FAU

Friedrich-Alexander-Universität
Erlangen-Nürnberg

EBAM 2023

4th International Conference on Electron Beam Additive Manufacturing

22 - 24 March 2023
Erlangen, Germany

WTM

ENGINEERING
OF ADVANCED
MATERIALS
COMPETENCE UNIT

Welcome

It is our pleasure to announce the **4th International Conference on Electron Beam Additive Manufacturing EBAM 2023**, which will take place from 22 – 24 March 2023 in Erlangen, Germany. EBAM 2023 is organized by the Chair of Materials Science and Engineering for Metals with support of the FAU Competence Unit Engineering of Advanced Materials (EAM) at the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU).

Carolin Körner
Conference Coordinator

The conference aims to discuss specific challenges and opportunities offered by the electron beam. After a long period of virtual meetings, EBAM 2023 will bring together researchers and industrial users in person to achieve 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 conference in 2016, interest in this topic has been increasing, which is reflected in an enormous number of contributions for EBAM 2023 from all over 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.

Matthias Markl
Head of the Local Organization Committee

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

Carolin Körner
Conference Coordinator

Matthias Markl
Head of the Local Organization Committee

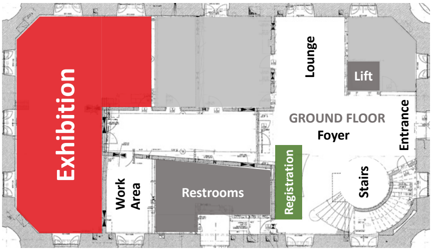
Table of Contents

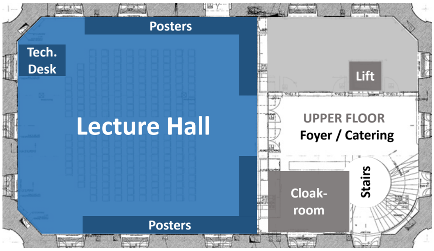
Conference Venue

Kreuz+Quer
Haus der Kirche Erlangen

Bohlenplatz 1
91054 Erlangen

© Bernd Böhner 2017





Registration & Help Desk

The registration and help desk is located in the lower foyer. Registration starts on Wed, 22 March, 9:00 and is open during the whole conference.

The conference fee includes entrance to all sessions (except exhibitor participants), the exhibition, coffee breaks, lunches and the conference dinner, as well as the conference material.

Please let us know during registration if you take part in the conference dinner.

Oral Presentations

All oral presentations take place in the lecture hall. They are limited to a total of 20 minutes; keynote speakers have 30 minutes. This time includes a short discussion of about 5 minutes on the presented topic.

Speakers are expected to respect the schedule, to keep the time of their presentation and to present themselves to their session chair in advance to the session.

Speakers are requested to provide their presentation at least 15 minutes before the beginning of the session at the technical desk in the lecture hall. If necessary, speakers can use their own laptops for their presentation. Please inform the technical desk accordingly.

Conference Publications

After the conference, the authors of the most impressive contributions are invited to publish a journal publication within a special issue **Progress in Electron Beam Additive Manufacturing** in *Progress in Additive Manufacturing* (Springer, impact factor of 4.97 in 2022). The scientific advisory board is requested to recommend suitable contributions.

Poster Presentations

Posters are displayed in the lecture hall surrounding the presentation area. Please mount your poster immediately after registration. The poster boards are marked by contribution ID, presenting author and title. The poster session starts on Wed, 22 March, 18:00. Posters should be displayed until the end of the conference.

Poster Awards

All attendees are invited to vote for the best poster presentation until Thu, 23 March, 14:00. The three posters with the most votes will be awarded with a poster prize during the concluding remarks on Fri, 24 March, 13:00.

Exhibition

The exhibition is located behind the lower foyer on the ground floor. The exhibition area is accessible during the whole conference. The main exhibition time is parallel to the poster session and starts on Wed, 22 March, 18:00.

Lunches, Coffee Breaks & Refreshments

Lunch, beverages and light refreshments will be served in the lower and upper foyer. There are several tables and bar tables located in the lecture hall, the lounge, the work area and the upper and lower foyer to enjoy the breaks and to exchange ideas.

Conference Dinner

The conference dinner starts on Thu, 23 March, 18:45.

Unicum Erlangen
Carl-Thiersch-Str. 9
91054 Erlangen

© Unicum Erlangen 2023

Keynote Speakers

The keynote speakers are sorted according to the program.

Prof. Andrey V. Koptyug

Sports Tech Research Centre
Department of Quality Management and Mechanical Engineering (KMT)
Mid Sweden University, Östersund, Sweden

Are we already utilizing everything electron beam melting can deliver?
Wed 22 March, 9:30 - 10:00

Andrey Koptyug is PhD in Chemical Physics (since 1988), joined Mid Sweden University, Östersund, Sweden, in 1999. He is Associate Professor of Mechanical Engineering since 2014, and is an active member of Additive Manufacturing group at Sports Tech Research Centre. This group is among the pioneers of using electron beam melting in research and development. At present, his main interests are within further developments of EBM technology, development of new processes and materials for EBM, new methods of component post-processing and in different applications of additive manufacturing.

Dr. Markus Ramsperger

Sr. Specialist Process & Material
GE Additive Arcam EBM Center of Excellence
Mölnlycke, Sweden

Electron beam melting as an enabler for difficult to process materials
Wed 22 March, 11:20 - 11:50

Markus Ramsperger is a material engineer with extensive experience in additive manufacturing of Ni-based Superalloys and Tool Steels. He holds a PhD degree in Material Science from the Friedrich-Alexander-Universität Erlangen-Nürnberg. He joined GE Additive in 2017 and is responsible for developing new materials and advanced process strategies for the Arcam EBM process. Before joining GE, Markus worked as a metallurgist in medical industry.

Prof. Paria Karimi

Assistant Professor
Multi-Scale Additive Manufacturing (MSAM) Lab
Department of Mechanical and Mechatronics Engineering
University of Waterloo, Waterloo, Canada

Towards microstructure engineering via electron beam powder bed fusion

Wed 22 March, 14:10 - 14:40

Paria Karimi earned her doctorate in Manufacturing Engineering from University West in Sweden in 2020. During her PhD, she concentrated on microstructure formation and grain structure tailoring of nickel-based superalloys in electron beam-powder bed fusion (EB-PBF). She was awarded a postdoctoral fellowship in 2021 at the University of Waterloo, Canada, focusing on the development of the EB-PBF technique on other alloys, such as Ti64, TiAl, and non-weldable nickel-based superalloys for medical and (aero)space applications. Dr. Karimi has been an Assistant Professor at the University of Waterloo since 2022.

Dr. Karimi's research focuses on revolutionary additive manufacturing technologies, the processability of high-temperature materials, particularly precipitation-hardening Ni- and Ni-Fe-based superalloys, alloy design, and process development. Her research concentrates on removing environmental impact and reducing energy consumption in energy sector using EB-PBF. Her primary interest is the microstructure engineering and subsequent properties using EB-PBF to produce complex components of various alloys with improved performance. Her long-term research goal is on the development of novel manufacturing strategies to improve the sustainability of the manufacturing supply chain. She has been leading a number of innovative initiatives with a focus on the sustainability elements of aeronautical applications. By partnering with other research teams from around the world and winning multiple awards, she has earned a reputation in her field. Her work has appeared in 30+ prominent journals, and she has reviewed 50+ articles for various prestigious journal.

Dr. Karin Ratschbacher

Product Manager Powders
GfE Metals and Materials GmbH
Nürnberg, Germany

Challenges and opportunities on the way to advanced powders for new applications of EB-PBF
Thu 23 March, 9:00 - 9:30

Karin Ratschbacher obtained her PhD from the Montanuniversity Leoben in Austria for inventing and upscaling an industrial process to recycle Molybdenum, Niobium, Rhenium and Tungsten alloys, used in sputter targets. After her postdoctoral assignment at FEM-Research institute for precious metals, Karin Ratschbacher joined Modine Manufacturing Company as a vacuum brazing engineer for automotive coolers, working on an assignment in Shanghai. In 2019 she joined GfE Materials and Metals GmbH as Product Manager Powders and focuses on the atomization of specialized powders on an EIGA furnace.

Dr. Christian Haase

Steel Institute
RWTH Aachen University, Germany

Design of alloys for additive manufacturing by efficient combination of experiments, simulation and machine learning
Thu 23 March, 14:10 - 14:40

Christian Haase obtained his PhD in physical metallurgy and metal physics at RWTH Aachen University in 2015. Since 2016, he is head of the research group Integrated Computational Materials Engineering at the Steel Institute of RWTH. Dr. Haase is an active member of several regional and international additive manufacturing research initiatives as well as head of an independent research group focusing on alloy development for additive manufacturing of automotive applications.

His research groups work on the efficient integration of experimental and computational approaches to understand and design processes and alloys for high-performance applications. During the last years, understanding the mechanisms that govern the microstructure evolution during additive manufacturing as well as the influence on the resulting plastic deformation behaviour became one of their core research topics. These include development of novel high-strength steels tailored for laser-powder bed fusion, crack-resistant nickel-base and aluminium alloys, as well as high-entropy and ODS alloys for high-temperature applications. Recent activities focus on high-throughput alloy design approaches for additive manufacturing based on a holistic design framework combining high-throughput experimental and computational approaches, detailed materials simulations and machine learning.

Prof. Norbert Enzinger

Joining Technology Group
Institute of Materials Science, Joining and Forming
Graz University of Technology, Austria

Wire-based additive manufacturing using electron beam to process advanced materials

Thu 23 March, 16:20 - 16:50

Norbert Enzinger heads the Joining Technology Group at the Institute of Materials Science, Joining and Forming at Graz University of Technology. After studying mechanical engineering, he worked on the numerical simulation of welding, damage analysis and the investigation and further development of various welding processes and wire-based additive manufacturing. He has contributed to over 100 peer-reviewed publications and is one of the editors of the book series "Mathematical Modelling of Weld Phenomena".

Prof. Akihiko Chiba

Chiba Laboratory
Deformation Processing, Institute for Materials Research
Tohoku University, Sendai, Japan

Additive manufacturing of high-entropy alloys with EBM

Fri 24 March, 9:00 - 9:30

Akihiko Chiba obtained his PhD in Engineering Materials from Tohoku University, Japan, in 1994. Responsible Professor, Department of Material Processing and Assessment research, Tohoku University. Professor, Institute for Materials Research, Tohoku University.

Professor Chiba conducted studies on Metallic Materials Science and Materials Processing, to develop new materials and new processing technologies by macroscopic, microscopic, or atomic-scale microstructure based on material processing and heat treatment methods. He developed novel biomedical metallic materials based on Co-Cr-Mo alloys, COBARION®. He proposed the intelligent forging concept to determine the optimum processing condition through quantitative evaluation of microstructure evolution based on material science. In recent years, E-beam additive manufacturing is introduced and integrated existing material processing technology into developing new-type and high-energy material. He made innovative outcomes in respect to metal materials, thermo-mechanical processing, and electron beam melting, etc..

Prof. Bianca Maria Colosimo

AddMe Lab – Additive Manufacturing for Metal materials
Department of Mechanical Engineering
Politecnico di Milano, Italy

Zero-waste additive manufacturing via big data mining, modeling and monitoring: opportunities and challenges

Fri 24 March, 11:10 - 11:40

Bianca Maria Colosimo is Full Professor in the Department of Mechanical Engineering of Politecnico di Milano, where she is Deputy-Head of the Department. Politecnico di Milano is the first Engineering school in Italy, ranked among the top 20 universities worldwide in Engineering and Technology (QS world Ranking by subject- 2022). Her research interest is mainly in the area of advanced manufacturing, with special attention to additive manufacturing data modeling, monitoring and control.

Since 2021, she is Associate Editor of Progress in Additive Manufacturing, Senior Editor of the Informs Journal of Data Science, Department Editor of IISE Transactions, member of the Editorial Board of Additive Manufacturing Letters. She served as Editor-in-Chief of Journal of Quality Technology from 2019 to 2021.

She is co-leading the research laboratory AddMe Lab, one of the leading lab on Additive Manufacturing in Europe, equipped with all the relevant technologies for metal additive manufacturing. She has recently funded a new laboratory named 3D Cell lab for 3D bioprinting of living tissues.

She is member of the platform Manufuture of the European Commission, member of the Steering Committee of the EU Vanguard initiative on 3D printing and member of the Board of Directors of EIT manufacturing (CLC south).

She is included among the top 100 Italian woman scientists in STEM.

Exhibitors

ALD Vacuum Technologies GmbH

Otto-von-Guericke-Platz 1
63457 Hanau, Germany

ALD Vacuum Technologies GmbH, based near Frankfurt am Main, is one of the world's leading manufacturers of vacuum systems for vacuum metallurgy and heat treatment. ALD supplies plant technology for the thermal and thermochemical treatment of metallic materials in solid and liquid form. The company's expertise lies in its mastery of vacuum process technology and its know-how in designing customized system solutions for these fields.

ALD is the supplier of EBuild®, the world's largest E-PBF system, which can produce parts up to 850 x 850 x 1000 mm. EBuild® complements ALD's inert gas atomisers, which are market leaders in the production of high quality spherical metal powders. The combination of large scale powder production and EBuild® systems establishes E-PBF as an economically viable process on an industrial scale.

Freemelt AB

Bergfotsgatan 5A
43135 Molndal, Sweden

Freemelt is a high-tech growth company whose ground-breaking solutions create new opportunities for rapid growth in 3D printing, also known as additive manufacturing. The company's protected technology, which is already installed at major companies and universities, takes 3D printing to a new level and provides new opportunities for printing products in a cost-effective way, to a consistent and high quality. By choosing an open-source solution, the conditions are created for strong growth that enables Freemelt to develop products for universities and manufacturing markets.

