processes and materials database

Granta Design and Senvol have announced that the Senvol Database™, a comprehensive database of Additive Manufacturing materials and machines, will now be available within Granta's GRANTA MI™ and CES Selector™ software. As a result of the collaboration, it was stated that users will be better able to find valuable data and identify the best machines and materials for their projects.

The Senvol Database™ provides details of over 550 machines and over 700 materials. Within the Granta software, users can search and compare materials based on properties, type, or compatible machines. They can identify and compare AM machines based on supported processes, manufacturer, required part size, cost, or compatible materials.

"We're pleased to be working with Senvol to further extend Granta's solution for Additive Manufacturing," stated Dr Patrick Coulter, Chief Operating Officer at Granta Design. "The Senvol Database provides us with the best available Additive Manufacturing reference information, which both adds to our solution in this area and reinforces Granta's strategy to provide the best single source of materials data across the broad range of engineering applications."

The GRANTA MI: Additive Manufacturing package provides best practice data structures and tools to manage AM data, capturing valuable IP for re-use, avoiding wasted effort and building the knowledge base required to understand and improve processes. Integration within this system makes the Senvol Database™ instantly accessible and searchable for users through the same web browser interface that they use for routine access to their proprietary AM data and their company's wider materials and process information.

CES Selector™ software is used for plotting, comparison and materials selection using materials data. Now its charting tools can analyse and present data from the Senvol Database™, for example, quickly generating a plot to compare the properties of all Ti-6Al-4V materials that are compatible with a specific machine. CES Selector systematic selection features can filter machine and material options based on their properties and help the user to assess trade-offs in order to identify candidate machines and materials for a particular application.

"We're extremely excited to announce this partnership with Granta. Granta is one of the clear leaders in materials information technology and, through their platform, for the first time ever engineers will have the ability to compare AM data against conventional manufacturing data," stated Senvol President Zach Simkin.

www.grantadesign.com
www.senvol.com

World PM2016: Global metal AM materials suppliers, manufacturers and researchers prepare to meet in Hamburg

The technical programme for the World PM2016 Congress & Exhibition has just been published by the European Powder Metallurgy Association. The event, which takes place in Hamburg, Germany, from October 9-13, 2016, includes more than 450 keynote, oral, poster and special interest presentations.

More than 65 technical papers relate directly to metal Additive Manufacturing technology, with many more addressing the latest advances in metal powder production, making the technical programme one of the world's largest to-date on the subject of powder-based metal AM.

AM related papers have been accepted from authors based throughout Europe, North America and Asia/Pacific, reflecting the truly global nature of the event. Presenting companies include Airbus Group, Saab Aeronautics, Siemens Industrial Turbomachinery, European Space Agency, European Commission, ONERA, Altair Engineering, GKN Sinter Metals Engineering GmbH Germany, Schneider Electric France and Materialise, to name just a few.

A Special Interest Seminar will additionally provide an update on the global progress of metal Additive Manufacturing, with presentations covering global research activities, industrial and aerospace developments, advances in production technologies and other AM related topics that will give broad coverage of activities in the AM metal arena.

The full technical programme consists of some 70 technical sessions, seven keynote paper award winners and five special interest seminars.

Dr Michael Krehl, World PM2016 Congress Chairman, stated, "Due to the high volume and quality of the abstracts submitted to the event, the Steering Committee took the unanimous decision to increase the number of technical sessions during the congress, which will make for an extensive programme covering all areas of PM."

Major exhibition features leading metal powder suppliers

A major exhibition will run in parallel to the technical sessions. Congress Centre Hamburg's Hall H will host the four-day exhibition, making it, stated the EPMA, the largest international metal powder focused exhibition in 2016. The exhibition area features over 150 companies representing all aspects of the Powder Metallurgy supply chain.

To visit the World PM2016 exhibition free of charge register as an exhibition visitor at www.worldpm2016.com using *Metal AM* magazine's promotional code/password WPM2016-199. Please note that this only allows access to the exhibition and separate paid registration is required to attend technical sessions.

Full information on the event and details of how to register are available from the event website.

www.worldpm2016.com

Dassault Systèmes and Airbus Group to extend collaboration in AM

Dassault Systèmes, a developer of 3D design software, 3D digital mock up and product lifecycle management solutions, has announced that Airbus Group is extending its use of Dassault Systèmes' 3DEXPERIENCE platform in its Additive Manufacturing programmes.

Following a two-year benchmarking process, Airbus Group will now deploy the collaborative design and simulation applications as part of a 'Co-Design to Target' industry solution experience. The platform will be used in the Additive Manufacturing of tooling, prototyping and parts for test flights and for production use on commercial aircraft.

"Numerous projects across Airbus are accelerating the use of Additive Manufacturing to produce prototypes as well as production components, potentially delivering lighter and less expensive parts that meet technological, performance, safety and cost standards," stated Robert Nardini, Senior Vice President Engineering Airframe, Airbus. "Airbus has long used Dassault Systèmes' simulation applications to accelerate the structural analysis and virtual testing of aircraft and now we can define a new way of designing parts by leveraging simulation-based design to better answer aviation market needs."

The software from Dassault Systèmes will provide Airbus Group with digital continuity to optimise its conceptual designs by virtually validating each phase of the Additive Manufacturing process.

www.3ds.com

Höganäs adds 17-4 stainless steel to Digital Metal range

Sweden's Höganäs AB has extended the range of materials suited to its Digital Metal® Additive Manufacturing technology by including high performance 17-4 PH stainless steel. According to Höganäs, 17-4 PH enables production of components with high strength and hardness.

The material is a hardening grade exhibiting considerably higher strength compared to the more commonly used austenitic 316L. It also provides improved corrosion resistance compared to 400 series ferritic stainless steels.

Digital Metal is a 3D metal printing technology enabling production of small and complex objects that would be costly, if not impossible, to produce using traditional methods.

www.hoganas.com

Quintus to supply Hot Isostatic Press to Sintavia's metal AM facility in Florida

Quintus Technologies has announced that it is to ship a Hot Isostatic Press to the new metal Additive Manufacturing centre recently opened by Sintavia, LLC, in Davie, Florida, USA. The model QIH 15L press is reported to give Sintavia serial production capability for metal parts that meet the exacting quality control standards required by the aerospace and defence industry.

"Without HIP technology, additively manufactured parts are susceptible to porosity and lack of fusion. HIP allows for near 100% net-density parts," stated Sintavia founder Brian Neff, who recognised the promise of AM during a long career in aviation and parts manufacturing. The press for Sintavia is equipped with Quintus's proprietary Uniform Rapid Cooling (URC™), which, by incorporating densification and heat treatment in the same equipment, shortens cycle times for higher productivity.

The QIH 15L will play a key role in allowing Sintavia's aviation customers to respond to the mandate to compress build-to-fly time. The press features a hot zone capability of 186 x 500 mm (7.3 x 19.7 inches), enables pressures up to 207 MPa (30,000 psi) and handles temperatures up to 1400°C (2550°F). Its new modular design shortens installation time and reduces space requirements. It is delivered as a complete unit, with gas compressing system, cooling unit, transformers, electrical cabinets and pressure vessel.

Founded in 2012, Sintavia provides metal Additive Manufacturing solutions, including serial production and development. The company's state-of-the-art facility in Davie, Florida, offers on-site metal Additive Manufacturing via the powder bed fusion process, as well as metrological and metallurgical testing.

"As one of the first facilities of its kind, Sintavia is at the forefront of the Additive Manufacturing revolution," stated Jan Söderström, CEO of Quintus Technologies. "We are pleased to support their contributions to the aerospace and defence industry."

www.sintavia.com
www.quintustechnologies.com ■

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Additively manufactured mountain bike offers flexibility and customisation

Robot Bike Co is a UK based specialist designer and manufacturer of lightweight, custom geometry mountain bike frames. The company has recently introduced its R160 mountain bike frame, developed with partner companies Altair, HiETA Technologies and Renishaw, that utilises metal Additive Manufacturing to tailor each frame to a customer's individual specifications.

The unique bike frame construction consists of titanium lugs, carbon fibre tubing and a double lap joint bonding concept. As well as offering numerous customisation opportunities, the use of metal AM has the added benefit that the frame can be constantly improved as new technologies emerge, due to the fact that the production process is not constrained by use of costly moulds.

"If you are trying to produce the very best frame it makes no sense to then only offer it in a small number of sizes when the people you are selling it to come in all shapes and sizes. Think of Robot Bike Co as the Savile Row of the bike world," stated Ed Haythornthwaite, one of Robot Bike Co's founders.

The titanium lugs are manufactured at Renishaw's Additive Manufacturing Solutions Centre in Stone, Staffordshire, UK. The production process starts with bespoke CAD geometries that are tailored to the individual customer. These are imported into Renishaw's QuantAM build preparation software, where the optimum orientation for each part is selected and the support structures required for a successful build are specified.

The eleven lugs are grouped together to be produced in a single build. The combined CAD geometry is then 'sliced' into over 2,500 layers, each 60 microns thick. Finally, the QuantAM software defines the scan paths that will be used to melt the titanium powder to produce each layer.

The build process takes place on a Renishaw laser melting machine. The melting process is performed under

Altair performed design optimisation with solidThinking Inspire and design verification with OptiStruct an inert Argon atmosphere to ensure that the purity of the titanium alloy is preserved for optimum strength and durability. The build plate with the eleven lugs attached is removed from the AM machine and heat treated, also under Argon. Some of the lugs require finish machining to produce precision bearing features. The machining processes are set up and controlled using on-machine probing systems. Finally, the lug production process is completed with inspection on a co-ordinate measuring machine.

"We have been delighted to lend our expertise in Additive Manufacturing, machining and metrology to deliver a high quality bike frame from an initial design concept. This typifies the approach that we are taking with our Solutions Centres, where we are working closely with our customers to create designs that maximise the production and lifetime benefits that can be gained from using an Additive Manufacturing process," stated Marc Saunders, Director – Global Solutions Centres for Renishaw.

HiETA has extensive experience in designing for AM and has created a parametric 3D CAD design to enable rapid tailoring to the individual rider. This involves optimising the 11 titanium lugs and the eight carbon tubes to create a unique suite of solid models for each customer. This sophisticated configurator sits behind the Robot Bike Co website and does its work in just 20 seconds.

"One of the great aspirations of Additive Manufacturing has always been 'mass customisation'. Leading this project has allowed us to see integration of all the elements – a great new frame design, the use of state of the art software tools for optimisation and automation, the flexibility of the manufacturing process itself and effective collaboration between our partners is a great advert for the technologies," stated Mike Adams CEO of HiETA, a specialist Additive Manufacturing development and project engineering company based in the Bristol and Bath Science Park, UK.

Simulation specialist, Altair, was responsible for the optimisation of the bike's additively manufactured connecters. Using solidThinking Inspire, Altair was able to maximize the benefit of Additive Manufacturing by identifying where material in the connectors could be removed to save weight and reduce part count without compromising performance. These engineering techniques are commonly used throughout the automotive and aerospace industries to maximise product performance but are equally valuable to bike manufacturers.

www.robotbike.co

The R160 Build Plate with printed titanium lugs from the Renishaw AM 500M

Aerospace supplier Kanfit to add metal Additive Manufacturing

Kanfit Ltd., Israel, is a manufacturer of components, sub-assemblies and ready to fly assemblies made from metal and composite materials for the aerospace and medical device industries. The company recently announced that it plans to add metal Additive Manufacturing to its range of production technologies following the purchase of an M290 system from EOS.

The new system for Additive Manufacturing of Ti64 G5 is the latest technology to be introduced at Kanfit and can be used for high-quality metal parts and prototypes. Last year, Kanfit inaugurated its new autoclave facility for the production of composite parts, including hybrid main landing gear and avionic doors and wing-to-belly fairings.

"This new addition to our technological capabilities is another step in our strategy to provide top quality innovative solutions to our customers. The addition of the 3D printer to our other technological capabilities such as the autoclave enables us to enlarge our product and service offerings and puts us in a position to competitively bid and participate in a wider range of industry projects than ever before," stated Shai Fine, Founder and General Manager of Kanfit.

"Our reputation as a reliable and trusted manufacturer of both high quality composite and metal parts is spreading, as more and more companies turn to us for cost-effective, lightweight, fuel-efficient products," added Fine.

www.kanfit.com

Materialise introduces Magics 3D Print suite

Materialise NV, Leuven, Belgium, has announced the launch of its new Magics 3D Print Suite. The software suite is said to combine the functionality of multiple applications into one complete set of business solutions, giving users the possibility to utilise data generated from numerous sources, convert it into innovative applications and print it with any printer available in the market.

"We believe that the Materialise Magics 3D Print Suite offers customers a complete software backbone and unmatched versatility for their 3D Printing needs. We purposely built the suite to adapt to new industries embracing 3D Printing and are still adapting to meet our existing customers' evolving production requirements," stated Stefaan Motte, Vice President of Materialise.

Materialise software has become an industry standard for Additive Manufacturing in service bureau environments and has also entered the industrial manufacturing scene through partnerships and collaborations with every major manufacturer of Additive Manufacturing machines.

www.materialise.com

Puris develops new titanium powder optimised for Additive Manufacturing

Puris, LLC has announced that it has filed a patent for Puris 5+TM, a new titanium powder formulation offering a high-strength, low-oxygen formulation specifically designed to meet the demands of Additive Manufacturing. Puris 5+ is reported to be a custom composition of Ti-6Al-4V that meets all the specifications of Grade 5.

Typically, engineers seek to balance the oxygen levels needed to obtain the desired strength properties with the increases in oxygen levels inherent in some Additive Manufacturing processes. This creates a challenge in laser melt or e-beam direct melt 3D printing, as both processes experience increases in oxygen content with each recycle of excess powder from the build box. By starting with Puris 5+, Puris claims that customers can manage this balance of oxygen and strength better throughout the life cycle of the titanium powder.

"The introduction of low-oxygen, high-strength Grade 5 titanium powder represents a major breakthrough that equips our customers to better control the oxygen pickup inherent in their processes. The result is more efficient utilisation without compromising powder strength," stated Puris CEO Craig Kirsch.

"Puris 5+ is an exciting example of our company's continuing leadership in advanced titanium powder for Additive Manufacturing, made possible by our deep metallurgy and Powder Metallurgy expertise," Kirsch added. "The efficacy of AM ultimately depends on such powder quality and advancements."

www.purisllc.com

Arcam expands in Germany

Sweden's Arcam AB has announced further expansion in Germany following the establishment of a new sales operation. Arcam Cad to Metal GmbH will be based in Stuttgart and led by Peter Jain.

"I am enthusiastic about joining Arcam, being part of the team bringing state-of-the-art Additive Manufacturing solutions into production. I look forward to leading our German operations for continued growth," stated Peter Jain, Managing Director of Arcam Cad to Metal GmbH.

Germany is an important market for Arcam, who already have long term relationships with significant clients such as Fruth Innovation Technology, Fraunhofer Institute and Implantcast. The new sales office will provide initial sales and liaison as well as local support to its German customer base.

www.arcam.com

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Laser Power (W)	40 / 100
Layer Thickness (㎛)	200 ~ 300
Laser Wavelength(㎛)	10.6 (CO_2)

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www.sentrol.net

Additive manufactured fuel pump tested for liquid methane NASA rocket in Mars project

NASA has reported that it recently tested a complex additive manufactured rocket engine turbopump with liquid methane, an ideal propellant for engines needed to power spacecraft for NASA's journey to Mars.

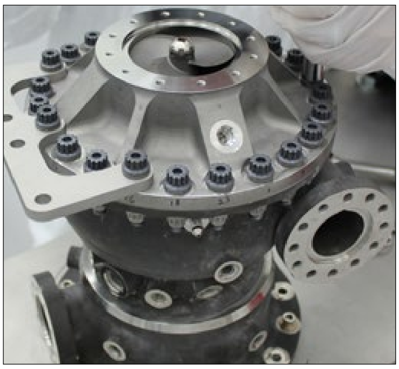
The turbopump consists of turbines that spin to drive the pump, which is used to supply fuel to the engine. During the full power test the turbines generated 600 horsepower and the fuel pump turned at over 36,000 revolutions per minute, delivering 600 gallons of semi-cryogenic liquid methane per minute, enough to fuel an engine producing over 22,500 pounds of thrust. Three other tests were completed at lower power levels.

"This is one of the most complex rocket parts NASA has ever tested with liquid methane, a propellant that would work well for fuelling Mars landers and other spacecraft," stated Mary Beth Koelbl, the manager of the Propulsions Systems Department at NASA's Marshall Space Flight Center in Huntsville, Alabama. "Additive Manufacturing, or 3D printing, made it possible to quickly design, build and test two turbopumps with identical designs that worked well with both liquid methane and liquid hydrogen propellant."

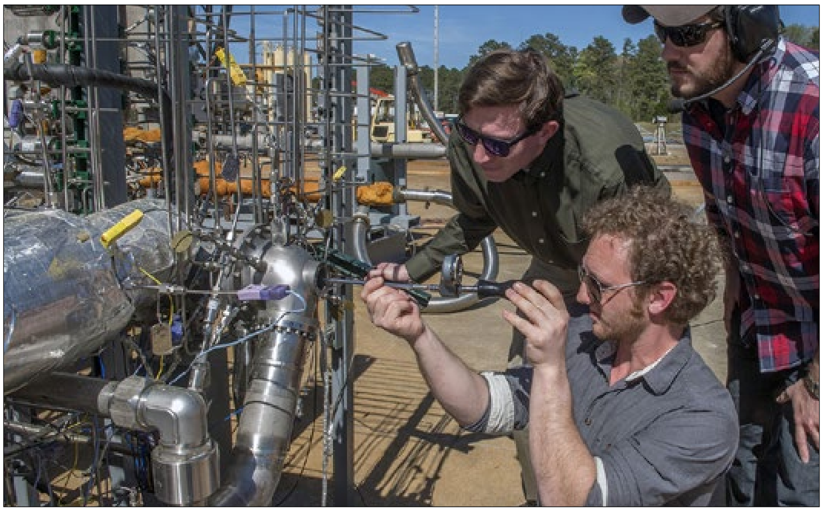
Hydrogen turbopump component testing and testing with a liquid oxygen/liquid hydrogen breadboard engine were completed in 2015. These tests along with manufacturing and testing of injectors and other rocket engine parts are paving the way for advancements in Additive Manufacturing of complex rocket engines and more efficient production of future spacecraft including methane-powered landers.

"Methane propulsion and Additive Manufacturing are key technologies for the future of exploration including NASA's journey to Mars," stated Graham Nelson, a Marshall propulsion engineer who helped with the testing. "We're excited to complete testing that advances both these technologies at the same time and improves the capabilities of future missions."

Liquid methane is cooled to -159°C whereas liquid hydrogen is cooled to -240°C. The higher temperature of liquid methane means it boils off more slowly and thus is easier to store for longer periods, a benefit for Mars missions. Also, technologies exist today to make it possible to manufacture methane rocket fuel from carbon dioxide, which is plentiful in the Mars atmosphere.



This rocket engine fuel pump has hundreds of parts including a turbine that spins at over 90,000 rpm. This turbopump was made with additive manufacturing and had 45% fewer parts than pumps made with traditional manufacturing (Courtesy NASA)



Engineers prepare the additive manufactured turbopump for a test at NASA's Marshall Space Flight Center in Huntsville, Alabama. The turbopump was tested at full power, pumping 600 gallons of liquid methane per minute (Courtesy NASA)

"By demonstrating the same turbopump can work with different fuels, we've shown that a common design would work for either engines fuelled by methane or hydrogen," added Marty Calvert, the Marshall engineer who designed the turbopump. "Because liquid methane is much more dense than hydrogen, it requires the turbopump to spin at a different speed to deliver the same amount of mass flow to the engine."

Testing ensures AM parts operate successfully under conditions similar to those in landers, ascent vehicles and other space vehicles. All data on materials characterisation and performance are compiled in NASA's Materials and Processes Technical Information System, called MAPTIS, which is available to approved users.

"Additive Manufacturing allowed us to build the turbopump with 45% fewer parts," stated Nick Case, the Marshall propulsion engineer who led the testing. "Our next step will be to test the liquid methane turbopump with other 3-D printed engine components in a similar configuration to the liquid hydrogen tests completed last year."

www.nasa.gov

Latest HyperWorks simulation software from Altair

Altair, headquartered in Troy, Michigan, USA, has released HyperWorks® 14.0, an open architecture CAE simulation platform that now includes several new products, feature enhancements, updated functionalities and licensing methods.

Key highlights offered by the release include updates to OptiStruct, where capabilities have been elevated to include more nonlinear analyses, new contact and optimisation algorithms and numerous improvements in solution speed. "With OptiStruct 14.0, it is now possible to run larger, full vehicle NVH models for more accuracy without the errors generated by our existing NVH solver on the same computer," stated Tae-Won Park of SsangYong Motors.

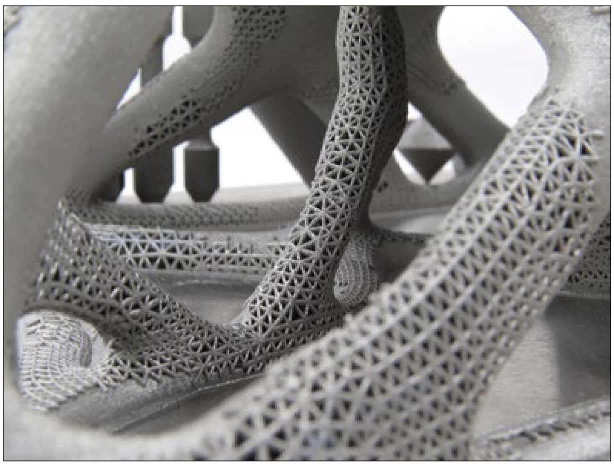
Updates to HyperMesh allow new part and assembly workflow which promotes flow of data directly from Product Data Management (PDM) data structures. Combined with the new high-velocity graphics engine tuned to handle even the largest models, HyperMesh 14.0's performance is up to fifteen times faster for large FE models with solid elements and up to sixty times faster for geometry models, while using less hardware memory.

"With this release of HyperWorks we've introduced parts and assemblies in HyperMesh that directly correspond to those in the CAD and PDM world," stated James P Dagg, Chief Technical Officer, User Experience at Altair. "The new assemblies are extremely flexible, allowing for modular modelling where entire subsystems can be replaced or updated automatically, keeping your CAE model synchronized with design."

The software package now includes Multiscale Designer, a practical tool for the seamless integration of modelling, simulation, testing and optimisation of engineered products using complex materials.

Altair has more than 2,000 employees and operates over 45 offices in 22 countries. The company serves more than 5,000 corporate clients across broad industry segments.

www.altair.com



OptiStruct can be used to optimise lattice structures

Combined design and topology software package from Frustum

Frustum is launching a suite of software products that will allow design engineers to create improved geometries through topology optimisation. The company's Generate software package is reported to reduce the time it currently takes to generate optimised topology designs, allowing for more rapid delivery of designs that are ready for manufacturing either through additive or traditional manufacturing. The product is being released in beta test with a limited purchase planned for July 2016.

"Our Generate design software product offering was developed with the design engineer in mind. They get the best of both worlds, an easy to use design tool that offers superior topology optimisation capabilities. What is appealing is the geometry output coupled with the ability to do optimisations in parallel based upon the use of the cloud. Generate is a tool that's a true ally for designers and offers them the opportunity to unleash their design vision. It is the intersection of design and topology optimisation," stated Jesse Blankenship, CEO of Frustum.

The new software is claimed to seamlessly grow material between the given design features to make stiff and lightweight structures. The smooth and blended surfaces reduce weight and minimise stress concentrations, enabling designs to be ready for manufacturing without the need to manually redesign.

"Many key industries, especially aerospace and automotive, were instrumental in driving what Generate needed to deliver from a feature and benefit perspective. The overwhelming market driver was the need to reduce the amount of development time required in topology optimisation and the back and forth with stress analysts. Generate has the ability to cut weeks and even months out of the development cycle by getting parts into manufacturing and production faster," added Blankenship.

Part developed by Frustum Generate

There is built-in user flexibility with Generate that allows for individual or corporate-wide use. Designers have the ability to use Generate through a variety of methods, either through their enterprise or in the cloud.

www.frustum.com

PyroGenesis to form stand-alone AM powder and equipment company

PyroGenesis Canada Inc. has announced that plans to spin-off 80% of its Additive Manufacturing business into an independent publicly-traded company have been approved by its Board of Directors. Following the successful spin-off, the new company will have all rights to produce metal and alloy powders for the AM industry using PyroGenesis' plasma atomisation process and to distribute powder production systems and equipment under an exclusive world-wide licence with PyroGenesis.

PyroGenesis will continue to benefit from supplying systems and equipment to the new company with traditional margins, whilst also providing standard maintenance and technical support services for each system purchased for up to $750K per system per year. The transaction is expected to be staged over the next four months, at which time PyroGenesis' shareholders will own and control all the issued and outstanding shares of both companies, either directly or indirectly through their holdings in PyroGenesis.

"Spinning off will help attract an investor base best suited to the company's unique value proposition, particular business operations and financial characteristics, thereby maximising shareholder value and placing it in a better position to ramp up, generate revenues and develop strategic relationships/partners than had it remained part of PyroGenesis" stated P Peter Pascali, President and CEO of PyroGenesis.

The new company is expected to be in commercial production of metal powders as early as Q3 2016, with a second system coming online in Q1 2017.

www.pyrogenesis.com

Premium Aerotec and toolcraft sign cooperation agreement

Toolcraft, Georgensgmünd, Germany, has announced the signing of a cooperation agreement with Premium Aerotec, Augsburg, Germany, to advance the rapid industrialisation of metal laser melting for use in aerospace applications and utilise toolcraft's expertise in the supply of laser-melted parts.

