FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

EBAM 2018

2nd International Conference on Electron Beam Additive Manufacturing

11 – 13 April 2018 · Nürnberger Akademie, Nuremberg, Germany

www.eam.fau.de/EBAM2018

Welcome

It is our pleasure to announce the second **International Conference on Electron Beam Additive Manufacturing EBAM 2018**, which will take place from 11 – 13 April 2018 in Nuremberg, Germany. EBAM 2018 is organized by the Chair of Materials Science and Engineering for Metals in cooperation with the Cluster of Excellence – Engineering of Advanced Materials (EAM) at the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU).

The conference aims to discuss specific challenges and opportunities offered by the electron beam. EBAM2018 will bring together researchers and industrial users to accomplish improvements in this technology. Keynote presentations from academics as well as industry will give high level insight into this fabrication technology.

Since the first EBAM 2016, the interest in this topic has increased even further with an enormous number of submissions from around the world. We hope that the wide range of inspiring talks – including the invited keynote presentations in combination with high-quality poster presentations – initiates various fruitful discussions and future cooperation.

Warm thanks go to our organization team for the help and support during preparation and the following three intense days.

We are looking forward to the scientific program full of expertise from all over the world.

Carolin Körner

Conference Coordinator

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Keynote Speakers

Sara Biamino	Politecnico di Torino, Italy
Akihiko Chiba	Tohoku University, Japan
Ryan Dehoff	Oak Ridge National Laboratory, US
Martin Franke	Neue Materialien Fürth GmbH, Germany
Eduard Hryha	Chalmers Unversity of Technology, Sweden
Feng Lin	Tsinghua University, China
Vasily Ploshikhin	University of Bremen, Germany
Mohsen Seifi	ASTM International / Case Western Reserve University, US
Anders Snis	Arcam AB, Sweden
Sam Tammas-Williams	University of Sheffield, Great Britain
Yohsuke Yoshinari	JEOL Ltd., Japan

International Advisory Board

Ulf Ackelid	Freemelt AB, Sweden
Akihiko Chiba	Tohoku University, Japan
Ryan Dehoff	Oak Ridge National Laboratory, US
Tadashi Fujieda	Hitachi Ltd., Japan
Paolo Gennaro	Precicast Additive, Switzerland
Ulric Ljungblad	Freemelt AB, Sweden
Thomas Niendorf	University of Kassel, Germany
Lars-Erik Rännar	Mid Sweden University, Sweden
Iain Todd	University of Sheffield, Great Britain

Conference Coordinator

Carolin Körner	WTM, FAU Erlangen-Nürnberg

Program Coordinator

Matthias Markl	WTM, FAU Erlangen-Nürnberg

Administration

Aline Looschen	EAM, FAU Erlangen-Nürnberg

Local Organization Committee

Lucas Adler	ZMP, FAU Erlangen-Nürnberg
Julia Bieske	Neue Materialien Fürth GmbH
Maximilian Wormser	ZMP, FAU Erlangen-Nürnberg

Conference Venue


© Christine Dierenbach / Stadt Nürnberg

Nürnberger Akademie
Marmorsaal
Gewerbemuseumsplatz 2
90403 Nürnberg

Registration & Help Desk

The registration desk will be located in the foyer of the Marmorsaal. It will be in service on 11 April 2018 from 9:00 to 11:00. Late registration is possible during the whole conference at the help desk at the entrance to the Marmorsaal. During registration the whole conference material is handed over.
The conference fee includes entrance to all sessions, coffee breaks, lunches and the social event including the conference dinner as well as the conference material. Please indicate during registration if you will take part at the social event and the conference dinner. Outstanding payments will be directly sorted at the registration or help desk.

Instructions for Oral Presentation

Oral presentations are limited to a total of 20 minutes; invited speakers will have 30 minutes. This time includes a short discussion of about 5 minutes to the presented topic. Speakers are requested to respect the schedule, to keep the time of their presentation and to present themselves to their session chairman directly before the session. Speakers are requested to provide their presentation at least 15 minutes before the beginning of the session. The Marmorsaal is equipped with a data projector (aspect ratio 4:3) connected to a local computer operating under Windows 10 and PowerPoint 2016. PowerPoint and PDF presentations are appreciated; CD drive, USB port and laser pointers are available. If necessary, speakers can use their own laptops for their presentation. While adapters for many video output formats are available, please provide a suitable adapter to VGA if possible.

Instructions for Poster Presentation

The posters will be displayed in the Marmorsaal surrounding the presentation area. Boards and mounting material for posters will be ready for poster installation. The size of the poster boards is 1 m x 2 m (width x height). For safety mounting and readability please consider the maximum poster size of 0.98 m x 1.5 m. The poster session will be held on 11 April 2018 from 17:00 to 19:00 with some light refreshments. Posters should be displayed until 14:00 on 12 April 2018. They must be removed until 17:30 on 12 April 2018.

Poster Prize

Every attendee will be able to vote for the best poster presentation until 15:40 on 12 April 2018. The three best poster presenters will be awarded a prize.

Lunches, Coffee Breaks & Refreshments

Lunch, coffee and light refreshments will be served in the foyer of the Marmorsaal. There are several tables and bar tables located in the Marmosaal, the foyer, at the entrance and on the gallery to enjoy the breaks and to exchange ideas.

Social Event & Conference Dinner

The social event will start on 12 April 2018 from 17:30 with a guided historical tram ride through Nuremberg. Subsequently to the social event, the conference dinner will take place at "Zum Spießgesellen" between 19:00 and 22:00.

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Zum Spießgesellen
Rathausplatz 4
90403 Nuremberg

Accommodation

Contact information to hotels for participants who made use of our room contingent.

AZIMUT Hotel Nuremberg
Kaulbachstrasse 1 D
90408 Nuremberg
info.nuernberg@azimuthotels.com
+49 (0) 911 3657-0

Maritim Hotel Nuremberg
Frauentorgraben 11
90433 Nuremberg
reservierung-nur@maritim.de
+49 (0) 911 2363-0

Hotel NH Collection Nürnberg City
Bahnhofstrasse 17-19
90402 Nuremberg
nhcollectionnuernbergcity@nh-hotels.com
+49 (0) 911 99990

Important Phone Numbers

Conference Help Desk	**+49 9131 85 27537**	
Taxi	**+49 911 19410 / 21111 / 21555 / 24444**	
Police	**110**	
General Emergency	112	(e.g. ambulance, fire)
Medical standby duty	+49 116 117	
Pharmacy	+49 22833	
Electronic locking service	+49 116 116	(e.g. lock lost credit card)

Map

A map with the points of interest during your stay at the conference is available for your smart phone by scanning the QR code on the side. Alternatively, you can find the map at the following URL:
`http://l.ead.me/barQhu`

9^{00}–10^{00} Registration

10^{00}–10^{10} **Welcome**
Carolin Körner · FAU Erlangen-Nürnberg, Germany

Technologies

Chair: Ryan Dehoff

10^{10}–10^{40} **The Hybrid Process Approaches for Electron Beam Selective Melting** Keynote
Feng Lin · Tsinghua University, China

10^{40}–11^{10} **High Power 6 kW EBM Machine and Supporting Technologies - JEOL's Challenge** Keynote
Yohsuke Yoshinari · JEOL Ltd., Japan

11^{10}–11^{30} **A.T.H.E.N.E. - Expanding the Potential of SEBM through Improved Electron Beam Technology**
Fuad Osmanlic · FAU Erlangen-Nürnberg, Germany

11^{30}–11^{50} **Laser Heated Electron Beam Gun Optimizaton to Improve Additive Manufacturing**
Ralf Edinger · Canmora Tech, Canada

11^{50}–12^{10} **Surface Texture Optimization of Additive Manufactured Components: Surface Finishing of AM-metal Components for Optimal Mechanical Performance**
Agustin Diaz · REM Surface Engineering, United States

12^{10}–13^{10} Lunch

Materials I

Chair: Mohsen Seifi

13^{10}–13^{40} **Electron Beam Melting for the Production of Titanium Aluminides Alloys** Keynote
Sara Biamino · Politecnico di Torino, Italy

13^{40}–14^{00} **Processing Fe_3Al based Iron Aluminides via SEBM - Processing Window, Microstructure and Properties**
Lucas Adler · FAU Erlangen-Nürnberg, Germany

14^{00}–14^{20} **Electron Beam Melting of Non-rare-earth MnAl-C Permanent Magnets**
Vladimir Popov · Technion - Israel Institute of Technology, Israel

14^{20}–14^{40} **Impact of Artificially Generated Imperfections on Very High Cycle Fatigue (VHCF) Behaviour of EBM Manufactured Specimens**
Philipp Drescher · Rostock University, Germany

14^{40}–15^{00} Coffee Break

Simulation & Steel

Chair: Martin Franke

15^{00}–15^{20} **Numerical Prediction of Grain Structure Evolution during Additive Manufacturing**
Johannes Köpf · FAU Erlangen-Nürnberg, Germany

15^{20}–15^{40} **Mechanical Modeling of SEBM Manufactured Material: Tailored Grain Structures and Nonlocal Crystal Plasticity**
Andreas Kergaßner · FAU Erlangen-Nürnberg, Germany

15^{40}–16^{00} **Investigation on the Composite Distribution with Keyhole and Molten Pool Dynamics Behavior Simulation in Additive Manufacturing of FGMs**
Wenjun Ge · Guangdong University of Technology, China

16^{00}–16^{20} **EBM Processing of Weak-textured and Defect tolerant Material – A New Alloy Design Approach**
Johannes Günther · University OF Kassel, Germany

16^{20}–16^{40} **Selective Electron Beam Melting of Austenitic Stainless Steels**
Alexander Kirchner · Fraunhofer IFAM, Germany

16^{40}–17^{00} **Microstructure and Nanomechanical Behavior of Modified 316L-based Materials Fabricated using EBM**
Carlos Botero · Mid Sweden University, Sweden

Poster Session

17^{00}–19^{00} Poster Presentation and Light Refreshments

Impression: Poster Session at EBAM 2016

Powder

Chair: Akihiko Chiba

9:00–9:30 **Surface Chemistry of Powder for Additive Manufacturing and its Changes during EBM Processing** — Keynote
Eduard Hryha · Chalmers Unversity of Technology, Sweden

9:30–9:50 **The Influence of Raw Powder to the Microstructure of a Nickel-based Superalloy GH4099 Processed by Electron Beam Melting**
Hui Peng · Beihang University, China

9:50–10:10 **Comparison of IN718 Powders from Different Producers in EBM**
Markus Uhlirsch · Swerea KIMAB, Sweden

10:10–10:30 **The Effect of Particle Size Distribution on Powder Thermal Diffusivity and Parameter Selection in Electron Beam Selective Melting Proccesses**
Di Cui · EPFL, Switzerland

10:30–10:50 **Computational Modelling of Powder Flow in Metal Additive Manufacturing Systems**
Gary Delaney · Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia

10:50–11:10 Coffee Break

Materials II

Chair: Ulf Ackelid

11:10–11:40 **Exploration of Preheating Temperature Control Techniques for Simultaneously Removing Residual Stresses and “Smoke” in Additive Manufacturing with Electron Beam Melting (EBM)** — Keynote
Akihiko Chiba · Tohoku Univeristy, Japan

11:40–12:00 **Microstructure and Mechanical properties of EBM processed High and Low Carbon Co28Cr6Mo Before and After HIP’ing**
Fouzi Bahbou · Arcam AB, Sweden

12:00–12:20 **Fabrication of WC/Co Hard Alloy using Electron Beam Melting**
Chao Guo · QuickBeam Tech. Co., Ltd., China

12:20–12:40 **Pure Copper Processed by Electron Beam Melting (EBM) Technology for Industrial Applications**
Luis Portoles · AIDIMME, Spain

12:40–13:40 Lunch

Process

Chair: Lars-Erik Rännar

13^{40}–14^{10} **Understanding and Exploiting Variability in Electron Beam Melted Components** — Keynote
Sam Tammas-Williams · The University of Sheffield, Great Britain

14^{10}–14^{40} **Utilization of In-Situ Process Monitoring, Process Modeling and Data Analytics for Materials Development** — Keynote
Ryan Dehoff · Oak Ridge National Laboratory (ORNL), United States

14^{40}–15^{00} **In-Process EBM Monitoring with Electronic Imaging**
Hay Wong · University of Liverpool, Great Britain

15^{00}–15^{20} **Energy and Charge Transport during Pulsed Electron Beam Melting**
Paul Carriere · McGill University, Canada

15^{20}–15^{40} Coffee Break

Titanium

Chair: Sara Biamino

15^{40}–16^{10} **Multi-Scale Microstructural and Mechanical Characterization of EBM Titanium Alloys for Critical Applications** — Keynote
Mohsen Seifi · ASTM International / Case Western Reserve University, United States

16^{10}–16^{30} **Mechanical Properties of Ti-6Al-4V Octet Truss Lattices Fabricated via EBM**
Abbas Moftakhar · University of Virginia, United States

16^{30}–16^{50} **Enhancing the Fatigue Properties of EBM Ti-6Al-4V Thin Parts: Effect of Various Post-Treatments**
Rémy Dendievel · Université Grenoble Alpes, France

16^{50}–17^{10} **Wire-based Additive Manufacturing of Ti6Al4V using Electron Beam Welding**
Norbert Enzinger · Graz University of Technology, Austria

17^{30}–19^{00} **Social Event**
Guided Historical Tram Ride from the Conference Venue to the Dinner Location

19^{00}–22^{00} **Conference Dinner**
Zum Spießgesellen, Rathausplatz 4, 90403 Nuremberg

Simulation

Chair: Matthias Markl

9^{00}–9^{30} Towards Simulation-based Thermal Management for Metal Additive Manufacturing **Keynote**
Vasily Ploshikhin · University of Bremen, Germany

9^{30}–10^{00} An Efficient Approach for Solving the Time-dependent Heat Equation with a Moving Gaussian Beam Source **Keynote**
Anders Snis · Arcam AB, Sweden

10^{00}–10^{20} Three-dimensional Thermomechanical Simulation of Electron Beam Melting Processes for the Melt Pool Geometry Prediction
Manuela Galati · Politecnico di Torino, Italy

10^{20}–10^{40} Prediction and Optimization of Powder Bed Manufacturability
Mustafa Megahed · ESI Group, Germany

10^{40}–11^{00} Coffee Break

Superalloys

Chair: Eduard Hryha

11^{00}–11^{30} Processing Nickel-based Superalloys by Electron Beam Melting **Keynote**
Martin Franke · Neue Materialien Fürth GmbH, Germany

11^{30}–11^{50} Cracking Mechanism in a Non-weldable Gamma Prime Precipitation-strengthened Nickel-base Superalloy Processed by Electron Beam Melting
Bo Chen · Coventry University, Great Britain

11^{50}–12^{10} Hot Cracking Mechanism Affecting a Non-weldable Ni-based Superalloy Produced by Selective Electron Beam Melting
Guilhem Martin · Université Grenoble Alpes, France

12^{10}–12^{30} Fatigue Properties of EBM built Alloy 718 – Effect of As-built surface and HIP
Arun Ramanathan Balachandramurthi · University West, Sweden

12^{30}–12^{50} Effect of Heat Treatment and Hot Isostatic Pressing on Oxidation Behavior of EBM-additive Manufactured Alloy 718
Esmaeil Sadeghimeresht · University West, Sweden

12^{50}–13^{00} Concluding Remarks

13^{00}–14^{00} Lunch

The Hybrid Process Approaches for Electron Beam Selective Melting

Keynote

Feng Lin [1,2,3,*], Bin Zhou [1,2,3], Jun Zhou [1,2,3], Ya Qian [1,2,3] and Hongxin Li [1,2,3]
(1) Department of Mechanical Engineering, Tsinghua University, Beijing, China
(2) Key Laboratory for Advanced Materials Processing Technology, Ministry of Education of China
(3) Biomanufacturing and Rapid Forming Technology Key Laboratory of Beijing
e-mail: linfeng@tsinghua.edu.cn

Electron beam selective melting (EBSM) possesses the advantages of high energy transition and absorption by variant material, high powder bed temperature to reduce thermal stress, high scan speed and high build efficiency. But the surface produced by EBSM is much more rough than that by SLM, particularly the inner surface, which is hard to be polished and limits EBSM to fabricate the channel or cavity structure, such as the cooling system in mold or turbine blades. So, hybrid approaches of combination variant processes have been proposed to improve the surface roughness. One approach is the combination of laser selective melting, called as EB-Laser hybrid selective melting (EB-LHM, Fig. 1), in which a laser beam is assigned to scan the outer and inner contour of the part section, and EB is assigned to fill the area of the part section. Due to the smaller focus spot of laser, EB-LHM could product more smooth surface of the part than EB, but still rougher than SLM in our current experiment. Therefore, a second approach based on the additive/subtractive hybrid strategy is proposed, called as EB hybrid manufacturing (EBHM, Fig. 2), in which EB contour cutting (EBCC) technique is applied after the EB selective melting the powder bed to form the part section. The EB gun will be redesigned to be able to work in both EBSM and EBCC modes, in which the EB scans the section contours with a much higher EB power and much faster speed than those of EBSM mode to ensure the material evaporation dominated and heat transfer limited.