With a high energy output, combined with vacuum technology and high process temperatures, provides our technology with advantages such as increased productivity and superior material properties.

We are the only manufacturer to combine open-source and open parameter settings. This combination enables materials development, which is crucial for market development in 3D printing.

GE Additive Germany GmbH

Freisinger Landstrasse 50
85748 Garching bei München, Germany

There are no shortcuts when it comes to additive. No skipping steps.

But for the ready, there is a way to get there faster.

To accelerate your path from prototype to full production.

To put the people who pioneered full metal additive production to work for you.

At GE Additive, we have the machines, powders, software and knowhow to help you to find a faster path to production.

pro-beam additive GmbH

Zeppelinstr. 26
82205 Gilching, Germany

pro-beam additive GmbH is part of the pro-beam Group, a global leader in the field of electron beam technology. The company enables two additive manufacturing processes for metal components – EBM (Electron Beam Melting) and WEBAM (Wire Electron Beam Additive Manufacturing) – as well as corresponding machines.

EBM is especially suitable for compact as well as highly detailed metal components. With the company's efficient EBM system PB EBM 30S customers can build parts from a batch size of 1 up to serial production in a powder bed. The process is reproducible and ensures high-quality and fast production. At the same time, processes are parallelized so that users benefit from maximized productivity.

WEBAM is suitable for large components made of high-performance metals as well as reactive metals. With the wire-based PB WEBAM 100 customers can manufacture their components in a flexible, quick and material-efficient manner, while multi-material components are possible. The process is reproducible and leads to very good surface qualities.

SENTES-BiR

Sanayi Sitesi No.343
Kemalpasa/Izmir, 35730, Turkey

Sentes-BIR is a manufacturer of metal powders. With VIGA (vacuum induction gas atomization) process, we are able to manufacture powders of;

- Pure Copper and Copper alloys (CuSn, CuCrNiZr, CuCrNiSi, etc)
- Nickel alloys (718, 625, Alloy X, C-276, etc)
- Cobalt alloys (CoCrMo, etc)

Thanks to our novel atomization technology, our powders are highly spherical and free of satellites.

Our metal powder production process has AS/EN 9100, ISO 13485, ITAF 16949 and ISO 9001 quality assurance systems.

Our laboratory is capable of many analyses for powder characterization and soon will be certified with ISO 17025 standard.

Steigerwald Strahltechnik GmbH

Emmy-Noether-Str. 2
82216 Maisach, Germany

Steigerwald Strahltechnik GmbH is a global acting company and one of the leading developers and manufacturers of electron beam machines. Customers across the globe benefit from our expertise as the pioneers of electron beam utilization in industrial application. Within the Global Beam Technologies Group, the company specializes in the manufacture of all types of Electron Beam machines.

We supply our wire-based Electron Beam Additive Manufacturing system, EBOADD, which can be integrated in nearly every SST Electron Beam machine and extends the functionality of these machines. The EBOADD process allows a layer-by-layer build-up of complex metallic components from the CAD data of the design department. It can be used to realize new geometries or material combinations and gives new possibilities for production of parts. Products can be realized in a flexible and fast way with less additional tools.

We also provide EB Generators for powder-based Electron Beam Additive Manufacturing. The highest precision of the printed part is ensured by a dynamic correction of Focus and Astigmatism over the entire deflection area.

Wayland Additive Ltd.

Unit 7, Park Valley Court
Huddersfield, HD4 7BH, United Kingdom

Wayland Additive was founded in 2019 to bring to market a new generation of electron beam additive manufacturing machines. Wayland's objective is to simplify the electron beam process and machine operation whilst increasing the breadth of process capability thereby increasing the technological and market reach for electron beam AM. Wayland's hot part process, as opposed to a hot bed process, creates stress free parts with less structural scaffolding, higher productivity and lower total part costs. With a strong heritage in electron beam systems, charged particle physics and additive manufacturing Wayland has created a new technology, NEUBEAM®, that builds on the best of electron beam's capabilities whilst taking away the constraints. With machines now in the field and in production Wayland is looking for pioneers and innovators to join them in their AM journey.

Sponsors

JEOL Ltd.

3-1-2, Musashino, Akishima
Tokyo, 196-8558, Japan

A little trip into space.

Space travel, which was only a story in science fiction movies, is about to become a reality. Yet, it is still not something that anyone can easily afford. One of the reasons space travel is so expensive is because of the cost of traveling by rocket.

JEOL's electron beam additive manufacturing technology has the potential to drastically reduce the cost of rocket development, manufacturing, and even fuel.

The electron beam metal AM machine "JAM-5200EBM" makes it possible to reduce fuel consumption and increase output, reduce the costs, and shorten development time by high quality and high repeatability modeling, integration of multiple parts, and weight reduction.

Together with JEOL's additive manufacturing technology, innovation is advancing at an unprecedented speed.

Making "a little trip into space" a reality. We are changing the world with electron beams.

Scientific Advisory Board

Ulf Ackelid	Freemelt AB, Sweden
Akihiko Chiba	Tohoku University, Japan
Paolo Gennaro	GF Machining Solutions, Italy
Ola Harrysson	North Carolina State University, US
Burkhardt Klöden	Fraunhofer IFAM, Germany
Feng Lin	Tsinghua University, China
Thorsten Löwer	pro-beam GmbH & Co. KGaA, Germany
Ulric Ljungblad	Freemelt AB, Sweden
Guilhem Martin	Université Grenoble Alpes, France
Lars-Erik Rännar	Mid Sweden University, Sweden
Anders Snis	GE Additive - Arcam EBM, Sweden
Iain Todd	University of Sheffield, UK

Local Organization Committee

Carolin Körner Conference Coordinator

Matthias Markl Scientific Organization

Christoph Breuning, Jonas Böhm, Alexander Fink, Martin Gardfjäll, Tobias Hirschfelder, Marcel Reith, Jakob Renner, Robert Scherr, Nick Semjatov

Angelika Mach Technical Organization

Simone Gehrer, Ina Viebach, Michael Hartmann
Laura Schuller, Athanasia Kaisa-Tsarpelas

ENGINEERING OF ADVANCED MATERIALS COMPETENCE UNIT

Neue Materialien Fürth

ZMP Zentralinstitut für Neue Materialien und Prozesstechnik

SFB 814 ADDITIVE FERTIGUNG

SFB/Transregio 103 SUPERALLOY SINGLE CRYSTALS

erc

9:00 - 9:40 Registration

9:40 - 9:50 Welcome
Carolin Körner · FAU Erlangen-Nürnberg, Germany

Wed, 22 Mar **Process Strategy** · *Chair: Ola Harrysson · NC State University, US*

11:00 - 11:20 Break

Wed, 22 Mar **Nickel** · *Chair: Guilhem Martin · SIMaP, France*

Wed, 22 Mar **Artificial Intelligence** · *Chair: Guilhem Martin · SIMaP, France*

13:10 - 14:10 Lunch

Thu, 23 Mar	**Powder** · *Chair: Ulf Ackelid · Freemelt AB, Sweden*	
9:00 - 9:30	**Challenges and opportunities on the way to advanced powders for new applications of EB-PBF** **Karin Ratschbacher · GfE Metals and Materials GmbH, Germany**	41
9:30 - 9:50	Flexible powder production for additive manufacturing of refractory metal-based alloys *Frauke Hinrichs · Karlsruhe Institute of Technology, Germany*	42
9:50 - 10:10	Evaluation of titanium aluminide powder *Alexander Kirchner · Fraunhofer IFAM, Germany*	43
10:10 - 10:30	A sintering model for prediction the neck evolution during an EB-PBF process *Manuela Galati · Politecnico di Torino, Italy*	44
10:30 - 10:50	KiSSAM 3D simulation of electron beam melting process with adaptive mesh refinement at mesoscale level *Andrey Zakirov · Kintech Lab Ltd, Russia*	45
10:50 - 11:10	Break	
Thu, 23 Mar	**Steel** · *Chair: Christian Haase · RWTH Aachen, Germany*	
11:10 - 11:30	Powder properties in EBAM: processing impacts and opportunities *William Alexander Sparling · Canmora Tech Inc., Canada*	46
11:30 - 11:50	Material properties and industrial applications of EBM-processed high-speed steels, stainless steels, and cemented carbides *Pär Arumskog · VBN Components AB, Sweden*	47
11:50 - 12:10	On microstructural evolution, heat treatment and mechanical behavior of a tool steel processed by electron beam powder bed fusion *Moritz Kahlert · University of Kassel, Germany*	48
12:10 - 12:30	Local mechanical behavior of super-duplex stainless steels manufactured by E-PBF *Carlos Botero · Mid Sweden University, Sweden*	49
12:30 - 12:50	Fatigue properties of a PBF-EB cold work tool steel for gear applications *Annika Strondl · Swerim AB, Sweden*	50
12:50 - 13:10	Fine-grained and texture-free microstructure of steel AISI 304L obtained by alloy adjustment for electron beam additive manufacturing process *Christina Burkhardt · TU Bergakademie Freiberg, Germany*	51
13:10 - 14:10	Lunch	

Thu, 23 Mar **Alloy Design** · *Chair: Norbert Enzinger · TU Graz, Austria*

14:10 - 14:40 **Design of alloys for additive manufacturing by efficient combination of experiments, simulation and machine learning**
Christian Haase · RWTH Aachen, Germany 52

14:40 - 15:00 Alloy design approach for reducing powder-originated gas pores in electron beam powder bed fusion
Kenta Yamanaka · Tohoku University, Japan 53

Thu, 23 Mar **Electron Beam** · *Chair: Norbert Enzinger · TU Graz, Austria*

15:00 - 15:20 The investigation on the evolution of smoking phenomenon in electron beam powder bed fusion process
Dongfang Wang · Tsinghua University, China 54

15:20 - 15:40 Minimization of electron beam drift during deflection in additive manufacturing
Avinash Kumar Mehta · IIT Bombay, India 55

15:40 - 16:00 A high-speed modulating electron source (HSES) for EBM
Takakuni Goto · Nikon, Japan 56

16:00 - 16:20 Break

Thu, 23 Mar **Titanium 2** · *Chair: Feng Lin · Tsinghua University, China*

16:20 - 16:50 **Wire-based additive manufacturing using electron beam to process advanced materials**
Norbert Enzinger · TU Graz, Austria 57

16:50 - 17:10 Towards graded porosity structures by spatial control of the scanning speed in electron beam powder bed fusion (PBF-EB)
Alexandre Marguerett · SIMaP, France 58

17:10 - 17:30 The impact of recycling on Ti6Al4V powder particles for the electron beam melting process
Rosario Borrelli · Italian Aerospace Research Centre - CIRA, Italy 59

17:30 - 17:50 Process monitoring with image data for EBM additive manufacturing of Ti6Al4V alloy
Laureana Stelmastchuk Benassi Fontolan · CTI, Brazil 60

17:50 - 18:10 Fatigue performances of EBM Ti6Al4V, comparison across surface finishing and thermal treatments on Arcam Q10+ platform
Riccardo Toninato · LimaCorporate S.p.A., Italy 61

18:45 - 21:45 **Conference Dinner**
Unicum, Carl-Thiersch-Str. 9, 91054 Erlangen

Fri, 24 Mar **Materials** · *Chair: Markus Ramsperger · GE Additive, Sweden*

10:50 - 11:10 Break

Fri, 24 Mar **Process Observation** · *Chair: Burghardt Klöden · Fraunhofer IFAM, DE*

13:00 - 13:10 Concluding Remarks
Carolin Körner · FAU Erlangen-Nürnberg, Germany

13:10 - 14:10 Lunch

Are we already utilizing everything electron beam melting can deliver?

A.V. Koptyug

Mid Sweden University, Akademigatan 1, Östersund, Sweden

e-mail: andrey.koptyug@miun.se

Powder bed additive manufacturing (AM) is rapidly gaining its deserved position in a variety of applications. This technology is rather young and is constantly developing further. Electron beam melting (EBM) as it was initially known or electron beam based powder bed fusion (E-PBF) as it is referred to now, is at the cutting edge of such developments. AM group at SportsTech Research Center, Mid Sweden University is among the pioneers in applying and developing E-PBF processes and technology. Here we would like to share our vision over the potential in expanding the well-established possibilities of E-PBF, and describe certain novel achievements and emerging challenges. Presented material is basing on the results gained through a number of different projects and will cover, in particular: modifications to the industrial-size machines for material/process development and small powder batch experiments; manipulations over the powder improving its processability by E-PBF; tailoring of the component microstructure and properties by locally steering beam parameters and scanning strategies ('4D printing'); uncommon applications of embedded themes (e.g. manufacturing of sheet-based porous structures using 'Wafer Theme'); blended powder and multi-powder applications (in-situ alloying, composites, layered and gradient structures); different 'tricks' connected to preheating (so-called 'cold start', infrared preheating); ceramic materials. By sharing this information, we would like to attract more attention to the emerging and already available opportunities for widening application areas of electron beam based AM technology.

PBF-EB process strategies on freely programmable machines

C. Breuning*, J. Böhm, M. Markl, C. Körner

Chair of Materials Science and Engineering of Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

e-mail: christoph.breuning@fau.de

The fabrication of complex geometries with uniform properties in electron beam powder bed fusion (PBF-EB) remains a significant challenge, with limited solutions. Commercial PBF-EB machines primarily implement process-parameter based compensation schemes for line-based melting strategies, that adjust beam power and velocity to control the energy input and maintain a uniform melt pool geometry. Process-parameter based compensation strategies however are limited by the ability of the machine to rapidly adapt the processing parameters, especially beam power. The advent of freely programmable PBF-EB machines opens up the possibility to develop scanning-strategy based compensation strategies, that can circumvent these limitations.