"We are pleased to partner with Aerotec, a company interested in advancing development in the area of metal laser melting," stated Christoph Hauck, Managing Director of toolcraft. As part of the cooperation, toolcraft's additive production area will receive its own building.

It was stated that a further goal is to obtain the certification of additive processes for the aerospace industry.

www.toolcraft.de

Wizit to build South Korea's first metal Additive Manufacturing facility

It has been reported that South Korea's Wizit Co. Ltd, a technology company specialising in LCDs and semiconductors, is planning to strengthen its business with a move into metal Additive Manufacturing. The company will establish a new manufacturing facility in Seoul to house a number of metal AM systems supplied by Sentrol, a local developer of mid- to large-sized metal AM systems for industrial production.

Kim Myung-Sik, Director of Wizit, stated, "there have been services that use 3D printers to print out customised products for consumers, but Wizit's plant will be the nation's first plant that prints out in metal on a large scale."

www.wizit.co.kr

Hans J Langer, EOS founder, receives SME industry award

Dr Hans J Langer, founder and CEO of EOS GmbH, received the SME Additive Manufacturing Industry Achievement Award at this year's RAPID 2016 show in Orlando, Florida, USA. The award is presented to individuals who have made significant accomplishments that greatly impact the Additive Manufacturing industry.

"RAPID is the authoritative industrial 3D-manufacturing event of the year," stated Glynn Fletcher, President of EOS North America. "This SME award is a reflection of both Hans Langer's innovative spirit and the growth and technological advancements his company has made over the past 27 years."

Langer founded EOS in 1989 and today is the major shareholder. Before founding EOS, he worked at the Max-Planck-Institute for plasma physics and received his Ph. D. with a thesis on laser technology from Ludwig-Maximilian University in Munich.

EOS' latest advancements in AM include the compact M 100 metal system and its EOSTATE MeltPool Monitoring technology. The latter is an automated, intelligent, real-time process that provides part traceability as well as surveillance and analysis of the melt pool during the Direct Metal Laser Sintering (DMLS®) process, helping minimise risk and reduce quality assurance costs.

www.eos.info

Dr Hans J Langer (right) receiving the SME Additive Manufacturing Industry Achievement Award

Research collaboration to explore Additive Manufacturing for aerospace repairs

A research collaboration between Canada and Europe is looking to Additive Manufacturing technology to repair components for the aerospace industry. The AMOS consortium, consisting of nine partners from Canada, France, Sweden and the UK, will look at direct energy deposition techniques that combine laser or arc welding tools with automated or robotic control to accurately deposit and melt metal powder or wire.

Many of these techniques are already used in aerospace and other industries to build new parts to near-net shape. AMOS will investigate their use to repair and remanufacture aerospace components such as turbine blades and landing gear. It was stated that this could significantly reduce the time and cost of regular maintenance and repair for the aerospace industry, while reducing material waste and extending the life of expensive components.

"There's a host of Additive Manufacturing technologies available to aerospace manufacturers, but they tend to be focused on new production rather than repairing damaged parts," stated Dr Rosemary Gault, European Project Coordinator at the University of Sheffield AMRC. "The AMOS project is bringing together some of the world's leading research organisations and companies to identify which additive technologies are best suited for repair and remanufacture, and develop them for commercial use."

"The research team is well balanced, consisting of industrial OEMs, repair providers and universities across the Atlantic," added Professor Yaoyao Fiona Zhao of McGill University's Additive Design and Manufacturing Lab. "The project will provide a fundamental understanding of thermal and mechanical behaviour of powder and wire material during deposition."

The project will research fundamental aspects of selected additive processes, including the material integrity of deposited metal, and the accuracy and limitations of the deposition process. The consortium will also investigate automated techniques to map damaged areas and calculate repair strategies, and look at how the near-net shape repairs can be effectively machined to a final seamless shape.

AMOS will also investigate how additive repair techniques can be factored into the design of new components to optimise efficiency over their life cycle, and the qualification of innovative repair processes which don't comply with current industry specifications.

The European partners are the University of Sheffield AMRC,UK; Ecole Central de Nantes, France; GKN Aerospace Engine Systems, Sweden; and DPS, France. Canadian partners are McGill University, Montreal; University of Ottawa; Pratt & Whitney Canada; Héroux-Devtek and Liburdi.

The project will involve a range of AM technologies used at the participating centres and companies, including laser powder and robotic laser wire systems operated by Liburdi, a CNC laser powder facility at Ecole Centrale de Nantes and robotic powder diode laser and wire-feed gas tungsten arc facilities at the University of Sheffield AMRC. Material research will focus on three widely used aerospace alloys: Ti6Al4V, Inconel 718, and 300M alloy steel.

The four-year, €2.6 million (C$3.8 million) project is supported by the European Commission through the Horizon 2020 programme and by Canadian funding agencies CARIC and NSERC. It is one of the first European-Canadian projects to be funded under the 'Mobility for growth' collaboration in aeronautics R&D.

www.amos-project.com

Standards for metal Additive Manufacturing: A global perspective

As the metal Additive Manufacturing industry moves towards industrial production, the need for international standards covering all aspects of the technology becomes ever more pressing. In the following exclusive report for *Metal Additive Manufacturing* magazine, Fraunhofer IFAM's Claus Aumund-Kopp and Frank Petzoldt review international progress to-date, summarise existing standards for metal AM and consider the challenges that lie ahead.

The more a technology develops and is established in the market, the greater the need becomes for a common understanding of technical terms and process details. Metal Additive Manufacturing has today reached a status where it is stepping towards industrialisation. The dental and aerospace industries in particular have already moved to commercial scale production and they are asking for standards for material properties, testing procedures and more besides.

Standardisation is a time consuming task undertaken by major stakeholders through participation in various standardisation committees worldwide. In the end, all parties, from AM machine and powder manufacturers to parts producers and end-users, will profit from these standards as they support reliability and confidence in the technology. This article presents an overview of the AM standards published by different organisations to-date (Fig. 1). It also offers some answers as to why standardisation is so important for AM, whilst highlighting the necessity for internationally concerted action.

The present situation

Additive Manufacturing is transforming industries across the globe and a diverse range of companies are seeing the multitude of ground-breaking opportunities that the technology offers. There are, of course, still many challenges ahead in order to make this technology a sustained success. In particular, the strong links between manufacturing process parameters and material properties require special attention compared to conventional metal shaping processes. The influence of different machine systems and production conditions, resulting in differing properties, also has to be taken into account.

Additionally, material properties are strongly related to the starting material (such as metal powder), combined with a reliable set of

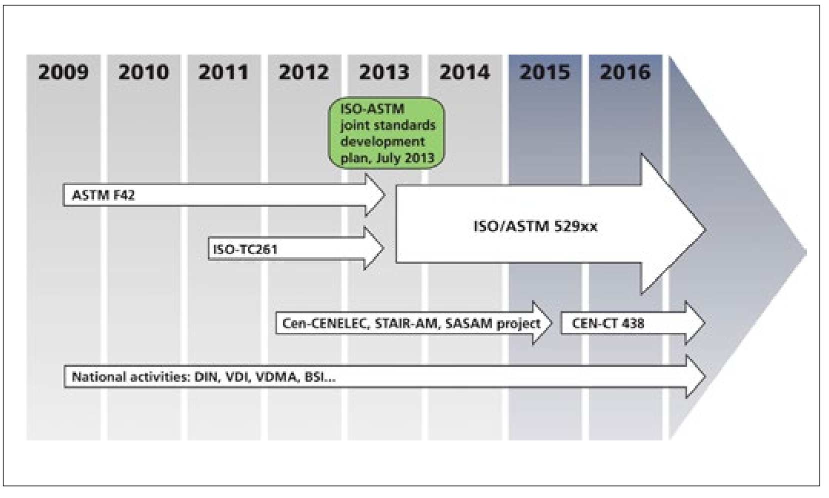


Fig. 1 International standardisation activities on Additive Manufacturing

ASTM International Committee F42

(Formerly American Society for Testing and Materials, Committee F42)

- Established in 2009
- Scope: The promotion of knowledge, stimulation of research and implementation of technology through the development of standards for Additive Manufacturing technologies
- Members: representatives of different stakeholders (companies, universities, research organisations etc.)
- One vote per organisation
- Presently more than 400 individual members representing 23 countries.

ISO Technical Committee 261

(ISO/TC261)

- Established 2011
- Scope: Standardisation in the field of Additive Manufacturing concerning their processes, terms and definitions, process chains (hardware and software), test procedures, quality parameters, supply agreements and all kind of fundamentals
- Membership is based on representation of different national standardisation organisations. Each member organisation may nominate experts for different workgroups.
- One vote per organisation
- Presently 20 participating countries + five observers.

Fig. 2 The variety of different terms in Additive Manufacturing

parameters within a process window. Knowing this, it is crucial to verify properties and create robust production processes for Additive Manufacturing. Quality management systems also require attention in terms of inspection and verification rules.

Most major companies using AM for end-use part production currently create their own internal set of materials and processing guidelines because of a lack of standards. It is therefore of extreme importance to improve process knowledge and create common technical standards. Additionally, design standards will help support the further acceptance of AM as most of the today's CAD tools do not make use of the full potential of Additive Manufacturing.

Standards help to build a level of trust in the achievability of properties, particularly in new manufacturing processes such as metal AM. Additive Manufacturing is a global business which requires international standards. Standardisation facilitates technical and economic co-operation at national, regional and international levels. Several countries and regions have already taken action to set up standardisation activities.

Two main international institutions, ISO (International Standardisation Organisation) and ASTM International, globally prepare, develop and publish standards relating to AM (see inset box for further information). The European Committee for Standardisation (CEN) has also formed standardisation committees for AM on a regional level. Additionally there are a number of national activities related to standardisation and guidelines. These include BSI (British Standards Institution) and France's AFNOR/UN (Union de Normalisation de la Mécanique). In Germany, the national standards body DIN (Deutsches Institut für Normung) publishes standards relating to AM in cooperation with VDMA (Verband deutscher Maschinen- und Anlagenbauer) and VDI (Verein Deutscher Ingenieure).

In 2009, ASTM International established Committee F42 on Additive Manufacturing Technologies. In the same year, national activities

Area	Organisation	Standard	Title
Nomenclature and data formats	ISO	ISO 17296-2:2015	Additive Manufacturing -- General principles -- Part 2: Overview of process categories and feedstock
		ISO 17296-4:2014	Additive Manufacturing -- General principles -- Part 4: Overview of data processing
	ISO/ASTM	ISO/ASTM 52900:2015	Additive Manufacturing -- General principles -- Terminology
		ISO/ASTM 52921:2013	Standard terminology for Additive Manufacturing -- Coordinate systems and test methodologies
		ISO/ASTM 52915:2016	Standard Specification for Additive Manufacturing File Format (AMF) Version 1.2
	VDI	VDI 3405	Additive Manufacturing processes, rapid prototyping - Baiscs, definitions, processes
Materials	ASTM	ASTM F2924-14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
		ASTM F3001-14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
		ASTM F3055-14a	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion
		ASTM F3056-14e1	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion
	VDI	VDI 3405 Blatt 2.1:2015-07	Additive Manufacturing processes, rapid prototyping - Laser beam melting of metallic parts - Material data sheet aluminium alloy AlSi10Mg
Testing	ASTM	ISO/ASTM 52921:2013	Standard terminology for Additive Manufacturing -- Coordinate systems and test methodologies
		ASTM F2971-13	Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
		ASTM F3049-14	Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes
		ASTM F3122-14	Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes
	ISO	ISO 17296-3:2014	Additive Manufacturing -- General principles -- Part 3: Main characteristics and corresponding test methods
	VDI	VDI 3405 Blatt 2	Additive Manufacturing processes, rapid prototyping - Laser beam melting of metallic parts - Qualification, quality assurance and post processing

Table 1 Published standards for metal Additive Manufacturing

in Germany and UK commenced. ISO started its TC261 activities in 2011 and in July 2013 both organisations, ASTM and ISO, set-up a joint standards development plan.

The first European initiatives were started in 2012. As an example, SASAM (Support Action for standardisation of Additive Manufacturing) was a project funded by the EU under the Framework Program 7. The mission of this project was to drive the growth of AM through activities that supported the integration and coordination of standardisation simultaneously whilst addressing production issues. The result of the project, which was completed in April 2014, was a roadmap for the standardisation of AM covering the stakeholders' requirements.

In March 2013 the STAIR-AM (STAndardisation, Innovation and Research) platform on AM within CEN-CENELEC, the European Committee for Standardisation (CEN) and the European Committee for Electrotechnical Standardisation (CENELEC), was created. This serves as a meeting point for stakeholders from the AM research, service provider and global standardisation community to discuss standardisation issues. There is a continuous dialogue with the so-called AM Platform, which is a European network working on the research agenda for Additive Manufacturing.

"A more general term for the whole field of AM is 3D-printing, which is mainly due to the hype surrounding low cost home printers. Additive Manufacturing implies more accurately the production of an end-use part"

In July 2015 the CEN/TC 438 committee was formed. Its main objectives and priorities are to standardise the processes of AM, their process chains (including both hardware and software), test procedures, environmental issues, quality parameters, supply agreements, fundamentals and vocabularies. In order to ensure consistency and harmonisation with international standards, the priority is to publish the ISO standards as EN ISO.

Intensive work is also underway within many different working groups. It is a huge challenge to harmonise all these different approaches to achieve a common set of accepted standards globally. To-date, standards have been published covering the following areas of Additive Manufacturing:

- Terminology and data formats
- Materials
- Testing

Table 1 gives an overview of already published standards for Additive Manufacturing. The purpose of this article is to give a condensed overview of the main content of the already available standards and over the following pages short summaries of each standard are presented.

Terminology

Terminology was the first item to be standardised due to the fact that there were so many different terms and abbreviations for AM technology, as well as about aspects of the process (Fig. 2). A more general term for the whole field of Additive Manufacturing is 3D-printing, which is mainly due to the hype surrounding low cost home printers. Additive Manufacturing implies more accurately the production of an end-use part and the more complex processes to manufacture metallic components.

ISO/ASTM 52900:2015

This establishes and defines terms used in Additive Manufacturing technology, which applies the additive shaping principle and thereby builds physical 3D geometries by successive addition of material. The terms have been classified into specific fields of application. New terms emerging from the future work within ISO/TC 261 and ASTM F42 will be included in upcoming amendments and overviews of this international standard.

ISO/ASTM 52921:2013

This standard includes terms, definitions of terms, descriptions of terms, nomenclature and acronyms associated with coordinate systems and testing methodologies for Additive Manufacturing technologies in an effort to standardise terminology used by AM users, producers, researchers, educators, press/media and others, particularly when reporting results from the testing of parts made on AM systems. Terms included cover definitions for machines/systems and their coordinate systems plus the location and orientation of parts. It is intended, where possible, to be compliant with ISO 841 and to clarify the specific adaptation of those principles to Additive Manufacturing.

ISO 17296-2:2015

This standard describes the process fundamentals of Additive Manufacturing. It also gives an overview of existing process categories, which are not and cannot be exhaustive due to the development of new technologies. ISO 17296-2:2015 explains how different process categories make use of different types of materials to shape a product's geometry. It also describes which type of material is used in different process categories. Specification of feedstock material and requirements for the parts produced by combinations of different processes and feedstock material will be given in subsequent separate standards and are therefore not covered by ISO 17296-2:2015. It describes the overreaching principles of these subsequent standards.

VDI 3405

This is aimed at users and producers of Additive Manufacturing processes. It covers the principal considerations which apply to the design, fabrication and assessment of parts produced by Additive Manufacturing and defines the scope of applications. It specifies terms and definitions and deals with the fundamentals of the processes involved. This standard contains relevant quality parameters and explains in detail component testing and the drawing up of supply agreements. It also covers safety-related and environmental aspects.

This guideline assumes that the reader has a basic understanding of the process flow of various different additive processes. It explains the processes used in practice in only as much detail as is necessary to understand the statements.

Data formats

The standardisation of data formats is aimed at users and producers of Additive Manufacturing processes and associated software systems. It applies wherever additive processes are used and to the following fields in particular:

- The production of Additive Manufacturing systems and equipment including software
- Software engineers involved in CAD/CAE systems
- Reverse engineering systems developers
- Test bodies wishing to compare requested and actual geometries.

ISO 17296-4:2014

The standard ISO 17296-4:2014 covers the principal considerations which apply to data exchange for Additive Manufacturing. It specifies terms and definitions which enable information to be exchanged describing geometries or parts such that they can be additively manufactured. The data exchange method outlines file type, data enclosed formatting of such data and what this can be used for. ISO 17296-4:2014 enables a suitable format for data exchange to be specified, describes the existing developments for Additive Manufacturing of 3D geometries, outlines existing file formats used as part of the existing developments, and enables understanding of necessary features for data exchange for adopters of the international standard.

Fig. 3 Two powders showing a different flow behaviour

ISO/ASTM 52915:2016

This provides the specification for the Additive Manufacturing File Format (AMF), an interchange format to address the current and future needs of Additive Manufacturing technology. The AMF may be prepared, displayed and transmitted provided the requirements of this specification are met. When prepared in a structured electronic format, strict adherence to an extensible markup language (XML) schema is required to support standards-compliant interoperability. It is recognised that there is additional information relevant to the final part that is not covered by the current version of this international standard. ISO/ASTM 52915:2016 does not specify any explicit mechanisms for ensuring data integrity, electronic signatures and encryptions.

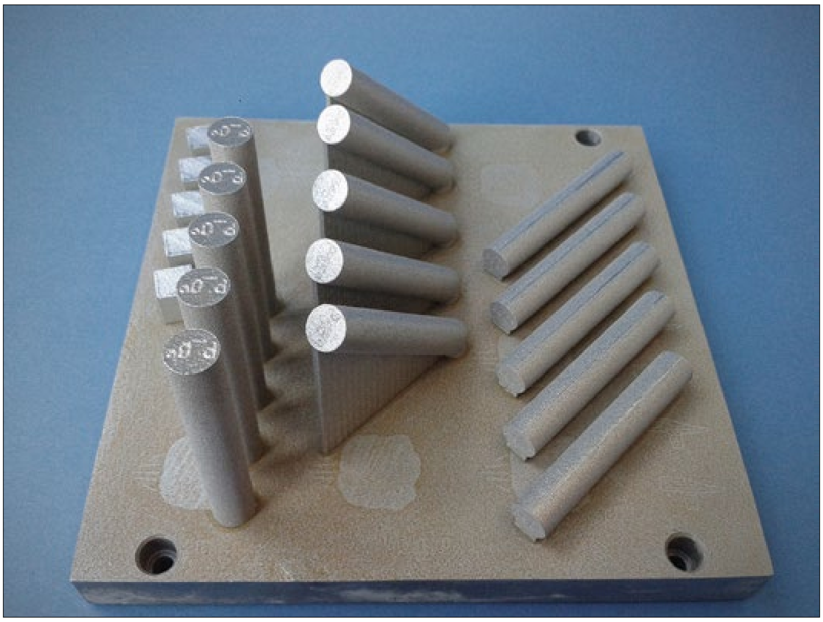


Fig. 4 Test specimen produced by Laser Beam Melting

Materials

Materials and their standardisation are important in achieving robust processes and reliable component properties produced using AM. Metal powders as raw materials require specialist handling and processing and the smallest deviations in powder properties can have an enormous influence on process-ability and component properties. Fig. 3 shows two powders behaving differently concerning flowability.

ASTM F2924-14
This standard covers additively manufactured titanium-6aluminum-4vanadium (Ti-6Al-4V) components using full-melt powder bed fusion such as electron beam melting and laser melting. It indicates the classifications of the components, the feedstock used to manufacture Class 1, 2 and 3 components, as well as the microstructure of the components. This specification also identifies the mechanical properties, chemical composition and minimum tensile properties of the components.

ASTM F3001-14
This establishes the requirements for additively manufactured titanium-6aluminum-4vanadium with extra low interstitials (Ti-6Al-4V ELI) components using full-melt powder bed fusion such as electron beam melting and laser melting. The standard covers the classification of materials, ordering information, manufacturing plan, feedstock, process, chemical composition, microstructure, mechanical properties, thermal processing, Hot Isostatic Pressing, dimensions and mass, permissible variations, retests, inspection, rejection, certification, product marking and packaging and quality program requirements.

ASTM F3055 - 14a
This covers additively manufactured UNS N07718 (2.4668 - NiCr19NbMo) components using full-melt powder bed fusion such as electron beam melting and laser melting. The components produced by these processes are used typically in applications that require mechanical properties similar to machined forgings and wrought products. Components manufactured to this specification are often, but not necessarily, post-processed via machining, grinding, electrical discharge machining (EDM), polishing and so forth to achieve desired surface finish and critical dimensions.

This specification is intended for the use of purchasers or producers, or both, of additively manufactured UNS N07718 components for defining the requirements and ensuring component properties.

ASTM F3056 - 14e1
Standard ASTM F3056 - 14e1 covers additively manufactured UNS N06625 (2.4856 - NiCr22Mo9Nb) components using full-melt powder bed fusion such as electron beam melting and laser melting. The components produced by these processes are used typically in applications that require mechanical properties similar to machined forgings and wrought products. Components manufactured to this specification are often, but not necessarily, post-processed via machining, grinding, electrical discharge machining (EDM), polishing, and so forth to achieve desired surface finish and critical dimensions.

It is intended for the use of purchasers or producers, or both, of additively manufactured UNS N06625 components for defining the requirements and ensuring component properties.

VDI 3405 Part 2.1:2015-07
This standard has been compiled on the basis of standard VDI 3405 Part 2, which is concerned with the beam melting of metallic parts as an Additive Manufacturing process and includes material data for grade 1.2709 tool steel (maraging steel).

This standard (VDI 3405 Part 2.1) contains material characteristic data for additively manufactured parts made from the aluminium alloy AlSi10Mg obtained in a round robin test. The test procedures and methods described in VDI 3405 Part 2 were used. Since all these procedures and methods correspond to recognised industry standards, it is possible to compare the characteristic values with those of conventional manufacturing processes.

Testing

Concerning testing procedures, several standards have already been published. Here it is vital to have a basis for comparing components coming from different sources of AM. Fig. 4 shows the set-up of specimen for further testing, produced by laser beam melting. The standard ISO/ ASTM 52921:2013 has already been covered in the section of this report on terminology.

ASTM F2971 – 13

This describes a standard procedure for reporting results by testing or evaluation of specimens produced by Additive Manufacturing. This practice provides a common format for presenting data for AM specimens, for two purposes; to establish further data reporting requirements and to provide information for the design of material property databases.

The standard was established because, due to variables unique to each AM process and piece of equipment, it is critical to standardise descriptions used to report the preparation, processing and post processing of specimens produced for tests or evaluation. The intent of this standard is to ensure the consistent documentation of the materials and processing history associated with each specimen undergoing test or evaluation. The level of detail for the documentation will match the application.

This practice establishes minimum data element requirements for reporting of material and process data for the purpose of:

- Standardising test specimen descriptions and test reports
- Assisting designers by standardising AM materials databases
- Aiding material traceability through testing and evaluation
- Capturing property-parameter-performance relationships of AM specimens to enable predictive modelling and other computational approaches.

ASTM F3049 – 14

This standard introduces the reader to techniques for metal powder characterisation that may be useful for powder-based Additive Manufacturing processes including binder jetting, directed energy deposition and powder bed fusion. It refers the reader to other, existing standards that may be applicable for the characterisation of virgin and used metal powders processed in Additive Manufacturing systems.

The intention of this article is to provide purchasers, vendors, or producers of metal powder to be used in Additive Manufacturing processes with a reference for existing standards or variations of existing standards that may be used to characterise properties of metal powders used for Additive Manufacturing processes.

It will serve as a starting point for the future development of a suite of specific standard test methods that will address each individual property or property type that is important to the performance of metal-based Additive Manufacturing systems and the components produced by them. While the focus of this standard is on metal powder, some of the referenced methods may also be appropriate for non-metal powders.

ASTM F3122 – 14

This standard serves as a guide to existing standards or variations of existing standards that may be applicable to determine specific mechanical properties of materials made with an Additive Manufacturing process.

As noted in many of these referenced standards, there are several factors that may influence the reported properties, including material, material anisotropy, method of material preparation, porosity, method of specimen preparation, testing environment, specimen alignment and gripping, testing speed and testing temperature. These factors should be recorded, to the extent that they are known, according to Practice F2971 and the guidelines of the referenced standards.

"there are several factors that may influence the reported properties, including material, material anisotropy, method of material preparation, porosity, method of specimen preparation, testing environment, specimen alignment and gripping, testing speed and testing temperature"

ISO 17296-3:2014

ISO standard 17296-3:2014 covers the principal requirements applied to testing of parts manufactured by Additive Manufacturing processes. It specifies main quality characteristics of parts, specifies appropriate test procedures, and recommends the scope and content of test and supply agreements.

It is aimed at machine manufacturers, feedstock suppliers, machine users, part providers and customers to facilitate the communication on main quality characteristics. It applies wherever Additive Manufacturing processes are used.

VDI 3405 Part 2

This is designed to complement the standard VDI 3405, which describes different Additive Manufacturing processes using a variety of materials. This standard covers the testing of components manufactured from metallic materials using additive technologies.

As with conventional manufacturing processes such as casting and milling, metallic parts produced by Additive Manufacturing technologies have critical-to-quality characteristics. In particular these include density, strength, hardness, surface quality, dimensional accuracy, residual stress properties, absence of cracks and structural homogeneity, which are typically tested in additively manufactured components. The quality of additively manufactured components is essential if functional components are produced on an industrial scale. Thus, it is necessary to qualify Additive Manufacturing processes according to uniform criteria and to apply standardised in-process testing.

VDI 3405 Part 3:2015-12

Apart from those already mentioned, there is the area of design for AM where there is also some activity concerning standardisation. One standard already published is VDI 3405 Part 3:2015-12 describing design rules for part production using laser sintering and laser beam melting. At ISO there is an activity for a standard named "Guide for Design for Additive Manufacturing" which today is still only a draft.