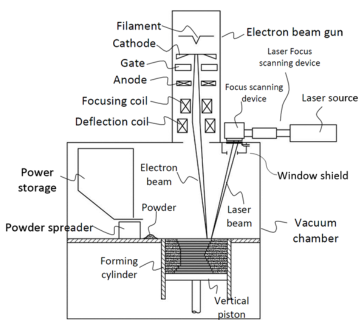

Figure 1: EB-Laser hybrid selective melting (EB-LHM).

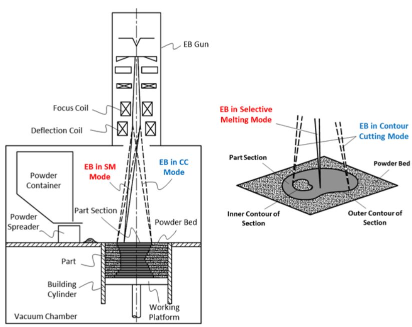

Figure 2: EB hybrid manufacturing (EBHM).

High Power 6 kW EBM Machine and Supporting Technologies – JEOL's Challenge

Keynote

Yohsuke Yoshinari [1,*]
(1) JEOL Ltd., 3-1-2 Musashino, Akishima, Tokyo 196-8558, Japan
e-mail: yoshinar@jeol.co.jp

Robust demand for high power machine of additive manufacturing (AM) has been gradually surfaced in the aim of better throughput of productions. One of the reasons would be due to the fact that AM technology is getting believed to have significant potential capable of replacing the existing production processes. Free-shaped and topologically optimized structures can be realized easily in AM, which contributes to reduction of costs in materials and secondary machining, also to shorten the development period. The AM machine by use of electron beam has demonstrated better performance than those of laser beam owing to the vacuum environment, the characteristic hot process and far better effectiveness of kinetic energy transformation to the internal heat. JEOL has been providing analytical instruments as well as industrial machines with electron beam (EB) technologies established for seven decades. Developing the electron microscopes to observe at atomic resolution, the electron beam lithography system to draw the incredibly dense integrated circuit and a few hundreds kilowatt strong EB gun, those accumulated knowledge of fine control of a variety of EB allowed us to start the development of high power EB machine for additive manufacturing. Supported by a japanese governmental project [1] since 2014, we have made efforts to launch 6kW EBAM machine and been trying to perform better AM work than ever. In this talk, an overview of our EB technologies and the specification of the 6kW EBAM machine will be briefly described. Our long-standing simulation technique for designing the electron optic system to best fit to AM, and a few more topics regarding manufactured parts and simulations for AM process parameters optimized with the use of an observed real EB profile would also be presented.

[1] Ministry of Economy, Trade and Industry, and New Energy and Industrial Technology Development organization (NEDO).

A.T.H.E.N.E. - Expanding the Potential of SEBM through Improved Electron Beam Technology

F. Osmanlic [1,*], C. Arnold [2], C. Pobel [1] and C. Körner [1,2]
(1) Friedrich-Alexander-Universität Erlangen-Nürnberg, Joint Institute of Advanced Materials and Processes, Dr. Mack-Straße 81, 90762 Fürth, Germany
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Selective electron beam melting (SEBM) is a process that enables the layered construction of complex metal components in a powder bed. Especially the stepless power control, the virtually inertia-free beam deflection and the absorption characteristic enable unique process control in beam-based additive production. These advantages provide the possibility for processing of various material classes such as copper, titanium alloys and high-temperature materials.

In order to expand this potential, an Arcam S12 was equipped with a new beam generator, deflection system, actuators and plant control system. The newly developed "A.T.H.E.N.E." machine offers a freely programmable beam guidance, a maximum power of 6 kW and electron optics. New melting strategies can be tested and process times reduced due to higher beam performance and control. Electron optics offer the possibility of in-situ melting surface analysis by taking non-reflective images in each layer. The newly implemented electron beam technology extends existing process windows, increases process stability and enables in-situ quality control.

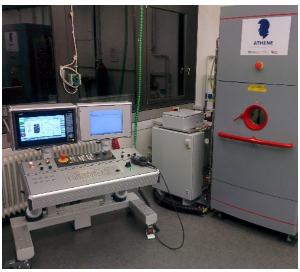

Figure 1: A.T.H.E.N.E.

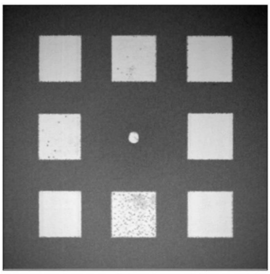

Figure 2: Electron-optical recording of a single layer.

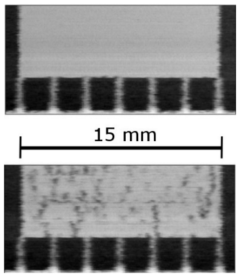

Figure 3: Cross section through specimen body reconstructed from images.

Laser Heated Electron Beam Gun Optimization to Improve Additive Manufacturing

R. Edinger [1,*]
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Electron Beam Additive Manufacturing (EBAM) is melting individual layers, which added together will result in a 3-dimensional part requiring many hours of continuous electron gun operation. As a result, the electron beam gun is exposed to thermodynamic loads, gas back spattering and process related variations which must be considered to improve part accuracy. Discussed will be solutions to improve systematic cooling and initial ideas to reduce cathode degradation during the melting process. Changes in the cathode emission impacts electron energies therefore changing beam deflection and focusing accuracy and repeatability. In addition to optimizing the machine hardware we will discuss dynamically adjusting control loops modifying process parameters based on an Open Source Additive Manufacturing platform/software. We like to thank the EBM facility at McGill University in Montreal and the new established UBC - Electron Beam Learning Factory at the University of British Columbia in Vancouver for supporting our work.

Figure 1: Early innovator McGill University, Montreal with small chamber LASTRON EBM facility.

Figure 2: New established UBC - Electron Beam Learning Factory at The University of British Columbia, Vancouver with a 11,000-liter vacuum chamber.

Surface Texture Optimization of Additive Manufactured Components: Surface Finishing of AM-metal Components for Optimal Mechanical Performance

Agustin Diaz [1,*], Lane Winkelmann [1] and Justin Michaud [1]
(1) REM Surface Engineering, 2107 Longwood Dr, Brenham, TX 77833 USA
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There is an undeniable growing demand for additive manufactured (AM) metal components in the aerospace and medical devices industries. However, the intrinsic rich surface texture of the AM-built components is still a significant problem. AM-built components show surfaces packed with multiple layers of partially melted/sintered powder, v-notches and significant surface and near-surface porosity. These defects hamper the mechanical performance of the AM-built component, causing early failures under mechanical stress. In order to be approved for aerospace or biomedical applications, the mechanical properties of these components need to be improved. This could be achieved by subjecting the AM-built components to a surface finishing process that removes the surface and near-surface defects, which should significantly improved the mechanical performance of the part [1]. With the intention of achieving a defect-free AM-built component, the R&D department at REM Surface Engineering is working towards a new program based on their already existing technology ISF® (isotropic superfinishing) Process, called the Extreme ISF® Process (see Fig. 1, p. 18).

This process has demonstrated to be one of the best approaches to surface finish AM-built components, because it significantly reduces their surface texture and improves their mechanical properties [2, 3]. In general, the process is based on the chemical activation of the surface, creating a weak self-assembled conversion coating that is easily removed by a mechanical stimulus in a vibratory finishing bowl. In this presentation, we will discuss in details how the Extreme ISF® process works, and how it overcomes the challenging surfaces that characterize AM-built components. The process has been shown to improve the surface of complex components, removing the partially melted/sintered metal particles from the surface, and improving tensile strength [2] and bending fatigue [3]. In addition, we will also discuss the best methods for the characterization of AM-built surfaces using surface texture parameters that show a closer correlation with the dynamic mechanical performance of the components. In this presentation, the attendees will learn the best-practices on surface texture characterization and surface finishing optimization to improve mechanical performance of AM-bilt components.

[1] J. Tong, J., C.R. Bowen, J. Persson and A. Plummer (2016) *Mater. Sci. Technol.* **Vol.**(33), pp. 138-148.
[2] A. Diaz, L. Winkelmann, J. Michaud and C. Terrazas (2016). *World PM2016 Proceedings.*
[3] D. Witkin, D. Patel, H. Helvajian and A. Diaz (2018) *Manuscript in Preparation.*

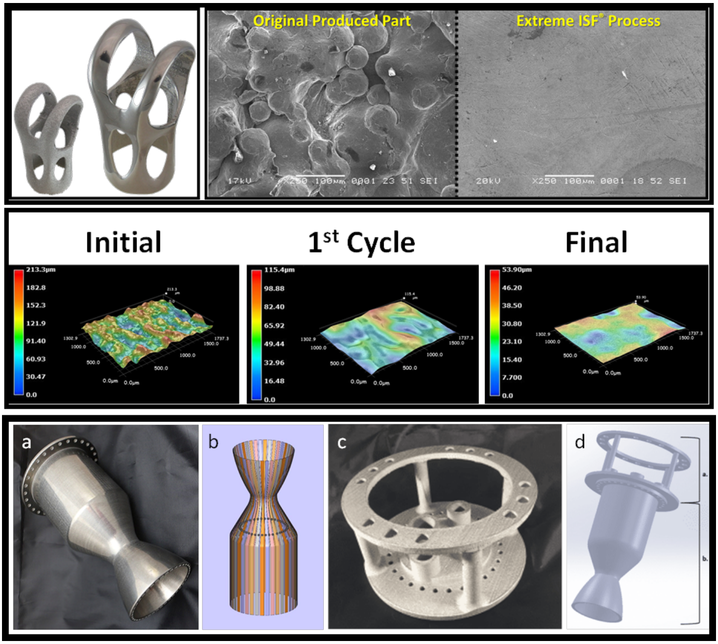

Figure 1: ARCAM A2X Ti-6Al-4V bike seatpost before and after the Extreme ISF® Process (top left) and the SEM image of the surface before and after finishing (top right). Optical microscopy 3-D images of the bike seatpost surface as-built and the subsequent surface after the first and final cycle of the Extreme ISF® process (middle). ARCAM A2X Ti-6Al-4V Rocket Nozzle surface-finished by the Extreme ISF® Process (a-bottom) and the STL showing the cooling internal channels (b-bottom); Ti-6Al-4V Injector Assembly (ARCAM Q20+) (c-bottom) and CAD Model of the full Rocket Assembly with the Injector and Rocket Nozzle (c-bottom). In collaboration with AddAero Mfg.

Electron Beam Melting for the Production of Titanium Aluminides Alloys

Keynote

Sara Biamino [1,*], Giorgio Baudana [1], Gloria Basile [1], Mariangela Lombardi [1], Daniele Ugues [1] and Paolo Fino [1]

(1) Department of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

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γ-TiAl materials represent an important class of structural materials and, due to their unique properties, recently are playing an important role in the aerospace and automotive industry. In particular, the low density of titanium aluminides makes their specific properties extremely interesting and comparable to those of nickel-based superalloys. High specific strength, stiffness and creep as well as corrosion and oxidation resistance are some of the attractive properties characterizing γ-TiAl materials. Despite these good properties, these alloys display some drawbacks such as low values of ductility and fracture toughness as well as sensitivity to contamination that make the component manufacturing methods quite difficult. Speaking about extrusion and forging, special chemical compositions have been developed in order to increase the high temperature ductility. On the other hand, concerning casting technologies several efforts have been made increasing the efficiency of mold injection, avoid contamination from the mold and recycling of scraps. Additive Manufacturing (AM) represents a promising alternative for the processing of TiAl alloys, particularly in the aerospace industry. Among the AM technologies, Electron Beam Melting (EBM) is the most suitable for TiAl because it is an hot process carried out in high-vacuum and this, respectively, reduces the residual stresses in the material thus avoiding crack formation and avoids impurities pick-up. The activities carried out at Politecnico of Torino are focused on four types of γ-TiAl alloys processed by EBM (48-2-2 alloy, TNM alloy, High Niobium alloy and RNT650 alloy) and regard the characterization and detection of residual defects such as porosity or microstructural dishomogenieties, understanding their cause and giving feedback for their reduction as well as the subsequent heat treatment optimization.

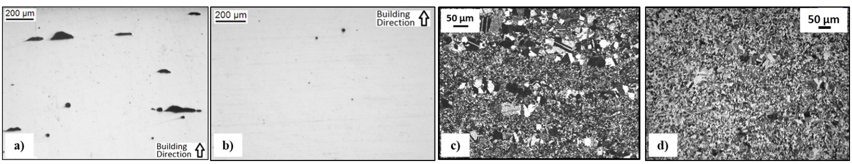

Figure 1: EBM process optimization: a) and b) pore reduction; c) and d) as-EBM microstructural homogeity increase.

Processing Fe_3Al based Iron Aluminides via SEBM – Processing Window, Microstructure and Properties

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Due to their outstanding resistance to oxidation and sulfidation iron aluminides are researched since the early 1930s [1]. In combination with the low costs of necessary elements Fe3Al based iron aluminides are promising candidates for high temperature application in hostile environments [2]. An inherent high hardness and a high brittle to ductile transition temperature of technical Fe_3Al based alloys rule out standard machining techniques for processing. The need for a near net shape processing technique for this class of intermetallics was found within the field of additive manufacturing. This contribution deals with the processability of iron aluminides using selective electron beam melting. Hereby density processing windows for a technical Fe_3Al based alloy with 28 at.% Al, 5 at.% Ti and 1.3 at.% B are provided. Furthermore, the resulting microstructure and Al content in dependency of the used melting parameters is discussed. Eventually room and high temperature properties of the first SEBM processed iron aluminides are presented.