In this contribution, we explore the potential of advanced scanning strategies, implement on freely programmable machines, in order to achieve uniform melt pool geometries over complex cross-sections. For this purpose, compensation strategies, addressing the main challenges in line-based melting, are proposed and validated using experiments and numerical simulations. Ultimately, a combination of the proposed strategies is integrated into a framework for the fabrication of complex geometries with uniform melt pool geometries and properties.

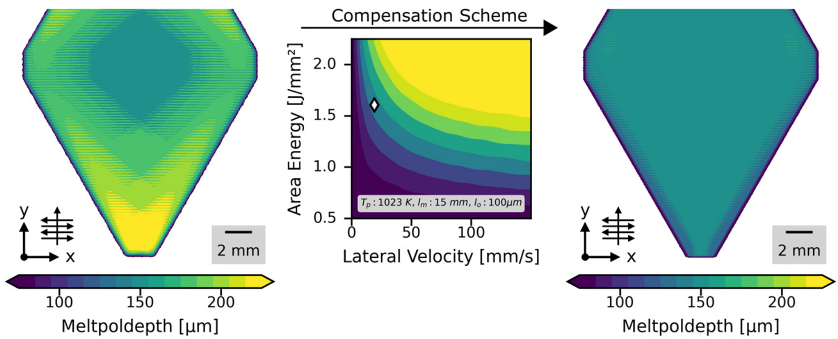


Figure 1: Melt pool depth of a complex model geometry fabrication according to a selected process parameters (center) with desired melt pool geometry without compensation (left) and with compensation (right).

Pixelmelt® software for generating innovative beam scanning patterns in E-PBF

P. Nilsson, J. Olsson, U. Ljungblad*

Freemelt AB, Bergfotsgatan 5A, 43135 Mölndal, Sweden

e-mail: philip.nilsson@freemelt.com, ulric.ljungblad@freemelt.com

The high beam jump speed inherent in e-beam technology enables creative melt strategies in E-PBF. To open up this opportunity for wider use, Freemelt has developed the Pixelmelt® software where several melt strategies can be used in the same build. Pixelmelt® is a tool for generating files in the open-source format, OBP (Open Beam Path). The input file is a sliced 3mf file. Pixelmelt® uses the object structure of the 3mf format to give the user the freedom of different melt strategies and different power inputs for each object. The microstructure and material properties of printed parts can be highly dependent upon the choice of melt strategy.

The software includes strategies for utilization of accumulated heat and for controlled cooldown of individual melt pools during the melt process. To control the heat distribution over the build area, the order in which objects are to be melted can easily be rearranged. Objects can also be partitioned in height based on slice layer thickness, enabling differing strategies for every layer.

The melt strategies available in Pixelmelt® will be described in detail in this presentation. We will show videos recorded in a Freemelt ONE system, illustrating various beam scanning patterns created with this software.

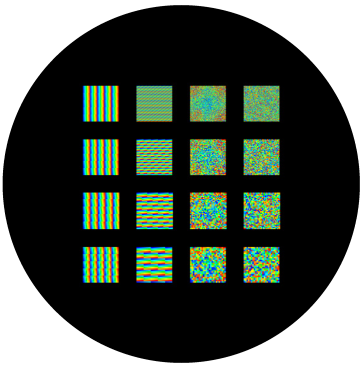


Figure 1: Squares generated by Pixelmelt® using 4 different melt strategies and 4 different mesh sizes.

Electron beam melting as an enabler for difficult to process materials

M. Ramsperger

GE Additive, Arcam EBM Center of Excellence Gothenburg, Sweden

e-mail: markus.ramsperger@ge.com

GE Additive is continuously working on expanding the Electron Beam Melting (EBM) material portfolio especially for high-temperature applications to meet customer's current and prospective needs. The fast and agile nature of electron beam deflection coupled with the ability to use the electron beam for both heating and melting make EBM well suited for additively processing "non-weldable" high-temperature application materials, such as the Ni-based Superalloy Alloy 247.

EBM processing of alloys like Alloy 247 to production quality on an industrial scale requires precise process control with a high-quality electron beam. To that end, an innovative point based melt strategy, a new temperature mapping capability and improvements on the Electron Beam Unit (EBU) hardware outlines a non-exhaustive list of advancements GE Additive has made over the last three years to achieve this level of process maturity.

This work outlines the development of the EBM manufacturing of crack and defect free components for Alloy 247, with material properties comparable or better than the traditionally casted material. We additionally demonstrate the flexibility that EBM offers for tailoring the Alloy 247 microstructure to a state suited for high-temperature performance. This makes EBM processed Alloy 247 ideal for applications including Flow-Path Hardware and components in the High-Pressure Turbine (HPT), where creep and fatigue properties are paramount.

Melt-pool Modeling of E-PBF with FaSTLaB Code: Sensor Signal Prediction and Validation, Effect of the Beam Energy Distribution, and Application to IN738

A. Meshkov[1,*], M. Rahmane[1], A. Snis[2]

(1) GE Research, 1 Research Circle, Niskayuna, New York 12309, USA
(2) GE Additive - Arcam EBM, Designvägen 2, 435 33 Mölnlycke, Sweden

e-mail: meshkov@research.ge.com

We present results of simulations performed with the FaSTLaB (FaST Lattice Boltzmann) metal powder bed fusion additive manufacturing code [1]. The model captures the key PBF-AM phenomena occurring at the mesoscale level, such as energy deposition, powder fusion, melt pool dynamics and solidification, which are responsible for the properties of the fused material, its morphology (pores, cracks, lack-of-fusion defects, etc.) and part surface quality. The model has been previously validated by a number of physical tests as well as a direct comparison of simulated single-track and layer morphologies with experimental data for a range of materials.

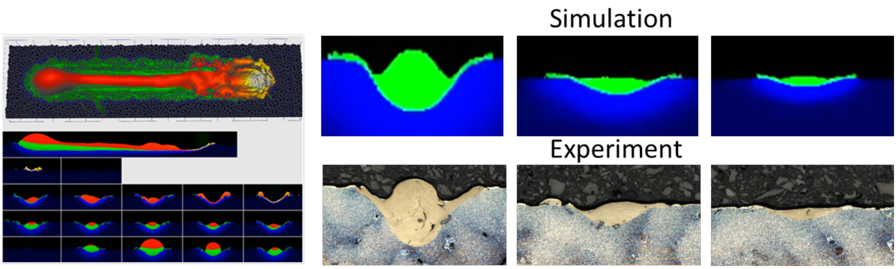


Figure 1: Electron beam powder bed fusion model illustration and IN738 single track validation examples.

Results presented in this study include a comparison between the model predictions and the experimental measurements of sensor signals, recorded from in-situ process monitoring, as well as demonstration of the electron beam shape and energy distribution effects on the melting process. As a materials application example, the model was applied to Inconel-738 alloy to predict the track morphologies on a plate, where melt pool geometry and dimensions were quantitatively compared to the measurements.

The application of the model to IN738 was supported by the DOD-DLA under Contract SP4701-22-C-003.

[1] A. Zakirov, S. Belousov, M. Bogdanova, B. Korneev, A. Stepanov, A. Perepelkina, V. Levchenko, A. Meshkov, B. Potapkin, 2020, *Additive Manufacturing* **35**, 101236.

Phase-field modeling of microstructure evolution during additive manufacturing of Ni-based superalloys

M. Uddagiri*, I. Steinbach

Ruhr-Universität Bochum, Bochum, Germany

e-mail: murali.uddagiri@rub.de

Phase-field models offer the possibility of simulating the microstructure evolution under rapid solidification conditions without having to neglect the key physical mechanisms such as nucleation, growth kinetics and solute diffusion which are active at microscopic length scale. However, until now the phase-field simulations are mostly restricted to binary alloys owing to the complexity of obtaining thermodynamic descriptions for technical alloy compositions. This gap is bridged by full coupling of phase-field evolution with a thermodynamic database with TQ-interface of Thermo-Calc [1]. A new interpolation scheme, called pair-wise interpolation, guarantees numerical stability, and offers significant improvements in computational efforts needed to simulate a multi-component alloy system.

In this work, we employ 3-D phase filed simulations to gain deeper understanding of microstructure evolution during AM solidification, especially the dendrite morphology, primary dendrite arm spacing and solute segregation of multi-component alloy system. The Multi Phase-Field model is coupled to both mass and heat transport phenomena including release of latent heat of solidification. The simulation studies are conducted for a quaternary model system of NiAlCrTaW [2]. A macroscopic CFD model is employed to obtain the heat fluxes at the boundaries (both the heat extraction rate and heat addition rate) which will act as accurate boundary conditions for microscopic PF simulation model.

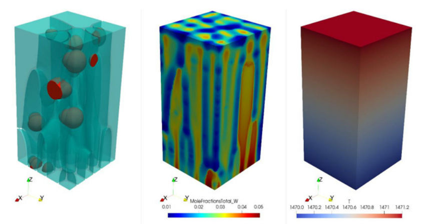


Figure 1: As-built microstructure of NiAlCrTaW model alloy system obtained by phase-field simulations directly coupled to TCNI9 thermodynamic database of ThermoCalc. a) Distribution of primary and secondary phases, b) Composition distribution of W, c) Temperature distribution.

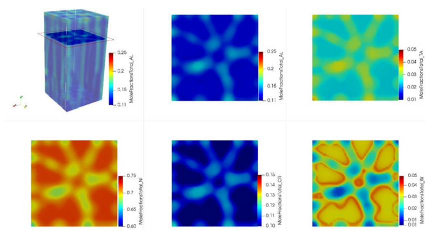


Figure 2: Cross-sectional view highlighting the composition distribution of all the alloying elements of NiAlCrTaW model alloy system.

The research was funded by the Deutsche Forschungsgemeinschaft (DFG) via projects C5 and B2 of the collaborative research center SFB/TR 103 "From Atoms to Turbine Blades".

[1] Eiken et al., 2006, *Phys. Rev E* **73**, 066122.

[2] Warnken et al., 2008, *Proceedings of the International Symposium on Superalloys* , 951-960.

Artificial intelligence for predicting the process stability during an electron beam powder bed fusion process

P. Antonioni[1,*], M. Galati[1], D. Cannizzaro[2], F. Ponzio[2], E. Patti[2], S. Di Cataldo[2], L. Iuliano[1]

(1) Department of Management and Production Engineering, Politecnico di Torino, C.so Duca degli Abruzzi, 24, 10129 Torino, Italy

(2) Department of Control and Computer Engineering, Politecnico di Torino, C.so Duca degli Abruzzi, 24, 10129 Torino, Italy

e-mail: paolo.antonioni@polito.it

Nowadays, additive manufacturing (AM) is a fast-expanding and rising field. Owing to the undeniable advantages, AM technologies are increasingly adopted for industrial production. For this reason, the market demands efficient and robust systems that must be equipped with various sensors that monitor all process phases and guarantee process stability and adequate quality of the produced component. Today, for AM technologies, monitoring and control techniques are still at an early stage and mainly consist of additional sensors that should be installed on the machine to provide some output such as an image of the actual processed layer. However, if properly monitored and interpreted, signals from simple diagnostic sensors present on each industrial device may already provide precious information on the job state and prevent process instability, such as job failure. This work presents the use of artificial intelligence (AI) algorithms to analyze the data collected by the system during an electron beam powder fusion process. The AI network has been trained with the standard data recorded in the machine log file and obtained by processing different materials and geometries. The data included successful jobs and failed ones for several reasons. The results revealed that the algorithm could predict the evolution of the process and, in some cases, well in advance, issues that may lead to a process failure.

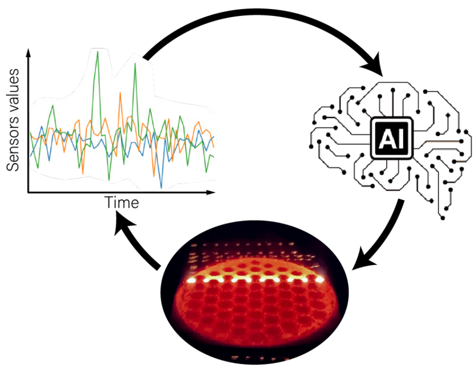


Figure 1: Graphical Abstract.

Development of auto process mapping technique for powder bed fusion using an electron beam

K. Aoyagi[1,2,*], M. Ono[1,2], K. Yanagihara[1,2], K. Wakoh[1,2], A. Chiba[1,2]

(1) Institute For Materials Research, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan

(2) Technology Research Association for Future Additive Manufacturing, Maruishi Building 5F, Kajimachi 1-10-4, Chiyoda-ku, Tokyo 101-0044, Japan

e-mail: kenta.aoyagi.e7@tohoku.ac.jp

Powder bed fusion using an electron beam (PBF-EB) is one of additive manufacturing technologies. In order to get defect free parts by PBF-EB, users usually constructed a process map which shows an optimized process window. Parts quality of PBF-EB depends on a process condition. In industrial applications, we need process map in a multi-dimensional process parameter space, yet process optimization for multi-dimensional process parameter space is complex and time consuming because many kinds of process parameters should be investigated (beam power, scan speed, beam diameter, line offset, layer thickness, building temperature, dimension of parts, and so on). Then, we need an efficient technique to reveal a process map in a multi-dimensional process parameter space. In this study, we have developed auto process mapping technique using data science approach.