Conclusion

Additive Manufacturing is a technology that enables and stimulates innovation. AM is growing fast, with enormous investments being made worldwide. Nevertheless we are just beginning to explore the many possibilities of AM technology. To exploit the full potential it is necessary to collect available knowledge and benefit from collaboration. New business models, advances in production technology and new services are constantly arising. Almost every sector of industry will be impacted in one or another way by AM. On the other hand AM is not going to replace all other manufacturing methods in the near future.

Additionally, new product designs are feasible. Product designers are defining the specific requirements of products based on specified manufacturing processes. To fulfill requirements like material properties and quality control issues it is necessary to have appropriate standards integrated in the product development process. Standards are a vital part of the evolution of technology. Several AM standards developed by different national and international organisations have been published and more are on their way.

International collaboration is definitely beneficial for everybody as nobody would benefit from competing standards. Therefore one set of standards used all over the world should be the common goal. A global roadmap for AM standards could be an orientation. To speed up this process, existing standards could for example be modified for AM. A good example of joint efforts is the collaboration between ASTM International and ISO which is formally established and has successfully published a first set of standards. A next step could be to transform ISO/ASTM standards to CEN standards.

More experts supporting ongoing efforts through ASTM, ISO or national standardisation organisations are needed.

More information

The basic information for this article was taken from published standards. More information is available from the websites listed below.

www.afnor.org
www.astm.org
www.bsigroup.com
www.cen.eu
www.din.de
www.iso.org
www.unm.fr
www.vdi.de
www.vdma.org

Authors

Prof. Dr.-Ing. Frank Petzoldt, Deputy Director, and Dipl. Ing. Claus Aumund-Kopp, Project Leader & Senior Scientist

Fraunhofer IFAM
Wiener Straße 12
28359 Bremen
Germany
Tel: +49 421 2246 0
Email: claus.aumund-kopp@ifam.fraunhofer.de
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GKN Sinter Metals: Global Tier 1 automotive supplier anticipates opportunities for Additive Manufacturing

GKN Sinter Metals, with more than 6,000 employees at 30 locations worldwide, is the world's leading Powder Metallurgy group. The company produces 11 million PM parts per day, with around 80% going into the automotive industry. The company started its metal Additive Manufacturing activities at its Innovation Centre in Radevormwald, Germany, in 2013. Dr Georg Schlieper visited the centre on behalf of *Metal AM* magazine and reports on the company's AM activities and ambitions.

Radevormwald, a small town in the rural hills of the region known as Bergisches Land, is located in the western part of Germany, not far from the cities Cologne and Düsseldorf on the Rhine River and close to the Ruhr region. The town has longstanding connections to Powder Metallurgy through Sintermetallwerk Krebsöge, the predecessor of the current GKN Sinter Metals plant. Powder Metallurgy parts, porous filters and self-lubricating bearings are produced here in extremely high volumes and the plant has an international reputation as a pioneer in the development and early adoption of cutting-edge Powder Metallurgy technologies. These technological developments included powder forging for the production of high-performance components such as connecting rods in the 1980s and Metal Injection Moulding for high volume automotive applications in the 1990s, as well as the development of PM aluminium components.

GKN Sinter Metals Engineering GmbH is responsible for new Powder Metallurgy related process and product developments within the global GKN Sinter Metals Group. The GKN Innovation Centre, constructed in Radevormwald in 2004 and the home of GKN Sinter Metals Advanced Engineering, is an architectural highlight (Fig. 1). With its convex glass front, the building resembles a huge eye overlooking the countryside. The building, which incorporates blue steel beams and expansive windows, communicates clearly that this is the home of

Fig. 1 The GKN Innovation Centre in Radevormwald (Courtesy GKN)

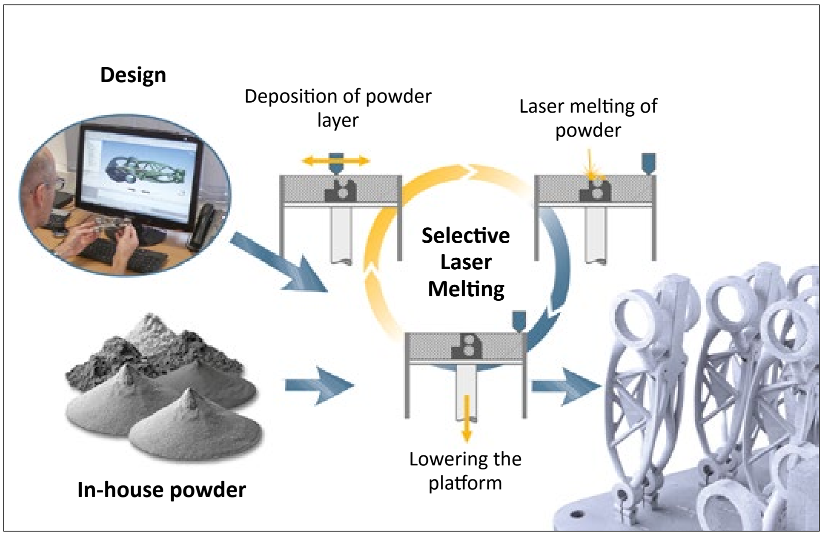


Fig. 2 Schematic depiction of the SLM process at GKN

Fig. 3 ExOne and Renishaw machines at the GKN Sinter Metals Innovation Centre in Radevormwald

advanced technology. When visitors enter the lobby, which extends over the entire height of the three-storey building, a broad curved staircase leads them to the upper floors. From the offices and meeting rooms one has a breathtaking view over the surrounding green hills.

The GKN Innovation Centre provides offices for around forty engineers and scientists as well as conference rooms and a large machine hall with a floor space of 900 m² equipped with modern presses, sintering furnaces and other facilities. Workshops and laboratories are set up for materials investigation, including metallography, tensile and fatigue testing.

GKN's approach to AM technology

The motivation for focusing on metal Additive Manufacturing is obvious. Considering GKN Sinter Metals' long tradition and expertise in Powder Metallurgy, it was a natural extension of its existing technologies when the Additive Manufacturing of metals emerged. Furthermore, there are many additional synergies within the GKN Group relating to AM.

The introduction of metal Additive Manufacturing technology within the GKN Sinter Metals Group is managed by Dr Simon Höges, who granted *Metal Additive Manufacturing* magazine an exclusive interview. Höges looks back on ten years of experience in Additive Manufacturing, having received a diploma in physics from RWTH Aachen, one of the most distinguished technical universities in Germany. His PhD thesis was focussed on AM technology and he worked on Selective Laser Melting (SLM) technology at the Fraunhofer Institute for Laser Technology (ILT) in Aachen. After a further four years of practical experience in the R&D department of a supplier of customised dental crowns, bridges and implants in Bremen, a sector where SLM is already a well established technology, he joined GKN Sinter Metals in 2014 as Manager Additive Manufacturing.

GKN as a group has, of course, a much longer history in metal Additive Manufacturing than that of the Sinter Metals division. One such example is GKN Aerospace in Bristol, UK, which primarily uses Electron Beam Melting (EBM) technology to produce components for the aerospace sector. EBM is advantageous for larger parts and is highly suited to the processing of titanium and nickel base alloys. The build rates are relatively high and the build space is larger than in most SLM machines. A truly unique feature with EBM is that it is a hot process in which the powder bed is pre-heated before melting each layer, offering several important advantages. Firstly, residual stresses are reduced which means that large and reasonably bulky components can be built very efficiently and without the risk of distortion. Secondly, it also means that titanium parts, for example, do not need to be heat treated after the build.

Höges told *Metal AM* magazine that besides the plant in Bristol, where the focus is on powder bed based processes, GKN Aerospace's plants in Trollhättan, Sweden, and St. Louis, USA, use metal deposition processes to manufacture very large aircraft components. These processes do not use powder bed systems and as such have far higher build rates. They are, however, much less accurate than SLM systems. GKN Sinter Metals therefore ruled them out as unsuitable for smaller, high precision components.

Hoeganaes Corporation, a part of GKN Sinter Metals with its headquarters in Cinnaminson, New Jersey, USA, is one of the world's leading metal powder producers with an estimated 25% share of the world market for ferrous metal powders. Hoeganaes' recent activities on gas atomised titanium powders for Additive Manufacturing have already been reported in *Metal AM* magazine (Vol. 1 No. 3, pp 71-74). Hoeganaes is committed to entering the fast growing market for AM metal powders and to develop better and less costly powder grades in close cooperation with its partners in the group. GKN will therefore be in a position to cover the entire AM value chain, from powder production to the finished product.

AM facilities at the GKN Sinter Metals Innovation Centre

The first SLM machine at GKN Sinter Metals, a Renishaw AM 250 with a build space of 250 x 250 x 300 mm, was installed in 2013 (Fig. 3). From the start the company decided to focus on powder bed based technology such as SLM with the highest accuracy and to use ferrous alloys to produce near-net-shape components. According to Höges, SLM offers a higher dimensional accuracy than EBM. "The cost pressure is much higher in the automotive industry than in aerospace", he stated, "therefore the reduction of manufacturing costs along the whole value chain, besides process consistency and reliability, is our first priority."

GKN has a broad technological base in metal Additive Manufacturing. Four AM machines are currently installed at the Innovation Centre; two SLM machines from Renishaw, one SLM machine from EOS and one binder jetting machine from ExOne. GKN recently announced that a further SLM machine, the MetalFAB1 from Additive Industries (Fig. 4) will be delivered in 2016. Other GKN Sinter Metals plants in Europe and North America also have Additive Manufacturing machines in operation.

Fig. 4 Additive Industries' MetalFAB1 system is due to be installed at GKN Sinter Metals before the end of 2016 and promises to open the door to the serial production of AM components for GKN's core markets (Courtesy Additive Industries)

SLM is the technology that is most widely used in the GKN Sinter Metals Group today because it is the most advanced and mature AM process for metals. With the MetalFAB1, GKN Sinter Metals will take part in the beta test program of Additive Industries, whose explicit strategy is to improve the productivity of metal AM by moving towards automation and integration. The MetalFAB1 is a first step that opens the door to the series production of AM components for GKN's core markets.

Out of the wide spectrum of materials that are available for AM today, GKN Sinter Metals is currently focusing on two ferrous alloys, the austenitic stainless steel 316L with excellent corrosion resistance and high ductility and, for high strength applications, the maraging tool steel 1.2709 which can attain a hardness of 54 HRC after ageing. Restricting development activities to ferrous alloys is down to the fact that, for cost reasons, the automotive industry has little interest in employing titanium or superalloy components. Ferrous alloys have thus absolute priority at GKN Sinter Metals and the development of further steels is on the agenda, with 20MnCr5 for gear prototyping given as an example.

Besides the production equipment, the design software is a key factor behind the success of AM. Once a CAD file of a part has been completed it can be used immediately to print the part anywhere in the world. There is no need for additional re-programming of machine parameters. The requirements on operating personnel are therefore lower than in machining or other Powder Metallurgy processes. This, it was stated, is another key advantage of AM.

Developing cost-effective powders for AM

The development and qualification of cost effective ferrous powders for AM is regarded as an important step towards overall cost reduction in metal AM and work on this is undertaken in close cooperation with Hoeganaes Corporation.

Currently, the majority of powders used in AM are produced by gas atomisation, a costly process that generates spherical particle shapes and the desired excellent flowability of the powder. GKN Hoeganaes has committed itself to enter the fast

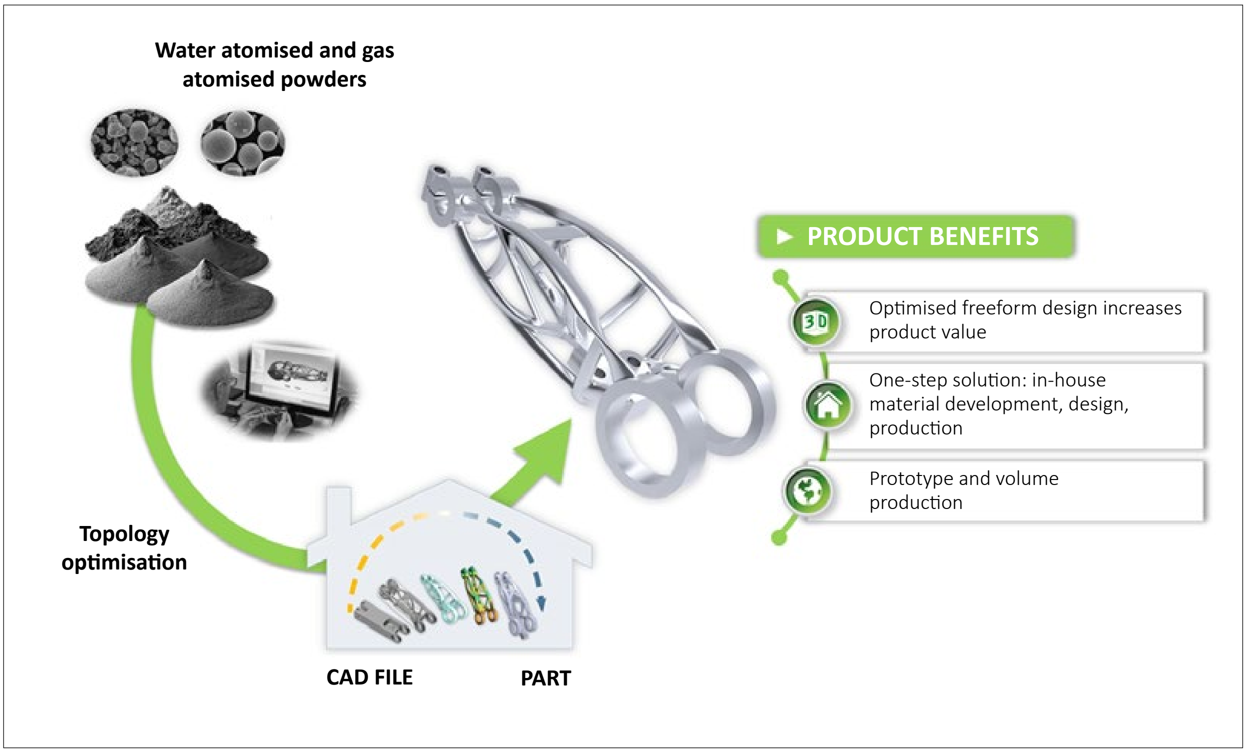


Fig. 5 Benefits of AM technology (Courtesy GKN)

growing market for AM powders with new powder grades including gas atomised titanium and water atomised specialty powders for AM. The company has also modified its water atomising processes for ferrous alloys to increase the proportion of spherical or near spherical particles. Water atomised powders will then partly or entirely replace the gas atomised grades, especially for Ni- and Fe-based materials. GKN Sinter Metals is testing these powders at its various AM facilities and is helping to develop powder specifications for AM processes.

Quality assurance

The design software for metal AM is based on Finite Element Analysis (FEA), which requires input of material characteristics, in particular the fatigue properties. GKN uses the facilities at its Innovation Centre to continuously determine tensile and fatigue characteristics of its AM materials. Materials testing is also used as a quality assurance method. Tensile test pieces are produced with each machine run and analysed to ensure the consistency of the material properties and consequently the reliability of the process.

The densities of SLM parts are typically above 99% of full density. However, the residual porosity is only an issue for components that operate under high fatigue loading. Nevertheless, Höges has concerns about porosity. "Residual porosity is our greatest concern when it comes to quality assurance," he stated. "The technology is just not yet capable of consistently delivering densities above 99.5%. Our hope is that in the future machine manufacturers will develop systems that automatically detect process irregularities and have a feedback system that corrects them immediately while the machine is operating."

Rapid prototyping

The initial approach to the commercialisation of metal AM by GKN Sinter Metals is rapid prototyping. The ability to supply prototypes of PM and forged components is, in the short term, regarded as a competitive advantage. In many cases, optimising the design of an assembly of new products can be achieved with AM even though the material properties of additive manufactured parts are not the same as, and usually far better than, those of pressed and sintered parts.

GKN Sinter Metals is working hard to get its AM processes certified according to the ISO/TS 16949 standard. With this strategy, GKN's AM technology is seeking to distinguish itself from prototype manufacturers who do not have a specific focus on automotive components and are therefore unable to be accepted by automotive OEMs as regular parts suppliers.

The prototyping of steel parts by AM is already widely practised in the automotive industry. "Most OEMs have their own AM facilities for prototypes, but for us as a parts supplier it is an advantage to be able to deliver AM prototypes that are planned to be produced as volume components by us later," stated Höges. "We already cooperate with our customers in the

Fig. 6 Simon Höges opening the Renishaw AM 250 (Courtesy GKN)

design phase, integrating more functions into a component and adapting the design for our processes. Rapid prototyping is definitely an opportunity to participate in the design phase with our customers. As a global parts supplier with local sites all over the world, GKN is in a position to serve our customers at first hand."

Noise reduction with AM design

The strategy pursued by GKN Sinter Metals for new AM products in the automotive sector can be seen in the design study shown in Fig. 7. Together with GKN Driveline, a conventional pulley was re-developed for AM with a honeycomb structure between the hub and the outer gear ring and cavities inside the hub and gear. These features not only reduce the mass of the component but, more importantly, offer a significant noise reduction.

Designing for noise reduction follows the principle of acoustically uncoupling the source of the noise from the noise transducing components. In the case of the pulley, the noise is generated by the gear teeth when the tooth flanks meet the teeth of matching gear or drive belt. The internal hollow structure minimises the noise transfer to the hub and shaft. AM technology produces a near-net shape preform of the pulley and only the functional inner and outer surfaces that need high precision are finish machined at affordable cost. With this approach it is possible to develop noise reducing lightweight components for applications where these properties are so valuable that the extra cost of AM processing is acceptable.

Further design options

In addition to conventionally shaped technical components such as the pulley in Fig. 7, bionic design is also applied by GKN. An example is the rocker component shown in Fig. 8. The component is part of a fatigue test rig and was selected to highlight the options that bionic design presents for weight saving. The design process is largely automatic, with only the fixtures and loading conditions entered into the software. When supplied with the material characteristics, the design software generates a lightweight structure that can further be optimised to accommodate other requirements such as aesthetic or functional features. "AM offers an enormous amount of design freedom that allows us to optimise for function without having to compromise with respect to the manufacturing process," explained Höges.

A unique AM design that cannot be produced by any other method is shown in Fig. 9. It is a planetary gearbox with a diameter of approximately 30 mm which has been produced in one piece. The outer ring holds seven moving planetary gears surrounding a central gear. The whole assembly consists of nine individual parts that cannot be separated without destroying the gearbox. This demonstrator was developed to highlight the unique possibilities of AM; monolithic and bionic design, internal structures for tailored material properties and noise reduction, as well as part assembly integration.

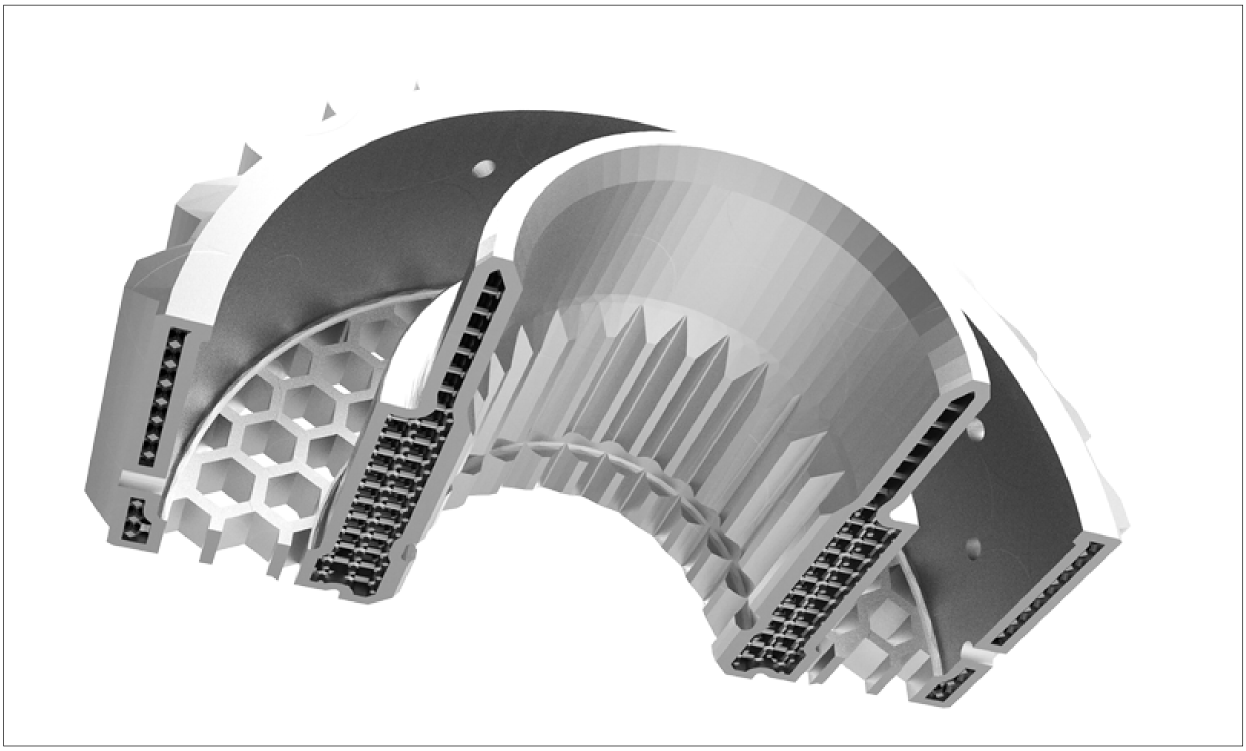


Fig. 7 Demonstration pulley designed for AM (Courtesy GKN)

Commercialisation

"Our market research has identified that chances for a successful business case are best for small and complex parts whose weight is as low as possible because the processing cost of Additive Manufacturing is mainly determined by the mass of the part," Höges told *Metal AM* magazine. "Each gram in the product means powder cost and energy required for melting the powder."

The search for new Additive Manufacturing applications is fully integrated into the global sales network of GKN Sinter Metals. Selected sales representatives have received sets of demonstration parts as inspiration for their customer contacts and feedback on this activity has been very positive. Currently, sales initiatives are primarily directed at prototyping, however potential is seen in the market for small to medium volume luxury cars. When this market becomes a reality, GKN's ambition is to be recognised as the leading supplier and a special sales force for additively manufactured products is planned.

"potential is seen in the market for small to medium volume luxury cars. When this market becomes a reality, GKN's ambition is to be recognised as the leading supplier"

The sales teams at GKN Sinter Metals are to a large extent focused on the automotive sector. The company therefore anticipates that it can build on its many existing relationships and as a result the best chances to identify new AM applications are expected here. However, there is also interest from other industries. Höges told *Metal Additive Manufacturing* magazine that specific application developments are under way with Otto Bock, a manufacturer of prostheses for the disabled.

A further step will be to supply customised spare parts for classic cars and specially designed components for motorsport that can be produced in small volumes. Looking beyond custom parts, the company is working towards equipping a whole series of new luxury class with exclusive components that can be produced in quantities of a thousand or more per year.

Further expectations for AM

The development of AM machinery is still in progress and it is likely that, besides further integration of existing systems, entirely new concepts for metal AM will emerge in the future. GKN Sinter Metals is actively involved in research projects on metal AM and, in close cooperation with its equipment suppliers, feedback is shared about the use of their machinery along with proposals to help them improve their products. Höges anticipates that there will be a substantial gain in productivity in the future due to faster processing and, in the long term, price reductions on raw materials and machinery for AM.

"The build space of our machines is sufficient in most cases," stated Höges, "because we rarely have very large products. The next machine that we will receive, however, has a build space of 420 x 420 x 400 mm. The higher capacity of this machine is a step forward towards the economic series production of automotive parts in small to medium numbers, because more parts can be built in each production run." Precision, in contrast, is much more important for small functional metal parts and an important economic factor. "A component that needs a lot of machining after AM processing will seldom be competitive," stated Höges. "We are dedicated to improving the productivity of our AM processes by intelligent use of the design advantages of AM and by reducing the necessary secondary operations as far as possible."

Particular attention is given at GKN Sinter Metals to the secondary operations that are required on AM parts. "For the technical function and the aesthetic appearance of AM products it is usually necessary to smooth the surface. We look for the most efficient secondary processes that allow for a high level of automation and try to organise our processes to be as lean as possible," stated Höges.

Beyond SLM, GKN is now also investigating the potential of ExOne's binder jetting technology. Whilst still in the early development phase within GKN, the higher productivity and similarity to Metal Injection Moulding makes this process interesting to GKN Sinter Metals.