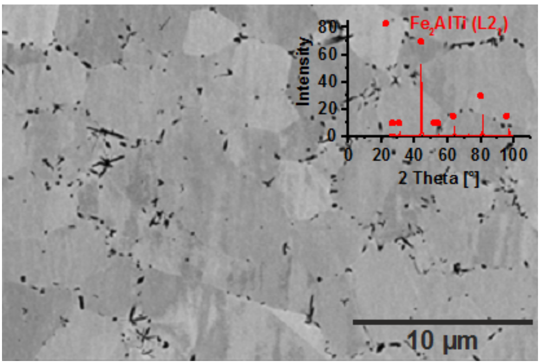

Figure 1: Microstructure of SEBM processed Fe28Al5Ti1.3B iron aluminide.

[1] C. G. McKamey, J. H. DeVan, P.F. Tortorelli, V. K. Sikka (1991) *Journal of Materials Research.* **Vol.**(6), pp. 1779-1805.
[2] M. Zamanzade, A. Barnoush, C. Motz (2016) *Crystals.* **Vol.**(6), pp. 1-29.

Electron Beam Melting of Non-rare-earth MnAl-C Permanent Magnets

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Vacuum environment and high temperature conditions of electron beam melting (EBM) additive manufacturing (AM) seem to be effective and suitable for permanent magnets (PM) production. However, until now no significant attempts to manufacture magnetic materials by EBM were reported.
It is known, that varying processing conditions in EBM it is possible to significantly vary the material microstructure [1], including producing metastable states. For example, successful manufacturing of bulk metallic glasses by EBM is already proven [2]. In such case all built area is kept at much lower temperature than usual processing temperatures (below glass transition point). These considerations point out to obvious possibilities for processing of PM.
Initial joint experiments were carried out to confirm prospects of the EBM-AM technology for PM production. Despite the not optimum process parameter settings, it was possible to manufacture solid Mn-Al-C samples for characterization. The future work will be focused on updating the powder compositions and optimization of EBM process parameters, aiming to reach optimal magnetic characteristics. Moreover, electron beam melting of the rare-earth magnets is in plan.
For EBM production of new Mn-Al printed samples, the modified table system with small round start platform was used. The diameter of start platform was 80 mm. The set of parameters used for electron beam melting was performed based on already known Ti-6Al-4V settings, because of close melting temperature of these materials. Build area during initial experiments was kept between 700 and 750 ℃. The examination of microstructure and magnetic properties show that EBM manufactured Mn-Al-C samples can reach the same coercivity as for sintered magnets.

[1] Koptyug A., Rannar L.-E., Backstorm M. and Shen Zh. (2017) *Materials Science Forum* **Vol.**(879), pp. 996-1001.
[2] Koptyug, A., Rännar, L., Bäckström, M. and Langlet, R. (2013). *I Proceedings from Additive Manufacturing & 3D Printing, Nottingham, UK, July 2013. Nottingham, UK.*

Impact of Artificially Generated Imperfections on Very High Cycle Fatigue (VHCF) Behaviour of EBM Manufactured Specimens

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Many components become loaded in the range of their conventional fatigue strength and reach lifetimes exceeding 10^8 cycles. Within this very high cycle fatigue (VHCF) regime the conventional fatigue limit is no longer valid [1]. Consequently, fatigue failure can occur beneath the classical fatigue strength whereby the crack initiation location is shifted from the surface to the interior of the specimen at different defect types like inclusions, pores, oxide layers or the microstructure itself.
Additively manufactured parts often have imperfections that result in the change of mechanical properties and fatigue behaviour. In order to understand the impact of such defects, EBM manufactured specimens with and without artificially generated defects were investigated. Different pore sizes in the center of the specimens were generated, with defect sizes of $\sqrt{area}$ = 150, 200, 300 µm. Analysis of the size and positioning of the pores were carried out with micro computer tomography (µCT). The impact of artificially generated imperfections on VHCF behaviour of the specimens were investigated.
The results show an increased fatigue strength of artificially generated defect samples. Further, the sizes of the fine granular areas (FGA) surrounding the defects are significant higher in the samples with artificially generated defects (see Fig.1). A defect size of below 200 µm lead to no clear crack initiation at the artificially generated defects specimen. Only larger defects resulted in a reliable subsurface crack initiation.

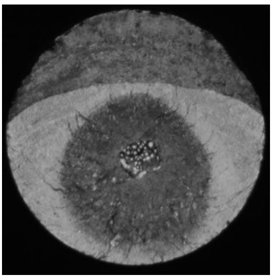

Figure 1: Specimens with artificially generated defect of $\sqrt{area}$ = 400 µm with formation of fine granular area (FGA) in VHCF regime surrounding defect type.

[1] C. Bathias (1999) *Fat. Fract. Eng. Mater. Struct.* **Vol.**(7), pp. 559-565.

Numerical Prediction of Grain Structure Evolution during Additive Manufacturing

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Powder bed fusion additive manufacturing is a production technique for near net shape fabrication of complex parts. The shape is generated layer wise by consecutively melting of powder in selected areas. The resulting microstructure depends strongly on the process parameters, like the beam power and scanning velocity. Exploiting this dependence for the manufacturing of tailored components requires time-consuming and cost-intensive trial-and-error experiments.
Numerical simulations enable the prediction of the microstructure resulting from specific process parameters, dispensing with the need for tedious calibration experiments. We present a 3D cellular automaton based model to simulate the grain structure evolution during powder bed fusion additive manufacturing. The predictive capabilities of the model were demonstrated in the recreation of the microstructure of an additively built component from IN718 using SEBM (Selective Electron Beam Melting). [1]
The model is applied to predict the resulting texture from specific scanning strategies. In addition, by analyzing the thermal conditions at the time of solidification, the evolution of individual grains is explained and the numerical determination of the optimal build parameters for a desired microstructure is supported.

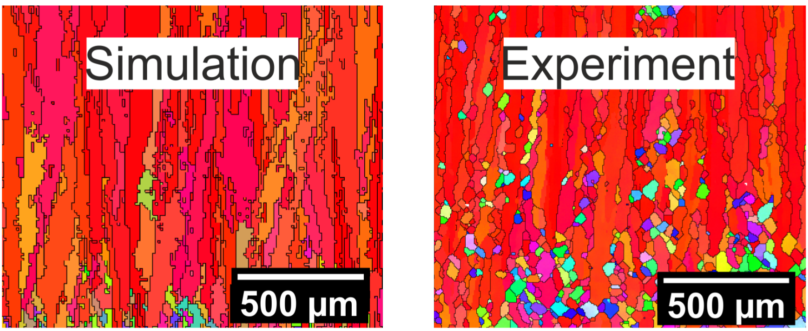

Figure 1: Comparison of numerical results and electron backscatter diffraction (EBSD) measurements in the bulk material of IN718-samples manufactured by SEBM.

[1] Koepf J, Gotterbarm M, Markl M and Körner C. *Multi-Layer Grain Structure Simulation of Powder Bed Fusion Additive Manufacturing, submitted to Acta Mat. 2018*

Mechanical Modeling of SEBM Manufactured Material: Tailored Grain Structures and Nonlocal Crystal Plasticity

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In selective electron beam melting an electron beam, guided by electromagnetic fields, is used to locally melt metal powder and build a part in a layer-wise manner. The electron beam allows for very fast deflections und various scan strategies. By using these scan strategies it is possible to tailor the resulting mesostructure in the material which may range from a columnar to an equiaxed grain structure. For altered grain structures, different macroscopic mechanical properties are expected. Long and similarly oriented grains cause highly anisotropic behavior. In contrast, a uniform grain structure results in isotropic mechanical behavior. The different orientations and the effects of grain size and boundaries strongly influence the macroscopic mechanical properties.
In this contribution, the mesoscopic material behavior is simulated by means of Finite Element simulations. A Voronoi tessellation based method [1] is used to model the grain structure of columnar grained Inconel 718. The resulting geometries for different scan strategies are taken into account. On the mesoscale, the thermo-mechanical behavior is modeled using a thermal gradient-crystal-plasticity model [2], accounting for relative misorientations on the grain boundaries with a formulation as given in [3]. Computational homogenization and macroscopic experimental data are used to inversely identify elastic and plastic temperature-dependent mesoscopic mechanical parameters. With this approach at hand, the macroscopic mechanical properties, such as the anisotropic Young's moduli and the yield surface, are modeled for varying grain structures.

[1] A. Kergaßner, J. Mergheim, and P. Steinmann (2016) *PAMM* **Vol.**(16), pp. 355-356.
[2] A. Kergaßner, J. Mergheim, and P. Steinmann (2016) *Proceedings of iCAT.*
[3] M. E Gurtin, L. Anand, and S. P Lele (2007) *Journal of the Mechanics and Physics of Solids* **Vol.**(55), pp. 1853–1878.

Investigation on the Composite Distribution with Keyhole and Molten Pool Dynamics Behavior Simulation in Additive Manufacturing of FGMs

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Functionally graded materials (FGMs) are a class of materials with properties that vary over one or more dimension by progressively changing the chemistry or microstructure with position. Additive manufacturing is a key enabling technology in the layer-by layer fabrication of metal FGMs with composite variations over large length scales. In this study, a 3D numerical model was proposed that uses the computational fluid dynamics (CFD) method to investigate molten pool formation and composite distribution towards electron beam melting and selective laser melting FGMs. In the numerical model, ray-tracing method was used to determine the electron beam and laser beam energy deposition in the powder bed model. The 3D mesoscale model revealed that it is possible to obtain different molten pool flow patterns, composite distribution and top surface morphologies using different process parameters. Detailed analysis of composition distribution was performed on the keyhole mode melting in selective laser melting. The simulation results of the molten pool characters were compared with experimental results and showed good agreement.

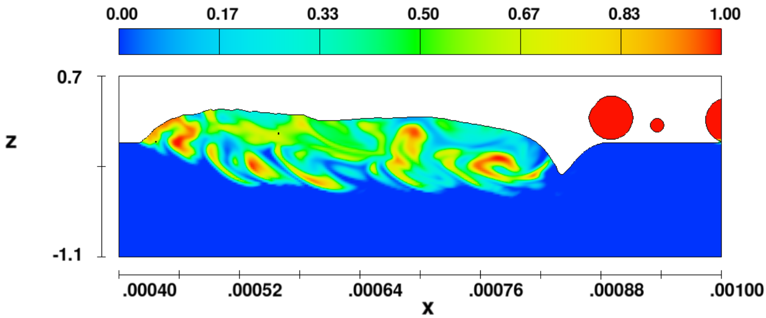

Figure 1: Composite distribution in the longitudinal section.

EBM Processing of Weak-textured and Defect-tolerant Material – A New Alloy Design Approach

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Besides the well-known advantages of additive manufacturing, i.e. the production of complex shaped components and efficient synthetization of advanced materials, powder-bed based processes such as Electron-Beam Melting (EBM) still face major challenges. The limited number of certified materials, the evolution of strong textures and corresponding anisotropy imposed by epitaxial grain growth upon layer-wise consolidation of the initial powder as well as process-induced defects are detrimental in terms of multi-axial static and cyclic loading.

In the current study these issues are addressed by presenting a new alloy designed for meeting the requirements set by current AM technologies. A metastable austenitic steel is introduced that shows a distinct solidification mode and due to the presence of multiple solid state transformations induced by process-inherent intrinsic heat-treatment in EBM an equiaxed fine grained microstructure develops. Moreover, the alloy shows deformation induced phase transformation yielding good mechanical properties despite the presence of large process-induced inhomogeneities. By controlling the process-parameters and the evaporation of volatile elements the deformation mechanisms and, thus, strength and ductility can be tailored for certain loading scenarios. For characterization X-ray diffraction, scanning electron microscopy and tensile testing have been employed. The presented alloy design could pave the way for a significant broadening of possible applications of powder-bed based AM components.

Selective Electron Beam Melting of Austenitic Stainless Steels

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Austenitic stainless steels are characterized by their high corrosion resistance, high toughness at cryogenic temperatures, strength at elevated temperatures, and good weldability. Thus, their typical application are in the food and chemical industry, marine and medical sector. 304L and 316L are among the most common grades. 316L contains more nickel and molybdenum for enhanced resistance to chlorides.
In this paper the selective electron beam melting (SEBM) of 304L and 316L is studied. Specifics of the SEBM process and the parameter window based on density are presented. In addition, characteristics of the metal powders used and their degradation by recycling are addressed. Metallographic investigation reveal grain and melt pool boundaries as well as a sub-grain cellular structure. Mechanical properties are characterized in build direction and perpendicular to it by tensile test. As-built material combines high strength with ductility.

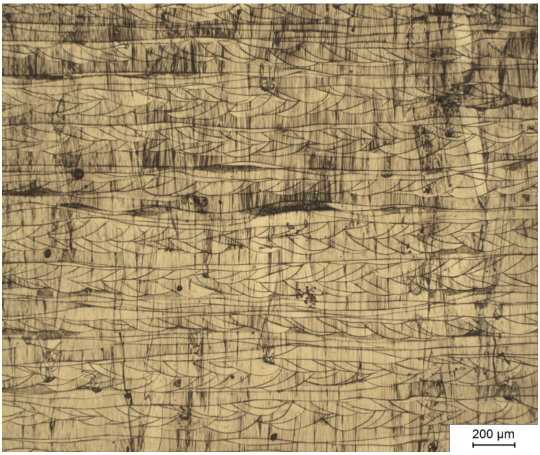

Figure 1: Microstructure of EBM-built 316L material.

Microstructure and Nanomechanical Behavior of Modified 316L-based Materials Fabricated using EBM

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(2) Department of Materials Science and Metallurgical Engineering, Universitat Politècnica de Catalunya, Campus Diagonal Besòs-EEBE, Barcelona, 08019, Spain
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Stainless steel 316L based materials modified by the additions of iron-based wear-resistant alloys (Colferoloy@ 103 and 139) used for thermal spray coatings applications were fabricated by EBM. Process parameters were tailored to fabricate compact specimens of 1cm^3 in an Arcam A2 (Arcam AB, Mölndal, Sweden) at Mid Sweden University. Microstructural features of the materials obtained were characterized by OM and SEM in polished and etched samples. Nanoindentation tests carried out at different penetration depths were performed on selected areas of the polished specimens to evaluate the materials micro/nano mechanical behavior and to establish correlations with the observed microstructure.