The sequence of process mapping is as follows: (1) setting conditions to get data for machine learning, (2) evaluation of parts fabricated by using the conditions which are planed at step (1), (3) constructing process map using machine learning, and repeating these 3 steps to obtain and update a process map which can predict optimized process window. In order to automate these steps, we have developed software consisting of auto condition setting module, auto monitoring data evaluation module, and auto constructing process map module. In the auto condition setting module, uniform design is used to design initial conditions for process mapping, and Bayesian optimization is used to deduce condition to update a process map. In the auto monitoring data evaluation module, a convolution neural network is used to judge whether or not parts include defects from in-process monitoring data. The in-process monitoring data is a backscattered electron image of a surface of parts. In the auto constructing process map module, the machine learning model (support vector machine with several kernels and random forest) and their hyper parameters are optimized by Bayesian optimization. We demonstrated auto process mapping by using these three modules.

This study was based on the results obtained from project JPNP19007, commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

Towards microstructure engineering via electron beam powder bed fusion

P. Karimi*, E. Sadeghi, Y. Hemmati, K. Taherkhani, E. Toyserkani

Multi-Scale Additive Manufacturing Lab (MSAM), University of Waterloo, Waterloo, Ontario N2L 3G1, Canada

e-mail: paria.karimi@uwaterloo.ca

Researchers utilizing the electron beam powder bed fusion (EB-PBF) technique have long desired to develop their own innovative scan strategies for applications requiring site-specific microstructures with tailored properties. In the present study, multiple conventional and novel point scan strategies have been programmed in Python and implemented on an EB-PBF machine equipped with Research EBM Control, a recently developed software by Arcam-EBM (a GE additive). The influence of new scan strategies on the melt pool shape, thermal gradient, and solidification rate of two titanium alloys, namely Ti6Al4V and γ-Ti48Al2CrNb, was investigated. The new knowledge will eventually be utilized to manipulate the grain morphology and crystallographic texture of the material in complex geometries [1-3].

[1] R. R. Dehoff et al., 2014, *Materials Science and Technology* **31**, 931-938.

[2] Kirka et al., 2017, *The Minerals, Metals & Materials Society* **69**, 523-531.

[3] Plotkowski et al., 2012, *Additive Manufacturing* **46**.

Design, processing, microstructures of a defect-tolerant Ti-alloy with outstanding energy absorption properties

M. Duport[1], R. Dendievel[1], F. Prima[2], J-J. Blandin[1], P. Lhuissier[1], G. Martin[1,*]

(1) Univ. Grenoble Alpes, CNRS, Grenoble INP, SIMAP, 38000 Grenoble, France
(2) PSL Research University, Chimie ParisTech, Institut de Recherche de Chimie Paris, CNRS UMR 8247, 75005, Paris, France

e-mail: guilhem.martin@simap.grenoble-inp.fr

Ti-alloys are usually considered good candidates for structural applications requiring a combination of properties such as high strength, low density, and corrosion resistance. However, heritage alloys such as the Ti-6Al-4V or Ti-5Al-5V-5Mo-3Cr alloy suffer from a lack of ductility (uniform elongation of nearly 0.10) and most importantly from a lack of work-hardening. Thus, heritage alloys are not suitable for shielding applications requiring damage-tolerant materials. Here, we designed a β-metastable binary Ti-Mo alloy showing a TWIP effect to overcome the limitations of the heritage alloys. The powder of the selected composition was gas atomized and loaded in an E-PBF machine to build some parts. Samples with a relative density >99.95 % measured by X-ray computed tomography were fabricated [1]. Microstructural observations reveal that the as-built microstructure shows a graded α+β microstructure along the building direction. Thus, a post-fabrication heat treatment is required to achieve a fully β-metastable microstructure exhibiting a TWIP effect. We show that an additional ageing treatment to trigger nanoprecipitation of the ω_{iso} phase can also be applied to the β-metastable microstructure to reach a better strength-ductility trade-off [1]. The mechanical performances (hardness, tensile testing, and impact energy) of the different microstructures were evaluated. Finally, lattice structures made of this defect-tolerant Ti-alloy were fabricated and the energy absorption properties were evaluated [2].

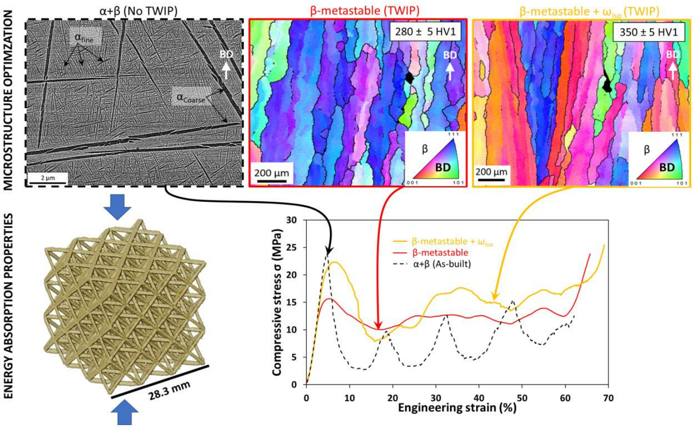


Figure 1: Energy absorption properties of lattice structures built using the defect-tolerant Ti-alloy designed in this study.

[1] M. Duport, P. Lhuissier, J-J. Blandin, R. Dendievel, M. Veron, F. Prima, and G. Martin, 2022, Addit. Manuf., Under Revision.

[2] M. Duport, G. Martin, P. Lhuissier, J-J. Blandin, F. Prima, and R. Dendievel, 2022, *Scripta Mater.* **219**, 114887.

E-PBF manufacturing of a topology optimized mechanical stopper and validation based on working conditions

E. Ercan, B. İ. Danış, C. Köseoğlu, U. Gövez, O. Aşık*, E. Tan

ASELSAN Inc., Ankara, 06830, Turkey

e-mail: emreercan@aselsan.com.tr

Electron Powder Bed Fusion (E-PBF) is one of the prominent and proven metal powder bed fusion approaches in Additive Manufacturing (AM) technology. The structures fabricated by E-PBF shows full density and offer superior mechanical strength without need of extra HIPping. Industry is becoming aware of the importance of metal AM technology and intend to implement it into the product development to take advantage of design complexity and mass reduction [1].

The main aim of this study is to integrate metal AM into product development consisting of design, manufacturing and validation stages. The mechanical stopper (Fig 1) is responsible of carrying impact load in a rotating system. The part material was originally AISI630 stainless steel. Mass reduction have been performed by using topology optimization (TO) in ANSYS and ALTAIR Inspire. Several TO studies were performed, aiming different objectives such as maximizing stiffness, frequency, etc. The TO results have been compared and the one with minimum mass and compliance has been selected for production. The initial production performed by SLA for manufacturability check, then, by using E-PBF with Ti-6Al-4V. MicroCT inspection is coupled for observation of the defects and imperfections in the part before and after the mechanical tests which are shock, vibration and static tests according to working conditions of original part. As a result, 83 % mass reduction is achieved while preserving the durability and functionality of the part. Therefore, the test results show us that by the help of E-PBF the optimized part can be used instead of the original one.

Figure 1: Assembly of Mechanical Stopper.

[1] D. S. Gonzalez, A. G. Alvarez, 2018, *Additive Manufacturing Feasibility Study & Technology Demonstration EDA AM State of the Art & Strategic Report* **26-27**.

Defect- and microstructure-based characterization of the fatigue properties of additively manufactured γ-TiAl with dual microstructure

M. Teschke[1,*], J. Knörlein[2], L. Telgheder[1], M. Franke[2], C. Körner[2,3], F. Walther[1]

(1) Chair of Materials Test Engineering (WPT), TU Dortmund University, Baroper Str. 303, 44227 Dortmund, Germany

(2) Neue Materialien Fürth GmbH, Dr.-Mack-Str. 81, 90762 Fürth, Germany

(3) Chair of Materials Science and Engineering for Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

e-mail: mirko.teschke@tu-dortmund.de

Recent research in the field of electron beam powder bed fusion (PBF-EB) has demonstrated that it is possible to adjust different microstructures within a titanium aluminide (TiAl) component [1, 2]. An in-depth mechanical characterization of the components produced in this way, in particular of the high temperature fatigue behavior, is particularly important concerning the possible application as turbine blade.

In this study, the fatigue behavior of the 4th generation TiAl alloy TNM with dual microstructure was investigated. The dual microstructure is processed with two different, well-adjusted AM process parameter sets leading to a significant change in localized aluminum (Al) loss via evaporation during PBF-EB melting. After heat treatment, the as-built microstructure, containing two different levels of Al, is transformed into customized microstructures: fully lamellar (FL) and nearly lamellar (NL + γ).

Constant amplitude fatigue tests were performed at room temperature and the application-relevant temperature of 750 °C. The strain was measured using digital image correlation (DIC) in order to localize strain differences in the two microstructure areas. With the help of fractographic and scanning electron microscopic examinations, the fracture behavior was analyzed. The failure occurred mostly in the FL area of the dual microstructure specimens, independent of the test temperature. The interface between FL and NL + γ microstructure did not cause any weakening. The fatigue strength related to the number of cycles to failure from 2E6 cycles was 350 MPa.

The authors thank the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) for its financial support within the research project "Microstructure and defect-controlled additive manufacturing of gamma titanium aluminides for function-based control of local materials properties" (project number: 404665753).

[1] J. Knörlein, M. Franke, M. Schloffer, C. Körner, 2022, *Addit. Manuf.* **59**, 103132.

[2] J. Moritz; M. Teschke; A. Marquardt; L. Stepien; E. López; F. Brueckner; F. Walther, C. Leyens, 2023, *Adv. Eng. Mat.* **25**, 2200917.

Surface finish improving by novel ECP process on Titanium EBM AM components

A. Tawfik[1,*], I. Laidler[2], P. Sperling[3], A. Holt[4], P. Bills[1], N. Dickinson[4], L. Blunt[1]

(1) Huddersfield University, Huddersfield HD1 3DH, United Kingdom
(2) Wayland Additive Limited, Huddersfield HD4 7BH, United Kingdom
(3) Volume Graphics GmbH, Heidelberg, Germany
(4) Holtex Innovations Group, Huddersfield HD4 7BH, United Kingdom

e-mail: A.tawfik@hud.ac.uk

Additive manufacturing (AM) is a process where the component is built layer-by-layer using powder or wire precursors. This novel technology offers advantages over conventional subtractive machining in terms of design optimization and weight reduction enabling the creation of complex internal and external features that are impossible to achieve with conventional subtractive machining.

It is known that parts produced by AM have a higher surface roughness compared to parts produced by subtractive manufacturing and this is more pronounced for EBAM parts. The AM surface finish is relatively rougher than those manufactured by subtractive machining. Additionally, the surface finish is also dependent on build orientation; thus, the surface finish is vastly different across the same part. Electrochemical polishing (ECP) is the process of removing material from a component surface to optimise the finish. In the ECP process the part is placed in pH neutral electrolytes and materials is removed by dissolution via a high electric current. Surface improvement of titanium AM parts has to date proven difficult. In this paper titanium parts produced by the NEUBEAM EBAM process are polished by an optimised ECM method. The artefact surface was characterised by using focus variation microscopy before and after polishing, and the parts were scanned X-ray computed tomography (XCT) to assess geometrical deviation. Finally, to verify the impact of ECP process on removing semi-fused powder, the artifacts were scanned by SEM before and after ECP. The surface measurement data processing was carried out per ISO 25178 standard using areal topography parameters, the XCT data processing and analysis was carried out with VGSTUDIO. The results shows that the surface roughness of EBM AM component can be improved from circa 30 μm to sub 10 μm, with a 120 μm dimensional loss. The focus of this study is identifying and optimising the impact of ECP on the relatively rough EBM AM surface.

Powder processing and high energy electron beam systems are key ingredients for new EBAM hybrid processes

R. Edinger

CANMORA TECH Inc., 5930 No. 6 Road, Unit 310, Richmond, BC, V6V 1Z1, Canada

e-mail: ralf@canmora.tech

Recent results in processing metal powders by ball milling allow us to melt such materials with high energy electron beams at lower temperatures [1]. Ball milling changes the electrical characteristics of the powder by reducing the capacitance and therefore removing "smoking" effects [2] when the electron beam is absorbed into the powder. By lowering the powder bed's temperature, the electron beam can now be combined with other processes. We will report on current work on an improved high energy electron beam gun and the control system melting metal powders without preheating. The presented electron beam gun can have an automatic beam changer allowing the fast in-process changing of cathodes/filaments and the associated anodes. This enables users to run different cathodes for different processes, for example an low current inspection cathode can be combined with a wide beam hatching cathode and a fine focus contour cathode. This high energy electron system can be integrated into a Monoblock housing with multiple independent beams operating on a powder bed layer. A device which could replace ball milling will be presented, showing an on-demand powder processing inside the vacuum chamber. This device will change the powder's electrical characteristics without impacting the powder particle geometry.

Figure 1: Electron beam melting of ball milled steel powder without preheating.

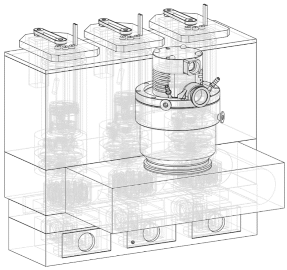


Figure 2: Monoblock electron beam system with 3 beams in liner configuration shown.

This presentation will include an overview of other hybrid processes currently under development that are only possible when working at lower powder bed temperatures.