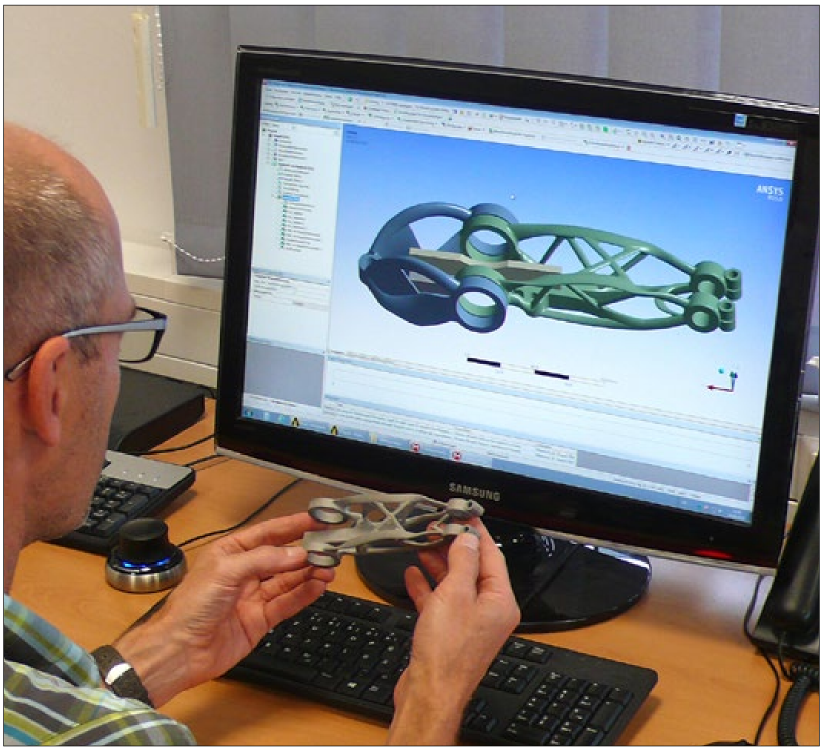


Fig. 8 Bionic design for AM of a rocker for a fatigue test rig (Courtesy GKN)

Fig. 9 Planetary gearbox made by AM (Courtesy GKN)

Outlook

The future of AM in the GKN Sinter Metals Group offers several options. "We see AM as a new, independent manufacturing technology of the family of PM processes," concluded Höges. "It's not competing with our established press and sinter, powder forging and MIM processes. AM can support these technologies with prototypes, but it will also find its own market segments independent from our other PM products."

Contact

GKN Sinter Metals Engineering GmbH
Dr Simon Höges
Dahlienstrasse 43
D-42477 Radevormwald
Germany
Tel: +49 2195 609 940
Email: simon.hoeges@gkn.com

Author

Dr Georg Schlieper
Alleestr. 101
D-42853 Remscheid
Germany
Tel: +49 2191 6889274
Email: info@gammatec.com

Metal AM in the automotive industry: New vehicle structures, series components for the luxury market and beyond

The automotive industry has successfully embraced metal Additive Manufacturing as a prototyping technology for a number of years. As the technology advances, however, the possibilities for the use of metal AM for series component production are now starting to be explored. In the following review the challenges and opportunities for metal AM in the automotive industry are presented, including a radical concept to use AM parts as key structural elements in the next generation of automotive spaceframes.

Automotive manufacturers are increasingly required to integrate a diverse range of drive types and energy storage systems into vehicle structures. The vehicle bodies of tomorrow will not only need to be lighter but will also require designs that are flexible enough in order to accommodate the large number of alternative drive systems, some of which may be produced in relatively low volumes. The consequence is an increasing number of vehicle derivatives which demand adaptable bodywork concepts that are economical to manufacture. In the foreseeable future, Additive Manufacturing could offer entirely new approaches.

One such approach is the EDAG Light Cocoon concept car, unveiled in March 2015 at the Geneva Motor Show and seen later that year at the International Motor Show (IAA) in Frankfurt (Fig. 1). The EDAG Light Cocoon concept is a compact sports car with a bionically designed and additively manufactured vehicle structure, covered with an outer skin made from weatherproof textile material. The intention with this vehicle was to trigger a debate among designers and break with conventional expectations of vehicle design and construction. The car's creators state that the vehicle highlights sustainable production and at the same time embodies the technological potential of Additive Manufacturing.

Fig. 1 The "EDAG Light Cocoon" concept car features a bionically optimised and additively manufactured vehicle structure

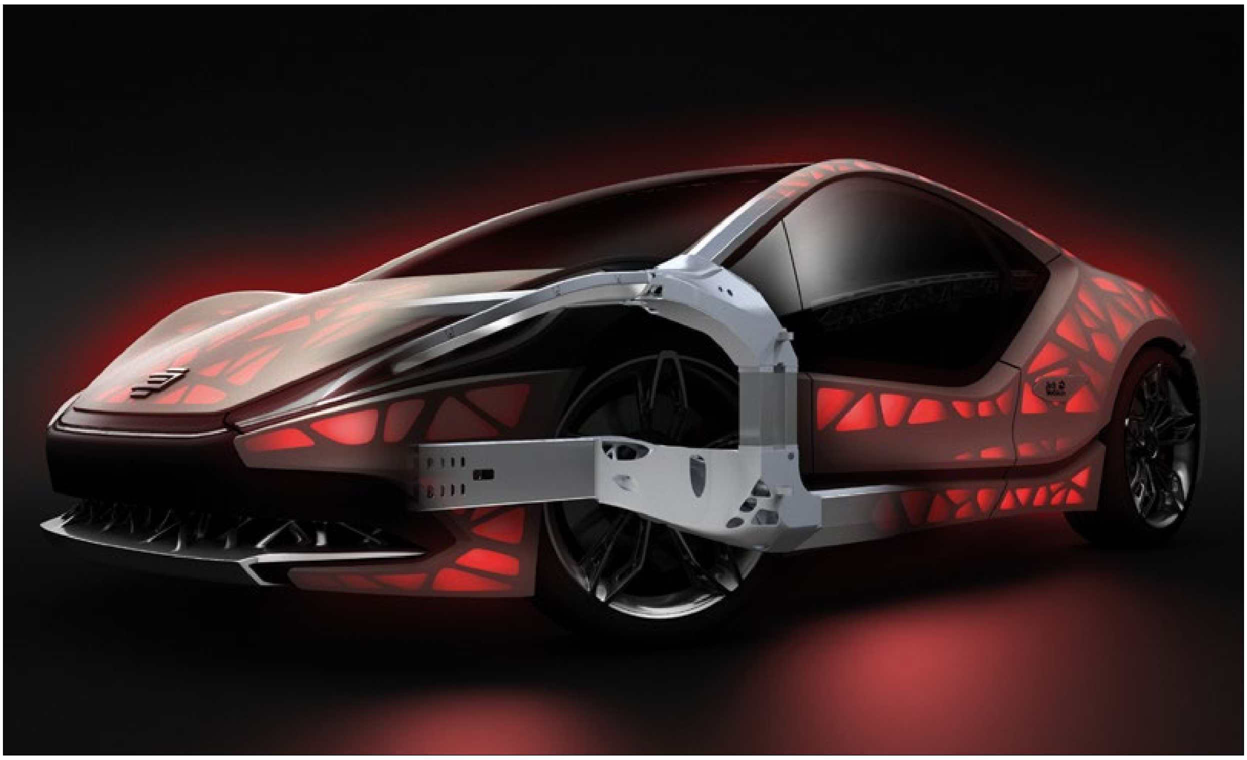


Fig. 2 The EDAG Light Cocoon concept car showing the use of additively manufactured nodes combined with steel profiles in the NextGen spaceframe

In a joint project, EDAG Engineering GmbH (Wiesbaden, Germany), Laser Zentrum Nord GmbH (Hamburg, Germany), Concept Laser GmbH (Lichtenfels, Germany) and the BLM Group (Cantù, Italy) created the bionically optimised spaceframe. This was produced by hybrid manufacturing to highlight one way in which car bodywork can be manufactured flexibly whilst at the same time accommodating the needs of an increasing range of different drive and performance requirements. Additively manufactured bodywork nodes and intelligently processed steel profiles are combined and, thanks to AM, the nodes can be configured to be highly flexible and multifunctional. In this way different versions of a vehicle can be produced on demand without any additional tooling, equipment and start-up costs. Steel profiles are used as connecting elements and these too can easily be adapted on an individual basis to the specified load levels by providing them with different wall thicknesses and geometries (Figs. 2 and 3).

The NextGen spaceframe in detail

The nodes on the NextGen spaceframe can be manufactured on-site 'just in sequence' (JIS), along with the steel profiles, which are cut to the appropriate shape and length initially using 3D bending and then by employing 2D and 3D laser cutting processes.

The focus is on joining individual components to create a hybrid structure to produce topologically optimised spaceframes that are simply not possible using existing technology. Laser welding is used as the joining method, characterised by precisely welded seams and low thermal input. The profiles are automatically aligned and fixed in place by the node and a high-brightness laser with robot-guided optics is used to perform the welding. In addition, the laser techniques used to produce profiles and nodes can largely be automated in assembly. This offers great potential when it comes to the manufacturing cost structure and time required to manufacture.

The AM nodes can be adapted to reflect each load stage, for example by incorporating additional stiffening elements to cater for high load requirements. This means that each version is designed for optimum weight and function. Both the nodes and the profiles were optimised using CAE/CAD and guarantee the requirements that are demanded of a bodywork structure.

As well as playing a coordinating role, EDAG Engineering GmbH was responsible for devising and optimising the spaceframe concept, Laser Zentrum Nord GmbH undertook the laser welding, the BLM Group undertook the 3D bending and laser cutting and Concept Laser GmbH performed the Additive Manufacturing of the nodes. The project could only be implemented successfully thanks to the interdisciplinary collaboration between the complementary partners and the high level of expertise of the individual technology specialists in their specific disciplines.

Fig. 3 In the NextGen spaceframe concept the AM nodes are part of an adaptable and flexible production concept that can produce vehicle structures 'just in sequence' (JIS), tailored for different load stages

Production of the AM spaceframe nodes

Concept Laser's powder bed laser melting process, LaserCUSING, was used for the production of the nodes. AM allows the production of components with complex geometrical shapes without the use of any tools and directly from 3D CAD data. With this type of design, the nodes cannot be manufactured by conventional steel casting. As with all parts produced by this process, support structures need to be provided on planes with an angle of less than 45° in relation to the build platform. As well as providing support, these structures also absorb internal stresses and prevent the components from warping. Because of the complex geometry of the nodes, good support preparation is essential for successful production. After generating the support structures, the component design is virtually 'cut' into individual slices. Once the data has been transferred to the LaserCUSING machine and the corresponding process parameters assigned, the build process is started.

The nodes were manufactured on a Concept Laser X line 1000R machine which has the necessary build envelope for such projects (630 x 400 x 500 mm) and operates with a 1 kW laser. The X line 2000R, also from Concept Laser, has a larger build envelope (800 x 400 x 500 mm) and is equipped with two 1 kW lasers (Fig. 4).

Digital 3D manufacturing strategy with laser technologies

The spaceframe concept combines the advantages of Additive Manufacturing, such as flexibility and the potential for lightweight construction, with the efficiency of proven conventional profile designs. The topologically optimised nodes enable the most efficient lightweight construction that is currently possible, as well as a high degree of functional integration.

Both the nodes and the profiles can be adapted to new geometries and load requirements without any additional outlay. This means that every single part can be designed to cater for a specific level of loading, rather than designing a single component to cope with the greatest load even if the majority of vehicle models do not demand it, as was previously the case. Nodes and profiles are therefore custom designed to reflect what a particular vehicle model requires, resulting in a spaceframe structure with an optimised load path. By employing processes which make limited use of tooling, it will be possible in the future to manufacture all bodywork versions of a vehicle economically and with the greatest possible flexibility.

Additive Manufacturing and the automotive industry: A broader view

The NextGen spaceframe system is just one example of how Additive Manufacturing has the potential to transform automotive production. Commenting on the challenge that the automotive sector faces in achieving sustainability targets,

Fig. 4 The successor to the X line 1000R, the X line 2000R from Concept Laser has what is currently the largest build envelope of a laser powder bed AM machine worldwide, at 800 x 400 x 500 mm. It is equipped with multi-laser technology and the 'R' variant of this system denotes that the machine is tailored to suit reactive metals such as titanium

Dr.-Ing. Martin Hillebrecht (Fig. 5), Head of Competence Centre for Lightweight Design, Materials and Technologies, EDAG Engineering GmbH, stated, "Automotive manufacturers are under great pressure to develop vehicles which are due to go into production between now and 2020. The new bodywork structures should weigh less, have high stiffness to ensure outstanding performance and satisfy demanding load scenarios in the event of a crash. In spite of all the ambitious targets for weight reduction, greater demands from customers, thinking of alternative drives, comfort, functionality and networking, as well as new safety requirements from international legislators are sales criteria that do not favour lightweight construction. From my perspective, the core concept of a visionary and bionic spaceframe would be, among other things, only to use materials where they are really needed to deliver a function, safety or rigidity. So a reduced approach based on the motto less is more. Thanks to Additive Manufacturing and the profiling method with minimal use of tools, it may even be possible in future to design all bodywork versions to suit the level of loading and manufacture them 'on demand'. Whatever happens, there is definitely potential here."

Sergio Raso (Fig. 6), Head of Strategic Marketing - Laser Products, BLM Group, commented on this theme, stating, "Sustainability is the overriding aim for the automotive industry. Various core technologies for the future of automotive production have so far been looked at. The frame structure of the EDAG Light Cocoon combines many of these technologies in one approach. For example, there is a lightweight hybrid design to achieve weight reduction and fuel efficiency, the use of additive methods for a bionically optimised design and the use of tubing and profiles to ensure that the vehicle frame can be manufactured in a highly flexible way."

Encouraging the adoption of new automotive concepts

As the example of electric vehicles demonstrates, it takes a long period of time to progress from initial innovative concepts to volume production. Automotive pioneers such as Hayek with the original Smart car, or Tesla Motors, are examples of how it can be challenging for innovation to be accepted. Commenting on whether the automotive industry is really ready to look at its products in completely new ways, Hillebrecht stated, "Experience shows that one possible way to embark on new manufacturing strategies such as lightweight design is often to produce small numbers of vehicles in the luxury and supercar segment. This clientele identifies with lightweight design, e-mobility and technical innovations much more than the mass market. These 'innovators' are willing to accept much higher manufacturing costs as a price worth paying for better driving dynamics, comfort, safety and for ecological reasons. If the technology shows suitable potential and as its development advances to allow mass automotive production, the processes can then be scaled up from a niche product to enable larger volumes to be produced. But this definitely requires a degree of patience, long-term investments in the future of the companies involved and a great deal of technical expertise. I don't accept that a long period of time is required, but it definitely takes some time to adapt new technologies."

Raso added, "In the automotive industry, the number of jobs depends to a large degree on the manufacturing methods and strategy employed. They have a crucial bearing on the cost structures, the achievable margins and the level of success. These factors shape the way we look at mobility and not least also the prosperity of many national economies. In order to maintain the level of automotive mobility that has been achieved, the automotive industry has continuously invested in making technological advancements to its automobiles and the production processes behind them. Investments in research and development are essential, and we at the BLM Group are also on this path of innovation and ongoing development."

Fig. 5 Dr.-Ing. Martin Hillebrecht, Head of Competence Center for Lightweight Design, Materials and Technologies, EDAG Engineering GmbH, Wiesbaden, Germany

Fig. 6 Sergio Raso, Head of Strategic Marketing - Laser Products, BLM Group, Cantù, Italy

Fig. 7 Prof. Dr.-Ing. Claus Emmelmann, CEO, Laser Zentrum Nord GmbH, Hamburg, Germany

Fig. 8 Frank Herzog, President & CEO, Concept Laser GmbH, Lichtenfels, Germany

Green technologies in the automotive sector

The conservation of resources and the use of green technologies are today important considerations in any industry. Commenting on how automotive manufacturers view this, Hillebrecht stated, "Thanks to smart lightweight design, particularly with composite construction, vehicles should be roughly 100 kg lighter than their predecessors, depending on the segment of the market. A further weight saving of 10 to 20% can be achieved in the bodywork and add-on parts. Many manufacturers have already succeeded in reversing the spiralling trend for increased weight. It is a balancing act that we are trying to achieve."

Raso believes that solutions for green technologies and intelligent energy management are heavily dependent on action by governments, with their political targets, laws and definitely also the incentives that they provide. He stated, "This focus, if we just look at the US state of California, is an increasingly prevalent fact that we must come to terms with. Automotive manufacturers are accepting these demands and also view political targets as an engine for driving innovation. So politicians and manufacturers share a common interest. Along with the known solutions for energy management, such as developing electric storage units and drives and also vehicles equipped with fuel cells, the manufacturing processes can also be heavily geared to reflect the visions of green technology. The manufacturing design with all-electric bending machines, laser cutting machines with a high level of efficiency or laser melting are examples of how the BLM Group is committed to a greener future. The path toward intelligent conservation of resources and sustainability is an irreversible mega trend. All of the stakeholders in the automotive industry are conscious of this."

The disadvantages of traditional body design

The development of the NextGen spaceframe serves to highlight the advantages and disadvantages of conventional car body designs. Today's car bodies are intelligent, load-optimised and crash-optimised structures whose material and design concepts have achieved a high level of maturity, both in terms of lightweight design and passenger protection. Prof. Dr.-Ing. Claus Emmelmann (Fig. 7), CEO, Laser Zentrum Nord GmbH, stated of the project, "The traditional tool-based manufacturing methods which are used are reaching their limits in terms of flexibility and feasibility. Laser Zentrum Nord was able to work with its project partners to overcome these limits conceptually with the bionic design principles modelled on nature. The spaceframe concept attempts to highlight what is possible beyond the current limits with regard to products, manufacturing and automation."

"The spaceframe concept attempts to highlight what is possible beyond the current limits with regard to products, manufacturing and automation"

Hillebrecht stated, "In a typical car body with a monocoque construction, panels, reinforcements, mounting plates and profiles are connected together using joining technology. All components act as shells. The required rigidity is produced by cross-sections of metal sheets. The advantage of this design is the low manufacturing cost associated with industrial mass production, which is the same worldwide. As well as inexpensive semi-finished products made from sheet metal, tried-and-tested and robust technologies such as forming and spot welding are used. The disadvantage here is that tooling and plant investments only make economic sense if there are large quantities and make it difficult to produce a wide variety of different versions. In addition, tool-specific parts are associated with tooling costs and periods of preparation for the tooling technology are required. Ultimately, the tools have to be available across the full life cycle of the product. The spaceframe design consists of closed hollow profiles which are linked together by nodes. Flat components such as the roof absorb the shear forces. In future, a spaceframe concept will enable new materials to be used. This will need to be investigated. But in general it is already the case today that the concept enables the manufacturer to achieve a significant weight saving and high torsional stiffness along with a high level of economic efficiency for vehicles produced in fairly small numbers."

Raso added, "A major advantage of the conventional structures for vehicle frames is the interplay between consolidated technologies which are available now for manufacturing and assembling the frame. Currently production lines must generally include various processes and phases prior to the final assembly of the vehicle frame. The disadvantage of this concept is the outlay and the limited flexibility in the assembly workflow. New ideas and, derived from them, economical and flexible concepts for future manufacturing are required here. I would put it this way: There are major challenges."

Unique features of the NextGen spaceframe

The NextGen spaceframe combines additively manufactured nodes with steel profiles in a hybrid design. Hillebrecht explained, "This approach promises to make production extremely flexible and it promises the possibility of a wide range of different versions without having to spend any money on making further investments in apparatus, tools and plant technology for each version of a vehicle. I think that a wide range of different models may emerge because restrictive cost barriers will no longer apply. In addition, Additive Manufacturing allows the greatest possible resource efficiency with regard to the materials that are used. Moreover, this process yields bionic structures with optimised load paths whose geometry means they simply cannot be produced using other manufacturing methods."

Emmelmann stated that the spaceframe concept combines the advantages of Additive Manufacturing, such as flexibility and the potential for lightweight construction, with the efficiency of a proven conventional profile design. "The laser plays the key role in both technologies. The bionically optimised nodes enable the maximum lightweight construction that is possible at the present time, and a high degree of functional integration. Both the nodes and the profiles can be adapted to new geometries and load requirements without any additional outlay. This means that they offer the possibility of designing every single part to cater for the level of loading, and not dimensioning the components to reflect the greatest motorisation, as was previously the case. The basic idea then is to have a frame design which can be optimally customised to reflect what the particular model requires."

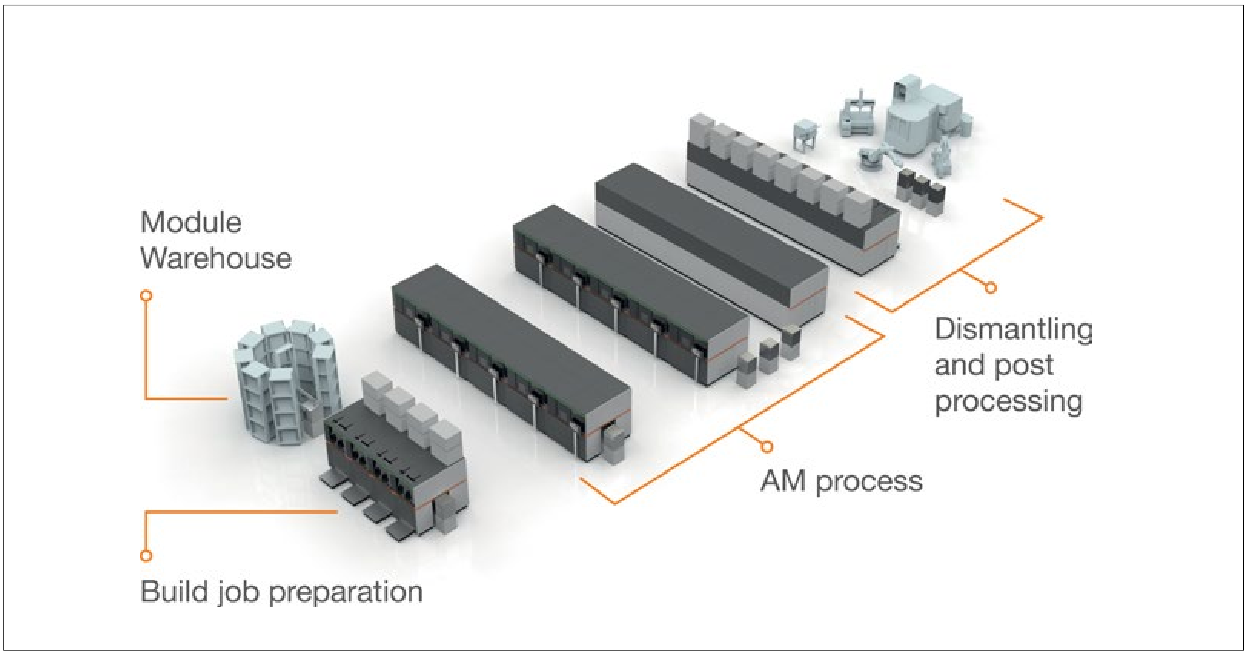


Fig. 9 In Concept Lasers' vision of the AM factory of tomorrow, production is decoupled, in machine terms, from the preparation and finishing processes. The time window for AM production is thereby increased to twenty four hours a day, seven days a week, resulting in higher availability of all components. 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 post-processing and finishing

A key feature of the NextGen spaceframe concept is the consistent focus on keeping the manufacturing and assembly processes extremely flexible. Raso stated, "Additively manufactured free-form nodes enable new design solutions and a large number of different varieties of models. The incorporation of bionic structures, a hollow design or lattice structures allows the frame to display optimised mechanical properties. The integration of force absorption characteristics in the profiles and nodes permits controlled deformation of the frame and delivers increased safety for passengers. The inclusion of AM and configuration of interfaces for laser welding optimises the manufacturing process. So firstly flexibility, secondly safety and thirdly simplification of processes are just a few examples of the advantages of this approach."

Frank Herzog (Fig. 8), President & CEO, Concept Laser GmbH, believes that hybrid construction is already being used in other sectors. "Relatively simple or excessively long geometries, such as the profiles used here, are produced by traditional machining, and more complex geometries are then manufactured additively. This phenomenon reflects the economics. Composite construction is of interest in many sectors where there is a need to bridge a gap between function and economic efficiency," he stated.

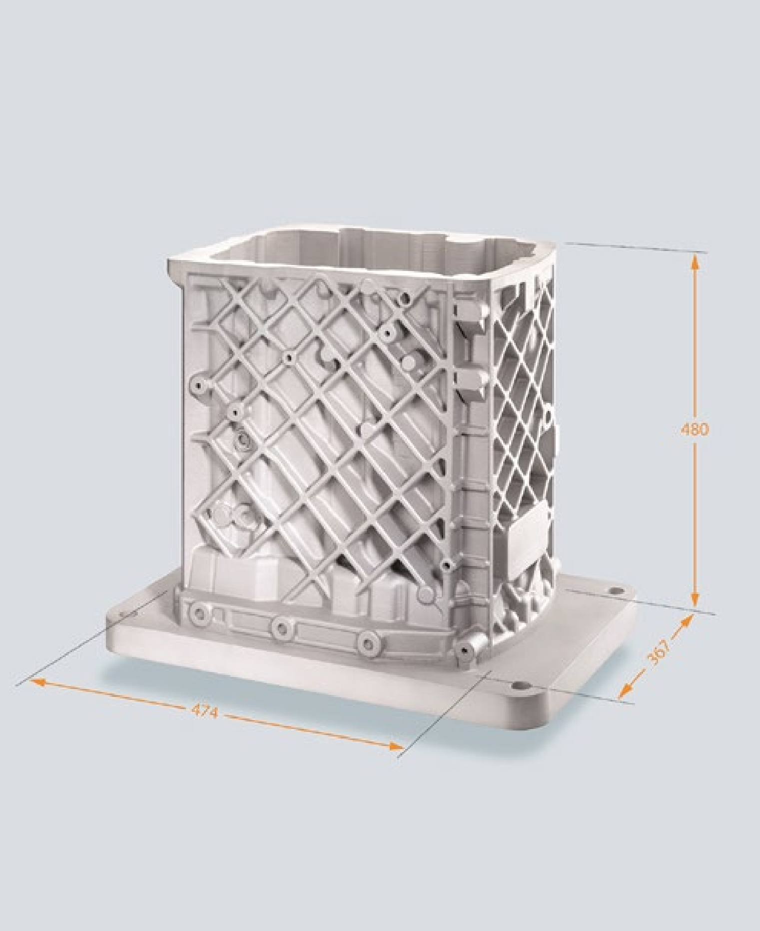
Using bionic design and hybrid construction to enable lightweight design

The potential for hybrid construction lies in flexible design that caters for specific load situations, along with the opportunity to use bionic structures to maximise lightweight design on a scale that was previously unimaginable. Emmelmann stated, "At Laser Zentrum Nord we develop design guidelines to be able to successfully transform bionic prototypes such as a bamboo structure or bird-bone structure into such sophisticated technical lightweight components with weight savings of between 30 and 50%. Bionic design, which is possible thanks to Additive Manufacturing, provides numerous options. Manufacturing benefits from these new manufacturing processes in many ways: it is not just that the costly tools are no longer required, but flexible small batches or even modifications to components within the life cycle of a model can be produced instantly without any additional outlay."