Surface Chemistry of Powder for Additive Manufacturing and its Changes during EBM Processing

Keynote

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Metal powders used for additive manufacturing are characterised by the large surface area that is about 10 000 times larger than the surface of the bulk material of the same mass. This results in high surface reactivity of the powder and hence high sensitivity to the powder handling and recycling. This is especially important in case of the complex alloys containing elements with high sensitivity to oxygen (Cr, Mn, Si, V, Zr, etc.) as Ni-base super-alloys, stainless steels, tool steels, as well as Ti- and Al-alloys, etc. In addition, taking into account harsh conditions during AM process, as for example long exposure of the powder to high temperature during EBM process, significant changes in the powder surface chemical composition take place. This strongly depends on the alloy composition and processing conditions and hence has to be taken into account to establish limits of powder recyclability. Hence, quality and usefulness of the powder for additive manufacturing (AM) are strongly determined by the surface composition of the powder. In particular, knowledge regarding amount of oxides, their composition and spatial distribution on the powder surface determines further powder recycling, see Figure 1, even though bulk oxygen content does not indicate any significant differences.
Paper provides an overview of the different methods for qualitative and quantitative analysis of the powder surface chemistry, such as surface-sensitive chemical analyses using X-ray photoelectron spectroscopy (XPS), Auger spectroscopy (AES), high-resolution SEM, thermal analysis, etc. Based on the experimental finding and thermodynamic simulation of the oxide stability for different systems, generic model of the oxide distribution and its changes during EBM processing is developed.

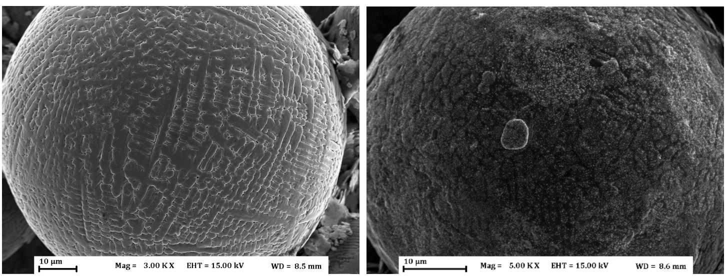

Figure 1: SEM micrographs of the Inc 718 before (virgin) and after (recycled) EBM process.

The Influence of Raw Powder to the Microstructure of a Nickel-based Superalloy GH4099 Processed by Electron Beam Melting

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Electron beam melting (EBM) is promising approach for fabricating nickel-based superalloys. A lot of recent work has focused on understanding the relationship between processing parameters and alloy microstructure, including both the weldable and non-weldable superalloys. However, although the non-weldable superalloys (e.g. Rene142 and CMSX-4) can always withstand higher temperatures than the weldable ones (e.g. Inconel 718), thermal stress induced hot cracks exist even under elevated preheating temperaures (e.g. 1000 ℃). It has now been acknowledged that weldable alloys are more friendly to the EBM process. In this work, a weldable nickel-based superalloy GH4099 was fabricated by EBM, aiming for the application temperature up to 900 ℃. Both plasma rotation electrode process (PREP) powders and argon atomized (AA) powders were used as raw material for comparative study. The results show that dense and crack-free samples can be produced by using both powders. However, the as-EBM samples exhibit different microstructure mainly due to the different processing parameters and the resultant thermal history. A volume fraction of γ' phase of ~20% can be observed in the PREP sample (Fig. 1b), which is higher than that of the AA sample (volume fraction of γ' phase still needs to be determined). Heat treatment and mechanical properties of the samples at 900 ℃ will also be concerned.

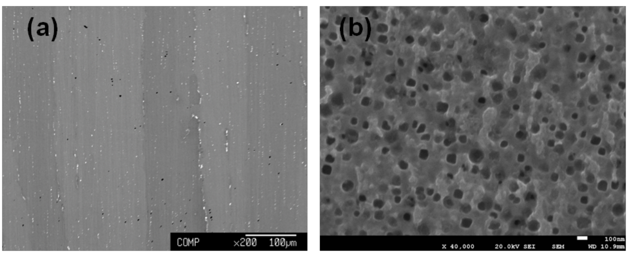

Figure 1: Columnar microstructure of the as-EBM GH4099 superalloy processed by using PREP powder (a); and the morphology of the γ' precipitates (b).

Comparison of IN718 Powders from Different Producers in EBM

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Electron beam melting (EBM®) is an additive manufacturing (AM) process which creates components by successive, partial melting of numerous thin layers of metal powders. The characteristics of the powders used have a significant impact on the spreading behavior and therefore on the density and homogeneity of the generated layers. Furthermore, the quality of the resulting powder bed strongly influences the properties of the manufactured parts. However, the same chemical composition of powders does not guarantee the same powder behavior, since the powder properties are significantly affected by its production and handling. [1]

Procuring powders from the AM machine manufacturer is accompanied by the lowest risk, but also by comparatively high costs. Hence, purchasing less expensive AM powders from other providers is aimed at. However, in many cases, the effects of a replacement are unknown.

For this study, three virgin Inconel 718 powders have been procured by the EBM machine manufacturer Arcam and two other suppliers. The feedstock is characterized inter alia by dynamic image analysis, funnel methods and a Revolotion Powder Analyzer. Subsequently, the powders are used to produce various test specimens in an Arcam EBM S12-AX machine. Both microstructural and mechanical analysis are carried out on the generated samples. Finally, the gained results are correlated to the powder properties and possible connections are discussed.

[1] J. Dawes, R. Bowerman and R. Trepleton (2015) *Johnson Matthey Technol. Rev.* **Vol.**(59), pp. 243-256.

The Effect of Particle Size Distribution on Powder Thermal Diffusivity and Parameter Selection in Electron Beam Selective Melting Processes

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Electron beam selective melting (EBSM) process utilizes an electron beam to induce fusion between powder particles layer by layer to build 3-dimensional parts. Although this method possesses various advantages by its nature, any unsuitable parameter in both the electron beam and powder aspects can generate defects such as lack of fusion, single track nonuniformity and inter-track voids, largely affecting quality of the as-built parts. Focusing on the powder factors, we find in experiments that powder with a smaller mean diameter generally has a lower thermal diffusivity. This phenomenon agrees with the simulation result that powder with a smaller mean diameter leads to a narrower single track with the same beam power, spot size, scanning speed, etc. We then incorporate the spread of particle size distribution (PSD) as well in analyzing the effect of PSD on powder thermal diffusivity and melting pool profiles by means of computational simulation and laboratory experiments. The results provide an important consideration for the selection of process parameters like powder layer thickness, hatch spacing, etc. by PSD of the powder, to help eliminate defects like single track nonuniformity and inter-track voids.

Computational Modelling of Powder Flow in Metal Additive Manufacturing Systems

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In powder-bed based metal additive manufacturing applications, the addition of the powder layers is the crucial first step in building up of the part in 3D and has a significant impact on final part quality. A common technique employed is to add successive layers of metal powder by raking a new layer across the existing surface. Understanding this raking process and how the properties of the powder particles (e.g. size, shape, density, interaction properties) and process parameters (e.g. height of powder layer, rake geometry, rake speed) affect the properties of the bed after raking is crucial in optimizing the performance of the system and ensuring the quality of the 3D-printed part. We will present results of a computational model of this raking process using the discrete element method (DEM). This model directly incorporates the powder's particle size distribution, particle shapes and experimental measurements of the powder flowability. We have applied this model to simulating raking of both Arcam Titanium powder and CSIRO Manipulated Titanium Powder and it is being applied in improving the performance of existing 3D powder-bed systems and exploring new rake designs and powder morphology combinations in order to deliver products with improved performance. We will also describe how this model fits within a complete modelling framework we are developing for the other key physical processes in powder based metal additive manufacturing including the transfer of energy from the laser or electron beam to the metal, the melting and solidification of the powder, the flow of liquid metal in the melt pool, the heat transfer from the melt pool to the surrounding powder and solid metal, the evolution of the microstructure of the component, and the residual stress and deformation of the component that result from the non-uniform heating and cooling.

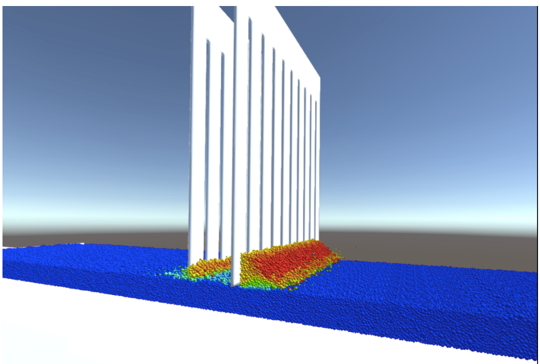

Figure 1: Discrete Element Method Simulation of the addition of a layer of metal powder via raking in a 3D printing device. Particles are coloured by velocity.

Exploration of Preheating Temperature Control Techniques for Simultaneously Removing Residual Stresses and "Smoke" in Additive Manufacturing with Electron Beam Melting (EBM)

Keynote

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Additive manufacturing with electron beam melting (EBM) is a process that produces components by selectively melting layers of metal powder from 3D CAD data. Compared to the laser beam additive manufacturing technique, EBM process has many advantages if we consider the processing speed, energy density, residual stresses after build, applicability to the metal powders with high melting temperatures such as Ta and W, and so forth. However, because the electron beam has a negative charge, the several complexities to control the EBM process stem from the negative charge of electron beam. For instance, so-called, "smoke" phenomenon of powder bed, or powder spreading due to electron beam irradiation, is an intrinsic problem in EBM process to be solved to expand the application of EBM process. Currently prevailed technique to prevent the "smoke" is to preheat the powder bed prior to proceeding the melting process. The preheating is effective for removing the residual stresses accumulated during layer by layer melting processing. Too much higher temperatures for preheating, however, causes for solid-sintered powder bed (SSPB), responsible for the difficulty in removing the un-melted powder from the parts. Thus, the preheating temperature, depending on the powder used, is normally determined by considering the lowest temperatures at which the "smoke" does not occurs.
In this paper, the factors to influence the "smoke" is investigated to pursue the possibility to optimally control the preheating temperature for simultaneously removing the residual stresses and SSPB from the parts without occurring "smoke" during the building process. At the beginning of the talk, the recent progress of Japan's TRAFAM project will be introduced. Electrical resistivity of the powders is thought to be related to the susceptibility to the "smoke". We systematically measured the electrical resistivity of the various powders (Inconel 718, Ti alloy, Fe-C steel, Cu, Al alloy, etc.) and have established the relationship between smoke and electrical resistivity of the powders. It is found that the powders having lower electrical resistivity exhibit no "smoke" without preheating.

Microstructure and Mechanical Properties of EBM Processed High and Low Carbon Co28Cr6Mo Before and After HIP'ing

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Co28Cr6Mo material is commonly used for orthopedic implants; carbon content is specified to max. 0,35% which leads to carbide precipitation in the EBM as built condition thus requiring additional homogenization heat treatment to dissolve those precipitates to achieve more ductile material. The aim of this study is to test a material with extremely low carbon content and to evaluate whether the ductility can be improved already in the as built condition so that the HOM treatment can be avoided.
Microstructure is evaluated in both optical microscope on etched samples and in SEM microscope with EDS elemental mapping as well as XRD phase analysis. Mechanical properties are evaluated through tensile testing and hardness measurements.
Preliminary results show that the decrease of carbon content in the CoCrMo material seems to slightly improve the ductility of the EBM built material while the HIP treatment improves it significantly for both high and low carbon content by transforming the brittle ε-phase into a ductile γ-which seems to be the reason behind brittleness in as built condition. The columnar structure is also recrystallized into equiaxed structure and carbides are dissolved into the matrix. HIP treatment is also effective in closing pores and cracks. It seems that the HOM treatment is not needed to fulfill the ASTM F75 requirements.

Fabrication of WC/Co Hard Alloy using Electron Beam Selective Melting

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The traditional powder metallurgy method for building hard alloy parts has some disadvantages, such as long process flow, high energy consumption, difficult to form complex shapes. The Electron Beam Selective Melting (EBSM) additive manufacturing technology was used to fabricate the hard alloy in this study. To obtain the spherical powder suitable for additive manufacturing, the WC+20% Co powder for powder metallurgical purposes was treated by plasma spheroidization method. The samples were built layer by layer using a commercial open-source EBSM machine (QbeamLab) developed by QuickBeam company of China. Benefit from the high building temperature during the EBSM process, crack-free samples can be successfully fabricated. Because of the evaporation in vacuum, the Co content was reduced to about 11.5%. The density of the samples was about 13.9 g/cm^3 and the hardness was about 83 HRA, which are comparable to the properties of W +11%Co hard alloy formed by powder metallurgy method. The research shows that the EBSM is a potential feasible additive manufacturing technology to directly build hard alloy parts.

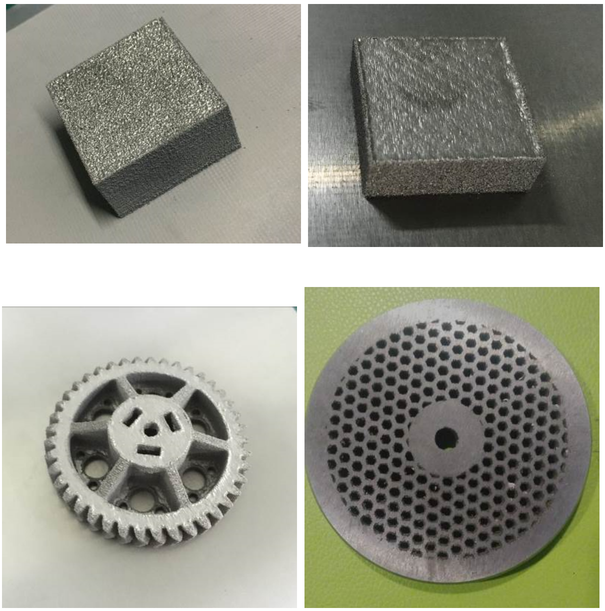

Figure 1: WC/Co hard alloy samples and parts fabricated by EBSM.

Pure Copper Processed by Electron Beam Melting (EBM) Technology for Industrial Applications

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The technology Electron Beam Melting (EBM) was developed and patented by the company Arcam AB, which launched the first industrial equipment to the market on 2002. This technology enables to melt metal powders for building parts with near full density from a 3d file. The powder is processed in a vacuum chamber reaching values of temperature close to 50% of the melting point of the metal alloy. Most common materials ready for the market are Ti6Al4V, Ti6Al4V ELI, Titanium Grade 2 and Cobalt Chromium ASTM F75. A wider range of materials suitable to be processed shall allow expanding the industrial applications of this technology.

AIDIMME has been researching on the development of the process parameters setup for processing pure Copper by means of EBM. This research was done along the last 3 years for a specific and patented industrial application [1]: Induction heating. Induction heating is the process of heating an electrically conducting object (usually a metal) by electromagnetic induction. Induction heating allows the targeted heating of an applicable item for applications including surface hardening, melting, brazing and soldering and heating to fit.

During this research, not only basic properties were analyzed such as microstructure, thermal and electrical conductivity, and hardness; if not others for an industrial scale application were considered such as powder reusability, results reproducibility and technical specifications achievement. Results about this research will be exposed. Taking the advantages of Electron Beam Melting with a material with a high thermal/electrical conductivity, there is a huge horizon for expanding these results to other industrial applications moreover of the initial one.

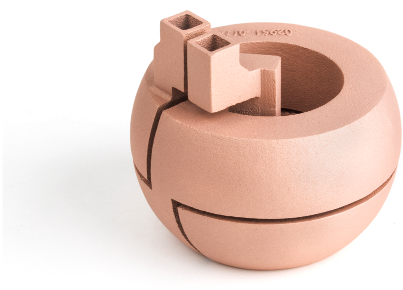

Figure 1: Induction coil of pure Copper processed by AIDIMME with EBM (courtesy of GH Induction).