[1] A. Chiba, Y. Daino, K. Aoyagi,K. Yamanaka, 2021, *Mater.* **14**, 4662.

[2] Z. Cordero, H. Meyer, P. Nandwana, R. Dehoff, 2017, *Acta Mater.* **124**, 437-445.

Active charge neutralisation in 'NeuBeam' electron beam PBF

M. Hussey[1], I. Laidler[1], M. Harvey[1], J. van den Berg[2], A. Rossall[2], S. Wilson[2]

(1) Wayland Additive Ltd, Unit 7, Park Valley Court, Meltham Road, Huddersfield, HD4 7BH, UK
(2) MEIS Laboratory, The University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, UK

e-mail: martyn.hussey@waylandadditive.com

Wayland Additive Ltd is an electron beam PBF [1] machine manufacturer formed in August 2019 and based in Huddersfield, UK. Wayland came from an industry-led multi-partner R&D project, started in 2016, the aim of which was to develop technology that overcame some of the main 'draw-backs' associated with e-beam PBF AM - the primary one being the requirement to sinter the powder bed to mitigate against excess negative charge accumulation, which may initiate build ending 'smoke events'. In collaboration with the University of Huddersfield, the project team developed the Active Charge Neutralisation (ACN) technology that forms the heart of Wayland's NeuBeam e-beam AM process. The first embodiment of the ACN technology has successfully been deployed on Wayland's Calibur3 production AMmachine (Fig 1a).

Figure 1: (a): Wayland's Calibur3 AM System; (b) Wayland's ACN technology.

The ACN technology in NeuBeam [2] removes the requirement of a wide area powder bed sinter prior to melting with the electron beam – which gives advantages in terms of reduced build time, increased process stability, improved powder morphology post-build, lower heat losses during build and 'looser' powder surrounding the part post-build. The ACN technology (Fig 1b) employs a flux of low energy ions incident over the full extent of the powder bed. The presence of the positively charged ions in the vicinity of the melt pool area mitigate excess charging of the powder bed by the incident electron beam. Details of the ACN process together with the challenges of developing and deploying the technology will be be presented at EBAM 2023.

[1] Z. Fu, C. Körner, 2022, *European Journal of Materials.* **2**, 54-117.

[2] J. van den Berg, M. Hussey, W. Richardson, I. Laidler, 2022, Patent US10879039B2.

EBuild® 850: industrial scale electron beam powder bed fusion

F. Osmanlic*, M. Kordik, R. Hönig, K. Löser

ALD Vacuum Technologies GmbH, Otto-von-Guericke-Platz 1, 63457 Hanau, Germany

e-mail: fuad.osmanlic@ald-vt.de

ALD's EBuild® 850 is the world's largest additive manufacturing system using a electron beam for the powder bed fusion process. The goal of the new system generation is to manufacture large components and increase productivity. The build envelope is 850 x 850 x 1000 mm^3, which gives unique challenges for powder application, beam generation, beam deflection and focusing. The gun used has an acceleration voltage of 150 kV and a maximum power of 45 kW. To ensure positioning accuracy and beam quality even at large deflection angles, a coil system is used that generates a homogeneous magnetic field over the entire electron beam cross-section. The integrated electron beam detector allows in-situ and in operando process monitoring.

Figure 1: ALD's EBuild® 850 is the world's largest E-PBF system located in Hanau, Germany.

The system was commissioned in early 2022 and has since been used for production and process development. The results to date show the potential for large-scale industrial use of the Electron beam Powder Bed Fusion process.

EBM machine concept for industrial serial production

S. Pohl*, A. Klassen, L. Sansonetti

pro-beam additive GmbH, Zeppelinstr. 26, 82205 Gilching, Germany

e-mail: sebastian.pohl@pro-beam.com

Some of the most important advantages of EBM is the processing at high vacuum and at elevated build temperatures. However, for conventional EBM machines, these advantages may have their shortcomings when considering the entire process chain.

Non-productive times like the evacuation process and the cool down time take place inside the build chamber, blocking the chamber for production. This leads to a low beam-on time, causing a low productivity which ultimately leads to high operating costs. Furthermore, conventionally the powders are handled in the open at the machine before and after each build job. When setting up and dismantling build jobs, this has a considerable impact on the machine's surroundings with the potential of powder contamination and the mode of operation.

These shortcomings may hinder the application of the EBM technology in an industrial environment and complicates its application in a serial production.

An innovative machine concept developed by pro-beam successfully eliminates the aforementioned drawbacks while creating additional benefits, which will be discussed in detail.

The novel machine concept is mainly characterized by three features:

1. Exchangeable units ("BuildUnits"), which combine build envelope, powder reservoir, powder overflow containers, raking platform and raking system. Therefore, all powder touching parts are mobile and exchangeable.

2. Besides the build chamber, the machine also includes an air lock directly adjacent to the build chamber.

3. Following the air lock, an additional enclosure section allows the transfer of the BuildUnit to and from an enclosed transport trolley.

These features allow the separation of the cooling, setting-up and dismantling from the process chamber, thus increasing the productivity of the machine significantly.

By using several BuildUnits, exchanging them in the air lock under vacuum conditions and transporting them inside the enclosed trolley, the EBM machine can be operated in an industrial environment and used for serial production.

The efforts on new machine development to promote the size and efficiency of electron beam powder bed fusion process

W. Kan[1,2,*], J. Wang[1,2], D. Zhao[1,2], L. Liu[1], F. Lin[2]

(1) Beijing QuickBeam Technology Co., Ltd., Beijing, China
(2) Department of Mechanical Engineering, Tsinghua University, Beijing, China

e-mail: kanwenbin@qbeam-3d.com, linfeng@tsinghua.edu.cn

At present and in the near future, the limitation of size and efficiency is the main obstacle to promote additive manufacturing technologies, especially for EB-PBF process, which is restrained by the electromagnetic deflection angle of the electron beam and the preheating procedure. Several efforts to expand the capabilities of EB-PBF, explored in QuickBeam Tech. and Tsinghua University, will be presented.

The first effort is the development of Qbeam S350 with a single 6 kV EB gun and a square scan region of 350 x 350 mm^2, which can provide a maximum 450 mm build dimension along the diagonal direction. The second effort is the development of Qbeam G350 with the same scan region of 350 × 350 mm^2 but equipped two guns, one of which is the individual preheating gun to provide nonstop preheating. This novel configuration can keep the powder bed temperature above 1100 °C constantly during EB-PBF process, and meet the requirements to fabricate large size superalloy parts efficiently.

The third effort is the development of Qbeam S600 with a four-gun array and 600 x 600 x 700 (DxWxH) mm^3 build envelope. The techniques developed for multi-gun skill includes the multi-gun electromagnetic shielding, multi-gun coordinated control strategy, and secondary electronic automatic calibration and will be reported.

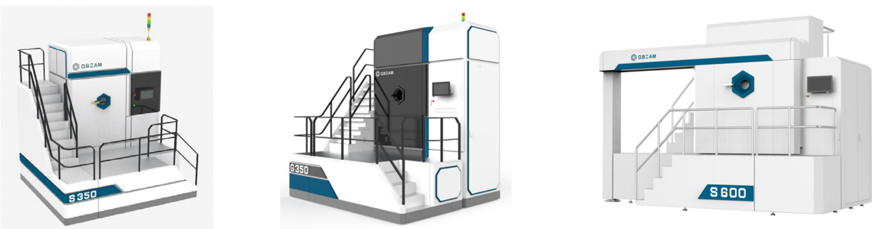


Figure 1: The machines developed to promote the size and efficiency of EB-PBF process. left: Qbeam S350 (1 EB gun), middle: Qbeam G350 (2 EB gun), right: Qbeam S600 (4 EB gun)

These efforts were supported by The National Key R&D Program of China: (2017YFB1103303) and (2018YFB1105204)

Challenges and opportunities on the way to advanced powders for new applications of EB-PBF

K. Ratschbacher

GfE Metals and Materials GmbH, Höfener Str. 45, 90431 Nürnberg, Germany

e-mail: karin.ratschbacher@gfe.com

Advances in Additive Manufacturing by powder bed fusion technologies based on EBM (Electron Beam Melting) or SLM (Selective Laser Melting) as well as other powder based additive routes such as LMD (Laser Metal Deposition) have led to an increase of demand on spherical powders [1]. However, most applications are realized through a handful of commercially available powders. Customized alloys and new materials are needed to enlarge the field of possible applications and enhance the performance of additive manufactured parts.

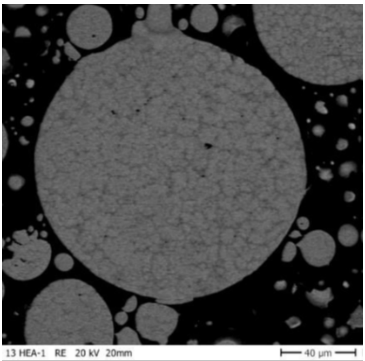


Figure 1: Homogeneously alloyed Powder particle containing Zr-Ti-Ta-Nb.

A novel processing route invented by GfE allows the production of feedstock for the EIGA of alloys with very high melting points. This includes brittle, high temperature intermetallics, as well as refractory based High Entropy Alloys with low melting alloying elements which cannot be processed by conventional meltmetallurgical technologies to stable EIGA electrodes. The availability of such powders represents a breakthrough, allowing results from fundamental research to be transferred into products and widening the application field of additive manufacturing.

[1] P. Sun, Z.Z. Fang, Y. Zhang. et al., 2017, *JOM* **69**, 1853–1860, doi: 10.1007/s11837-017-2513-5.

Flexible powder production for additive manufacturing of refractory metal alloys

F. Hinrichs[1,*], D. Schliephake[1], S. Seils[1], S. Obert[1], A. Kauffmann[1], K. Ratschbacher[2], M. Allen[2], A. Pundt[1], M. Heilmaier[1]

(1) Karlsruhe Institute of Technology (KIT), Institute for Applied Materials (IAM-WK), Engelbert-Arnold-Str. 4, 76131 Karlsruhe, Germany

(2) GfE Metals und Materials GmbH, Höfener Str. 45, 90431 Nürnberg, Germany

e-mail: frauke.hinrichs@kit.edu

Beyond the advantages that additive manufacturing (AM) offers through great freedom of design, it additionally opens up possibilities to build components from materials, which cannot be machined or deformed into required shapes conventionally due to their properties. However, the production of such metal alloy powders from these materials, especially refractory element based alloys, remains challenging, not only due to their high liquidus temperatures of more than 2000 °C and the reactivity of the constituting elements but also due to the formation of brittle intermetallic phases. The brittle nature of these alloys restricts application of commonly available gas atomization (GA) techniques, e.g. the casting of consumable electrodes for processes like electrode induction GA (EIGA) or plasma rotating electrode process (PREP). For an efficient development of new alloys, a processing route is proposed using a novel ultrasonic atomization (UA) process for laboratory scale powder production. For upscaling of suitable alloy compositions to industrial scale powder quantities, a modified EIGA process is used. This two-step powder development route is showcased through the refractory based alloy Mo-20Si-52.8Ti (at.% The recently developed alloy shows exceptional oxidation resistance at intermediate temperatures of about 800 °C [1], which is rarely observed for high-Mo containing alloys [2]. However, processing capabilities are limited due to the high amount of intermetallic (Ti,Mo)5Si3 phase up to now. The powders produced via UA and EIGA were analyzed and compared with regards to their suitability for AM. Furthermore, the process stability of UA for the production of reactive and refractory alloy powders was evaluated. It was found, that powders from both UA and EIGA produce spherical powder particles of narrow size distribution, suitable for AM. Oxygen levels were at satisfactory level for the development state of the processes but could yet be improved.

[1] D. Schliephake et al., 2019, *Intermetallics* **104**, 133–142, doi: 10.1016/j.intermet.2018.10.028.

[2] J. H. Perepezko, M. Krüger, and M. Heilmaier, 2021, *Materials Performance and Characterization* **10**, 20200183, doi: 10.1520/MPC20200183.

Evaluation of titanium aluminide powder

A. Kirchner[1,*], B. Klöden[1], M. Franke-Jurisch[1], T. Weißgärber[1,2]

(1) Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, 01277 Dresden, Germany

(2) Institute of Materials Science, Technische Universität Dresden, 01069 Dresden, Germany

e-mail: alexander.kirchner@ifam-dd.fraunhofer.de

As the source material metal powder is affecting competitiveness of powder bed fusion processes in several ways. Its chemical composition and impurities significantly impact the final material. Processability depends on the specific technology used. A certain flowability is necessary for the powder feeding process. Furthermore, the ability to form smooth, uniform, and dense layers is important for reproducible material quality. Also, the process stability is influenced by powder properties. In electron beam powder bed fusion (PBF-EB) very fine, spherical particles are most prone to explosive dispersion due to electrostatic charging. The powder fabrication process to achieve the mentioned properties, possible further conditioning steps and the yield determine the powder price. In operation also the number of permissible powder reuses impacts the economy of the additive manufacturing (AM) process.

The present contribution reports significant changes in powder processability when recycling electrode inert gas atomized titanium aluminide powder used in PBF-EB. Particle size distribution shows a distinct reduction of sub-20 μm particles after the first recycling steps. Characterization using revolution powder analyzer showed a reduction in avalanche angle and surface fractal demonstrating increased flowability. The rheometer enables the direct measurement of forces under different scenarios. For compression and aeration, a clear interpretation is possible. Reduced fraction of fine particles aids compressibility and the flow of fluidized powder. The results show that analytical techniques can help evaluate powder outside the AM equipment and understand process related behavior.