Hillebrecht added, "In addition, the ability to respond to fluctuations in sales volumes and 'updateable' components during the life cycle of a vehicle in the sense of Industry 4.0 should be emphasised. These are completely new ideas for the industry. We are very excited to see how our customers will react to this."

Raso believes that the new concept means great freedom of design for developers and designers. "The proposed concept provides the designers in the automotive industry with more lightweight solutions, more ecological approaches

CASE STUDY 1: GEARBOX



This gearbox is made of aluminium and manufactured on a Concept Laser X line 2000R machine. The material is CL 31AL (AlSi10Mg). Additive Manufacturing offered reductions in weight, cost and manufacturing time as well as giving the designer significant design freedom (Courtesy Concept Laser)

and improved safety solutions. In manufacturing, the adaptation of laser-based methods, such as Additive Manufacturing of nodes, laser cutting and laser welding of tubes and profiles, means an unparalleled degree of flexibility. Not least, these manufacturing strategies may help to increase the level of automation. These methods represent the innovation of manufacturing processes."

Industry 4.0, or the fourth industrial revolution, is a collective term embracing a number of contemporary automation, data exchange and manufacturing technologies. Herzog believes that the core aspects of this concept play a fundamental role in Concept Laser's recently presented AM Factory of Tomorrow (Fig. 9). "The objective is to automate and thus minimise manual processes in order to prevent any downtime in the production of components. Any desired number of machines which were previously designed to be stand-alone solutions will increasingly be linked together to embrace the notion of a smart factory. There will also be automation and inter-linking of additive and conventional technologies, in particular in the reworking of the components that are produced. Traditional manufacturing methods will then operate alongside additive methods. Our AM Factory of Tomorrow is aligned with the requirements of the basic idea behind Industry 4.0 and in the future will also make our process economically attractive for the mass production of metallic components. This will then undoubtedly also apply to the automotive industry where it is primarily all about large volumes and quantities."

Metal AM's future impact on the automotive industry

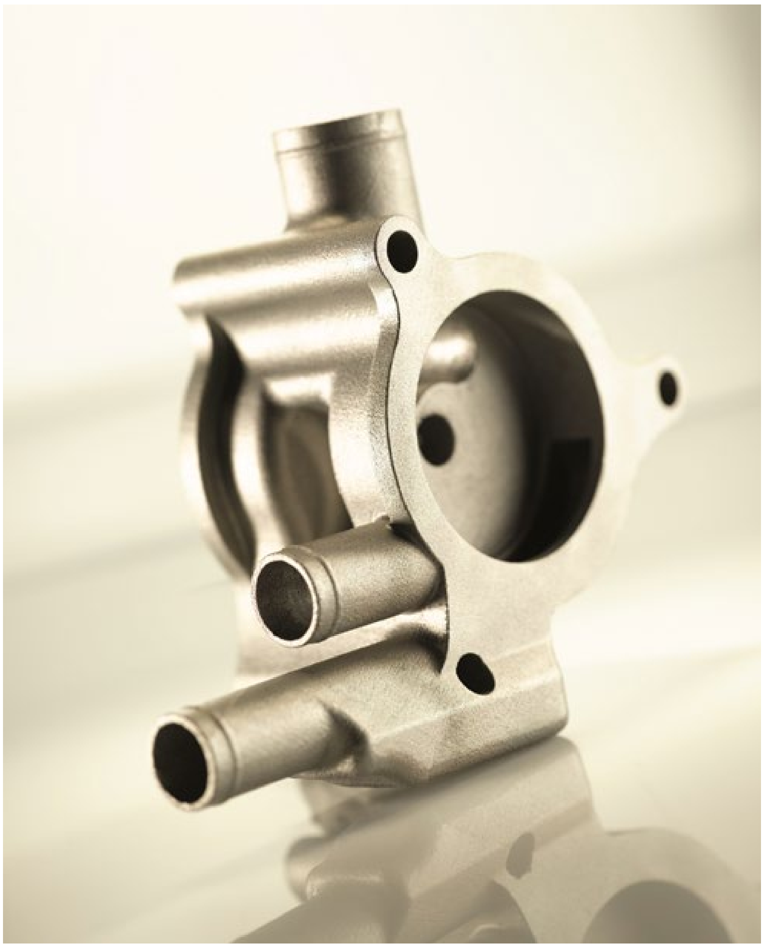
It is now almost impossible to imagine prototyping in the automotive industry without metal Additive Manufacturing. The technology makes it possible to produce fully resilient trial parts quickly and without the high tooling costs that are otherwise customary. However, the move to mass production has not happened yet. Emmelmann stated, "The continuous increase in the productivity of Additive Manufacturing machine technology means that this step will be made in the next five to ten years. The two projects which were presented at the IAA trade show in 2015, the bionic spaceframe and the housing for power electronics, demonstrated two specific ways in which this technology may shortly be employed economically in electric mobility vehicles or even other vehicles produced in low volumes."

Raso commented, "Additive Manufacturing techniques are today employed primarily in the automotive industry to manufacture small numbers of functional parts. However, as the aerospace industry has already demonstrated, we can see that the move over to Additive Manufacturing strategies significantly enhances product and process performance. The introduction of the 'Manufacturing for Functionality' paradigm instead of the rather restrictive 'Design for Manufacturing' as well as 'just-in-time manufacturing' and precision concepts have already begun to establish a foothold in the automotive industry. We are seeing the foundations of something completely new here."

Hillebrecht believes that the additive processes provide great potential in prototyping and tooling and the production of spare parts. "These processes have so far not caught on in automobile production. This is undoubtedly also due to the high prices of materials and machine technologies. We await the future with keen interest. We would be delighted if the sector were to embrace our ideas of tool-free manufacturing in combination with traditional manufacturing methods. There are definitely lots of opportunities here."

Herzog summarised the situation, stating that the level of interest will increase as the level of Additive Manufacturing technology advances. "A high level of acceptance in the automotive industry can of course only be expected if, as in the aerospace sector, the new design possibilities that Additive Manufacturing brings are embraced. Simply substituting parts made using traditional methods delivers few advantages. It is all about having a design to suit the method – and these parts then look different, are lighter and are often probably also more capable."

CASE STUDY 2: OIL PUMP HOUSING



This oil pump housing is made of aluminium alloy and manufactured on a Concept Laser M2 cusing machine from CL 31AL (AlSi10Mg). As well as offering a reduction in manufacturing time, AM enabled an optimum design in terms of flow properties as there are no sharp-edged transitions as a result of drill holes (Courtesy Concept Laser)

Changing design and project workflows for automotive components

The AM process development chain, including specification and topology analysis, the development of functions, bionic design and production-oriented design is currently very limited and time consuming. Hillebrecht stated, "CAD and CAE will increasingly merge together. Overarching CAx competence will be demanded. In addition, we require bionic components and tools, not least a working interface with the laser melting machine, so that 'anything imaginable' really could then be printed."

Raso believes that the use of 3D-bent and laser-cut tubes and profiles for structural assembly has already proved to be a way of saving weight in assembly while still retaining the mechanical properties. "In this design, the load-specific matching of laser-melted 3D nodes and laser-welded 3D profiles has an important role to play. Nodes produced by traditional casting technologies proved to be a trusted solution in the past. Thanks to bionics, hollow spaces and lattice structures, Additive Manufacturing now allows the 3D nodes to have even more options for design, variations and safety aspects. I see this as an important next step," he explained.

The safety limits of bionic AM designs

The Nexgen spaceframe concept serves to highlight some clear advantages for safety-relevant components. In the case of an accident, the functional design of the profiles and nodes ensures controlled deformation of the frame. Simulations have already shown that the interaction between nodes, cross members and longitudinal beams significantly improves performance under crash conditions. The dissipation of mechanical or kinematic energy is far better compared to a conventional frame structure.

Hillebrecht commented, "In the case of components which are stressed in a crash, for example the longitudinal beams and A-pillar nodes, energy is dissipated away by a 'defined buckling' of the beam. A corresponding CAE method for optimising the crash performance of bionic components has recently become a new and exciting topic for research and development. In addition, the range of materials on offer for use in Additive Manufacturing has not previously been matched to the requirements of automotive manufacturers. We are frequently asked to provide support and practical help here. Additive strategies change everything; structures, functions, choice of materials – and the possible range of quality and services."

Emmelmann believes that bionically optimised metal AM parts are on a par with conventional components when it comes to component strength. "The material and component properties can be adjusted to specific applications through targeted after-treatment of the component, for example sandblasting or thermal treatments. Essentially, it is now possible for the first time to 'design' performance characteristics in a convincing way. At Laser Zentrum Nord, the employees working in the area of research and development are engaged among other things with the issues of component optimisation, process qualification, quality assurance and also the calculation and targeted modification of key material parameters. Bionic optimisation offers the opportunity to use the material in an optimum way that reflects the load situation and thus implement maximum lightweight design," he stated.

Overcoming the automotive industry's reliance on volume and common platforms

The automotive industry is volume-driven and thinks in terms of high quantities and platform strategies in order to manage costs, making it challenging for a concept such as the NextGen spaceframe to overcome these traditional attitudes. Raso stated, "It is difficult to believe that this new hybrid lightweight design can lead to an immediate sweeping innovation in the mass production of frames for cars. A more realistic scenario is that the new concept will be adopted for small batches of high-value automobiles while alongside this traditional design paradigms are retained for low-cost mass production. A best of both worlds mindset could become established. That would be realistic in my view."

"Bionic optimisation offers the opportunity to use the material in an optimum way that reflects the load situation and thus implement maximum lightweight design"

Hillebrecht agrees that this project isn't currently appropriate for the cost-minimised production of a global mass product. "The appeal is of course also to consistently utilise enhanced functions and automation. I am also convinced that a consistent concept can only emerge if a large number of electric and non-electric alternative drives for vehicles also come into play as a general requirement. After all, the theme is only really just developing," he stated.

Herzog summarised stating, "Experience shows that innovations in the automotive sector first emerge in the premium segment. We only need to think about things like the airbag, LED lights or ABS. An innovation then gradually works its way down the product range. There are economies of scale here which have a positive effect on costs. If we assume that the costs of a kilogram of laser-melted products will fall over the long term due to technical progress, then the issue of Additive Manufacturing becomes more and more interesting to those in the automotive industry. According to the experts from Roland Berger, in 2012 the average price including all of the AM processing costs, so for machine technology, powder, energy costs, reworking, etc., was around €3.14 per cm³. These analysts predict a price of around €1.60 per cm³ by 2018 and €1.10 per cm³ has been estimated for 2023. All I want to say here is that there is probably a clear trend illustrating that there will be plenty of movement on the cost side."

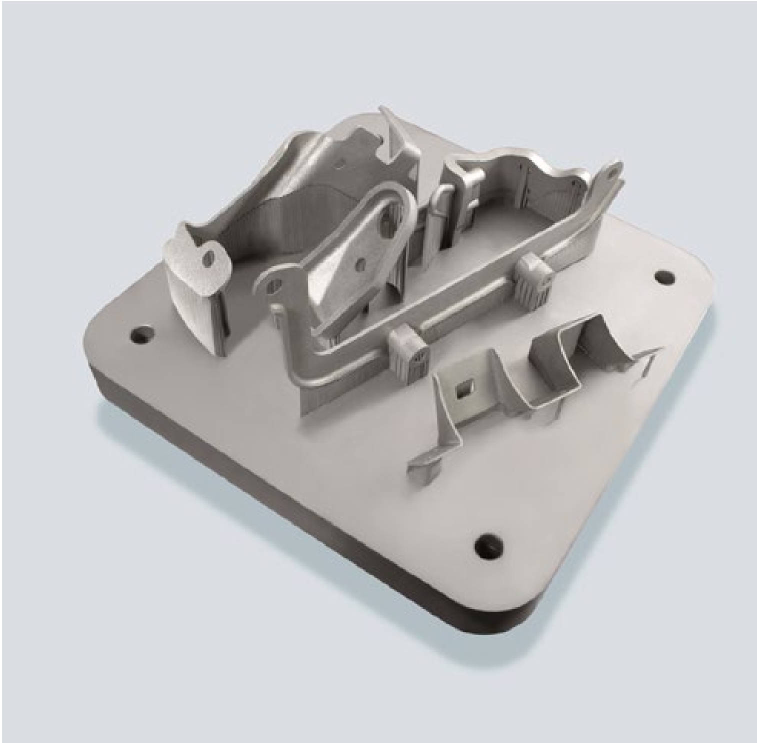
AM and the spare parts supply chain: a realistic proposition?

Spare parts for cars are regarded as a logistical and costly challenge. Global availability, warehousing, life cycles and the pressure of time are all challenges for the spare parts experts. Not least, spare parts are currently a blessing for automotive suppliers that operate as OEMs or retrofitters or even duplicators. Commenting on how Additive Manufacturing could change this situation, Hillebrecht stated, "Additive Manufacturing makes it possible above all to fabricate components at different locations. This means that local advantages can be exploited, and different versions can be produced later and close to production. There are thus no transports and logistics costs, different versions of components no longer need to be kept in stock and production close to the market and customers shortens the delivery time."

Emmelmann added, "Additive Manufacturing means that it is no longer necessary to send physical components around the world, but instead simply send CAD data records and then, if necessary, print out spare parts at a local level. One option is to have decentralised manufacturing, the effects of which we can only imagine. This approach will radically alter the supply of spare parts; delivery times will be reduced significantly and warehousing costs will be completely removed. This scenario is currently being actively implemented with the aviation industry. The foundation is thus being laid for this approach to be transferred to the automotive industry too."

Raso suggests that car frames based on the NextGen concept will also enable new paradigms for the management of spare parts and their logistics. "Fully automatic production of profiles and nodes based on just-in-time approaches would enable a drastic reduction in costs, also assuming that new guidelines for the repair of vehicles will be adopted," he stated.

CASE STUDY 3: SHEET METAL PARTS



These prototype sheet metal parts were part of a development vehicle and were manufactured on a Concept Laser M2 cusing machine from CL 20ES (1.4404). Using Additive Manufacturing meant that there was no need for any reshaping and embossing tools in the development phase. As a result, the first parts from moulds have a higher degree of maturity (Source: Daimler AG)

AM strategies for vehicles in the future

Hillebrecht states that Additive Manufacturing processes will move away from the traditional areas of application such as rapid prototyping, instead operating alongside the traditional manufacturing processes and offering a new dimension to the possibilities of constructive design. "For me this is in fact radical. Additive Manufacturing will make it possible to create very complex, functionally integrated and highly efficient structures that cannot be produced using other methods. It will therefore be possible in future to design complex components with a customised design for products available in lots of different versions, and manufacture them individually on demand without the use of tools to ensure optimum function, safety and weight. This is fundamentally new in the industry," he explained.

Herzog shared this assessment in the medium term, stating, "I also think that it must be clear that when it comes to design, as with the NextGen spaceframe, we will have to adopt completely new approaches to implement Additive Manufacturing more strongly in the automotive sector. The integration of functions, such as cooling capacity, may also be an important piece in the jigsaw. An additively manufactured product must be consistently developed starting from the performance criteria. If it can do more than the old product and also deliver lower costs and greater flexibility, it will appeal to people."

The impact of metal AM on new model development and vehicle cost

Commenting on whether these new approaches will be able to invigorate the development cycles, the range of models and their costs, Raso stated, "The great flexibility of the spaceframe design enables parametric construction of the car frame. In principle, we are pushing open a window for a much wider range of models or even personalised cars. What I am certain of is that the cost structure can be approved with this strategic approach and therefore hopefully also lower the final costs of the vehicle for the purchaser."

To a great extent the potential of this technology depends on the future direction of the automotive industry. Will volume strategies dominate or will there be a demand in the future for individualised car concepts in order to attract purchasers? "In the latter scenario, and it is possible that both trends will exist side by side, Additive Manufacturing will be able to lead the way in some respects," commented Herzog.

AM also offers the possibility in future automotive components for functional integration, such as cooling functions, or the ability to construct more powerful and capable components. Hillebrecht regards this as essential to justify the higher costs of AM components, stating, "Without this functional added value, which I take for granted in any concept, no matter which one, it will scarcely be possible to justify the currently high Additive Manufacturing costs."

Are current build volumes holding back Additive Manufacturing in the automotive sector?

Current build envelope limits and assembly speeds in powder-bed metal AM present limitations on the use of the technology in the automotive industry. Commenting on this, Emmelmann stated, "At the present time, the productivity of the process for certain applications, such as large-scale automotive production, is limited. To that extent, the argument is correct. In sectors such as medical technology or aviation, the process is already heavily used. I forecast that the technology will see a significant leap in productivity over the coming years and thus will also manage to gradually become an attractive proposition for large-scale automotive manufacturing. Laser Zentrum Nord works together closely with its partners to develop new machine and automation concepts designed to make this possible."

Hillebrecht stated, "The build envelopes are already more or less sufficient today, but typical materials are still not adequately developed and are much too expensive. We would like to see Additive Manufacturing processes which enable an assembly speed that is maybe 100 times greater while still retaining the same surface quality."

Raso believes that restrictions in terms of the build envelope and prices will be reduced in the near future thanks to the introduction of new laser systems for Additive Manufacturing with greater power and enhanced build rates. However, he stated that the hybrid design of the spaceframe featured in this article with nodes and profiles has been adopted for longer dimensions and already gives a hint of an economical approach today.

From a machine maker's perspective, Herzog stated, "Let's take a look back and a look ahead. The assembly speeds have already increased a great deal thanks to multilaser technology and increasing laser power. But it should also be borne in mind that each new laser source increases the complexity of the process and therefore also its susceptibility to errors. From today's point of view, I do not think that purely quantitative approaches are the best way to go. As we demonstrate with our AM Factory of Tomorrow, from our perspective the vital thing is to focus on downtimes during the production process with the ultimate aim of minimising them. They are usually associated with manual tasks in upstream and downstream stages of the process, such as supplying new powder or finishing the products. This is where in the first instance we see a much more important starting point for advancing our process to make it viable for economic mass production, even if the laser power certainly still offers plenty of scope to be increased."

"In addition, qualitative efforts are paramount for us because an additively manufactured product should of course also be able to win people over just in terms of its quality. If this basis is easy to control, progress can be made when it comes to performance. I would like to support the comment made by Dr Hillebrecht that the build envelopes are already large enough. Even larger parts may perhaps be possible, but with very large parts we start to reach the limits of physics: The stresses in the part would increase. This cannot be controlled by procedures today. One alternative is then always to use joining techniques in order, for example, to join together very narrow, long parts in a modular fashion. Despite all the euphoria surrounding Additive Manufacturing, we would be well advised to look to the future with realism and a sense of proportion," stated Herzog.

"AM also offers the possibility in future automotive components for functional integration, such as cooling functions, or the ability to construct more powerful and capable components."

Outlook

Standards for the AM industry and quality requirements are being drawn up by industry experts and will inevitably be based on the standards used for traditional manufacturing methods. Herzog commented, "We have a more or less 'blank canvas' as far as the Additive Manufacturing solutions of the future are concerned. But the NextGen spaceframe sends a sufficiently bold signal to the automotive industry to look at the issue more closely in terms of design. Maybe I see things too cautiously, but what we need in the future is a '3D generation', engineers and designers who are confident working with Additive Manufacturing, because young people today can barely imagine a life without their smartphone or the internet. The 3D generation is certainly still in its infancy, but it also needs specific projects in order to prove itself. However, I am confident that this 3D generation will search for its own themes."

Raso believes that metal AM has become established worldwide as a reliable technology. "From my point of view, it is better able to guarantee quality levels of the process and products than traditional manufacturing solutions. In this scenario, Additive Manufacturing processes are expected to take us to an even higher level of quality. Based on the digital process, the technology will be very capable of being integrated into digital production in the future. Along with the theme of automation, there is plenty of interesting potential for Industry 4.0 here," he stated.

Contact

Daniel Hund
Head of Global Marketing & Communications
Concept Laser GmbH
An der Zeil 8
96215 Lichtenfels
Germany

Tel: +49 9571 1679 251
Tel: +49 9571 1679 299
Email: d.hund@concept-laser.de
www.concept-laser.de

CASE STUDY 4: SEAT STRUCTURES

Using Additive Manufacturing to develop a front seat frame significantly shortened development time and reduced costs as conventional processes did not have to be used. On the top are the sections of the seat structure on the build plate and on the bottom is the completed frame. The components were made from a batch material with corresponding material properties to the final product. Direct fitting in the test vehicle was possible after the manufacturing process (Source: Johnson Controls Components GmbH)

Material selection for the production of injection moulding tooling by Additive Manufacturing

As one of the first major markets for metal additively manufactured products, the importance of the tooling industry has long been recognised. There is still, however, limited information available on what mechanical properties can be expected for the various materials used. This report by Harish Irrinki, Brenton Barmore, Kunal H Kate and Sundar V Atre reviews the published data on various steel powders and processing conditions as well as the mechanical properties that have been obtained using the Selective Laser Melting process.

The manufacture of tooling for injection moulding is a key business sector that has a significant impact on overall costs and lead times in the product development cycle. Long production lead times, design constraints and the need to cut manufacturing costs have driven the injection moulding industry to look to new technologies for fabricating moulding tooling.

Among the various innovative processes for the production of tooling, the Selective Laser Melting (SLM) process has the potential to address many of the challenges faced by the tooling industry. The SLM process is capable of producing defect-free parts from a variety of steel materials as well as offering the unique ability to introduce conformal cooling. However, it is important for a tooling design engineer to know the material options and corresponding process parameters to examine the suitability of the SLM process in order to obtain mechanical properties that may compare well with conventional handbook data. To this end, this article reviews the published data on various steel powders and processing conditions as well as the mechanical properties that have been obtained using the SLM process.

The current status of the injection moulding industry

Injection moulding is a $170 billion global industry for the manufacture of a multitude of consumer products [1]. In 2010 alone the US plastics industry produced an estimated 7 billion kg

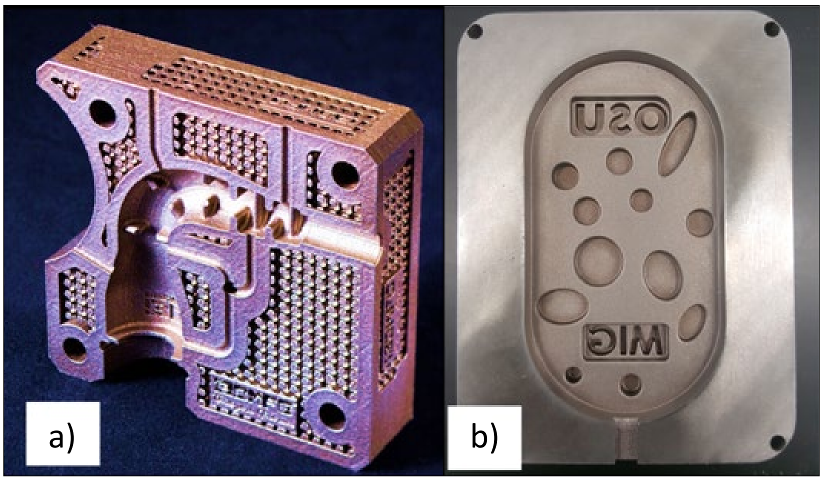


Fig. 1 Injection moulds manufactured using the SLM process (a) Maraging steel mould (Courtesy I3DMFG) (b) 17-4 PH stainless steel mould (Courtesy Materials Innovation Guild)

Steels	Application	Process
1020 carbon steel	Ejector plates	Injection moulding
1030 carbon steel	Mould bases, ejector housing and clam plates	Injection moulding
1040 carbon steel	Support pillars	Injection moulding
4130 alloy steel	Cavity retainer and support plates	Injection moulding
6145 alloy steel	Sprue bushings	Injection moulding
S-7 tool steel	Interlocks and hatches	Injection and compression moulding
O-1 tool steel	Small inserts and cores	Injection, compression and blow moulding, extrusion
A-2 tool steel	Injection and compression moulds	Injection and compression moulding
A-6 tool steel	Injection and compression moulds	Injection and compression moulding
D-2 tool steel	Gate inserts, lifters and sliders	Injection and compression moulding
H-13 tool steel	Injection mould cavities, dies and punches	Injection moulding
P-20 tool steel	Injection mould cavities, dies	Injection and blow moulding, extrusion
420 stainless steel	Injection mould cores and cavities	Injection, compression and blow moulding, extrusion

Table 1 Steel materials used in making mould by traditional processes [2], [5], [8]–[11]

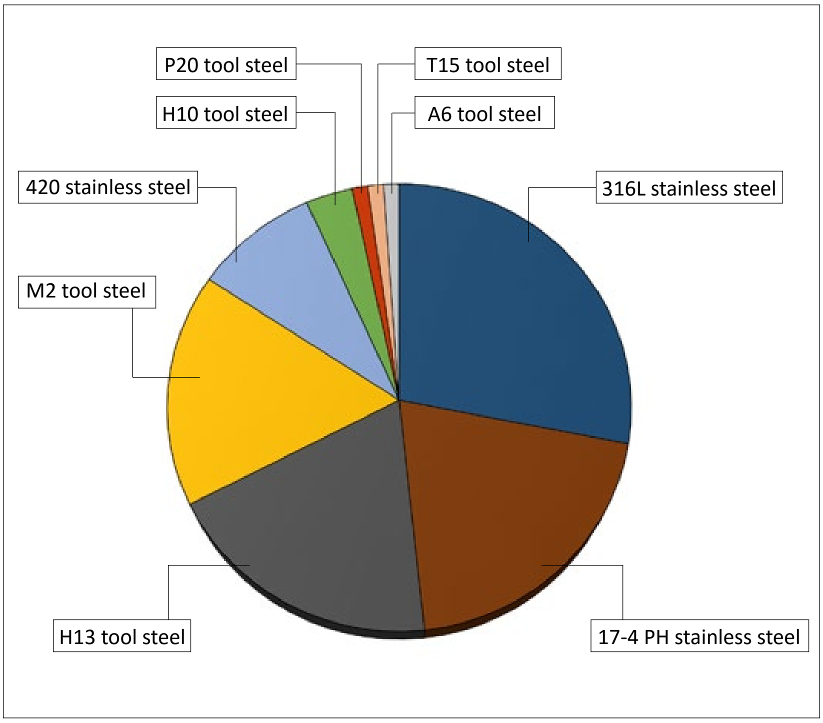


Fig. 2 Relative emphasis of steels reported in the literature using the SLM process

of injection-moulded products for applications in packaging, electronics, household goods and biomedical areas [1]. Common materials that are injection moulded include thermoplastics, thermosets, elastomers and filled polymers. More recently, Metal Injection Moulding (MIM) and Ceramic Injection Moulding (CIM) technologies have further expanded the materials design window for the process.