[1] Patented by GH Induction

Understanding and Exploiting Variability in Electron Beam Melted Components

Keynote

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Material and components produced by electron beam melting (EBM) often contain some level of unintentional variation, in microstructure, defect population and mechanical properties. While stochastic variation has obvious negative consequences when trying to qualify AM material, often what at first sight appears random, simply requires a deeper understanding of the manufacturing process in order to untangle the underlying relationships. Here, we will demonstrate how advanced characterisation techniques, both in-situ and ex-situ, can shed new light on why these variations occur. In addition, we will show how manufacturing processes can be altered to generate structures with changes in property built in.

Utilization of In-Situ Process Monitoring, Process Modeling and Data Analytics for Materials Development

Keynote

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Metal additive manufacturing processes, including the electron beam melting (EBM) technology developed by Arcam, have demonstrated the ability to fabricate complex geomety components with microstructures and mechanical properties suitable for many applications. The final properties of these components are directly linked to both the solidification dynamics and solid state phase transformations which play a significant role in the development of the final material state. Both of these phenomena are governed by the thermal profile, and subsequently the processing parameters utilized during the build. In an attempt to unify material quality and achieve isotropic material properties, Arcam has developed a proprietary algorithm to adjust the processing conditions and control the energy input during the process. Although many of the parameters such as beam power, beam speed and preheat temperature are obvious, there are many lesser known parameters that can significantly affect the build quality and resulting microstructure, mechanical properties, and final performance of the part. In addition to processing parameters, the scan strategies and infill patterns used to deposit material can also play a major role in microstructure and defect evolution. This talk will discuss in-situ process monitoring approaches to understand the unique scan strategies and infill patterns that have been developed, modeling of the EBM process, and the resulting microstructures and mechanical properties. The scan strategies utilize individual spots instead of lines or vectors to melt the material and can be used to control solidification dynamics in the material to create both columnar and equiaxed grains.

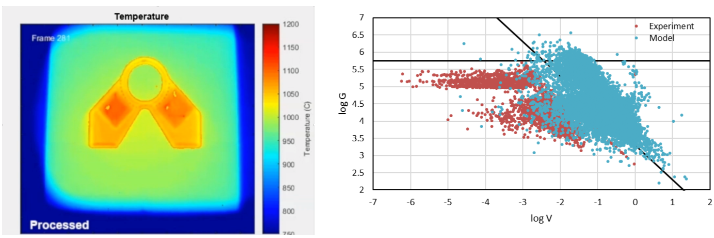

Figure 1: In-situ thermal image of an EBM component with the ability to measure key solidification parameters to predict microstructure. Comparison of the experiments to process models [1].

[1] Raplee et. al. (2017) *Scientific Reports* **Vol.**(7), 43554.

In-Process EBM Monitoring with Electronic Imaging

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Electron Beam Melting (EBM) is an increasingly used Additive Manufacturing (AM) technique by many industrial sectors. The application of this technology is, however, challenged by the lack of process monitoring and control systems to guarantee process repeatability and part-quality reproducibility. Monitoring techniques involving Infrared (IR) and optical cameras have been employed in previous attempts to study the quality of the EBM process. It is believed that these systems lack flexibilities in Field of View (FOV), pixel resolution, magnification and imaging time whilst the images generated suffered from keystone-distortion. In this study, a digital electronic imaging system prototype was put together and served as an alternative monitoring technique. Digital electronic images were generated with the use of Secondary Electrons (SE) and Backscattered Electrons (BSE) originated from interactions between the machine electron beam and the processing-area. Prototype capability verifications under room temperature and elevated temperatures were conducted and digital images with a range of FOVs, pixel resolutions and magnifications were generated. It is believed that this system prototype has the potential to be used for EBM in-process monitoring and closed-loop control.

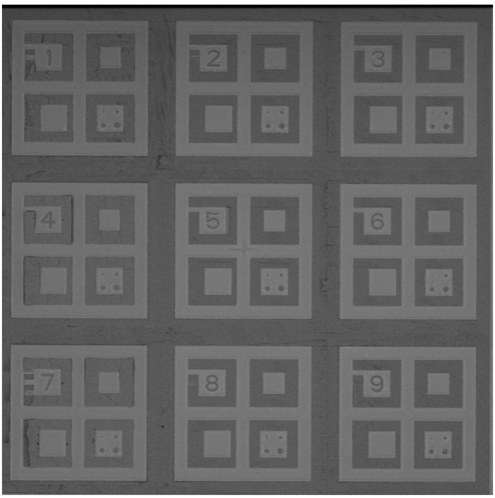

Figure 1: Electronic image showing contrast between Ti-6Al-4V melted surface and sintered powder under room temperature.

Energy and Charge Transport during Pulsed Electron Beam Melting

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The relationship between energy and charge transfer is experimentally investigated during pulsed electron beam melting of commercially pure Titanium in both the solid and powdered state. These measurements are conducted at V_{acc}= [60,80]kV, and I_b= [4, 8, 16]mA and Focus Offset = [-36,-33,. . . +33,+36]mA using high temperature fixturing instrumented as a Faraday Cup. A single layer powder deposition technique is presented, enabling experiments on both loose and semi-sintered powder with layer heights of 140µm and packing densities of 40-50%, as characterized using coherence scanning interferometer. The Faraday Cup measurements demonstrate the formation of a current which opposes the incident beam, and is dependent on both the beam irradiance [W/mm^2] and fluence [J/mm^2]. We attribute this signal to evaporation and ionization of the workpiece, with powdered material evaporating strongly compared to solid. A relationship between the counter-current and melt ball formation is also observed, suggesting that the associated vapor recoil pressure affects the wetting characterisitics. Pulsed melting of loose, room-temperature powder suggests this ionization current neutralizes some electrostatic powder charging. This measurement technique represent a new, low-cost method to characterize electron beam melting, following similar work on single layer laser powder melting.

Multi-Scale Microstructural and Mechanical Characterization of EBM Titanium Alloys for Critical Applications

Keynote

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In order to integrate additively manufactured materials to leverage their ability to produce novel lightweight designs for structural and high temperature applications, microstructureal and mechanical behavior of AM materials and components must be fully assessed and understood. AM of titanium alloys (e.g. Ti-6Al-4V, TiAl) is of particular interest due to their increased implementation in aerospace applications. While preliminary microstructural evaluations and quasi-static tensile properties extensively have been reported for some alloy systems, detailed microstructural characterization, damage tolerance and fatigue performance measurements are often more difficult, time consuming, costly and less reported. This work reports extensive microstructural characterization including texture, defect morphology/distribution, and multi scale mechanical behavior (e.g. tensile, fracture toughness, fatigue crack growth) of Ti alloys made with different vintages of EBM machines in both the as-deposited and post-processed conditions. Post thermal treatment (e.g. HIP and Heat Treatment) reduced materials hetrogenetity and anaistotropy to some extent but not completely. Evolving ASTM/ISO standards for additively manufactured materials were used to determine the location/orientation specific properties using standard and miniaturized scales specimens. Previous results obtained with the earlier generation of EBM machines exhibited anamolies at various build locations while latest generation of EBM machines demonstrated quality improvements. This overview will also capture some of the key considerations for AM materials qualification and standardization.

Mechanical Properties of Ti-6Al-4V Octet Truss Lattices Fabricated via EBM

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The octet truss lattice has attracted considerable recent interest since it is structurally more efficient than foams of a similar density made from the same material. Many fabrication routes have been developed to make octet truss lattices, including investment casting [1], and snap-fit assembly [2]. In this work, two sets of Ti-6Al-4V octet truss lattices have been manufactured via electron beam melting (EBM) technique. Set I contains the parasitic node volume (Fig.1a) that is present in all octet truss lattices fabricated via the snap-fit assembly route [2]. The set II lattices have vanishing node volume (Fig.1a) with the ideal octet truss lattice topology as studied by Deshpande etc [1].

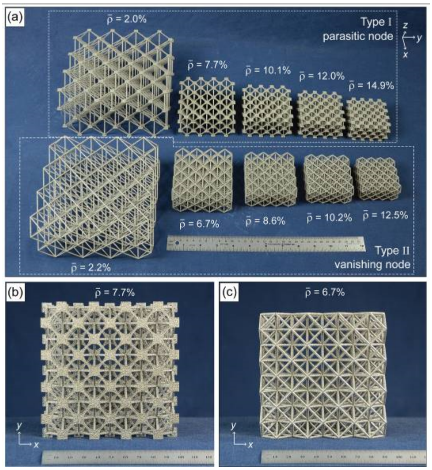

Figure 1: EBM fabricated octet truss lattices.

The two sets of octet truss lattices have identical strut aspect ratio (t/l), and using a strut length of 7-25mm results in a relative density of the lattices ranging from 2% to 15%. The ideal octet truss lattices (set II) have improved structural efficiency by minimizing the nodal mass and strut separations of the snap-fit lattice design (set I), and achieved 2% mass reduction at high relative densities compared with set I counterparts. Some of the lattices were tested in as the as-made condition while others were subjected to a thermo-mechanical treatment to remove internal pores and other defects of the EBM process. The lattice elastic stiffness constants and strengths have been characterized under through-thickness compression as a function of their relative density, and are shown to be well predicted by micromechanical models. The EBM fabrication route appears to be a promising manufacturing method for making octet truss lattices for high temperature applications where a robust mechanical performance is required.

[1] V.S. Deshpande, N.A. Fleck, and M.F. Ashby, (2001) *J. Mech. Phys. Solids.* **Vol.**(49), 1747-1769.
[2] L. Dong, V.S. Deshpande, and H.N.G. Wadley, (2015) *Int J Solids Struct.* **Vol.**(60), 107-124.

Enhancing the Fatigue Properties of EBM Ti-6Al-4V Thin Parts: Effect of Various Post-Treatments

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Designing structural parts including cellular or lattice structures fabricated by additive manufacturing is very promising. But applications will remain limited as long as long as the fatigue performances of such structures are not understood and controlled. The objective of this work is to study the fatigue properties of Ti-6Al-4V as-built thin parts produced by EBM. These thin parts represent the single beams constituting the lattice structures, for which finish machining is prohibited. Fatigue mechanisms have been first identified from cyclic tension-tension tests (constant stress amplitude R=0.1) performed on dog bone cylindrical specimens with an initial diameter of 2 mm. All the samples were systematically characterized by laboratory X-ray tomography before the fatigue test, revealing the characteristics inherited from the EBM process: porosity, plate-pile like defects, roughness . . . SEM and tomographic observations of the fracture surfaces reveal that crack initiation always occurs at the surface from thin and relatively deep (up to 200 µm) notch-like defects (figure 1). Fatigue performances of as-built samples are therefore rather low. Chemical etching, hot isostatic pressing as well as ultrasonic blasting have been performed. The effects of each of them on the fatigue properties are investigated and related to the "healing" of the aforementioned defects. Finally, adequate combinations of these post treatments are shown to significantly improve the fatigue performances.

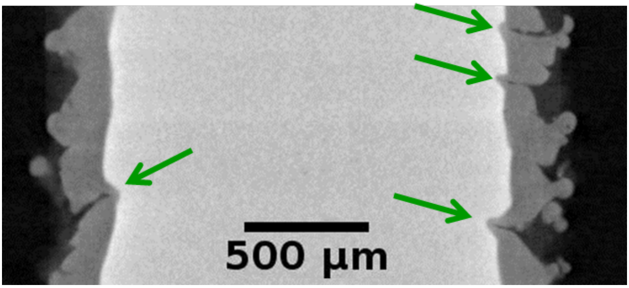

Figure 1: Notch-like defects present in the as-built struct (dark grey) and partially removed by chemical etching (light grey).

Wire-based Additive Manufacturing of Ti6Al4V using Electron Beam Welding

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Electron beam freeform fabrication is a wire feed direct energy deposition additive manufacturing (AM) process. This method enables a deposition rate higher than 200 cm^3/h using conventional welding consumables to create near net shape parts. The high vacuum atmosphere ensures an excellent shielding against atmosphere and enables processing of highly reactive alloys like titanium alloys.

In this work, the electron beam additive manufacturing (EBAM) technique was applied for the α-β-titanium alloy Ti6Al4V. First, the optimization of the machine settings for single bead-on-plate are considered. The identification of the correlation between dimensions and the dilution of single beads based on selected process parameters, leads to an overlapping distance in the range of 70-75% of the bead width, resulting in a multi-bead layer with a flat surface and a uniform height. The use of a layer dependent decreasing power input shows a quite linear growth rate. Stacking of layers with different numbers of tracks with a symmetric welding sequence allows the manufacturing of simple structures like blocks and walls. Microscopy investigations reveal that the primary structure consists of epitaxial grown columnar prior β grains, reaching over several layers with some random distribution of macro and micro pores. The final microstructure shows a very fine α-lamellar structure with a very likely presence of martensitic areas. A moderate hardness of 334 HV with small variations is observed in the AM part, whereas a hardness peak in the heat affected zone of the substrate plate is observed. Tensile testing of single sample shows a rather low elongation at fracture of 4,5% and a yield strength of 953 MPa. A subsequent heat treatment at 710 °C for two hours leads to an almost homogenous hardness and an increment of the elongation at fracture of 9,5%, with a decrease of the yield strength to 878 MPa. After heat treatment, the final microstructure consists mostly of a fine α-lamellar structure.

Towards Simulation-based Thermal Management for Metal Additive Manufacturing

Keynote

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This work represents simulation-based approach for optimization of thermal process by powder-bed metal additive manufacturing. The numerical analysis exhibits different ways to improve temperature distribution by appropriate changing of hatching sequence and part dependent regulation of layer exposure time.

An Efficient Approach for Solving the Time-dependent Heat Equation with a Moving Gaussian Beam Source

Keynote

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To minimize the amount of parameters used today for optimizing the electron beam melting (EBM) process new tools and approaches will be necessary. Detailed simulations are in many respects very efficient for understanding physical effects on a small scale and they provide valuable information of the local melting process. However, builds of today can be of length scale around 0.5 m. To control and verify the melt process for such large components new and very fast calculations have to be developed.
In this study an analytical approach for solving the time dependent heat equation with a moving Gaussian beam source is presented [1]. The approach can be used for any beam paths as long as the path can be divided into points or straight lines on which the beam parameters (speed, spot size and beam power) are constant over a specified time.
The approach is used for calculating thermal distributions generated from beam data obtained directly from the Arcam EBM machine controlling software EBMControl.
The calculations are very fast and the potential of using the approach as a tool for verification and processes optimization of complete builds is discussed

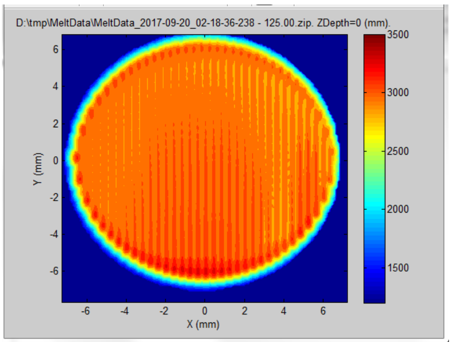

Figure 1: Calculated maximum surface temperature of a tensil rod.