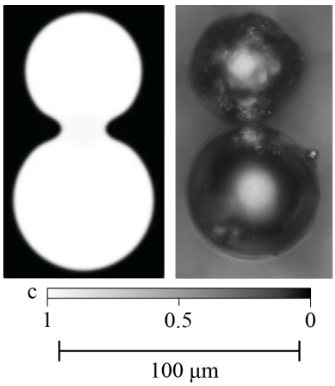
A sintering model for prediction the neck evolution during an EB-PBF process

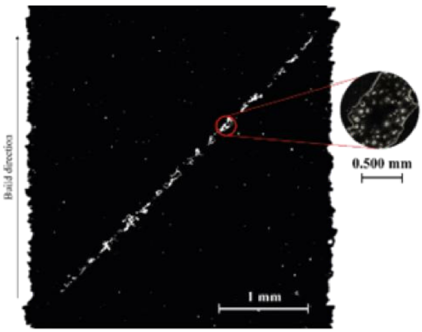
M. Galati*, G. Rizza, P. Antonioni, L. Iuliano

Department of Management and Production Engineering (DIGEP), Integrated Additive Manufacturing center (IAM@PoliTo), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

e-mail: manuela.galati@polito.it

The sintering process occurring during an electron beam powder bed fusion (PBF-EB/M) process is an important mechanism that can control many aspects of the process [1]. Chief among these aspects is the thermal and electrical conductivity of the powder bed. In addition, proper tuning of the sintering mechanism can also support the design and production of complex materials with tuned mechanical properties [2]. Practically, the control of the sintering means the analysis of the neck formation and tracking its evolution over the entire process. This work presents a numerical model using a phase field model combined with a novel definition of thermal load. In particular, the thermal load describes the working conditions during the whole PBF-EB, including the cooling step. The proposed modelling was validated against experimental data obtained by designing an ad-hoc experiment setup when processing Ti6Al4V material powder by EB-PBF. The results showed an excellent agreement between the neck dimension measured at the end of the process. The little deviation was explained by the influence of specific processing conditions, such as delay in sintering start, particle diameter and preheating [3].





[1] M. Galati, L. Iuliano, 2018, *Addit. Manuf.* **19**, 1-20.

[2] E. Bassoli, M. Galati, A. Gatto, L. Iuliano., 2021, National and international patent Priority number(s): 102021000015218.

[3] G. Rizza, M. Galati, L. Iuliano, 2022, *Int. J. Adv. Manuf. Technol.* **123**, 855-873.

KiSSAM 3D simulation of electron beam melting process with adaptive mesh refinement at mesoscale level

A. Zakirov*, S. Belousov, M. Bogdanova, B. Korneev, I. Iskandarova, A. Perepelkina, B. Potapkin

Kintech Lab Ltd., 123298, Moscow, 3rd Khoroshevskaya st., 12, Russia

e-mail: zakirov@kintechlab.com

KiSSAM Simulation Software for Additive Manufacturing (KiSSAM) is a multiphysics simulation software tool designed primarily for high-performance and high-fidelity modeling of metal powder bed fusion (PBF) additive manufacturing processes at the mesoscale level. The core of KiSSAM is based on a powerful and fast hydrodynamic solver for weakly compressible fluids based on the lattice Boltzmann method and has a number of extensions, providing high-fidelity simulation. Underlying physical models implemented in KiSSAM are described in [1].

The software takes advantage of modern Graphical Processing Units (GPU) to deliver significant performance in simulation. Multiscale simulation data is effectively stored using a special hierarchy of grids. Melt pool simulation data with resolution of 3-5 µm is stored in a fine uniform mesh adaptively resizable according to the melt-pool dimensions. Temperature data is stored on an adaptive non-uniform rectilineal "tractile" mesh on the scale of a 3D printing chamber (up to 100 cm^3). The geometry of the powder and melted material is adaptively tracked with the help of the openVDB library [2] and the resulting geometry grids are stored in VDB format with chamber dimensions and resolution of 3-5 µm. Performance of KiSSAM simulation is approximately 1 hour per single track, 10 hours per single layer, 100 hours per volume simulation on a single GPU.

Reasonable simulation time not only of the single track but the single layer and the multilayer simulation significantly widens possible KiSSAM application fields. User cases of KiSSAM usage for the PBF processes simulation are presented. For high-fidelity simulations with the powder, KiSSAM is equipped with a powder generation module based on fast and accurate GPU discrete element method implementation [3] adapted to simulate the powder feeding process in the PBF.

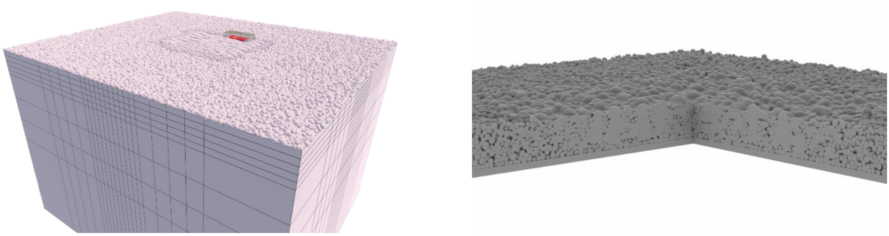


Figure 1: Left: Illustration of the modeled simulation scales. Right: Example of a volumetric build simulation.

[1] A. Zakirov et al., 2020, *Addit. Manuf.* **35**, 101236.

[2] K. Museth, 2013, *ACM Trans. Graph.* **32**, 1–24.

[3] N. Govender, D. Wilke, Sch. Kok, 2016, *SoftwareX* **5**, 62-66.

Powder properties in EBAM: processing impacts and opportunities

W. Sparling[1,2,*], R. Edinger[1,2], C. W. Sinclair[2]

(1) CANMORA TECH Inc., 5930 No. 6 Road, Unit 310, Richmond, BC, V6V 1Z1, Canada
(2) University of British Columbia, 6350 Stores Road Vancouver, BC, V6T 1Z4, Canada

e-mail: will@canmora.tech

Many challenges in EBAM are associated with the properties of the powders used in the process. The thermal properties of the powder bed and its evolution as a result of the thermal cycles present in EBAM processes are not well studied yet influence the thermal boundaries of melt tracks in their geometry, as seen in the extreme case of overhanging features. Likewise, the electrical capacitance of the powder impacts its tendency to smoke, which could cause defects in EBAM parts [1]. Various techniques have been employed to treat powder ahead of the EBAM process and reduce or eliminate smoking [2]. Flowability is likewise a limiting factor in the EBAM process as the raking systems often used in EBAM limit the process to only highly spherical flowable powders. Such powders are often produced through gas atomization or the plasma rotating electrode process. However, these processes are expensive and greatly increase the cost of the powder used in the EBAM process. Alternative feeding mechanisms to rake systems have been shown to be able to feed water atomized powders [3].

This presentation explores recent work done to characterize the thermal conductivity, electrical characteristics, and flowability of powder used in EBAM. Powder processing techniques may improve one or more of these properties, though may also impact the others. The evolution of the thermal conductivity of EBAM powder is studied under controlled sintering conditions. Experimentally derived thermal conductivity is then used to inform thermal models to improve melt track geometry predictions. The electrical response of powders to exposed to a novel treatment method is discussed. Lastly, the properties of parts produced with water atomized powders presented.

[1] Z. Cordero, H. Meyer, P. Nandwana, R. Dehoff, 2017, *Acta Mater.* **124**, 437-445.

[2] A. Chiba, Y. Daino, K. Aoyagi, K. Yamanaka, 2021, *Mater.* **14**, 4662.

[3] C.W. Sinclair, R. Edinger, W. Sparling, A. Molavi-Kakhki, C. Labrecque, 2021, *Mater.* **14**, 3548.

Material properties and industrial applications of EBM-processed high-speed steels, stainless steels, and cemented carbides

P. Arumskog*, U. Beste

VBN Components AB, Verkstadsgatan 8, Uppsala, Sweden

e-mail: par.arumskog@vbncomponents.com

Most metal AM materials are relatively soft, such as Ti and Al alloys for aerospace, Ni and Co base alloys for high-temperature applications, and stainless steels such as 316L. Low-carbon martensitic steels are printed industrially, and printing of tool steels is increasing, but even H13 only reaches a hardness of 55 HRC. Carbide-containing materials possess high hardness but printing these was for long considered impossible, as they tend to crack due to the rapid cooling in most AM processes.

However, as VBN Components demonstrated several years ago, it is possible to print high-C materials using EBM. The vacuum environment ensures stable, or even improved material chemistry, and maintaining the part at elevated temperatures during printing prevents cracking.

Since then, VBN Components has developed and commercially released five different hard AM materials with extreme wear and heat resistance under the brand name Vibenite®. Their hardness ranges from 55 to 72 HRC, and they all contain fine, uniformly distributed carbides in a fine-grained matrix.

The Vibenite® range of high-speed steels contains 7–25 vol% carbides and have hardnesses of 55–72 HRC, with Vibenite® 290 being the world's hardest, commercially available steel. These materials have fatigue properties comparable to PM-HSS and excellent wear resistance. Vibenite® 350 is a stainless martensitic steel with 20 vol% carbides, a hardness of 60 HRC, good corrosion resistance, and 6-7 times better wear resistance than 316L [1].

Vibenite® 480, the world's first commercially available 3D printed cemented carbide, has 65 vol% carbides, a hardness of 67–70 HRC and excellent thermal stability. Combining the hot hardness of hardmetals with the toughness of HSS, Vibenite® 480 out-performs high Cr white iron in wet wear.

Furthermore, new process parameter development has recently resulted in improved material properties. Successful application examples from different fields, such as the energy, tooling, and food industry, will also be presented.

[1] E. Iakovakis, E. Avcu, M.J. Roy, M. Gee, A. Matthews, 2022, *Scientific Reports* **12**, 12554.

On microstructural evolution, heat treatment and mechanical behavior of a tool steel processed by electron beam powder bed fusion

M. Kahlert*, M. Vollmer, T. Niendorf

Institute of Materials Engineering, University of Kassel, Moenchebergstr. 3, 34125 Kassel, Germany

e-mail: kahlert@uni-kassel.de

Steels are the most commonly used materials in industry for high-performance applications and therefore in focus of numerous studies. Thus, it is not surprising that an increased interest in additively manufactured tool parts, e.g. drills and mold inserts with integrated cooling channels, evolved in recent years. The majority of studies on this topic focuses on laser-based AM technologies. However, studies on such materials processed with electron-based AM technologies are still lacking in open literature, although Electron beam powder bed fusion of metals (PBF-EB/M) offers several inherent process advantages for these types of materials. In particular, the electron beam heats the powder bed up to 1000 °C, resulting in slow cooling rates and, thus, to higher ductility and damage tolerance compared to parts produced by laser beam powder bed fusion of metals (PBF-LB/M). In the present study, investigations of AISI H13 (X40CrMoV5-1) tool steel produced by the PBF-EB/M process are presented and discussed. In particular, the microstructures and mechanical properties after processing and after subsequent heat treatments were investigated. Advances characterization techniques such as high-resolution microscopy, scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) and electron backscatter diffraction (EBSD) were used for microstructural characterization, whereas mechanical properties were evaluated by nanoindentation analysis and tensile tests. The results clearly reveal that PBF-EB/M is very promising for the production of complex parts from tool steels.

Local mechanical behavior of super-duplex stainless steels manufactured by E-PBF

C.A. Botero[1,*], S. Roos[1], E. Jiménez-Piqué[2,3], L-E. Rännar[1]

(1) Department of Quality Technology, Mechanical Engineering and Mathematics, Sports Tech Research Center, Mid Sweden University, SE-83125 Östersund, Sweden

(2) Department of Materials Science and Metallurgical Engineering, Universitat Politècnica de Catalunya, Campus Diagonal Besòs-EEBE, Barcelona, 08019, Spain

(3) Barcelona Research Center in Multiscale Science and Engineering, Universitat Politècnica de Catalunya, Campus Diagonal Besòs – EEBE, Barcelona, 08019, Spain

e-mail: Carlos.Botero@miun.se

Super-duplex stainless steels are a special category of stainless steel that besides high corrosion resistance offer high strength, which makes them applicable in the oil and gas, as well as in chemical industries. The duplex designation attends to the dual ferrite-austenite microstructural phase combination which is responsible for their increased strength. Most of the applications for duplex steels are suitable for conventional manufacturing, such as tubing, sheets etc, but there is an upsurge in applications where the end-product is characterized by for example small size, one-off or low-series manufacturing and a complex geometry. For these products, additive manufacturing is a promising manufacturing method that can offer a solution to the challenges above and will also enable minimal waste due to the layer-by-layer approach.

In a current (Swedish) research project called AMUSS, a super duplex stainless steel powder alloy (2507 Osprey Sandvik) is investigated for the EBM process, one of the E-PBF methods available commercially (GE Additive/Arcam AB, Gothenburg, Sweden). Solid cubes and bars were manufactured using different process strategies, and the density as well as the as-built microstructure is characterized on polished and etched specimens by means of optical and scanning electron microscopy. As-built microstructure consist on ferrite, austenite and sigma phases. Microstructural features such as phase fraction and distribution are evaluated and discussed. Nanoindentation tests carried out at different penetration depths and locations of the specimens allowed to investigate the local mechanical behavior of the individual phases as well as their contribution to the overall mechanical behavior of the alloy. Specific heat treatments were applied to the specimens to optimize the microstructure towards final application. The impact of the applied heat treatments on the microstructure and phase-related features, as well as on the micro/nanomechanical behavior of the alloy is finally discussed.