Materials for manufacturing tools for injection moulding are selected depending on the type of polymer, production volume, mould cavity complexity and the type of tool component. Table 1 summarises several types of steels used for manufacturing tools, including carbon steels (1020, 1030, and 1040), tool steels (S-7, O-1, A-2, D-2, H13, and P-20) and stainless steels (420 and 17-4 PH). Additionally, the type of steel selected depends on mechanical properties requirements for the tooling components, such as ejector pins, clamp plates, inserts, cores, spruce bushings, gate inserts, support pillars, mould base plates, lifters, sliders and interlocks [2–10].

Injection moulding tools are most widely manufactured with conventional processes such as milling, lathe or CNC lathe. Over the years these conventional manufacturing processes have developed with the onset of computer aided technology used for designing tools, high-speed machining, improved precision and process automation. Although this has led to the faster production of tools, product development cycles are still long and expensive. Tooling costs account for 15% of injection moulded part costs [12]. However, considering global competition and the requirement for shorter manufacturing times, innovative manufacturing methods for tool production such as Additive Manufacturing have been explored to manufacture tools for injection moulding [13–21]. Moulding cycle times account for 35% of the part cost [11, 21], and innovative mould designs and materials using Additive Manufacturing appear to offer the promise for further impacting the cost-per-part produced by injection moulding [22, 23].

Powder	C	Mn	Si	Cr	Mo	Ni	V	Nb	Cu	S	W	Ref.
316L stainless steel	0.03	1.4	0.23	16.9	2.3	11.8	-	-	-	0.01	-	[33] - [37]
17-4 PH stainless steel	0.07	1.0	1.0	15-17.5	0.5	3.0-5.0	-	0.2-0.4	3-5	-	-	[38] - [42]
420 stainless steel	0.4	1.0	1.5	11-14	0.5	1	-	-	-	0.04	-	[43] - [45]
P20 stainless steel	0.3-0.4	0.3-1.0	0.2-0.8	1.4-2	0.3-0.55	-	-	-	-	-	-	[46]
H10 tool steel	0.3-0.45	0.2-0.7	0.8-1.2	3-3.75	2-3	0.3	0.3-0.75	-	-	-	-	[47, 48]
H13 tool steel	0.3-0.45	0.2-0.5	0.8-1.2	4.8-5.5	1.1-1.75	0.3	0.8-1.2					[28, 30, 31, 49, 50]
A6 tool steel	0.6-0.75	1.8-2.5	0.5	0.9-1.2	0.9-1.4	0.3	-	-	-	-	-	[51]. [52]
M2 tool steel	0.8-1.05	0.2-0.4	0.2-0.45	0.2-0.45	4.5-5.5	0.3	1.8-2.2	-	0.25	0.03	5.5-6.7	[48, 53, 54]
T15 tool steel	1.5 - 1.6	0.2 - 0.4	0.2 - 0.4	3.8 - 5.0	1.0	0.3	4.8 - 5.25	-	-	0.3	11 - 13	[55]

Table 2 Material composition of steel powders used in different AM processes

One such Additive Manufacturing process used to manufacture tools for injection moulding is known as the Selective Laser Melting (SLM) process, alternately known as Laser-Powder Bed Fusion (L-PBF), Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS) [12, 16, 20, 24]. Fig. 1 shows an example of a tool manufactured using the SLM process for the injection moulding of plastics. The tool was fabricated using a maraging steel powder and is used for making injection moulded plastic cable connectors that are complex in shape and difficult to manufacture using conventional techniques [13].

In order to manufacture injection moulding tools using SLM, it is critical for the design engineer to have an awareness of the various material options and the corresponding process conditions to obtain useful mechanical properties from the process. Variations in powder characteristics and process parameters will affect the mechanical properties of tools [15, 18, 25, 26]. Many independent research studies have shown the successful fabrication of fully dense components using the SLM process for various steel powders by changing process parameters [28–32]. This report reviews over a hundred sources from the literature that cover different types of steel powder and SLM process conditions to successfully manufacture parts. Further, material properties typically obtained from the SLM process such as density, hardness, yield strength, ultimate tensile strength and elongation are compared to properties obtained from Metal Injection Moulded and wrought components. Additionally, SLM process conditions such as laser power and scan speed that are typically used for various types of steel powders in order to obtain competitive mechanical properties of fabricated components are summarised. It is hoped that this report will provide a convenient starting point for a tooling design engineer to select material and process options for fabricating injection mould tooling using the SLM process.

Materials

The pie chart in Fig. 2 represents around a hundred SLM studies that have used steels powders of various compositions. It was observed that the most researched steel powders were 316L and17-4 PH stainless steels followed by H-13 and M-2 tool steels. In contrast, only a limited amount of SLM studies have been reported on using P20, T15 and A6 tool steels. The material compositions of steel powders used in the SLM process are listed in Table 2.

Powder characteristics

Table 3 summarises powder characteristics (shape and size distribution) for five types of steels from 25 sources and presents typical sintered densities (represented as % theoretical) obtained from the SLM process when different types of powder production routes and particle size distributions are used.

It can be seen that, for various types of steels, densities between

Material	Powder type	Powder size distribution (µm)	Density (%)
316L stainless steel [33-37, 56]	Gas-atomised	0 - 60	99.5 ± 0.3
17-4 PH stainless steel [38-40, 57-61]	Gas-atomised	0 - 45	98.5 ± 1.3
17-4PH stainless steel [40, 41, 60]	Water-atomised	0 - 45	98.5 ± 1.3
420 stainless steel [29, 62]	Gas-atomised	0 - 50	N/A*
H13 tool steel [30, 44, 49, 63, 64]	Gas-atomised	50 - 150	90 ± 3
H13 tool steel [28, 30, 48, 49, 53]	Water-atomised	50 - 150	80 ± 3
M2 tool steel [50, 53, 54, 66]	Gas-atomised	0 - 45	99 ± 0.8
M2 tool steel [50, 53, 54, 65, 66]	Water-atomised	0 - 45	95 ± 4
N/A density data not reported for used gas atomised powders*			

Table 3 Densities obtained for various types of gas and water atomised steels manufactured with the SLM process

95 and 99% are achievable for parts processed with the SLM process. For parts fabricated from 316L stainless steel powders, most research groups studied gas-atomised powders with powder size distribution of 0-60 µm and obtained 99.5 ± 0.3% density. In the case of 17-4 PH stainless steel, gas and water-atomised powders were used with powder size distribution of 0-45 µm and theoretical densities of 98.5 ± 1.3% were obtained. In contrast, a coarser particle size distribution of 50-150 µm has been used to used manufacture parts from H13 tool steels with the SLM process resulting in densities of 90 ± 3% and 80 ± 3% for gas and water atomised powders, respectively. For M2 tool steel powders, densities of 99 ± 0.8% and 95 ± 4% were achieved when gas and water-atomised powders of powder size distribution 50- 150 µm were used.

The extent of influence of powder production techniques, namely gas versus water atomisation, on the sintered density obtained from the SLM process showed conflicting results. For instance, parts produced from 17-4PH stainless steel using gas and water atomised powders had a similar density of around 98.5%, but parts manufactured from M2 tool steels showed that the use of gas-atomised powders resulted in parts with higher density (99 ± 0.8%) when compared with water-atomised parts (95 ± 4%). Therefore, it can be noted that the composition of steel and powder characteristics could largely affect the densification and consequently material properties of SLM parts. It was evident from the survey that an important knowledge gap exists in the SLM literature regarding the influence of particle size distribution, alloy composition, surface chemistry and packing density on process conditions, microstructures and mechanical properties.

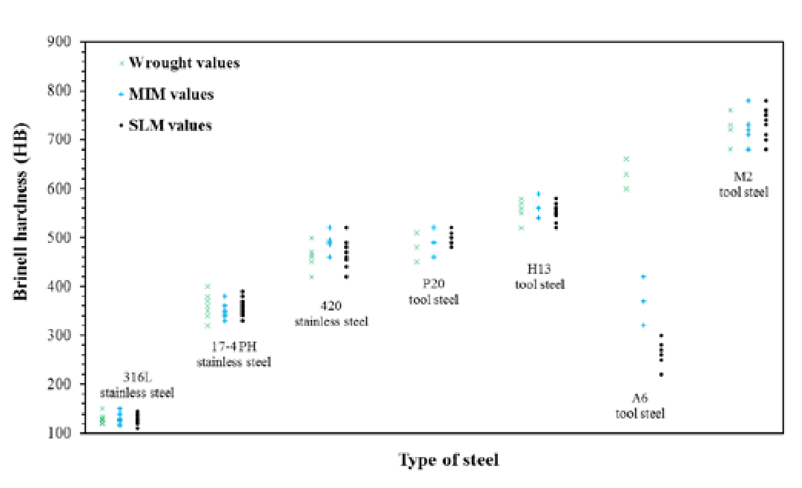


Fig. 3 Literature data on the hardness of steels fabricated using the SLM process

Hardness

The most common mechanical property reported in the literature for various steels was hardness. Fig. 3 shows the hardness of various steels obtained using the SLM process. Data collected from nearly 70 studies were compared to the corresponding data obtained from wrought and MIM products. It was found that the hardness values of 316L stainless steel and M2 tool steel were the most reported data in the literature. Components fabricated using the SLM process exhibited comparable hardness values to those of MIM and wrought parts for all alloys with the exception of A6 tool steel. Fig. 3 also shows that 316L stainless steels components have the lowest hardness values and M2 tool steels have the highest hardness values.

Additionally, P20 and H-13 tool steels, that are typically used in manufacturing injection moulding tools, also showed comparable hardness values for SLM, MIM and wrought parts.

Table 4 summarises the average and standard deviation of hardness values for SLM, MIM and wrought parts based on the above data. It was observed that A6 tool steel had a rather low hardness of 260 ± 40 HB when fabricated using the SLM process [67]. The hardness values of SLM samples fabricated from 316L and 17-4 PH stainless steel were 230 ± 40 HB and 360 ± 40 HB respectively and were comparable to the wrought and MIM hardness values. Among stainless steels, 420 stainless steels had the highest hardness value of 470 ± 50 HB when processed using SLM. Among tool steels, M2 had the highest hardness (730 ± 30 HB) when processed using SLM. Moreover, M2 and H13 tool steel showed suitable compatibility with the SLM process since it was possible to achieve hardness similar to the wrought and MIM values.

Brinell hardness (HB)			
Material	**Wrought**	**MIM**	**SLM**
316L stainless steel	130 ± 40 [28-35]	115 ± 50 [32, 33, 36-40]	120 ± 20 [41-47]
17-4 PH stainless steel	360 ± 40 [71, 73, 74, 87, 88]	340 ± 40 [73, 77–79, 89–93]	360 ± 30 [32, 42, 58, 94–103]
420 stainless steel	460 ± 40 [71, 73, 104–109]	490 ± 30 [71, 73, 77–79, 105, 108, 110]	470 ± 50 [29], [108], [111–116]
P20 tool steel	480 ± 30 [71, 73, 74, 109, 117–119]	490 ± 25 [73, 78, 79, 120]	500 ± 20 [121]
H13 tool steel	550 ± 30 [71, 73, 74, 106, 107, 109, 117, 122, 123]	560 ± 25 [73, 77–79, 106, 124, 125]	550 ± 25 [47], [63], [126–128]
A6 tool steel	630 ± 20 [73, 104, 129]	370 ± 50 [77–79, 124, 129]	260 ± 40 [67]
M2 tool steel	720 ± 40 [71, 73, 104, 107, 130, 131]	730 ± 50 [73, 77–79, 107, 109, 124, 131]	730 ± 50 [30, 31, 54, 132–134]

Table 4 Literature data on the hardness (HB) of steels produced by wrought, MIM and SLM processes

Ultimate tensile strength

Fig. 4 shows the ultimate tensile strength of various steels fabricated using the SLM process. The data were collected from nearly fifty studies and the strength values were compared to data obtained from wrought and MIM processes. 316L and 17-4 PH stainless steel strength values had the most reported data in the literature. Stainless steel components fabricated with the SLM process exhibited comparable ultimate tensile strength values to those of MIM and wrought parts. Fig. 4 shows that 316L stainless steels components have the lowest ultimate tensile strength values and H13 tool steels have the highest strength values. Additionally, 420 stainless steel and H-13 tool steels that are often used for manufacturing tooling for injection moulding also showed ultimate tensile strength values using SLM that were comparable to MIM and wrought parts.

Table 5 presents the average and standard deviation of ultimate tensile strength values for SLM, MIM and wrought parts. The ultimate tensile strength of SLM parts fabricated using 316L and 17-4 PH stainless steel samples were 550 ± 20 MPa and 1080 ± 30 MPa respectively and were comparable to the wrought and MIM ultimate tensile strength values. Among stainless steels, 420 series stainless steel had an ultimate tensile strength value of 1600 ± 50 MPa when processed using SLM. Among tool steels, H13 tool steel had the highest tensile strength value of 1850 ± 25 MPa when processed using SLM.

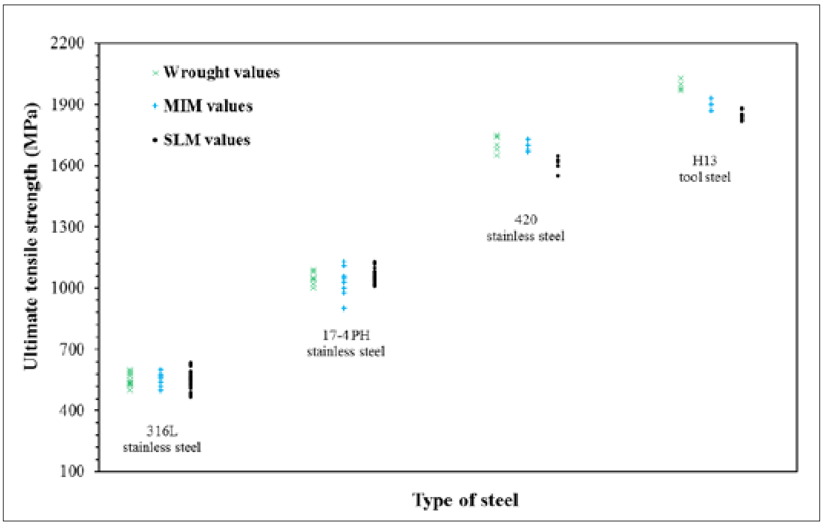


Fig. 4 Literature data on the ultimate tensile strength of steels fabricated using the SLM process

Ultimate tensile strength (MPa)			
Material	**Wrought**	**MIM**	**SLM**
316L stainless steel	550 ± 40 [68–75]	520 ± 50 [72, 73, 76–80]	550 ± 20 [37, 81–86, 135–137]
17-4 PH stainless steel	1050 ± 40 [71, 73, 74, 87, 88]	1070 ± 40 [73, 77–79, 89–93]	1080 ± 30 [32, 39, 41, 42, 94–103, 138, 139–141]
420 stainless steel	1700 ± 40 [71, 73, 104–109]	1700 ± 30 [71, 73, 77–79, 105, 108, 110]	1600 ± 50 [29, 108, 111–116]
H13 tool steel	2000 ± 30 [71, 73, 74, 106, 107, 109, 117, 122, 123]	1900 ± 25 [73, 77–79, 106, 124, 125]	1850 ± 25 [47, 63, 113, 126–128, 142–144]

Table 5 Literature data on the ultimate tensile strength of steels produced by wrought, MIM and SLM processes

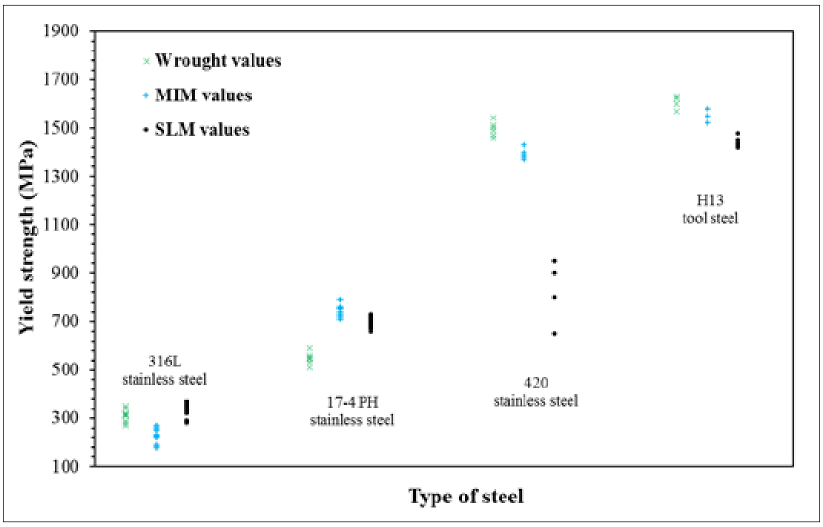


Fig. 5 Literature data on the yield strength of steels fabricated using the SLM process

Yield strength

Fig. 5 shows the yield strength of various steels compiled from nearly fifty studies that used the SLM process. These values were compared to yield strength values obtained from wrought and MIM processes. The majority of reported yield strength data were for 316L and 17-4 PH stainless steels. Stainless steel components fabricated with the SLM process exhibited comparable yield strength values to those of MIM and wrought parts, with the exception of 420 stainless steel which showed lower values. Fig. 5 shows that 316L stainless steel has the lowest yield strength values and H13 tool steel has the highest yield strength values. Additionally, H-13 tool steel that is typically used in manufacturing injection moulding tools also showed yield strength for SLM parts that were comparable with MIM and wrought parts.

Table 6 summarises the average and standard deviation of yield strength values for SLM, MIM and wrought parts. The yield strength of SLM fabricated 316L and 17-4 PH stainless steel samples were 350 ± 20 MPa and 700 ± 30 MPa respectively and were comparable to the wrought and MIM yield strength values. Among stainless steels, 420 stainless steels had the highest yield strength value of 800 ± 150 MPa when processed in SLM. Among tool steels, H13 had the highest yield strength value of 1450 ± 25 MPa when processed by SLM.

Elongation

Fig. 6 shows the elongation (%) data of various steels compiled from nearly 50 studies obtained using the SLM process. The data were compared with elongation values obtained from wrought and MIM processes. The majority of elongation data from the literature were obtained for 316L and 17-4 PH stainless steels. Stainless steel components fabricated with the SLM process exhibited comparable elongation values to those of MIM and wrought parts with the exception of 420 stainless steel. Fig. 6 shows that 316L stainless steel had the highest elongation values and H13 tool steel had the lowest elongation values. Additionally, 420 stainless steel and H-13 tool steel that are typically used in the manufacturing of injection moulding tools also showed low elongation values for SLM comparable to MIM and wrought parts.

Table 7 presents the average and standard deviation of elongation (%) values for SLM, MIM and wrought parts. The elongation values of SLM fabricated 316L and 17-4 PH stainless steel samples were 20 ± 10% and 15 ± 5% respectively and were comparable to the wrought and MIM elongation values. Among stainless steels, 420 stainless steel had lowest elongation value of 2 ± 1% when processed by SLM. Among tool steels, H13 had an elongation value of 6 ± 2% when processed by SLM. However, no conclusions can be drawn for other steel samples fabricated by SLM due to a lack of data reported in literature.

Microstructures

Studies that examined the microstructures of SLM fabricated steel parts are summarised in Table 8. The purpose of the table is to show the typical microstructures observed in

SLM fabricated steel parts to achieve the desired mechanical properties mentioned in Table 8.

In 316L stainless steel parts fabricated by the SLM process a duplex microstructure with austenite and ferrite was typically found. This duplex microstructure resulted in parts with improved tensile strength and ductility. In SLM fabricated 17-4 PH stainless steel parts, the microstructures typically had a presence of martensite and metastable austenite that may have contributed to the tensile strength and hardness but produced parts with lower ductility. Heterogeneous martensite, austenite and ferrite phases were typically found in 420 stainless steel parts and such microstructures resulted in improved tensile strengths. In H13 and M2 tool steels, the SLM fabricated parts generally displayed both martensite and austenite phases. Additionally, carbide phases were generally found in the microstructure and resulted in the production of parts with desired properties. However, not much research has been reported on the effects of size, morphology and packing density of the powders on the microstructures and mechanical properties of steel parts.

Fig. 7 shows examples of quite different microstructures obtained for parts manufactured with the SLM fabricated parts when different powder sizes and shapes were used under the same processing conditions, to illustrate the importance of the scientific gap that needs to be addressed in the future.

Process conditions

Process parameters reported for the SLM process for various steels were examined from around nearly a hundred studies in order to associate them with the obtained mechanical properties. The most common SLM process conditions that were reported were laser power, scan speed, scan spacing, layer thickness and laser beam diameter. Fig. 8 provides a comparison of laser power and scan speed that were reported for various

Yield strength (MPa)			
Material	Wrought	MIM	SLM
316L stainless steel	310 ± 40 [68–75]	220 ± 50 [72, 73, 76–80]	350 ± 20 [37, 81–86, 135–137]
17-4 PH stainless steel	550 ± 40 [71, 73, 74, 87, 88]	750 ± 40 [73, 77–79, 89–93]	700 ± 30 [32, 39, 41, 42, 94–103, 138, 139–141]
420 stainless steel	1500 ± 40 [71, 73, 104–109]	1400 ± 30 [71, 73, 77–79, 105, 108, 110]	800 ± 50 [29, 108, 111–116]
H13 tool steel	1600 ± 30 [71, 73, 74, 106, 107, 109, 117, 122, 123]	1500 ± 25 [73, 77–79, 106, 124, 125]	1450 ± 25 [47, 113, 126–128, 63, 142–144]

Table 6 Literature data on the yield strength of steels produced by wrought, MIM and SLM processes

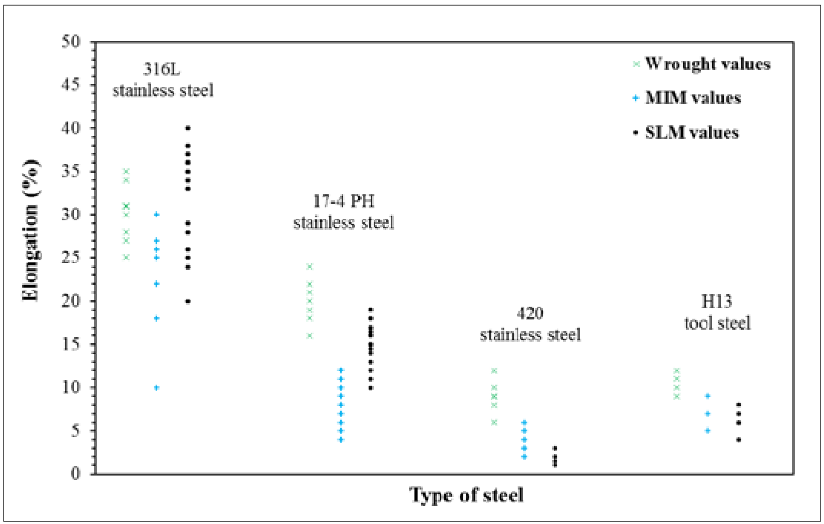


Fig. 6 Literature data on the elongation of steels produced by the SLM process

Elongation (%)			
Material	Wrought	MIM	SLM
316L stainless steel	25 ± 5 [68–75]	20 ± 10 [72, 73, 76–80]	25 ± 5 [37, 81–86, 135–137]
17-4 PH stainless steel	20 ± 4 [71, 73, 74, 87, 88]	8 ± 4 [73, 77–79, 89–93]	15 ± 5 [32, 39, 41, 42, 94–103, 138, 139–141]
420 stainless steel	8 ± 4 [71, 73, 104–109]	4 ± 2 [71, 73, 77–79, 105, 108, 110]	2 ± 1 [29, 108, 111–116]
H13 tool steel	10 ± 2 [71, 73, 74, 106, 107, 109, 117, 122, 123]	7 ± 2 [73, 77–79, 106, 124, 125]	6 ± 2 [47, 113, 126–128, 63, 142–144]

Table 7 Literature data on elongation of steels produced by wrought, MIM and SLM processes

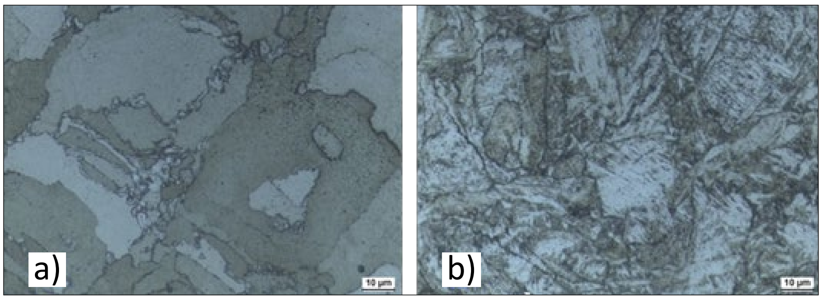


Fig. 7 Microstructures of the SLM 17-4 PH stainless steel samples produced from (a)gas-atomised powder D_{50} = 13 µm and (b) water-atomised powder D_{50} = 24 µm (Laser power: 150 W, scan speed: 1550 mm/s) [60]

Material	Microstructure	Mechanical properties
316L stainless steel [33-37, 56]	Austenite and ferrite	Tensile strength, hardness and ductility
17-4 PH stainless steel [38-41, 57-61]	Martensite and metastable austenite	Tensile strength, hardness and ductility
420 stainless steel [29, 62]	Martensite, austenite and ferrite	Tensile strength, hardness and ductility
H13 tool steel [28, 30, 48, 49, 53]	Martensite, austenite and carbides	Tensile strength, hardness and ductility
M2 tool steel [50, 53, 54, 65, 66]	Martensite, austenite and carbides	Tensile strength, hardness and ductility

Table 8 Typical microstructures observed in SLM fabricated steel parts and their effect on mechanical properties

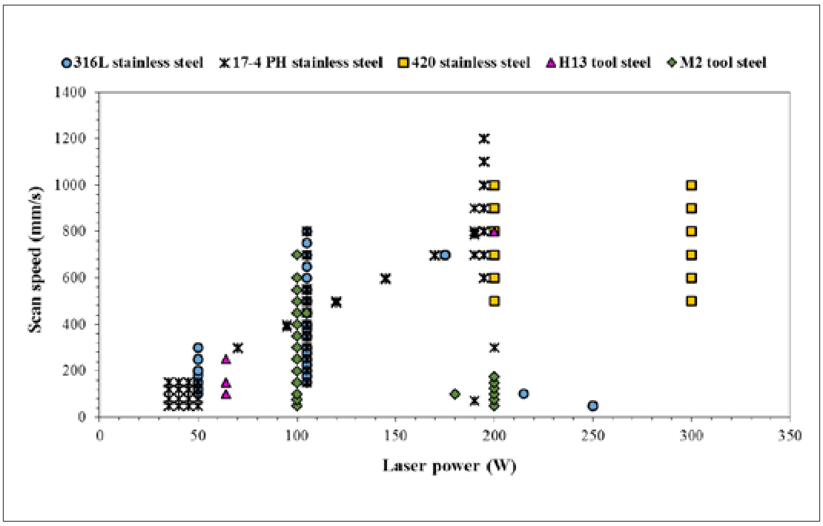


Fig. 8 Laser power and scan speed explored in the SLM of steel powders

types of steels in order to identify starting points for specifying process condition window.