[1] J. Bodenstam Malmberg and M. Wallenås (2012) *Master's thesis, "Solving the heat equation in connection with electron beam melting"*

Three-dimensional Thermomechanical Simulation of Electron Beam Melting Processes for the Melt Pool Geometry Prediction

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Due to the complexity of the physics, many finite element models presented in the literature for Electron Beam Melting simulations are considering thermal aspects only [1]. However, heat transfer may be affected by the change of the material properties during the melting and the cooling phases. Therefore, uncouple thermal models may not be well adapted for predicting the temperature distribution of the melt zone, and thus they may not be able to realistically calculate for instance melt depths and melt widths.
In this work, an improved but still rather simple computational analysis is presented for a more detailed prediction of heat transfer and melting pool geometries in the Electron Beam Melting process simulations. In particular, the work presents an up-to-date three-dimensional numerical local-scale model for a coupled thermo-mechanical analysis based on a numerical approach recently developed [2]. Nonlinearities due to the variation of material properties when the material melts are considered in the analysis. Particularly, temperature dependent mechanical coefficients are used to account for physical aspects such as: solid phase transformation, powder layer shrinkage during melting, thermal expansion and shrinkage of solid material during heating and cooling, and stress formation within the solid material. Representative simulations of single line melt tracks are performed, and a comparison between uncoupled thermal model, coupled thermo-mechanical model and experiments is carried out.

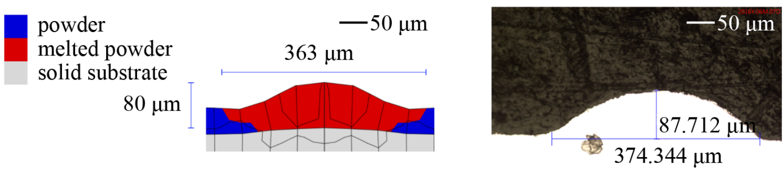

Figure 1: Cross section of the melted track: simulated (left) experimental (left).

[1] M Galati and L Iuliano (2017) *Additive Manufacturing.*
[2] M Galati, L Iuliano, A Salmi and E Atzeni (2017) *Additive Manufacturing.* **Vol.**(14), pp. 49-59.

Prediction and Optimization of Powder Bed Manufacturability

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Additive Manufacturing is an interesting manufacturing route for Aeronautics and Aerospace industries, that offers increased design flexibility and reduced material space. Due to the energy required during the additive manufacturing process the work piece undergoes distortions due to material shrinkage and phase transformations during cooling. Support structures are usually introduced to hold the work piece reducing distortions to a level that ensures work piece manufacturability. The design of support structures is very challenging: They must be sufficiently strong to withstand the residual stresses accumulated throughout the build process and yet they must be accessible and easily removed during post processing of the work piece.

In order to guide designers and prevent such process failures, efforts on simulation and modeling were focused on developing fast and accurate tools. Residual stresses of the as-built component are accurately predicted enabling improved planning of post processing steps. This paper will describe the modelling steps towards optimizing component orientation and support structure towards improved manufacturability. The tools' accuracy is evaluated by comparing the shape predictions with experimental scans. Alternative aspects such as supports relocation or optimized orientation are analyzed to support designers fine tuning their workpiece geometries.

Processing Nickel-based Superalloys by Electron Beam Melting

Keynote

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(2) Friedrich-Alexander-Universität Erlangen-Nürnberg, Chair of Materials Science and Engineering for Metals, Martensstraße 5, 91058 Erlangen, Germany
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Ni-based superalloys used for high temperature applications, e.g. power generation turbine blades and aerospace engine components, display complex chemical compositions designed for conventional manufacturing techniques like the investment casting process, forging and powder metallurgy processing (sintering). Both, alloys and techniques, are well established since several decades. In comparison, selective electron beam melting (SEBM) represents a new manufacturing process for Ni-based superalloys. SEBM reduces design limitations and can be used for repair applications by rebuilding worn-down areas from turbine blades. However, Ni-based superalloys used for high temperature applications like IN738LC and CM247LC are challenging for SEBM due to their chemistry. Superalloys exclusively designed for selective electron beam melting are not available so far. The current approach to process challenging Ni-based superalloys by SEBM is based on computer-aided parameter optimization (e.g. scan velocity, power, focus offset) and modifications of chemical composition. This contribution reveals both, computer-aided optimization tools and the impact of minor elements.

Cracking Mechanism in a Non-weldable Gamma Prime Precipitation-strengthened Nickel-base Superalloy Processed by Electron Beam Melting

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A non-weldable Ni-base superalloy was processed by electron beam melting (EBM). A range of processing parameters were developed to achieve desired microstructures. Microstructural characterisations were performed to provide quantitative information about grain size and shape, micro-texture as well as size and volume fraction of γ' precipitates. As-EBM samples exhibited a relatively homogeneous microstructures (e.g. γ' precipitates and columnar grain width) along the build z-direction (the total build height z=80 mm). There was no pores and lack-of-fusion defects in the as-EBM samples. These results are very promising in particular considering a recent work [1] which reported both inhomogeneous microstructures along the build direction and pores were found in a γ' precipitation-strengthened Ni-base superalloy processed by EBM. Nevertheless, the presence of intergranular cracks were observed in our as-EBM samples. Hot isostatic pressing (HIP) was applied to close these intergranular cracks, however reappearance of intergranular cracks was observed in heat treated EBM samples. These EBM post-processing induced intergranular cracks showed a much wider crack opening width and the crack density was much higher. The heat treatment was given to the HIPped samples to provide optimised shape of γ' precipitates. Although hot cracking mechanism as used in [1, 2] could be responsible for the presence of intergranular cracks in our as-EBM samples, the mechanism of EBM post-processing induced crack formation is less clear. This paper provides a systematic study about the crack formation in post-processed EBM samples made of a non-weldable Ni-base superalloy. Through clarifying the crack formation mechanism, we proposed a crack mitigation strategy and designed a dedicated heat treatment cycle. Experimental validation demonstrates that no intergranular cracks was formed in post-processed EBM samples. It is also found that intergranular cracks only formed when the given solution treating time is longer than what is needed. Based on further collected microstructure evidence, it is concluded that strain-age cracking mechanism is responsible for the EBM post-processing induced crack formation.

[1] E. Chauvet, P. Kontis, E.A. Jagle, and et al. (2017) *Acta Mater.* **Vol.**(142), pp. 82-94.
[2] M. Cloots, P.J. Uggowitzer, and K. Wegener (2016) *Mater. Des.* **Vol.**(89), pp. 770-784.

Hot Cracking Mechanism Affecting a Non-weldable Ni-based Superalloy Produced by Selective Electron Beam Melting

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A non weldable nickel-based superalloy was fabricated by powder bed-based selective electron beam melting (S-EBM). The as-built samples exhibit a heterogeneous microstructure along the build direction. A gradient of columnar grain size as well as a significant gradient in the γ' precipitate size were found along the build direction. Microstructural defects such as gas porosity inherited from the powders, shrinkage pores and cracks inherited from the S-EBM process were identified. The origins of those defects are discussed with a particular emphasis on crack formation. Cracks were consistently found to propagate intergranular and the effect of crystallographic misorientation on the cracking behavior was investigated. A clear correlation was identified between cracks and high angle grain boundaries (HAGB). The cracks were classified as hot cracks based on the observation of the fracture surface of micro-tensile specimens machined from as-built S-EBM samples. The conditions required to trigger hot cracking, namely, presence of a liquid film during the last stage of solidification and thermal stresses are discussed within the framework of additive manufacturing. Understanding the cracking mechanism enables to provide guidelines to obtain crack-free specimens of non-weldable Ni-based superalloys produced by S-EBM.

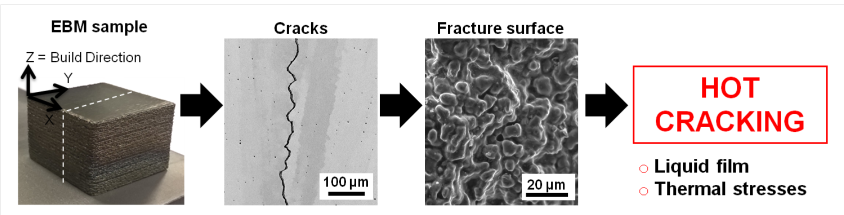

Figure 1: Investigation of the hot cracking mechanism affecting a non-weldable Ni-based superalloy fabricated by S-EBM.

Fatigue Properties of EBM-built Alloy 718 – Effect of As-built Surface and HIP

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Electron beam melting (EBM) is a powder bed based additive manufacturing (AM) process. The EBM process offers several advantages such as manufacturing complex geometries with a design space that was previously not accessible with conventional manufacturing processes, operating under vacuum – hence avoiding pickup of oxygen or other impurities during processing, high processing temperature leading to a lower overall residual stress in the as-built part etc. The aerospace industry has shown interest in EBM mainly for weight reduction either through topology optimization or through introduction of lighter materials such as TiAl; another design aspect of potential interest is part integration to reduce the number of assemblies and hence improving the reliability. However, to realize such advantages in the aerospace sector, factors affecting the mechanical properties have to be well understood – especially the fatigue properties. In the context of fatigue performance, the effect of defects in terms of both the amount and distribution, the effect of different phases in the material and the effect of "rough" as-built surface have to be studied in detail. Fatigue properties of Alloy 718, a superalloy widely used in the aerospace engines, is investigated in this study. Four point bending fatigue tests have been performed at 20 Hz in room temperature at three different stress ranges to compare the performance of EBM material to wrought material. A 2^2 full factorial experimental design, to assess the effect of two post-treatment methods namely – machining and hot isostatic pressing (HIP), is utilized. The specimens are in either machined or as-built surface condition and either in HIP+heat treated or just heat treated condition. Fractography and metallography including crack path analysis have been performed to explain the observed properties. Both HIPing and machining improve the fatigue performance; however, a large scatter is observed for machined specimens. Further, another set of machined specimens with the contour part completely removed have been tested and compared with the previous test group.

Effect of Heat Treatment and Hot Isostatic Pressing on Oxidation Behavior of EBM-additive Manufactured Alloy 718

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Effect of standard heat treatment and hot isostatic pressing (HIP) on oxidation behavior of Alloy 718 manufactured by electron beam melting (EBM®) process was investigated. The oxidation exposures were performed in ambient air at 650 and 800 ℃ up to 168h. The results were compared with two reference specimens of wrought Alloy 718 and as-fabricated EBM without post treatment. The modifications in grain size, grain orientation, as well as level of segregations, precipitates, and pores as a result of such post processing significantly affected the diffusion mechanisms, accordingly the oxidation performance. The oxide scales formed on the surface of the heat treated, HIPed and as-fabricated EBM specimens had varied thickness, morphology, and adherence to the substrate due to the change in microstructure, particularly the grain structure.

Development of Informatics Approach to Determine the Process Window for Electron Beam Melting Process: Demonstration in CoCrMo alloy

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An electron beam melting (EBM), a powder-bed type additive manufacturing technology using electron beam as a energy source, is one of the promising technologies to fabricate complex shaped metallic components using three dimensional computer aided design data. In expanding the application of EBM, one of the problems is the cost required to optimize the process parameters for getting metal parts without process defects such as a lack of fusion, key-hole type defects, and so on. These process defects accompany the interior free surface of a melt pool and can act as nucleation sites, resulting in the equiaxed microstructure even if we select the process condition for the columnar grain growth mode. In order to develop an efficient approach to optimize the process parameters, therefore, we have proposed a simple method to determine the process window by using a support vector machine, one of the machine learning techniques. This proposed method consists of four steps; (1) selecting the data points by a design of experiments (DoE); (2) building the objects using the process conditions determined by DoE; (3) observing the surface morphology of EBM-built objects; (4) classifying the objects into two categories, flat or non-flat, by using a support vector machine. The process window is given by the process conditions with a high value of the decision function. One of the advantage of this method is that we do not need an apparatus to evaluate samples.
In this study, we demonstrated our proposed method in a biomedical CoCrMo alloy. The two parameters, current and scan speed, could be optimized within one day. It was also revealed that the net-shaped objects could be built under the predicted process condition.

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Specificity of the Microstructure of Samples Fabricated by Electron Beam Additive Manufacturing

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Despite the similarity of EBAM to conventional surfacing and casting, the microstructure of the resulting samples has its own features, which are specific only for layer-by-layer processes [1]. The authors made a series of experiments on EBAM of various wire materials (stainless steel, Ti, Al). The diameter of used wires was 1.2 mm. The experiments were carried out on the electron beam welding equipment with a gun power of 15 kW. Analysis of the obtained samples microstructure revealed the following features.

For example, it was observed that during the deposition of the layer in case of stainless steel samples, the previous layers were remelted several times because of the deep penetration effect. The structure of zones after repeated remelting had a grainy nature, while the rest of the sample was dendritic. This allows us to assume that we can achieve a grain structure in the entire body of the resulting sample by adding intermediate remelting to the technology of layer-by-layer process. The grain structure will ensure more homogeneous chemical composition, mechanical and physical properties of the samples and also allow to avoid intergranular corrosion.

The structure of the main part of the sample fabricated from technical titanium consisted of large grains (up to several millimeters in diameter) of irregular shape. However, the central part of the sample section had a plate structure with colony about 1 mm consisting of α-titanium and thin layers of the second phase. The second phase in technical titanium is a concentration heterogeneity or β-phase (presence of β-phase in this alloy is permissible due to the presence of a sufficient number of impurities). Such character of the structure is usually observed at low cooling rates of the alloy that can occur at electron beam concentrated heating in the case of heat removal retardation into the metal of the workpiece because of its high temperature. In the process temperature of the sample increases gradually. So, the zone with the lamellar structure located only in the middle of the samples section. Also, there is acicular structure along the walls at a distance of 1 mm, which is obviously related to the cooling regime, since the character of the heat sink along the edges of the workpiece differs from other zones

[1] K.M.B. Taminger, R.A. Hafley, (2002) *Proceedings of 13th SFF Symposium 482-489.*

Vacuum Improvements on the Arcam Electron Gun for EB Additive Manufacturing: Effects on Cathode Life Time and Beam Quality

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Arcam EBM is currently working on improving the vacuum quality and reducing contamination of the EBU/electron gun, thereby reducing the wear on cathodes. The next, higher power, generation of EBU will include a pumping stage located between the emission and the magnetic lenses.
Comparative studies have been made regarding EBU performance, spot quality and cathode life time. Parameters discussed include nominal and trace gas pressures in the emission area, cathode contamination, emissivity drift during a build, beam FWHM at the build plane and over all cathode life time.

A Multi-Step Optimization Scheme for Electron Beam Control

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We formulate an optimization scheme specifically suited for the electron beam melting (EBM) process. Today, the control of the EBM process is governed by an excessive amount of parameters and extensive experimental work is required in order to determine their values. The present study is part of an effort that aims to reduce the number of parameters and, consequently, simplify the optimization and control of the melting process. We formulate a type of beam control problem in which the parameters under consideration are the beam spot size and beam velocity. The remaining process parameters such as beam energy, beam path, melt depth, and material data are preset. During heating, the solidification rate of the melt pool is high and therefore the pool travels with, and is localized to, the beam. The optimization scheme utilizes this locality as it motivates a divide and conquer approach where an optimization problem with a large solution space is divided into several small ones.