The project "Additive Manufacturing of Super-dUplex Stainless Steels" (AMSUSS) is funded by the Knowledge Foundation, #20200269.

Fatigue properties of a PBF-EB cold work tool steel for gear applications

E. Strandh[1], Å. Gustafson[2], M. Uhlirsch[1], C. Oikonomou[3], M. Åsberg[4], P. Krakhmalev[4], M. Fallqvist[4], P. Alm[5], A. Lindahl[6], A. Strondl[1,*]

(1) Swerim, Isafjordsgatan 28 A, 164 40 Kista Sweden
(2) Scania, 151 87 Södertälje, Sweden
(3) Uddeholm, 683 85 Hagfors, Sweden
(4) Karlstad University, Universitetsgatan 2, 651 88 Karlstad, Sweden
(5) SECO Tools, Björnbacksvägen 10, 737 82 Fagersta, Sweden
(6) Freemelt, Bergfotsgatan 5A, 431 35 Möndal, Sweden

e-mail: annika.strondl@swerim.se

This work was performed in the project ADROAM, Application driven development for increased robustness and reliability utilized in metal additive manufacturing, including development of in-situ monitoring in PBF-EB, process parameter development in PBF-EB as well as mechanical, wear, machinability, and fatigue testing of the manufactured material. The alloy in question was a cold work tool steel and the intended applications are gears for a planetary transmission box and a punch tool, which is used for punching high strength sheet metal. This presentation focus on the fatigue properties of planetary gears evaluated with tooth root bending. Five of these gears are fitted into every heavy-duty vehicle leaving Scania, and test was in accordance with Scania's standard validation methods, analyzing fatigue and material properties in service-like conditions. The material developed and produced by PBF-EB in the project showed in many cases equal or improved properties compared to the conventionally produced material. Where it did not show equal properties was mostly due to pores in non-HIPed samples.

Figure 1: Tooth root bending fatigue testing of a planetary gear.

This work was funded by Sweden's innovation agency Vinnova through SIP Metallic Materials.

Fine-grained and texture-free microstructure of steel AISI 304L obtained by alloy adjustment for electron beam additive manufacturing process

C. Burkhardt[1,*], M. Wendler[2], R. Lehnert[1], M. Hauser[2], O. Volkova[2], H. Biermann[1], A. Weidner[1]

(1) Technische Universität Bergakademie Freiberg, Institute of Materials Engineering, Gustav-Zeuner- Straβe 5, 09599 Freiberg, Germany

(2) Technische Universität Bergakademie Freiberg, Institute of Iron and Steel Technology, Leipziger Straβe 34, 09599 Freiberg, Germany

e-mail: Christina.Burkhardt@iwt.tu-freiberg.de

Powder-bed based processing of austenitic stainless steels often results in a columnar microstructure with strong texture caused by the high temperature gradient. The resulting anisotropic mechanical properties are undesirable for the majority of applications. The present study shows the transition from columnar to fine-grained and texture-free microstructure of austenitic stainless steel AISI 304L via electron-beam powder-bed fusion (EB-PBF) by alloy adjustment. The resulting material properties are discussed on the base of the solidification behavior by means of thermodynamic calculations as well as microstructural investigations and are compared with steel 304L in its standard composition. Tensile tests carried out parallel and perpendicular to build direction revealed an ultimate tensile strength up to 715 MPa and an elongation to fracture up to 70 %. Under monotonic loading, the steel modifications exhibited a high damage tolerance against process-induced defects due to the TRIP (Transformation Induced Plasticity) effect.

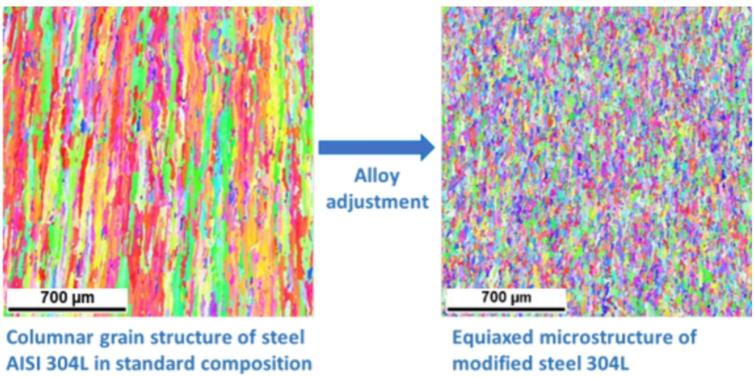


Figure 1: Change from a columnar to a fine-grained microstructure of steel 304L through special alloy design.

Design of alloys for additive manufacturing by efficient combination of experiments, simulation and machine learning

C. Haase

Steel Institute, RWTH Aachen University, Intzstraße 1, 52072 Aachen, Germany

e-mail: christian.haase@iehk.rwth-aachen.de

Additive manufacturing (AM) techniques have gained industrial importance during the last years. In contrast to the AM machines with high technology readiness levels, specific alloys that have been adapted to the AM processing conditions do hardly exist. However, precise adjustment of process and material is necessary to uncover the full potential of AM. It requires the establishment of a methodology to describe and predict the complex process-microstructure-property relationships.

In this presentation, the current state of alloy design for AM will be reviewed critically. Furthermore, the often underestimated/insufficiently considered influence of microstructure heterogeneities on the material properties is discussed [1]. Finally, a comprehensive design approach comprising experimental high-throughput methods, ICME (Integrative Computational Materials Engineering) and machine learning is presented [2, 3]. Based on this methodology, exploration of the high-dimensional AM design space as well as quantification of the process-microstructure-properties relationships becomes feasible.

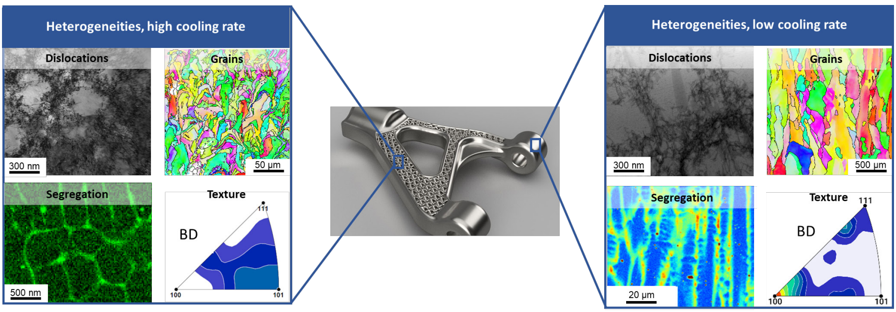


Figure 1: Microstructure heterogeneities in AM metallic components.

[1] T. Allam, K.G. Pradeep, P. Köhnen, A. Marshal, J.H. Schleifenbaum, C. Haase, 2020, *Additive Manufacturing* **36**, 101561.
[2] P. Köhnen, S. Ewald, J.H. Schleifenbaum, A. Belyakov, C. Haase, 2020, *Additive Manufacturing* **35**, 101389.
[3] S. Motaman, F. Kies, P. Köhnen, M. Létang, A. Lin, A. Molotnikov, C. Haase, 2020, *JOM* **72**, 1092-1104.

Alloy design approach for reducing powder-originated gas pores in electron beam powder bed fusion

K. Yamanaka[1,*], S. Aota[1], M. Mori[1,2], J. Adrien[3], E. Maire[3], D. Fabrègue[3], A. Chiba[1]

(1) Institute for Materials Research, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan

(2) National Institute of Technology, Sendai College, 48 Nodayama, Medeshima-Shiote, Natori 981-1239, Japan

(3) INSA-Lyon, UMR CNRS 5510, 20 Avenue Einstein, 69621 Villeurbanne, France

e-mail: kenta.yamanaka.c5@tohoku.ac.jp

Mitigating porosity/defects is essential in metal additive manufacturing. Although process-induced defects (e.g., lack-of-fusion) can be reduced via process optimization, eliminating powder-originated gas pores is a challenge. In this study, porosity in the raw powders and specimens prepared by electron beam powder bed fusion (EB-PBF) was examined in Co−27Cr−6Mo−(0.04−2.5)C (wt.%) alloys [1]. Quantitative X-ray computed tomography clarified a continuous increase in the powder's porosity with the carbon content, as a potential effect of the significant decrease in the liquidus temperature. In contrast, the as-built specimens with 0.04 and 0.22 wt.% carbon contained negligible pores, while a maximum porosity was detected at 2.0 wt.%. Notably, further carbon addition decreased the porosity remarkably. This indicates that migrating smooth solidification front during the cellular/eutectic solidification effectively eliminates gas bubbles from the solidified portion, whereas the complicated solid−liquid interfaces during dendritic solidification entrap gas bubbles. The obtained findings can be extended for alloy design concept towards mitigation of gas pores in EB-PBF.

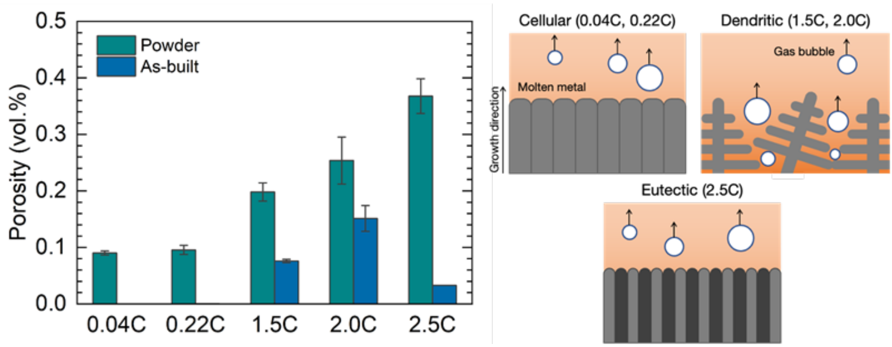


Figure 1: Porosity in the powders and as-built samples as a function of the carbon content.

[1] S. Aota, K. Yamanaka., M. Mori, N. Sasaki, J. Adrien, E. Maire, D. Fabrègue, A. Chiba, 2022, *Addit. Manuf.* **59**, 103134.

The investigation on the evolution of smoking phenomenon in electron beam powder bed fusion process

D. Wang[1], D. Zhao[1,2], X. Liang[1], X. Li[1], F. Lin[1,*]

(1) Department of Mechanical Engineering, Tsinghua University, Beijing, China
(2) Beijing QuickBeam Technology Co., Ltd., Beijing, China

e-mail: linfeng@tsinghua.edu.cn

Smoking is a unique phenomenon in the electron beam powder bed fusion (EB-PBF) process, which stems from the area of interaction between the powders and the electron beam and then rapidly expands outward in an explosive type [1,2]. The far-field effect and rapid expansion of smoking can destroy the powder bed and result the process failure or even equipment damage, which seriously restricts the adoption of EB-PBF. So, it is necessary to investigate the smoking evolution and reveal its mechanism.

The optical & electronic monitoring system was established to observe the smoking evolution and collect its electronic signals. According to the optical images, the smoking evolution can be divided into four stages based on the size and expansion rate of the powder cloud, such as nurture, start, grow and explosion. In each stage, the motion of powder particle and the electronic signal of the powder cloud has different characteristics. The characteristic and mechanism of variant stages in smoking evolution will be discussed. Additionally, a potential approach based on the electronic signal for real-time monitoring and smoking prevention will be proposed as well.

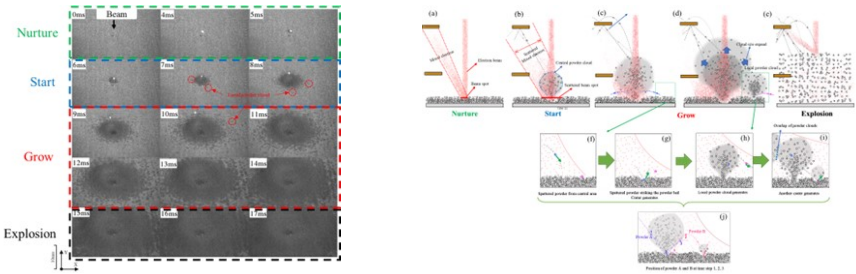


Figure 1: High-speed photographic images and schematic illustration of smoking evolution.

This research is supported by the NSFC-DFG Joint Research Program (52061135113).

[1] MF. Zäh, M. Kahnert, 2006, EuroRapid2006, Frankfurt/Main, 27.

[2] J.Milberg, M.Sigl, 2008, *Prod. Eng. Res. Devel.* **2**, 117-122.

Minimization of electron beam drift during deflection in additive manufacturing

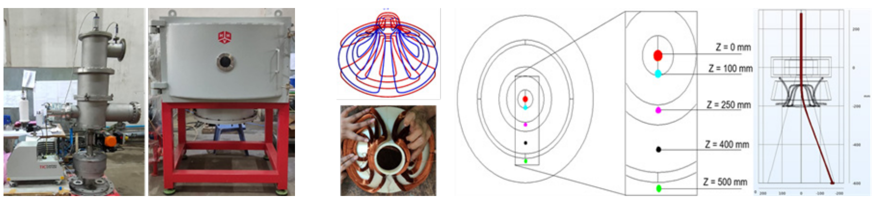
A. K. Mehta[1,*], A. Moon[1], G. D. Gote[1], A. Guram[1], Y. Mittal[1], V. Puttige[2], G. T. Reddy[3], V. N. Ramani[3], K. P. Karunakaran[1]

(1) Indian Institute of Technology Bombay, Powai-400076, Mumbai, Maharastra, India
(2) Amace Solutions, Peenya Bengaluru-560058, Karnataka, India
(3) Plasma and Vacuum Technologies, GIDC kathwada-382430, Ahmedabad, Gujarat, India

e-mail: avinashkumarmehta1993@gmail.com

Powder-Bed Fusion (PBF) is a popular Additive Manufacturing (AM) approach for complex and precise parts. While laser hitherto has been popular for all materials, Electron Beam (EB) is more promising for metals due to its minimal residual stress, versatility in material and operations, high energy efficiency and productivity, and low impurity. The positioning and shaping of EB, at the powder bed, are achieved through a magnetic field system. Precise deflection of EB is challenging because of the interfering magnetic fields, which cause aberration. Therefore, the deflection coil's design is crucial for the precise functioning of PBF-AM using EB.