From Fig. 8, it can be seen that the reported values of typical laser power ranged from 50-200 W and scan speed values varied from 50-1200 mm/s for various types of steels. Additionally, it was observed that, for slow scan speeds (<350 mm/s), typically low laser powers (<100 W) were used and, with additional increase in laser power, a wide range of scanning speeds was used to selectively melt the steel powders. Out of all the process conditions reported for steel powders, the most broadly studied process window was observed for 17-4 PH stainless steels, while the least number of studies were for H13 tool steel. Within the dataset of reported process conditions, a relatively higher laser power was used for fabricating components from 420 stainless steel and M2 tool steel compared to 316L and 17-4 PH stainless steels.

Table 9 summarises the typical mechanical properties that can be obtained for four types of steel powders for laser power of 50, 100, 105, 195, 200 W and scan speed values between 50 mm/s and 1200 mm/s. In order to understand the evolution of mechanical properties of printed parts with process conditions, the majority of the studies focused primarily on laser power and scan speed. To standardise comparisons for process parameters used to print a part with the SLM process, beam diameter values of 30 ± 5 µm, scan spacing values of 100 ± 15 µm and layer thickness of 50 ± 20 µm were taken as a basis. It was noted that the majority of the studies failed to report powder characteristics of the steels and, hence, the influence of particle attributes on process conditions and mechanical properties could not be considered in this analysis.

For 316L stainless steel powders, when the laser power was varied between 35-100 W and scan speed between 50-800 mm/s, the ultimate tensile strength values ranged between 500-600 MPa, the yield strength was between 300-450 MPa, and the elongation was between 10-30% . For 17-4 PH stainless steel powders, when the laser power was varied between 35-200 W and scan speed between 50 -1200 mm/s, the ultimate tensile strength values ranged between 1000-1100 MPa, the yield strength was between 550-700 MPa and the elongation was between 5-20%. For H13 tool steel powders, at a laser power of 200 W and scan speed between

Steel	Laser power (W)	Scan speed (m m/s)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Hardness (HB)
316L stainless steel [37, 81–86, 135–137]	50	100 - 300	550 ± 50	350 ± 50	20 ± 10	120 ± 20
	105	150 - 800	550 ± 50	400 ± 50	20 ± 5	130 ± 10
17-4 PH stainless steel [31, 61–72, 110–116]	35	50 - 150	1020 ± 20	550 ± 50	15 ± 5	350 ± 30
	40	50 - 150	1020 ± 30	550 ± 50	15 ± 5	350 ± 30
	50	50 - 150	1030 ± 20	550 ± 50	15 ± 5	350 ± 30
	70	300	1030 ± 50	550 ± 50	13 ± 5	360 ± 25
	105	150 - 800	1050 ± 50	650 ± 50	10 ± 5	360 ± 25
	195	600 - 1200	1050 ± 50	650 ± 50	10 ± 5	360 ± 25
420 stainless steel [43, 45, 112, 145]	200	500 - 1000	1600 ± 50	800 ± 150	2 ± 1	470 ± 50
M2 tool steel [30, 31, 54, 132–134]	200	50 - 200	-	-	-	700 ± 100
H13 tool steel [82, 95–99, 117–119]	200	500 - 800	1850 ± 50	1400 ± 90	6 ± 2	550 ± 25

Table 9 Summary of mechanical properties of steels with corresponding process conditions in terms of laser power (W) and scan speed (mm/s)

500-800 mm/s, the ultimate tensile strength ranged between 1750-1900 MPa, the yield strength between 1200-1500MPa, and elongation between 4-9%. For 420 stainless steel powders, at a laser power of 200W and scan speed varied between 500-1000 mm/s, the ultimate tensile strength values ranged between 1500-1650 MPa the yield strength was between 700-900 MPa and the elongation was between 1-3%. However, for M2 tool steel powders; when the laser power was 200 W and the scan speed varied between 50-200 mm/s, the hardness was between 550-850 HB.

Conclusions

This report surveyed the use of SLM for the fabrication of components using tool steels (H13, M2, A6, P20, T15) and stainless steel (316L, 17-4 PH, 420) powders. It is evident that steel powders processed by SLM can attain mechanical properties comparable to wrought or MIM properties.

Only limited sets of processing parameters have been reported in the literature that provide a useful starting point for studying any steel alloy. However, a detailed understanding of the influence of process parameters on mechanical properties and microstructures of SLM steels is clearly lacking.

The SLM of steel gas-atomised powders has received a lot of interest. However, there have been relatively few studies reported using water-atomised powders in the SLM process. The main difference between the two types of powder is their particle shape. However, the accompanying influences of particle size distribution, surface chemistry and packing density on ensuing microstructures and mechanical properties have not received much attention. Steel powders vary widely in size and shape. As a consequence, processing conditions in the SLM process would need to be adjusted in order to obtain desired properties. Choosing the optimum parameters for a desired application can reduce the production time as it reduces the number of trial experiments. However, based on this review, the selection of process parameters depending upon variation in powder characteristics is another scientific gap that needs to be addressed in the future.

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Authors

Harish Irrinki[a], Brenton Barmore[b]
Kunal H. Kate[a] and Sundar V. Atre[a]

[a] Materials Innovation Guild
University of Louisville
Louisville
KY 40292
USA

[b] Mechanical, Industrial and Manufacturing Engineering
Oregon State University
Corvallis
OR 97330
USA

Contact: Sundar V. Atre, sundar.atre@louisville.edu

References

[1] "2015 Plastics Processing Capital Spending Report : Gardner Web." [Online]. Available: www.gardnerweb.com/articles/2015-plastics-processing-capital-spending-report.

[2] "About Injection Moulding | Xcentric Mould & Engineering." [Online]. Available:

www.xcentricmould.com/about-injection-moulding.php.

[3] ASM Specialty Handbook: Stainless Steels - ASM International. .

[4] D. V. Rosato and M. G. Rosato, Injection Moulding Handbook. Springer Science & Business Media, 2012.

[5] D. M. Bryce, Plastic Injection Moulding: Manufacturing Process Fundamentals, First edition. Dearborn, Mich: Society of Manufacturing, 1996.

[6] D. M. Bryce, Plastic Injection Moulding: Mould Design and Construction Fundamentals. Society of Manufacturing Engineers, 1998.

[7] "Plastic Moulding Techniques - Rotational, Injection, Compression, Blow." [Online]. Available: www.plasticmoulding.ca/techniques.htm.

[8] "Mould Design,Mould & Die Knowlege,Tool Materials,Machining,C ost,Injection moulding cycle,Injection process,Moulding trial,Moulding defects." [Online]. Available: www.dswmould.com/injection-mould-die-tooling.html.

[9] "Tooling + Injection Moulding | Materials," Stratasys Direct Manufacturing.

[10] R. Ivory, "Understand Common Steels Used in Injection Mould Making." [Online]. Available: info.crescentind.com/blog/bid/66085/Understand-Common-Steels-Used-in-Injection-Mould-Making.

[11] "Advanced Alloys Alloy Selection for the Injection Molding Industry." July 12, 2009. [Online]. Available: http://www.ibcadvancedalloys.com/clientuploads/Technical Resources/MoldWhitepaper.pdf.

[12] D. V. Rosato, Injection Moulding Handbook: The Complete Moulding Operation: Technology, Performance, Economics, 2nd edition. New York: Springer, 1994.

[13] "3D Printed Tooling Archives • I3dmfg." I3dmfg. [Online] Available: http://www.i3dmfg.com/category/3d-printed-tooling/.

[14] D. King and T. Tansey, "Alternative materials for rapid tooling," *J. Mater. Process. Technol.*, vol. 121, no. 2–3, pp. 313–317, Feb. 2002.

[15] S. Bobby and S. Singamneni, "Conformal cooling through thin shell moulds produced by 3D printing," *Aust. J. Multi-Discip. Eng.*, vol. 9, no. 2, 2013.

[16] A. Simchi and H. Pohl, "Direct laser sintering of iron–graphite powder mixture," *Mater. Sci. Eng. A*, vol. 383, no. 2, pp. 191–200, Oct. 2004.

[17] "EOS 3D Printing for Tooling - Applications and Benefits." [Online]. Available: www.eos.info/tooling.

[18] J. C. Ferreira, A. S. Mateus, and N. F. Alves, "Rapid tooling aided by reverse engineering to manufacture EDM electrodes," *Int. J. Adv. Manuf. Technol.*, vol. 34, no. 11–12, pp. 1133–1143, Oct. 2007.

[19] S.S. Dimov, D.T. Pham, F. Lacan, and K.D. Dotchev, "Rapid tooling applications of the selective laser sintering process," *Assem. Autom.*, vol. 21, no. 4, pp. 296–302, Dec. 2001.

[20] A. Le and ri, "What Can Additive Manufacturing Do for Tooling?," 3DPrint.com, 04-Apr-2015.

[21] M. Cotteleer, M. Neier, and J. Crane, "3D opportunity in tooling."

[22] R. Folgado, P. Peças, and E. Henriques, "Life cycle cost for technology selection: A Case study in the manufacturing of injection moulds," *Int. J. Prod. Econ.*, vol. 128, no. 1, pp. 368–378, 2010.

[23] C. M. Taylor, I. P. Ilyas, K. W. Dalgarno, and J. Gosden, "Manufacture of production quality injection mould tools using SLS and HSM," in 2007 ASME International Conference on Manufacturing Science and Engineering, January 15, 2007 - October 18, 2007, 2007, pp. 9–16.

[24] J. 23 and 2014 Lindsey Frick, "The Difference Between Machined and 3D Printed Metal Injection Moulds." [Online]. Available: machinedesign.com/3d-printing/difference-between-machined-and-3d-printed-metal-injection-moulds.

[25] M. Somasekharappa, "Additive Manufacturing and Industrial Tooling (Part 1)," *3D Printing Industry*, 04-Jul-2013. .

[26] J. P. Kruth, L. Froyen, J. Van Vaerenbergh, P. Mercelis, M. Rombouts, and B. Lauwers, "Selective laser melting of iron-based powder," *J. Mater. Process. Technol.*, vol. 149, no. 1–3, pp. 616–622, Jun. 2004.

[27] H. J. Niu and I. T. H. Chang, "Selective laser sintering of gas and water atomised high speed steel powders," *Scr. Mater.*, vol. 41, no. 1, pp. 25–30, Jun. 1999.

[28] J.-H. Lee, J.-H. Jang, B.-D. Joo, H.-S. Yim, and Y.-H. Moon, "Application of direct laser metal tooling for AISI H13 tool steel," *Trans. Nonferrous Met. Soc. China Engl. Ed.*, vol. 19, no. SUPPL. 1, pp. s284–s287, 2009.

[29] L. Sun, Y.-H. Kim, D. Kim, and P. Kwon, "Densification and properties of 420 stainless steel produced by three-dimensional printing with addition of Si3N4 powder," *J. Manuf. Sci. Eng. Trans.* ASME, vol. 131, no. 6, pp. 0610011–0610017, 2009.

[30] C. Hauser, S. Akhtar, J. Xie, T. H. C. Childs, C. M. Taylor, M. Baddrossamay, C. S. Wright, M. Youseffi, P. Fox, and W. O'Neill, "Direct selective laser sintering of tool steel powders to high density. Part A: Effects of laser beam width and scan strategy," Proc. 2003 Solid Free. Fabr. Symp., 2003.

[31] S. Akhtar, C. S. Wright, M. Youseffi, C. Hauser, T. H. C. Childs, C. M. Taylor, M. Baddrossamay, J. Xie, P. Fox, and W. O'Neill, "Direct selective laser sintering of tool steel powders to high density: Part B - The effect on microstructural evolution," Proc. Solid Free. Fabr. Symp., pp. 656–667, 2003.

[32] W. Meiners, K. Wissenbach, and R. Poprawe, "Direct selective laser sintering of steel powder," ResearchGate, pp. 615–622.

[33] S. A.B and L. G, "Comparison of density of stainless steel 316L parts produced with selective laser melting using different powder grades."

[34] C. Kamath, B. El-dasher, G. F. Gallegos, W. E. King, and A. Sisto, "Density of additively-manufactured, 316L SS parts using laser powder-bed fusion at powers up to 400 W," *Int. J. Adv. Manuf. Technol.*, vol. 74, no. 1–4, pp. 65–78, May 2014.

[35] A. Simchi, "Direct laser sintering of metal powders: Mechanism, kinetics and microstructural features," *Mater. Sci. Eng. A*, vol. 428, no. 1–2, pp. 148–158, Jul. 2006.

[36] A.B. Spierings, N. Herres, and G. Levy, "Influence of the particle size distribution on surface quality and mechanical properties in AM steel parts," *Rapid Prototyp. J.*, vol. 17, no. 3, pp. 195–202, Apr. 2011.

[37] L. Bochuan, W. Ricky, T. Christopher, and A. Ian, "Investigation of the effect of particle size distribution on processing parameters."

[38] S. A.B, W. K, and L. G, "Designing Material Properties Locally with Additive Manufacturing Technology SLM," Dec. 2014.

[39] P. B. M. Averyanova and V. B, "Effect of initial powder properties on final microstructure and mechanical properties of parts manufactured by selective laser melting."

[40] T. LeBrun, T. Nakamoto, K. Horikawa, and H. Kobayashi, "Effect of retained austenite on subsequent thermal processing and resultant mechanical properties of selective laser melted 17–4 PH stainless steel," *Mater. Des.*, vol. 81, pp. 44–53, Sep. 2015.

[41] T. Lebrun, K. Tanigaki, K. Horikawa, and H. Kobayshi, "Strain rate sensitivity and mechanical anisotropy of selective laser melted 17-4 PH stainless steel," *Mech. Eng. J.*, vol. 1, no. 5, pp. SMM0049–SMM0049, 2014.

[42] L. E. Murr, E. Martinez, J. Hernandez, S. Collins, K. N. Amato, S. M. Gaytan, and P. W. Shindo, "Microstructures and Properties of 17-4 PH Stainless Steel Fabricated by Selective Laser Melting," *J. Mater. Res. Technol.*, vol. 1, no. 3, pp. 167–177, Oct. 2012.

[43] X. Zhao, Q. Wei, B. Song, Y. Liu, X. Luo, S. Wen, and Y. Shi, "Fabrication and Characterization of AISI 420 Stainless Steel Using Selective Laser Melting," *Mater. Manuf. Process.*, vol. 30, no. 11, pp. 1283–1289, Nov. 2015.

[44] W.-N. Su, P. Erasenthiran, and P. M. Dickens, "Investigation of fully dense laser sintering of tool steel powder using a pulsed Nd: Yag (neodymium-doped yttrium aluminium garnet) laser," *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.*, vol. 217, no. 1, pp. 127–138, Jan. 2003.

[45] J.-Y. Chen, L. Xue, and S.-H. Wang, "Microstructure characterization of laser-consolidated AISI 420 stainless steel," in Materials Science and Technology Conference and Exhibition, MS and T'08, October 5, 2008 - October 9, 2008, 2008, vol. 3, pp. 1388–1396.

[46] J. Y. Chen and L. Xue, "The microstructural characteristics of laser clad AISI P20 tool steel," in Proceeding of the 1st Congress, 7-10 October 2002, Columbus, Ohio USA, 2003, pp. 198–205.

[47] A. Angelastro, S. Campanelli, G. Casalino, and A. Ludovico, "Analysis of a tool steel sample obtained by direct laser deposition," in Annals of DAAAM for 2007 and 18th International DAAAM Symposium on Intelligent Manufacturing and Automation: Focus on Creativity, Responsibility, and Ethics of Engineers, October 24, 2007 - October 27, 2007, 2007, pp. 23–24.

[48] A. Simchi, "Direct laser sintering of metal powders: Mechanism, kinetics and microstructural features," Mater. Sci. Eng. A, vol. 428, no. 1–2, pp. 148–158, 2006.

[49] J. Chen and L. Xue, "Comparison study of H13 tool steel microstructures produced by laser cladding and laser consolidation," in Materials Science and Technology 2005 Conference, September 25, 2005 - September 28, 2005, 2005, vol. 3, pp. 23–31.

[50] M. Badrossamay and T. H. C. Childs, "Further studies in selective laser melting of stainless and tool steel powders," *Int. J. Mach. Tools Manuf.*, vol. 47, no. 5, pp. 779–784, Apr. 2007.

[51] P. Vallabhajosyula and D. L. Bourell, "Modeling and production of fully ferrous components by indirect selective laser sintering," *Rapid Prototyp. J.*, vol. 17, no. 4, pp. 262–268, Jun. 2011.

[52] M. Agarwala., D. Bourell., J. Beaman., H. Marcus, and J. Barlow., 1995. Direct selective laser sintering of metals. *Rapid Prototyping Journal*, 1(1), pp.26-36.

[53] A. Simchi and H. Asgharzadeh, "Densification and microstructural evaluation during laser sintering of M2 high speed steel powder," *Mater. Sci. Technol.*, vol. 20, no. 11, pp. 1462–1468, Nov. 2004.

[54] H. Asgharzadeh and A. Simchi, "Effect of sintering atmosphere and carbon content on the densification and microstructure of laser-sintered M2 high-speed steel powder," *Mater. Sci. Eng. A*, vol. 403, no. 1–2, pp. 290–298, 2005.

[55] R. Vilar, R. Sabino, and M. A. Almeida, "Laser surface melting of sintered AISI T15 high-speed steel," in Proceedings of the Laser Materials Processing Symposium - ICALEO'91, November 3, 1991 - November 8, 1991, 1992, vol. 74, pp. 424–434.

[56] R. Morgan, C. J. Sutcliffe, and W. O'Neill, "Density analysis of direct metal laser re-melted 316L stainless steel cubic primitives," *J. Mater. Sci.*, vol. 39, no. 4, pp. 1195–1205, Feb. 2004.

[57] P. B. M. Averyanova, "Studying the influence of initial powder characteristics on the properties of final parts manufactured by the selective laser melting technology," *Virtual Phys. Prototyp.*, pp. 1–9, 2011.

[58] L. E. Murr, E. Martinez, J. Hernandez, S. Collins, K. N. Amato, S. M. Gaytan, and P. W. Shindo, "Microstructures and Properties of 17-4 PH Stainless Steel Fabricated by Selective Laser Melting," *J. Mater. Res. Technol.*, vol. 1, no. 3, pp. 167–177, Oct. 2012.

[59] T. Lebrun, K. Tanigaki, K. Horikawa, and H. Kobayashi, "Strain rate sensitivity and mechanical anisotropy of selective laser melted 17-4 PH stainless steel," *Mech. Eng. J.*, vol. 1, no. 5, pp. SMM0049–SMM0049, 2014.

[60] H. Irrinki, M. Dexter, B. Barmore, R. Enneti, S. Pasebani, S. Badwe, J. Stitzel, R. Malhotra, and S. V. Atre, "Effects of Powder Attributes and Laser Powder Bed Fusion (L-PBF) Process Conditions on the Densification and Mechanical Properties of 17-4 PH Stainless Steel," *JOM*, vol. 68, no. 3, pp. 860–868, Jan. 2016.

[61] G. Hengfeng, G. Haijin, P. Deepankar, R. Khalid, S. Thomas, and S. Brent, "Influences of Energy Density on Porosity and Microstructure of Selective Laser Melted 17-4PH Stainless Steel," Dec. 2014.

[62] X. Zhao, Q. Wei, B. Song, Y. Liu, X. Luo, S. Wen, and Y. Shi, "Fabrication and Characterization of AISI 420 Stainless Steel Using Selective Laser Melting," *Mater. Manuf. Process.*, vol. 30, no. 11, pp. 1283–1289, Nov. 2015.

[63] J. W. Xie, P. Fox, W. O'Neill, and C. J. Sutcliffe, "Effect of direct laser re-melting processing parameters and scanning strategies on the densification of tool steels," *J. Mater. Process. Technol.*, vol. 170, no. 3, pp. 516–523, 2005.

[64] J. Brooks, C. V. Robino, T. Headley, S. Goods, and M. L. Griffith, "Microstructure and property optimization of LENS deposited H13 tool steel," presented at the Solid Freeform Fabrication Symposium, Sandia National Laboratories, 1999.

[65] A. Fedrizzi, M. Pellizzari, and M. Zadra, "Influence of particle size ratio on densification behaviour of AISI H13/AISI M3:2 powder mixture," *Powder Technol.*, vol. 228, pp. 435–442, 2012.

[66] H. J. Niu and I. T. H. Chang, "Liquid phase sintering of M3/2 high speed steel by selective laser sintering," Scr. Mater., vol. 39, no. 1, pp. 67–72, 1998.

[67] P. Vallabhajosyula and D. L. Bourell, "Production of fully ferrous components using indirect selective laser sintering," in 4th International Conference on Advanced Research in Virtual and Physical Prototyping, VRAP 2009, October 6, 2009 - October 10, 2009, 2010, pp. 251–256.

[68] M.-S. Huang and H.-C. Hsu, "Effect of backbone polymer on properties of 316L stainless steel MIM compact," *J. Mater. Process. Technol.*, vol. 209, no. 15–16, pp. 5527–5535, Aug. 2009.

[69] X. Miao, A. J. Ruys, and B. K. Milthorpe, "Hydroxyapatite-316L fibre composites prepared by vibration assisted slip casting," *J. Mater. Sci.*, vol. 36, no. 13, pp. 3323–3332, Jul. 2001.

[70] J. R. J Marcuci, E.C.D. Souza, C. C. Camilo, P. L. D Lorenzo, and J. M. D. A. Rollo, "Corrosion and microstructural characterization of martensitic stainless steels submitted to industrial thermal processes for use in surgical tools."

[71] R. M and M.Actis Grande, "High density sintered stainless steels with improved properties." [Online]. Available: www.journalamme.org/papers_vol21_2/1542S.pdf.

[72] M. Dewidar, "Influence of processing parameters and sintering atmosphere on the mechanical properties and microstructure of porous 316L stainless steel for possible hard-tissue applications."

[73] R. M. German, Powder Metallurgy of Iron and Steel, 1 edition. New York: Wiley-Interscience, 1998.

[74] M. Blair and T. L. Stevens, Steel Castings Handbook, 6th Edition. ASM International, 1995.

[75] S. El-Hadad, W. Khalifa, and A. Nofal, "Surface modification of investment cast-316L implants: Microstructure effects," *Mater. Sci. Eng. C*, vol. 48, pp. 320–327, Mar. 2015.

[76] ASM Specialty Handbook: Stainless Steels - ASM International. .

[77 R. M. German and A. Bose, Injection Moulding of Metals and Ceramics. Princeton, N.J., U.S.A: Metal Powder Industry, 1997.

[78] R. M. German, Metal Injection Moulding: A Comprehensive MIM Design Guide. Princeton, N.J.: MPIF, 2011.

[79] "Metal injection moulding: materials and properties." [Online]. Available: www.pim-international.com/designing_for_PIM/materials.

[80] "MIM-316L (as sintered)," Dynacast. [Online]. Available: /mim-316l-as-sintered.

[81] A. K. Jyotsna Dutta Majumdar, "Direct laser cladding of SiC dispersed AISI 316L stainless steel," *Tribol. Int.*, vol. 42, no. 5, pp. 750–753, 2009.