The optimization method currently uses a simple goal functional where the maximum temperature with respect to time is integrated over lines along the beam path. The functional attempts to represent a melt pool that retains its size throughout the melting of a layer. The scheme partitions the beam path into line segments and optimization problems are then restricted to small subsets containing these segments. Since the time-dependent heat equation enters as a constraint, the optimization method is general in the sense that it can be combined with any thermal model. Here, results are based on an analytical solution of the heat equation with constant material coefficients. The analytical solution is more efficient than finite element based continuum thermal models since the temperature can be expressed explicitly and evaluated pointwise, and it is particularly beneficial in optimization since the heat equation needs to be solved in each iteration. Results are obtained for beam paths on the centimetre scale, including turning points.

In situ Neutron Diffraction of Additive Manufactured Ti6Al4V under Tensile Stress

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Additive Manufacturing (AM) of Ti6Al4V alloy specimens by Electron Beam Melting (EBM) results in a unique isotropic microstructure characterized by micron and sub-micron sized grains. The phase content of the specimens is primarily (>95%) α phase the rest is β phase. As part of ongoing research pertaining to the mechanical properties of AM Ti6Al4V, specimens in the as built (AB), heat treatment (HT) (<800 °C), or hot isostatic pressing (HIP) conditions were subjected to tensile stress in-situ neutron diffraction in the SMARTS facility in the Los Alamos Neutron Science Center. Specimens initially loaded until certain stress in the elastic region then unloaded, while measurements took place at selected stress intervals during loading and unloading. After reaching yield stress, specimens underwent strain to 1%, 4%, and 10% strain with repeated *in-situ* measurements during loading and unloading. No hysteresis was detected in all these samples neither in the elastic nor in the plastic regimes. Another specimen underwent a HT at 1000 °C that generated a more substantial βphase content and larger grains, is under investigation the results will be presented and discussed. Further study is required to understand why AM EBM Ti6Al4V samples are not prone to hysteresis.

Automatic High Power Electron Beam Calibration Method Using X-ray

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Electron beam calibration is used in many areas, especially in SEM. Electron Beam Melting (EBM) conditions are very far from SEM conditions and need to consider problems such as non-gaussian spots, high power beam (3kW), calibration probe heat input and beam positioning accuracy. The currently used calibration on Arcam EBM systems only calibrate at low beam power and smallest beam size. This research describes a method and implementation of a full-range calibration setup for an electron beam additive manufacturing machine.

Beam characteristics of Arcam machines in the Qplus-series are sampled at different beam currents and coil settings to create a uniform calibration throughout the beam currents used during melting. The method used to characterize the beam is x-ray detection during beam translation over an etched tungsten foil calibration reference. By using a set of different edge angles the beam shape can be approximated and by adjusting the coil powers the beam shape is modified. By modelling the beam shape vs. beam current vs. position using only measurements from the tungsten edge response it is possible to fit the data to a low degree polynomial solution.

The results shows that a coherent calibration for position and beam size is possible in the melt range of the Arcam EBM Qplus-systems.

A New Heat Model for Improved Control of Build Temperature

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To obtain an improved control of build temperature, a new heat model has been developed. From bitmaps depicting melt and preheat regions for each slice, a simplified 3D geometry of the build is constructed. In the current implementation, we solve the static heat equation with heat input given by the summed energy from the different steps of the Arcam build process. By treating the post-heating/cooling time as an optimization variable, surface temperature variations from a defined build temperature are minimized. In comparison with the earlier Arcam 1D heat model, the new model is able to better adapt to build density (sparse vs dense builds) and area transitions, and examples of this are discussed.
Physical properties are taken from literature where available, but model parameters are also tuned to give postheating times similar to the old heat model for cases where the latter works well. Further calibration is done using LayerQam images and detailed FEM simulations of the entire EBM machine. With this model as basis, our ability to accurately control the build temperature both between different layers (z) and within layers (xy) is improved.

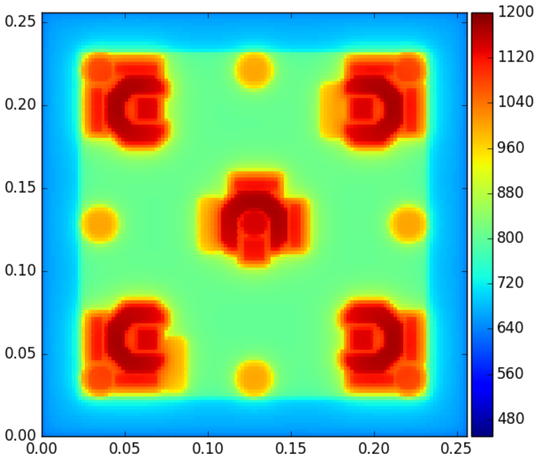

Figure 1: Calculated build temperature (K).

Process Development and Properties of a Cold Working Tool Steel Manufactured by Electron Beam Melting

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Reduction of time-to-market, higher part qualities and functional integration are drivers for the launch of additive technologies in the tooling sector. Although Laser Beam Melting has proven as a suitable method, there are still some challenges like material diversity that limit the use for processing of tool inserts. The tooling market shows a wide range of materials but most of them demand high wear resistance, hardness and heat conductivity. Electron Beam Melting (EBM) is able to overcome this dilemma as it is capable of processing materials that are high melting or highly reactive. The tendency to form cracks due to martensite formation or thermal stresses during processing can be reduced or even eliminated by the use of the EBM process as the powder bed is preheated before melting. In this study a cold working tool steel with a carbon content of 0.6 wt-% was investigated. Besides the development of a process window for this tool steel and the built up of first demonstrators (Fig. 1) findings on the relationship between processing parameters and microstructural evolution are discussed. Therefore, measurements on powder properties, density, microstructures and mechanical properties were done and resulted in a homogeneous microstructure with a hardness profile that is comparable to the conventional processed steel.

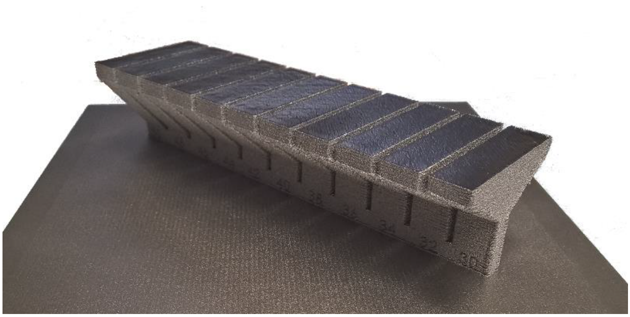

Figure 1: Design demonstrator based on a cold working tool steel processed via EBM.

Influences of Thermal Cycles on Microstructure Evolution by Building Single Walls in EBM-Manufactured Alloy 718

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A single track with a various number of layers (i.e., 1, 2, 3, and up to 10, followed by 25, and 50) has been deposited to study the transient phenomena of repeated melting and solidification during electron beam melting (EBM) process of Alloy 718. The microstructural characteristics such as the cellular/dendritic structure, grain structure and phases (carbides, Laves and δ- phase) were of high interest of the as-built EBM specimen in this study. The variations of primary dendrite arm spacing were also investigated as a function of cooling rate. The successive thermal cycling affected the microstructure of the as-built material, resulting in a heterogeneous structure within the building direction. Primary dendrite arm spacing were larger (~30-70%) in top layers than the bottom layers of the single walls. Epitaxial growth of the grains were observed in all samples due to partially melting of grains in previous layers. Surface grain nucleation was also observed in all samples, see Figure 1.

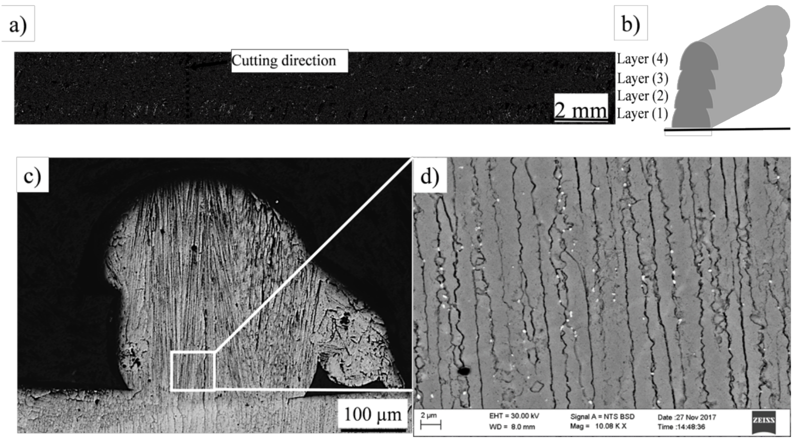

Figure 1: a) scanning electron microscopy (SEM) image from top view of sample, b) schematic of single wall with four layers, c) optical microscopy of cross-section of sample with four layers, d) SEM image showing dendrites in the microstructure.

Mechanical Property Response of Porosity Structure Design

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Nowadays, various porosity structures were introduced into the design and application of medical devices due to the maturity of additive manufacturing technology. Meanwhile, high porosity is required for the porous Titanium materials to meet the mechanical compatibility with human bone. However, higher porosity of porous materials means that the pore size would be larger and the strut size would be smaller and thus the whole structure would be more unstable and thus affect the deformation stability. The compromise between the porosity structure design and mechanical property response is the key point of safety and reliability for medical device application. This study explores the porosity structure design effects on mechanical properties of the porous materials. The mechanical property results of the EBAM samples with various design would be examined and discussed.

Advantages of Open Source Additive Manufacturing

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Additive manufacturing is a business area where most of the companies, whether hardware or software providers, have employed a closed source approach in their business model. As a result it has been cumbersome for academic users to uncover the true potential of this technology. It has for instance been difficult to develop melt strategies tailored for many new materials which could unlock a vast potential for applications using additive manufacturing.

The term "open source" refers to something people can freely modify and share because its design is publicly accessible. Open source originated in the context of software development as a specific way of building computer code with open access for anyone providing benefits such as a broader knowledge base and innovative environments. This has evolved into a much broader set of values applicable to other areas than software promoting open exchange, collaborative participation, transparency, and community-oriented development. An open source approach to research and development has the benefit that it provides a perfect foundation and seed for efficiency in later steps leading to manufacturing in what is called a business ecosystem. This concept, originally presented by James F. Moore [1], means an economic community or business branch wherein different producers, service providers and customers interact closely to the benefit of the entire community.

Typical open source characteristics are transparency, inclusivity, adaptability and collaboration making it possible for all members of an open source business ecosystem not only to interact efficiently but also to develop products and services in a much faster way than otherwise possible. This approach is proven in business areas such as for instance mobile phones (Android), computer operating systems (Linux, BSD, OSX), general machine control (OSADL, Siemens Open Library, Rapid SCADA) and microprocessors (RISC-V, OpenSPARC).

Freemelt is a new company that develops an electron beam powder bed fusion (EPBF) system constituting an AM research platform with direct and fully open access to beam steering and other system functionality to academic customers, which is the topic of our presentation.

[1] J. Moore, (1993) *Harvard Business Review 71.*

Influence of Process Parameters on Microstructure of VT22 Alloy (Ti-5Al-5V-5Mo-1Cr-1Fe) Processed with an Electron Beam Melting Technology

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The VT22 is a near-β titanium alloy used mostly in aircraft and aerospace industries for critical components. It is one of alloy considered as part of the β phase group of alloys and is designed for thermal and mechanical machining. Comparing the typical heat treatment of VT22 alloy with the conditions in EBM process, it can be seen that parts, during the manufacturing process, in the initial phase, are subject to the cyclical rapid cooling. From the melting temperature to temperature of about 600℃ - 650℃ and then remain at this temperature for about 2-10 hours, depending on process length.
The microstructure of samples obtained during this studies differed depending on combinations of process parameters, scanning speed and cathode current. On figure 1, four different microstructures are shown. For constant cathode current and different scanning speed, there is no typical for EBM column grains growth. For lower values of scanning speed, this type of grains may be noted (figure 1 b-d). With the decrease of scanning speed more α phase precipitates on the boundaries of the primary β phase.

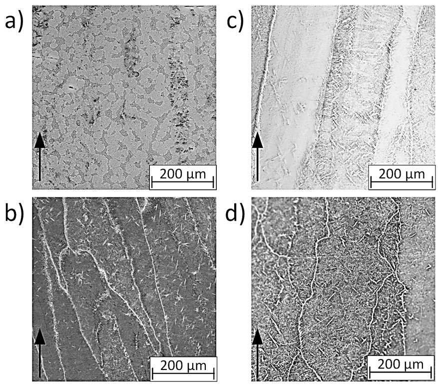

Figure 1: Microstructure of samples manufactured with different scanning speed and with same cathode current 14,5 mA, a) 8700 mm/s, b) 5800 mm/s, c) 4350 mm/s and d) 3480 mm/s.

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NANOTUN3D: Development of the Complete Workflow for Producing and Using a Novel Nanomodified Ti-based Alloy for Additive Manufacturing in Special Applications

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NANONTUN3D [1] will take advantage of the possibilities of Additive Manufacturing (AM) together with the development of a specially tailored Ti- based nano-additived material to achieve dramatic improvements in structural parts of aero, space, mobility, and equipment sectors, reaching expected savings between 40% and 50% of material in critical applications. Inherent benefits of AM will be kept.
By adding nano-particles (NPs) to metal matrixes through an innovative core-shell treatment of the NPs that suits the Ti-matrix, whole life cycle of the NANOTUN3D material has been designed with AM processability in mind: safety and handling issues, processing in SLM/EBM technologies, postprocessing and eventual certification issues are dealt with. A whole Health, Safety and Environmental (HSE) management system will also be developed, as well as all the protocols to start qualification/certification of material and process.
Some results are achieved over the objectives foreseen. Five core-shell systems developed in lab and industrial scale. Two routes for manufacturing powder particles are defined (GA/EIGA). Decision made on early screening of the mixed/consolidated samples on AM techniques (SLM/EBM). Qualification approach developed of material and process. Data on exposure and effects, together with available data from literature and physico-chemical characteristics is integrated to obtain a HSE management system.
NANOTUN3D addresses the combination of AM and nanotechnology for creating a breakthrough in morphology and property of structural parts. Not only ensuring an improved nano-additived material, but also taking advantage of topologic optimization and freeform manufacturing to sum up a dramatic saving of material and energy in AM parts.

[1] NANOTUN3D project received funding from the European Union's Horizon 2020 Programme for research and innovation under grant agreement no 685952. http://www.nanotun3d.eu

The Last Barrier to Additive Manufacturing

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Some of the greatest barriers to full scale adoption of Additive Manufacturing have been noted as process repeatability, reliability, robustness and standardisation, i.e. qualification. The main reason for these challenges in qualification has been a lack of full scale mapping, study and understanding of the process variables in AM. In addition, the known process variables pose further complexities in understanding their relevance (key process variables), their impact on the material and subsequent mechanical properties and their influence on other process variables (compounded variables). Work at The Manufacturing Technology Centre Ltd has been on-going to map, study and categorise process variables associated with the Electron Beam Melting process and define them as either key process variables, non-essential variables, compounded variables, continuous variables or discrete variables. Further work has been undertaken to apply lower and upper limits, statistical minimums and maximums, and associated patterns to these variables i.e. freeze the process. This has been taken further and assessed for compliance to a known aerospace product and its associated requirements. That work is presented here.

Studies on Electron Beam Melting Process with Mesoscopic Simulation and Data Mining

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The process of electron beam selective melting (EBSM) is characterized by numbers of physical phenomena and processing parameters within a meso-scale area, thus it is difficult to observe its dynamic evolution and the influences of different variables. Recently mesoscopic models based on computational fluid dynamics accomplish to reveal the mechanism of defects formation and surface morphologies. However, the full integration of all processes and physical effects is hardly achieved, moreover the vast parameters remain to be identified and optimized. In the presentation, the approach to construct a high fidelity mesoscopic CFD model of EBSM coupled with the powder spreading model using discrete element method (DEM) is introduced. The effects of powder size and shape distribution are analyzed from single and double line scan simulations. By integrating the selective melting and powder spreading model, it is realized to simulate the multi-layer processing cycle and investigate the inter-layer bonding features. Defects like lack of fusion and keyhole collapse are studied regarding to different energy inputs. Upon the mesoscopic simulation model, data mining technique is utilized to help analyze results from each computing sample, in order to describe the relationship between input parameters and finishing characters. We attempt to build evaluation and prediction models with machine learning (ML), which include: 1. Training each mesh cell data with support vector mechine (SVM) to predict the deposited line contours; 2. Training different parameter groups based on single line scan to predict the melting pool shape and porosity; 3. Proposing a multi-scale ML structure that utilizing simulation or experiment data to predict the final product properties. Results about single line finish predicted by learning algorism show acceptable similarities compared to simulations, while the global ML structure remains to be fulfilled by massive sample data.

Mechanical Characterisation of Ti6Al4V Including Results from Digital Image Correlation

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Additive manufacturing in metal is growing rapidly but there are still many challenges to overcome before it can be considered to be an industrialised process. For powder bed fusion methods (PBF), productivity and efficiency is greatly hampered due to more or less manual methods to remove support structures and residual powder and there are also great challenges when it comes to polishing complex geometries, where traditional methods may be inapplicable. This study presents first results on Hirtisation [1], a multi-purpose post-processing method that involves electro-chemical, chemical and hydrodynamic features, which all together are able to form an automated process for removing support structures as well as polishing of AM surfaces with great opportunities for complex geometries. The material for the tensile test specimens were manufactured using Arcam Q20plus, subsequently lathed and post-processed by means of Hirtisation. The quasi-static tests are part of a larger study of the mechanical properties that includes high and low cycle fatigue tests, Charpy tests and microstructural analyses. Here, only the quasi-static tensile tests are discussed and the determined mechanical properties. The tests were monitored using digital image correlation (DIC) [2], in addition to a standard extensometer. Using DIC, being an optical full-field strain analysis method, gives an enhanced understanding of how strains are locally distributed along the test specimen. Thus, from the DIC data true stress and strain were determined together with e.g. Poisson's ratio, Young's modulus and strain hardening coefficient. Ultimately, the DIC data can be used for calibration and validation of material models and finite element (FE) simulations for additively manufactured Ti6Al4V.

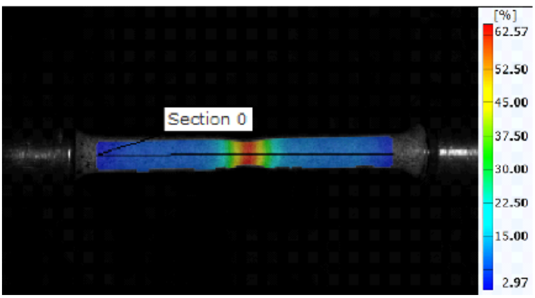

Figure 1: DIC image showing the strain distribution in a Ti6Al4V tensile specimen.

[1] Hirtenberger Engineered Surfaces (2017) *Available from: http://hes.hirtenberger.com/en/*
[2] M.A. Sutton, J-J. Orteu and H.W. Schreier, (2009) *Image correlation for shape, motion and deformation measurements, Springer, New York.*

Simulation of the Selective Electron Beam Melting Process Using Adaptivity in Space and Time

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In selective electron beam melting (SEBM) an electron beam locally melts powdered material to realise complex part geometries in a layer-wise build. The numerical sibling of the process itself, especially from a macroscopic point of view, is a model that is usually accompanied by high computational cost. This is mainly due to (i) the dynamic growth of the computational domain, which denotes the layer-wise built; (ii) the non-linear material behavior, for instance the effects of latent heat; and (iii) different involved time and length scales. Hence, a combination of several numerical methods has to be applied in order to lower computational cost. In this contribution we present a Finite-Element based tool for the simulation of the temperature fields for SEBM manufactured parts, including a suitable energy input model [1]. This tool may be used on different scales. First, for the computation of temperature fields which act as an input for grain growth simulations, i.e. on a mesoscopic scale (see Fig.1), requiring a relatively fine discretisation in space and time. Then, for computations on a scale for smaller part geometries, which are realised by combining multiple numerical methods to reduce the associated computational cost.

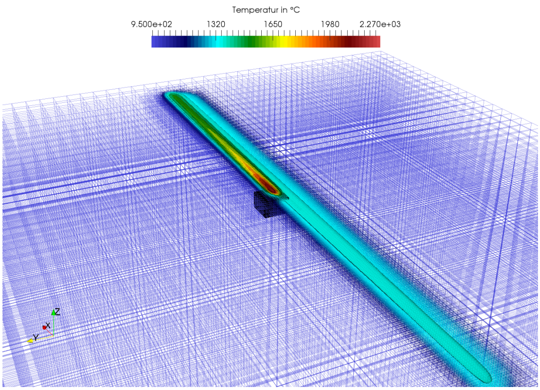

Figure 1: Finite-Element simulation of the temperature field for SEBM manufactured IN718.

[1] A. Klassen et al. (2014) *Journal of Physics D: Applied Physics* **Vol.**(47), 065307.

Investigation on Geometrical Accuracy's and there Measuring Capabilities in Electron Beam Melting for Different Machine Generations and Process Parameters.

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During the last years, additive manufacturing via selective electron beam melting (EBM) showed high potential to build parts with less design restrictions e.g. due to thin support structure needed. However, there are still some geometrical restrictions in dimensioning and part accuracy especially on small parts. In addition to that, the main goal of new machine generations is to achieve higher build rates to decrease the build time. This could lead to a decrease in part accuracy. To investigate this proposition, a geometrical demonstrator is manufactured in Ti-6Al-4V on an Arcam Q20 plus system with 90 µm and 50 µm build theme. The demonstrator involves features in build direction such as rectangles, cylinders, holes, and gabs from 0.1 to 2 mm. Furthermore, some features are built in different angles to the build plane. The measuring of the part is mainly done by 3D scanning and partially by computer tomography (CT). The results are summarised to design recommendation for small design structures on EBM Ti-6Al-4V parts and compared to previous investigations on an Arcam A2X system and a 50 µm theme.

Microstructure and Mechanical Property Grading by an Electron Beam Additive Manufacture – Hot Isostatic Pressing Hybrid Process

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Hot-isostatic-pressing has been shown to be a powerful technique when it applied to close porosity introduced during additive manufacturing [1]. As such, many companies are considering introducing it as a required step in the manufacture of service ready AM components. If we must apply the technique, we consider here whether we can use it as a benefit to produce material with improved properties over standard EBM manufacturing. We have demonstrated a methodology to produce Ti-6Al-4V with better mechanical properties than by standard EBM processing whereby EBM is used to create a preform, which is then HIPed to full density. This technique can also be extended to create material with graded microstructures and a corresponding variation in mechanical properties. Microstructure variation is quantified by the use of SEM and EBSD, while both hardness and tensile properties are reported. The variation in hardness possible exemplified in Figure 1 below, which shows how microstructurally variation can be tailored – in this case to the stylised shape of a beetle.

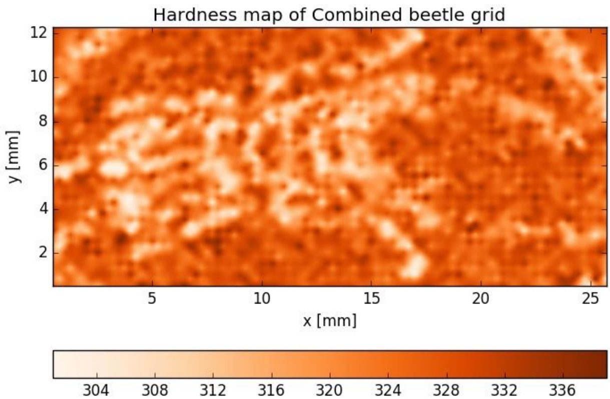

Figure 1

[1] S. Tammas-Williams, P.J. Withers, I. Todd, P.B. Prangnell (2016) *Metall. Mater. Trans.* **Vol.**(47), pp. 1939–1946.

Mapping the Tray of Electron Beam Melting (EBM) Ti-6Al-4V Samples – Properties and Microstructure

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We present a study on the dependency of physical properties (density, elongation, tensile strength and fatigue limit) and microstructure on the geometrical location in a tray of powder bed EBM. It was found that the mechanical properties slightly depend on the order of melting. It seems that when applying high percentage (above 50%) of melted surface, there are density variations and the mechanical properties deteriorate near the edges of the tray. Nevertheless, upon applying HIP (Hot Isostatic Pressure) post process, samples can reach higher density accompanied by higher elongation with uniform strength and fatigue limits.

Surface Modification with Thin Film Metallic Glasses on Ti-6Al-4V Parts Fabricated by Electron Beam Melting

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In recent years, additive manufacturing (AM) technology, also called 3D printing, has been well developed, especially powder bed fusion method. One of the powder bed fusion technologies is electron beam melting (EBM). However, the bad surface quality of electron beam melting is a common problem, which might lead to poor mechanical properties and the reduction of wear and corrosion resistance. In order to improve the rough surface, the sputtering process was used to deposit the Zr-based thin film metallic glasses. The thin film forms a better surface. Furthermore, thin film metallic glasses take advantage of high strength, homogeneous structure and good corrosion resistance. In this study, the parameters of sputtering process are controlled to obtain different improvement on surface modification. The results indicate that sputtering parameters are important to obtain the better quality of thin film and well improvement of surface roughness.

The Approaches on Secondary Electron Based Online Monitoring in EBSM Process

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Electron beam selective manufacturing (EBSM) is a promising technique. However the instability and lack of repeatability are obstacles which greatly limit EBSM applications. The online monitoring is a solution which can help to guarantee EBSM process stability and specimen quality, document the process and establish production manager system, and also realize the feedback control. Up to date, several monitoring methods have been developed, such as melten pool monitoring, printed layer tempreture monitoring and printed layer and powder bed morphology monitoring.
However, current monitoring methods are generally based on optical detectors which need stable detecting accesses. The serious vaporation during EBSM weakens the accuracy and stability of optical detection. Moreover because of the high speed beam deflection, molten pool originated in electron-meterial interaction is hard to track with mechnical apparatus. So the secondary electron monitoring is introduced to provide an online detection method with high dynamic response and high spatial and temporal resolution.
The secondary electron production is related to surface morphology when the scanning EB energy is low, while when the EB energy is high enough to form a melten pool, the secondary electron production is mainly affected by the stability of melten pool transition. The experimental results proved that secondary electron can not only monitor the interaction between electron beam and material, but also indicate the surface morphology after each layer-wise scanning, which means that secondary electron detection could be a promising online detection technique for EBSM. This paper will present current approaches on the secondary electron detection in EBSM process monitoring, including the apparatus, signal processing and sensitivity on the process parameters.

Microstructures and Mechanical Properties of Electron Beam and Laser Hybrid Selective Melting (EB-LHM) Ti6Al4V

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Electron beam and laser hybrid selective melting (EB-LHM) is proposed in this study. Laser is led into the vacuum chamber through a sealed window and scans the same area as electron beam (EB) does, which enable both EB and laser can scan and heat the powder bed simultaneously. In the presented study, the hybrid process is illustrated that EB was used to preheat the powder bed and melt the interior in each layer fabrication, while laser was used to melt the outside and inside contours. With the hybrid strategy, the selective melting process can obtain relative better surface roughness for electron beam selective melting (EBSM) and higher building rate for selective laser melting (SLM). Ti6Al4V samples were fabricated through EB-LHM. The mechanical properties of the parts were measured, the microstructures of the contour and interior were characterized using scanning electron microscopy (SEM). The results show that the hybrid process indeed can improve the surface quality and achieve the similar tensile strength and density, compared to the conventional EBSM process.

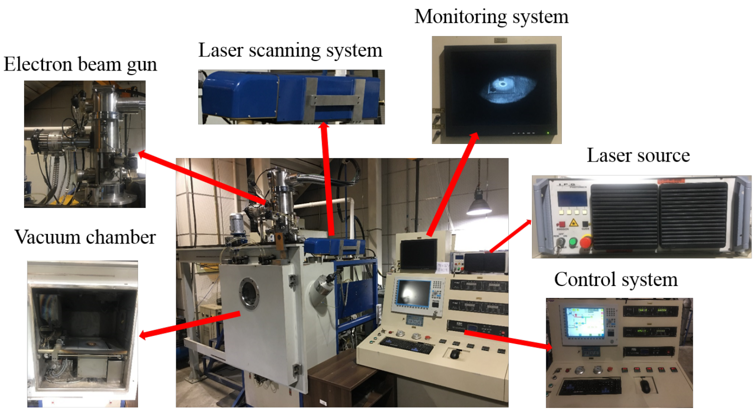

Figure 1: EB-Laser hybrid selective melting (EB-LHM) system.

Research on Al Component Change and Microstructure Evolution of Ti47Al2Cr2Nb Alloy in Electron Beam Selective Melting Process

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Electron beam selective melting (EBSM) could cause the evaporation of elements in γ-TiAl alloy because of high energy density and high vacuum environment, which changes the element composition of the alloy, and eventually affects the microstructure of the alloy. The composition change of Ti47Al2Cr2Nb alloy by EBSM was studied based on the following experiments. The electron beam current of 7, 8, 9, 10, 11 and 12 mA was used to melting the powder bed in a constant scan speed at 0.25m/s. The EBSM vacuum chamber was kept under a high purity argon atmosphere (99.996%) with an over pressure of 1 Pa. The experimental results show that when EB current increased from 7 to 8 mA, the aluminum component (at%) of the samples changed from 43% to 41%, while when the EB current increased from 8 to 11mA, the aluminum component quickly dropped from 41% to 35%, the change rate is 3 times higher than that in lower EB current. Furthermore, when the EB current increased from 11 to 12mA, the aluminum component rose from 35% to 37%, which means that the 11mA EB current causes the maximum aluminum component change.
Besides the component change, the microstructure evolution was investigated as well. Generally, the microstructure changed from lamellar to elongated elliptical grains, then transformed into lamellar grains as the EB current increasing continuously. When electron beam currents were 7 and 8 mA, the main components of the phase were γ phase with a small quantity of α_2 phase. When electron beam current increased to 9 and 10 mA, the γ phase decreased, the α_2 phase increased and B_2 phase began to appear. When electron beam current was 11 mA, the amounts of α_2 and B_2 were further increased. When electron beam current was 12 mA, the α_2 and B_2 decreased to some extent compared with that of the electron beam current of 11 mA.

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