[82] T. E. S. Tian Fu, "Evaluation of Direct Diode Laser Deposited Stainless Steel 316L on 4340 Steel Substrate for Aircraft Landing Gear Application," p. 9, 2010.

[83] M. B. Lekala, J. W. van der Merwe, and S. L. Pityana, "Laser Surface Alloying of 316L Stainless Steel with Ru and Ni Mixtures," *Int. J. Corros.*, vol. 2012, p. e162425, Aug. 2012.

[84] D. Wu, X. Liang, Q. Li, and L. Jiang, "Laser Rapid Manufacturing of Stainless Steel 316L/Inconel718 Functionally Graded Materials: Microstructure Evolution and Mechanical Properties," *Int. J. Opt.*, vol. 2010, p. e802385, Jan. 2011.

[85] A. P. J. Dutta Majumdar, "Mechanical and electrochemical properties of multiple-layer diode laser cladding of 316L stainless steel," *Appl. Surf. Sci.*, pp. 373–377, 2005.

[86] M. D. Vamsi Krishna Balla, "Laser surface modification of 316 L stainless steel with bioactive hydroxyapatite," *Mater. Sci. Eng. C*, vol. 33, no. 8, pp. 4594–4598, 2013.

[87] "Casting Mateiral: 17-4PH Precipitation Hardening Stainless Steel : Sand Casting, Investment Casting and Die Casting in China." .

[88] A. Szewczyk-Nykiel,(2015). The effect of the addition of boron on the densification, microstructure and properties of sintered 17-4 PH stainless steel. Czasopismo Techniczne.

[89] "AK Steels-17-4 PH stainless steel-MIM properties." [Online]. Available: www.aksteel.com/pdf/markets_products/stainless/precipitation/17-4_ph_data_sheet.pdf.

[90] A.R. Jeefferie, S. Nurhashima, M.Y., Yuhazri, Haeryip Sihombing, S., Mohd Shukor, N.S., Abdullah, and M.A., Omar, "Characterization of injection Moulded 17-4Ph Stainless Steel Prepared with waste rubber binder."

[91] "Kinetics MIM 17-4PH Stainless Steel (H900 Condition)." [Online]. Available: www.matweb.com/search/datasheettext.aspx?matguid=346e4ed0aeae4a7ab69a81e62491c3f1.

[92] M.-W. Wu, Z.-K. Huang, C.-F. Tseng, and K.-S. Hwang, "Microstructures, mechanical properties, and fracture behaviors of metal-injection moulded 17-4PH stainless steel," *Met. Mater. Int.*, vol. 21, no. 3, pp. 531–537, May 2015.

[93] R. Schroeder, G. Hammes, C. Binder, and A. N. Klein, "Plasma debinding and sintering of metal injection moulded 17-4PH stainless steel," *Mater. Res.*, vol. 14, no. 4, pp. 564–568, Dec. 2011.

[94] P. G. E. Jerrard, L. Hao, and K. E. Evans, "Experimental investigation into selective laser melting of austenitic and martensitic stainless steel powder mixtures," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 223, no. 11, pp. 1409–1416, Nov. 2009.

[95] A. B. Spierings, G. Levy "Designing material properties locally with Additive Manufacturing technology SLM, " ETH-Zürich; 2014.

[96] M. Averyanova, E. Cicala, Ph. Bertrand, and Dominique Grevey, "Experimental design approach to optimize selective laser melting of martensitic 17/4 PH powder: part I – single laser tracks and first layer," *Rapid Prototyp. J.*, vol. 18, no. 1, pp. 28–37, Jan. 2012.

[97] A. Gratton, "Comparison of Mechanical, Metallurgical Properties of 17-4PH Stainless Steel between Direct Metal Laser Sintering (DMLS) and Traditional Manufacturing Methods," 2012 NCUR, Aug. 2012.

[98] S. Kumpaty, S. Kamara, B. Tomlin, J. Yoo, H. Kumpaty, D. Anderson, M. Govindaraju, N. Kanoongo, and K. Balasubramanian, "Effect of Heat Treatment on Mechanical/Metallurgical Properties of Direct Metal Laser Sintered 17-4 Precipitate Hardened Stainless Steel," *Adv. Mater. Res.*, vol. 699, pp. 795–801, May 2013.

[99] L. W. Tsay, T. Y. Yang, and M. C. Young, "Embrittlement of laser surface-annealed 17-4 PH stainless steel," *Mater. Sci. Eng. A*, vol. 311, no. 1–2, pp. 64–73, Jul. 2001.

[100] T. LeBrun, T. Nakamoto, K. Horikawa, and H. Kobayashi, "Effect of retained austenite on subsequent thermal processing and resultant mechanical properties of selective laser melted 17–4 PH stainless steel," *Mater. Des.*, vol. 81, pp. 44–53, Sep. 2015.

[101] A. Yadollahi, J. Simsiriwong, S. M. Thompson, and N. Shamsaei, "Data demonstrating the effects of build orientation and heat treatment on fatigue behavior of selective laser melted 17–4 PH stainless steel," *Data Brief*, vol. 7, pp. 89–92, Feb. 2016.

[102] L. E. Murr, E. Martinez, K. N. Amato, S. M. Gaytan, J. Hernandez, D. A. Ramirez, P. W. Shindo, F. Medina, and R. B. Wicker, "Fabrication of Metal and Alloy Components by Additive Manufacturing: Examples of 3D Materials Science," *J. Mater. Res. Technol.*, vol. 1, no. 1, pp. 42–54, Apr. 2012.

[103] A. Yadollahi, J. Simsiriwong, S. M. Thompson, and N. Shamsaei, "Data demonstrating the effects of build orientation and heat treatment on fatigue behavior of selective laser melted 17–4 PH stainless steel," *Data Brief*, vol. 7, pp. 89–92, Feb. 2016.

[104] M. Blair and T. L. Stevens, Steel Castings Handbook, 6th Edition. ASM International, 1995.

[105] "Stainless Steel - Grade 420 (UNS S42000)." [Online]. Available: www.azom.com/article.aspx?ArticleID=972.

[106] Kevin M. McHugh and Bruce R. Wickham, "Spray-Formed Tooling For Injection Moulding and Die Casting Applications."

[107] P. Fallbo Èhmer, C.A. Rodrõ Âguez, T. O Èzel, and T. O Èzel, T. Altan, "High-speed machining of cast iron and alloy steels for die and mould manufacturing."

[108] X. Zhao, Q. Wei, B. Song, Y. Liu, X. Luo, S. Wen, and Y. Shi, "Fabrication and Characterization of AISI 420 Stainless Steel Using Selective Laser Melting," *Mater. Manuf. Process.*, vol. 30, no. 11, pp. 1283–1289, Nov. 2015.

[109] John L. Johnson, Lye King Tan, Ravi Bollina, Pavan Suri, and Randall M. German, "Bi-Metal Injection Moulding of Tough/Wear-resistant Components."

[110] "AK Steel- 420 stainless steel - MIM properties." [Online]. Available: www.aksteel.com/pdf/markets_products/stainless/martensitic/420_data_sheet.pdf.

[111] S. Nachum and N. A. Fleck, "The microstructure and mechanical properties of ball-milled stainless steel powder: The effect of hot-pressing vs. laser sintering," *Acta Mater.*, vol. 59, no. 19, pp. 7300–7310, 2011.

[112] M. Soodi, S. H. Masood, and M. Brandt, "A study of laser cladding with 420 stainless steel powder on the integrity of the substrate metal," in 2011 International Conference on Frontiers of Manufacturing Science and Measuring Technology, ICFMM 2011, June 23, 2011 - June 24, 2011, 2011, vol. 230–232, pp. 949–952.

[113] M. Soodi, M. Brandt, and S. Masood, "A study of microstructure and surface hardness of parts fabricated by laser direct metal deposition process," in 2010 International Conference on Material and Manufacturing Technology, ICMMT 2010, September 17, 2010 - September 19, 2010,

2010, vol. 129–131, pp. 648–651.

[114] X. Zhao, B. Song, Y. Zhang, X. Zhu, Q. Wei, and Y. Shi, "Decarburization of stainless steel during selective laser melting and its influence on Young's modulus, hardness and tensile strength," *Mater. Sci. Eng. A*, vol. 647, pp. 58–61, Oct. 2015.

[115] P. Krakhmalev, I. Yadroitsava, G. Fredriksson, and I. Yadroitsev, "Microstructure of SLM manufactured 316L and 420 grades stainless steel," ResearchGate, pp. 59–66.

[116] "Congresso Luso-Mocambicano .pdf"

[117] H. Halfa, "Characterization of Electroslag Remelted Super Hard High Speed Tool Steel Containing Niobium," *Steel Res. Int.*, vol. 84, no. 5, pp. 495–510, May 2013.

[118] "P20 Tool Steel - Low-Carbon Mould Steel UNS T51620." [Online]. Available: www.azom.com/article.aspx?ArticleID=6239. [Accessed: 13-Mar-2016].

[119] "P20 Steel Plate | P20 Mould Tool Steel | 1.2311 | 3Cr2Mo - Special Steel." [Online]. Available: www.astmsteel.com/product/p20-steel-plate-1-2311-3cr2mo-mould-tool-steel/.

[120] A. Gupta., H. Singh, and A. Aggarwal., "Taguchi-fuzzy multi output optimization (MOO) in high speed CNC turning of AISI P-20 tool steel". *Expert Systems with Applications*, 38(6), pp.6822-6828, 2011.

[121] J. Y. Chen., and L. Xue. "Microstructural characteristics of laser-clad AISI P20 tool steel." In Proceedings of 1st international surface engineering congress and 13th IFHTSE congress. Materials Park (OH): ASM International, p. 198. 2002. [122] A. Noorian, Sh. Kheirandish, and H. Saghafian, "Evaluation of the Mechanical Properties of Niobium Modified CAST AISI H 13 Hot Work Tool Steel."

[123] M. Ramezani, T. Pasang, Z. Chen, T. Neitzert, and D. Au, "Evaluation of carbon diffusion in heat treatment of H13 tool steel under different atmospheric conditions," *J. Mater. Res. Technol.*, vol. 4, no. 2, pp. 114–125, Apr. 2015.

[124] "MIM Material Properties," Dynacast. [Online]. Available: /mim-material-properties.

[125] "New Welding Procedures for Repairing H13 and P20 Tool Steels [Online]. Available:www.researchgate.net/publication/237428429_ New Welding Procedures for Repairing H13 and P20 Tool Steels.

[126] A. J. Pinkerton and L. Li, "Direct additive laser manufacturing using gas- and water-atomised H13 tool steel powders," *Int. J. Adv. Manuf. Technol.*, vol. 25, no. 5–6, pp. 471–479, 2005.

[127] J. Choi and Y. Chang, "Characteristics of laser aided direct metal/material deposition process for tool steel," *Int. J. Mach. Tools Manuf.*, vol. 45, no. 4–5, pp. 597–607, 2005.

[128] J. Mazumder, J. Choi, K. Nagarathnam, J. Koch, and D. Hetzner, "The direct metal deposition of H13 tool steel for 3-D components," *JOM*, vol. 49, no. 5, pp. 55–60, May 1997.

[129] "Speedy Metals Information for A6 Tool Steel." [Online]. Available:www.speedymetals.com/information/Material18.html.

[130] "M2 Molybdenum High Speed Tool Steel (UNS T11302)." [Online]. Available: www.azom.com/article.aspx?ArticleID=6174.

[131] C. Kim, A. R. Johnson, and W. F. Hosford, "Fracture toughness of aisi M2 high-speed steel and corresponding matrix tool steel," *Metall. Trans. A,* vol. 13, no. 9, pp. 1595–1605, Sep. 1982.

[132] S. Dolinek, "Wear characteristics of laser sintered moulding tools," 15th Int. Conf. Wear Mater., vol. 259, no. 7–12, pp. 1241–1247, 2005.

[133] H. J. Niu and I. T. H. Chang, "Selective laser sintering of gas atomised M2 high speed steel powder," *J. Mater. Sci.*, vol. 35, no. 1, pp. 31–38, Jan. 2000.

[134] H. J. Niu and I. T. H. Chang, "Selective laser sintering of gas and water atomised high speed steel powders," *Scr. Mater.*, vol. 41, no. 1, pp. 25–30, 1999.

[135] A.B. Spierings, N. Herres, and G. Levy, "Influence of the particle size distribution on surface quality and mechanical properties in AM steel parts," *Rapid Prototyp. J.*, vol. 17, no. 3, pp. 195–202, Apr. 2011.

[136] A. Mertens, S. Reginster, H. Paydas, Q. Contrepois, T. Dormal, O. Lemaire, and J. Lecomte-Beckers, "Mechanical properties of alloy Ti–6Al–4V and of stainless steel 316L processed by selective laser melting: influence of out-of-equilibrium microstructures," *Powder Metall.*, vol. 57, no. 3, pp. 184–189, Jul. 2014.

[137] D. Gu and Y. Shen, "Processing conditions and microstructural features of porous 316L stainless steel components by DMLS," *Appl. Surf. Sci.*, vol. 255, pp. 1880–1887, Dec. 2008.

[138] L. E. Murr, E. Martinez, K. N. Amato, S. M. Gaytan, J. Hernandez, D. A. Ramirez, P. W. Shindo, F. Medina, and R. B. Wicker, "Fabrication of Metal and Alloy Components by Additive Manufacturing: Examples of 3D Materials Science," *J. Mater. Res. Technol.*, vol. 1, no. 1, pp. 42–54, Apr. 2012.

[139] C. Zhichao, K. Chi Tat, and L. Kin Ho, "Laser Surface Melting of 17-4PH stainless steel."

[140] W. E. Luecke and J. A. Slotwinski, "Mechanical Properties of Austenitic Stainless Steel Made by Additive Manufacturing," J. *Res. Natl. Inst. Stand. Technol.*, vol. 119, p. 398, Oct. 2014.

[141] P. B. M. Averyanova, "Studying the influence of initial powder characteristics on the properties of final parts manufactured by the selective laser melting technology," Virtual Phys. Prototyp., pp. 1–9, 2011.

[142] H. J. Niu and I. T. H. Chang, "Instability of scan tracks of selective laser sintering of high speed steel powder," *Scr. Mater.*, vol. 41, no. 11, pp. 1229–1234, Nov. 1999.

[143] L. Xue and M. U. Islam, "Free-form laser consolidation for producing metallurgically sound and functional components," *J. Laser Appl.*, vol. 12, no. 4, pp. 160–165, 2000.

[144] V. E. Beal, P. Erasenthiran, N. Hopkinson, P. Dickens, and C. H. Ahrens, "Scanning strategies and spacing effect on laser fusion of H13 tool steel powder using high power Nd:YAG pulsed laser," *Int. J. Prod. Res.*, vol. 46, no. 1, pp. 217–232, 2008.

[145] "Microstructure of SLM manufactured 316L and 420 grades stainless steel." [Online]. Available:www.researchgate.net/publication/286022952_Microstructure_of_SLM_manufactured_316L_and_420_grades_stainless_steel.

Additive Manufacturing of a honeycomb structured Ti-6Al-4V oil-gas separation rotor for aero-engine applications

The aerospace sector has been a key driver in the commercial development of metal Additive Manufacturing. Whilst some of the major application announcements of recent years can be looked back upon as milestones for the industry, numerous lower profile developments continue to demonstrate how metal AM has the capability to increase efficiency and add value in a multitude of application areas. We review a paper published in the *Journal of the Minerals, Metals & Materials Society* highlighting the potential for an innovative oil-gas separation rotor for aero-engine applications.

A potentially significant novel aerospace application for Additive Manufacturing was the subject of a recent paper in the *Journal of the Minerals, Metals & Materials Society* (TMS) (JOM, Vol. 68, No.3, 2016, pp. 799-805) by a research team from the State Key Laboratory of Porous Metal Materials and the Shenyang Engine Design and Research Institute, China. The authors were HP Tang, Q B Wang, G Y Yang, J Gu, N Liu, L Jia and M Qian. Ma Qian was a Guest Research Professor at the State Key Laboratory for the period of the project.

Oil–gas separation is a key process in an aero-engine lubrication system. The lubrication and cooling of shaft bearings in an aircraft turbine are usually achieved through the injection of lubricating oil into various sealed bearing chambers that house the shaft bearings. The resulting oil–air mixture from the system is separated by an oil–gas centrifugal separator.

The core component of the oil–gas centrifugal separator is the separation rotor. In early designs, the rotor of an oil–gas separator was made from steel blades with the separation efficiency reaching only about 83%. Consequently, in the1970s, Rolls-Royce pioneered the use of metal foam or sponge as oil–gas separation rotors. When an oil–gas mixture passes through such a porous medium, small oil droplets are trapped in the pores allowing effective secondary separation or recovery. As a result, the separation efficiency improved significantly. Such rotors were subsequently employed in the Rolls-Royce Trent series engines and achieved an oil–gas separation efficiency of greater than 99.0%.

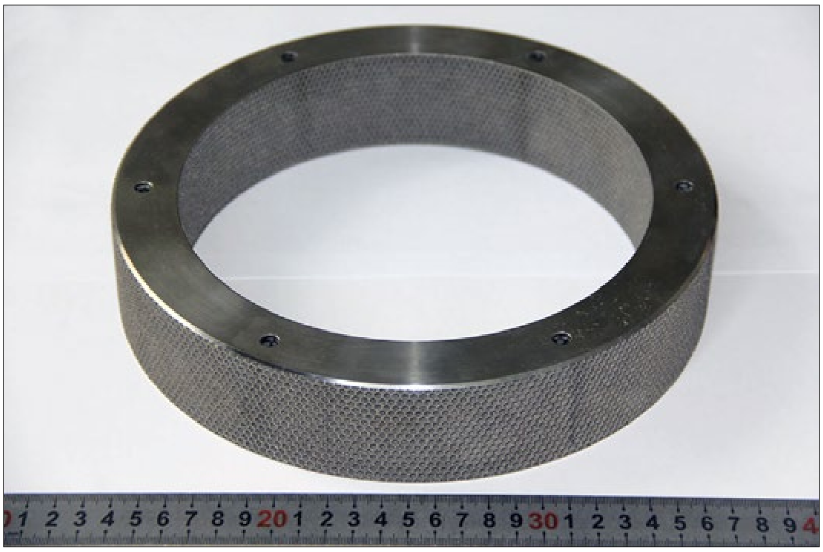

Fig. 1 Ti-6Al-4V honeycomb oil–gas separation rotor additively manufactured by SEBM

Fig. 2 Hexagonal structure on the outer cylindrical surface of the Ti-6Al-4V honeycomb oil–gas separation rotor

Fig. 3 Samples for compression testing

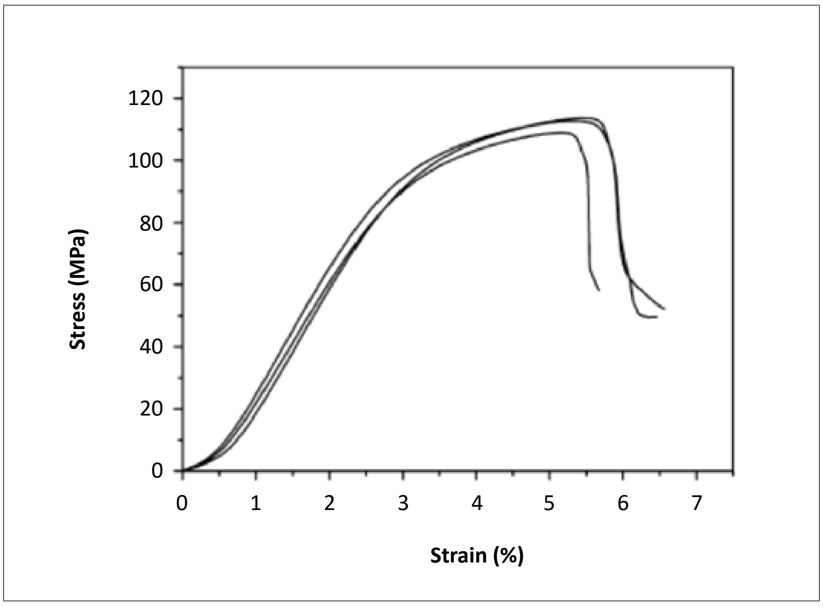

Fig. 4 Compressive stress–strain curves for Ti-6Al-4V honeycomb structure samples

Although metal foam rotors can be made to have porosity up to 95% and density down to 0.5 g/cm^3, they have low mechanical strength and, in addition, mass distribution can be inhomogeneous because of the non-uniform pore size distribution. Also, metal foams often show a high ventilation resistance due to the imperfect pore structure.

The research reported in this paper dealt with the design of a Ti-6Al-4V honeycomb structure with hexagonal cone-shaped pore channels, its manufacture by Selective Electron Beam Melting (SEBM) and the assessment of its mechanical strength and oil–gas separation efficiency. The design was awarded a patent (CN103273065 B) by the China Patent &Trademark Office on 1 April 2015.

In relation to the design of the honeycomb structure, to minimise the ventilation resistance of the separator, it is essential to adopt the shortest flow path while achieving high separation efficiency. The concept adopted by the authors was to make a honeycomb structure, which consisted of cone-shaped pore channels with a hexagonal cross-section, while avoiding communications between adjoining channels. Compared to circular pore channels, the use of hexagonal pore channels offered advantages in terms of:

- Higher porosity per unit area
- A design better suited to production by AM. When building such a structure by powder bed AM, the melting area is uniform in the bed in making each layer of hexagonal porous structure, whereas, in contrast, there is a significant variation in melting with respect to circular pore units.

Before determining that hexagonal-section channels offered the optimum solution, other channel shapes were also evaluated. A square or rectangular cross-section offers a smaller effective pore channel size than that with a hexagonal cross-section.

An octagonal or dodecagonal pore channel can offer a greater effective pore channel size than a hexagonal pore channel. However, every four octagons need to be connected by a small square, while every three dodecagons must be linked by a small triangle.

The hexagonal honeycomb structure was then designed using a Computer-aided three-dimensional interactive application (CATIA) 3D graphic design software suite. The final design was additively manufactured using SEBM, after a number of prior trials on smaller honeycomb units. The major problems encountered in these trials included formation of large defects due to lack of fusion and distortion due to thermal stress. Fig. 1 shows one of the manufactured honeycomb oil–gas separation rotors. SEBM enabled the manufacture of the complex honeycomb structure with uniform hexagonal conical unit cells (Fig. 2).

The compressive stress–strain curves for the honeycomb-structured Ti-6Al-4V samples as seen in Fig. 3 are shown in Fig. 4. The compression strength reached 110 ± 1.12 MPa. This high strength indicates that the pore shape and size in the Ti-6Al-4V honeycomb structure, additively manufactured by SEBM, is stable and promising for high-speed rotation oil–gas separation applications.

	Separation efficiency (%)		Ventilator resistance (KPa)	
Rotation speed 9 (rpm)	Sponge rotor	Honeycomb rotor	Sponge rotor	Honeycomb rotor
2000	99.8	99.4	18.5	16.6
3000	99.6	99.0	19.7	16.5
4000	99.9	99.7	20.3	16.7
4794	99.8	99.8	21.5	16.5
6000	99.7	99.8	23.5	17.3

Table 1 Oil–gas separation performance of honeycomb-structured Ti-6Al-4V rotor and Ni-Cr alloy sponge rotor

The oil–gas separation performance of the honeycomb-structured Ti-6Al-4V rotor was assessed in comparison with a Ni-Cr alloy sponge rotor manufactured by the research team. Table 1 summarises the results. The separation efficiency of the honeycomb-structured Ti-6Al-4V rotor was equivalent to that of the Ni-Cr alloy sponge rotor at rotation speeds above 4000 rpm, achieving 99.8% of separation, while being slightly lower at speeds below 4000 rpm. However, a distinct advantage is that the ventilation resistance of the honeycomb-structured rotor is noticeably lower than that of the Ni-Cr alloy sponge rotor, especially at rotation speeds above 4000 rpm. In addition, the ventilation resistance of the honeycomb-structured rotor is much less sensitive to rotation speed than that of the Ni-Cr alloy sponge rotor. Since high speed rotations (up to 18,000 rpm) are preferred for rapid and efficient separation, the honeycomb-structured rotor has a clear advantage over the Ni-Cr alloy sponge rotor in this regard.

The authors reached the final conclusion that, with further design optimisation based on both modelling and experimental evaluation, the novel honeycomb-structured Ti-6Al-4Vseparator rotors, additively manufactured by SEBM, have the potential to be used as the next generation oil–gas separation rotors in aero-engine lubrication systems.

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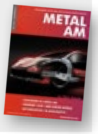
www.seam2016.com

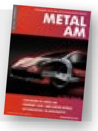
AM3D Additive Manufacturing + 3D Printing Conference & Expo
August 21–24, Charlotte, USA
www.asme.org/events/am3d



IMTS2016
September 12-17, Chicago, USA
www.imts.com

Asiamold 2016
September 20-22, Guangzhou, China
www.3dprintingasiaexpo.com.com

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



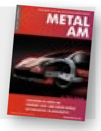
3D Print
October 4-5, Lyon, France
www.3dprint-exhibition.com

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 powered by TCT 2016
November 15-18, Frankfurt, Germany
www.formnext.com



Metal Additive Manufacturing Conference - Voestalpine
November 24-25, Linz, Austria
www.mamc2016.org

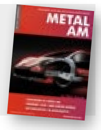
Euromold 2016
December 6-9, Düsseldorf, Germany
euromold.com

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

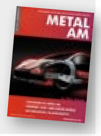
2017

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

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

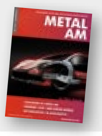


AMPM2017 - Additive Manufacturing with Powder Metallurgy Conference
June 13-15, Las Vegas, USA
www.ampm2017.org



Event listings

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



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Metal AM magazine is exhibiting at and/or being distributed at events highlighted with the Metal AM cover image

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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
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