In this work, a high-frequency deflection system has been developed to rapidly scan the powder bed at an angle of ±15° with minimal drift. For this, a complex saddle pole geometry has been used for further refining using an iterative approach. The iterations have been performed using COMSOL Multiphysics by analyzing the EB trajectory along equally spaced planes parallel to the bed. The deflection coil has been designed for in-house developed Electron Beam Additive Manufacturing (EBAM) machine. Figure 1 shows different parts of the EBAM machine along with the optimized deflection coil and its results. This coil is able to cope with the beam drift problem and able to produce a nearly circular beam of approximately 1 mm diameter within the radial distance of 150 mm from the center of the bed.



(a) EB Gun and Chamber

(b) Optimised Deflection coil design and its results

Figure 1: Electron Beam Additive Manufacturing Machine under Development at IIT Bombay.

A high-speed modulating electron source (HSES) for EBM

T. Goto[1,*], K. Higuchi[1], N. Iijima[1], K. Abe[1], K. Shimada[1], K. Takahashi[1], R. Sato[1], J. Matsui[1], Y. Naramoto[1], K. Yano[1], A. Yamada[1], B. Poorganji[2], M. Ishikawa[1]

(1) Nikon Corp., Shinagawa Intercity Tower C, 2-15-3, Konan, Minato-ku, Tokyo 108-6290, Japan

(2) Morf3D Inc., 821 N Nash St., El Segundo, CA 90245, USA

e-mail: Takakuni.Goto@nikon.com

Electron beam melting (EBM) is attracting attention as a means of manufacturing high-quality parts such as turbine blades and artificial joints due to the unique characteristics of the modeling environment and heat source. As a result, the equipment of EBM has achieved rapid development [1]. Also, the manufacturing process technology is evolving by devising a scanning strategy that utilizes the preheating capability and ultra-high-speed deflection of the electron beam. For example, it is now a well-known fact that it is possible to control the crystal structure from single crystals with extremely small misorientation compared to casting equiaxed crystals [2]. In order to make further improvements of the process quality and broaden the scope of application it is necessary to overcome difficult issues such as dealing with materials that are difficult to print and have sophisticated solidification behavior, complicated shapes and geometries including cavities with improved surface precision, and homogenizing the internal crystal structure. To address these issues, in our opinion, it is necessary to control the sub-millisecond scale dynamics of heat conduction, heat radiation, convection, evaporation, etc. that occur simultaneously in the melt pool. As far as we understand, current methods for controlling heat input values are based on modulating scanning speed and/or dwelling time with constant beam power [2,3]. We think that one of the ways to achieve the more active control of the mixture of the above-mentioned thermodynamic behavior is to increase the degree of freedom of heat input values, which is enabled by high-speed modulation of beam power and beam diameter. Based on this idea, we are working on the development of a high-speed modulation electron source (HSES) that can modulate the beam power and beam size on a microsecond scale. The functions of HSES will remarkably contribute to the further development of the scan strategies. Here, we introduce the concept of the HSES and the verification results of the prototype.

[1] Z. Fu and C. Körner, 2022, *Eur. J. Mater.* **1:2**, 54-117.

[2] J. Pistor and C. Körner, 2021, *Sci. Rep.* **11(1)**, 24482.

[3] A. T. Polonsky, N. Raghavan, M. P. Echlin, M. M. Kirka, R. R. Dehoff and T. M. Pollock, 2022, *Mater. Charact.* **190**, 112043.

Wire-based additive manufacturing using electron beam to process advanced materials

N. Enzinger*, F. Pixner, F. Warchomicka, R. Paiotti

Institute of Materials Science, Joining and Forming, Graz University of Technology, Kopernikusgasse 24/I, 8010 Graz, Austria

e-mail: Norbert.Enzinger@TUGraz.at

Wire-based electron beam additive manufacturing (EBAM) is a direct energy deposition technique to produce near-netshape geometries. The required vacuum atmosphere, in combination with a high-power electron beam as a very dynamic heat source with enormous energy density, enables processing and fabrication of additive manufactured structures consisting of advanced materials and alloys with superb properties, which are difficult or even impossible to process by conventional techniques. This work overviews the processing, post-treatment and characterization of titanium alloy Ti-6Al-4V, refractory metal tungsten, nickel-based superalloys, and Ni-rich NiTi shape memory alloy, with reference to characteristic features and current as well as future applications. Each material presents specific challenges to optimize the process, microstructure and resulting mechanical properties. The deposition strategy combined with contactless temperature monitoring enables the development of different tailor-made solutions to obtain high-performance manufactured components utilizing the special properties of the particular materials.

Towards graded porosity structures by spatial control of the scanning speed in electron beam powder bed fusion (PBF-EB)

A. Margueret*, G. Croset, G.Martin, P. Lhuissier

Univ. Grenoble Alpes, CNRS, Grenoble INP, SIMaP, Grenoble F-38000, France

e-mail: alexandre.margueret@grenoble-inp.fr

Additively manufactured parts often suffer from the presence of defects such as pores. Most studies in the AM field aim at suppressing or minimizing defect density. However, fabricating components with a mesoscale-controlled porosity might be of interest in biomedical applications. Here, we investigate the possibility to process porosity-graded materials using PBF-EB. To this end, we spatially control the beam velocity by taking advantage of the possibilities offered by the Freemelt ONE device. This system can be qualified as open source as it offers full control of the beam and scanning strategy. We first deployed a design of experiments (DOE) where the scanning speed was varied to deliberately produce Ti6Al4V samples with various levels of porosity (between less than 0.05 and up to 10 %. For a beam power set to 270 W, the beam velocity leading to dense samples (relative density >99.9 % is consistent with the one identified on a commercial A1 ARCAM machine. Based on the preliminary DOE allowing the identification of the processing window to fabricate porous samples, various samples exhibiting a controlled gradient in porosity have been produced and characterized using X-ray Computed Tomography (XCT). We show that local control of the scanning speed allows the production of controlled porosity-graded samples. Porosity-graded samples were generated in the building plane as illustrated in Figure 1 and along the building direction.

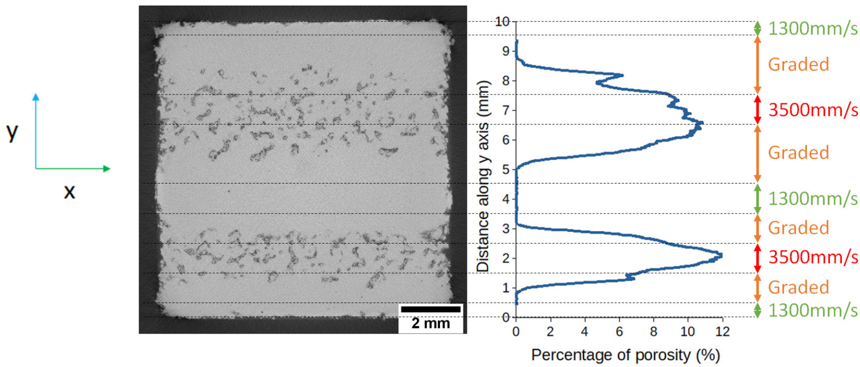


Figure 1: Cross-section obtained by X-ray micro-computed tomography for a porosity-graded sample in the building plane and the corresponding percentage of porosity evolution (melting scanning speeds are given, melting power remained constant equal to 270 W).

The impact of recycling on Ti6Al4V powder particles for the electron beam melting process

S. Franchitti[1], C. Bellini[2], F. Berto[3], R. Borrelli[1,*], V. Di Cocco[2], F. Iacoviello[2], L. Mocanu[2]

(1) CIRA – Italian Aerospace Research Centre, Via Maiorise snc, Capua (Ce), Italy
(2) Department of Civil and Mechanical Engineering, University of Cassino, Via G. Di Biasio 43, Cassino (Fr), Italy
(3) Department of Chemical Engineering, Materials and Environment, La Sapienza University of Rome, Piazzale Aldo Moro 5, Rome, Italy

e-mail: r.borrelli@cira.it

The possibility of reusing powders for several build jobs makes the Electron Beam Melting (EBM) process a particularly green technology, allowing material waste to be reduced with respect to traditional manufacturing process, which is extremely important in the context of sustainable manufacturing. However, the recycled powder has different chemical-physical characteristics from virgin powder, hence an issue of significant current interest is to understand how powder recycling affects the quality of the feedstock in an EBM process. Most of the studies that have been performed on the powder recyclability indicate that the EBM process affects the powder more than expected, due to the preheating stage and exposure of the build to quite high temperatures for long times. Recycling can affect many of the powder characteristics such as chemical composition, microstructure, surface morphology (surface roughness, particle roundness) and the physical properties (flowability, particle size distribution, etc.). Although it is generally accepted that the quality of the powder plays a major role in the quality of EBM manufactured parts, this topic still needs research as the influence of recycling on the powder characteristics is not fully understood and setting a limit to the number of allowed recycles can potentially impact the cost-effectiveness of EBM-made parts. In this study the effect of recycling on the physical/chemical properties of Ti6Al4V powder produced by plasma atomization, was investigated. In particular virgin and recycled powder were characterized in terms of chemical composition, morphology, microstructure, particle size distribution, apparent and skeletal density and fluxability.

This research was funded by CIRA in the framework of PRORA, the national (Italian) aerospace research programme, of which the TEAM project is part.

[1] H.P. Tang, M. Qian, N. Liu et al., 2015, *JOM.* **67**, 555-563.
[2] Y. Cao, M. Delin, F. Kullenberg, L. Nybor, 2019, *Surf. Interface Anal.* **52**, 1066-1070.

Process monitoring with image data for EBM additive manufacturing of Ti6Al4V alloy

L. S. B. Fontolan*, G. B. Nunes, T. Franco de Moraes, M. Fernandes de Oliveira, P. Y. Noritomi

Renato Archer Information Technology Center, Dom Pedro 1 Highway Km 143,
BR-13069901 Campinas, SP, Brazil

e-mail: lfontolan@cti.gov.br

The Renato Archer Information Technology Center (CTI Renato Archer) is a Brazilian research center located in Campinas, state of São Paulo. The 3D printing Open Lab (LAprint) supports academic and industrial research with additive manufacture techniques such as SLS, FFF, EBM, Polyjet, Binderjet, Waxjet. Due to the flexible demand in the research context, any standardization is rather efficient when focused on the process and monitoring, in contrast to emphasizing specific models or geometries. In-situ monitoring of the AM process on Arcam EBM technology is carried out using the LayerQamTM system embedded on the Q10 Plus machine variant. The use of image data to compare internal structure defects related to porosity and swollen regions can infer quality control criteria for parts manufactured [2]. The images collected during build fabrication were used for the reconstruction of 3D models with the InVesalius Software, a free software developed by our group and currently employed for generating 3D models from MRI and CT scans [1]. The build images dataset was subject to reducing, filtering or further worked using InVesalius tools to reduce computational demand. Preliminary data shows the effective reconstruction of 3D models, those files can provide clues to part quality and increase the credibility of the laboratory AM services.

This study was funded by Conselho Nacional de Pesquisas (CNPq).

[1] Raplee, J., Plotkowski, A., Kirka, M., Dinwiddie R., Okello A., Dehoff R. R., Babu S. S., 2007, *Sci Rep* **7**, 43554.

[2] Amorim, P. H., Moraes, T. F., Da Silva, J. V. L., Pedrini, H., 2015, *Adv in Vis Comput* **ISVC 2015**, 45-54.

Fatigue performances of EBM Ti6Al4V, comparison across surface finishing and thermal treatments on Arcam Q10+ platform

R. Toninato[1,*], M. Petruzzi[1], A. Lanzutti[2], F. Sordetti[2], E. Sbrizzi[2], L. Fedrizzi[2], M. Pressacco[1]

(1) LimaCorporate S.p.A., Via Nazionale 52 (33038) Villanova [UD], Italy

(2) Università degli Studi di Udine, Via delle Scienze 206 (33100) Udine, Italy

e-mail: riccardo.toninato@limacorporate.com

E-PBF additive technologies rely on relatively short industrial history if compared to traditional production processes. Data on new platforms for fatigue behavior and material characterization, which are fundamental for structural design of AM components [1], are still lacking. This study aims to find the fatigue limit of Ti6Al4V specimens, manufactured via GE Arcam Q10+ with EBMC 6.1.14.0.

Five batches of 25 samples each have been produced, which conditions are defined as follows: as-built "N", machined "NT", netted TT® "R", HIPped as-built "H", HIPped and machined "T". The specimens are compliant to ASTM E466-15 and uniaxial fatigue tests have been conducted at the University of Udine. The tests protocol uses a R=.1 stress ratio following a 5-pairs staircase approach [2]. Infinite fatigue life is defined upon reaching 10^7 cycles. Further collected data: fracture surfaces, surface roughnesses, microstructures, CT-scans.

The comparison of the results is expressed dimensionless, using the "N" condition as baseline. The relations between the five lots are: NT=240 %N; R=90 %N; N≈H; T=340 %N. Roughness surface data show an average Ra for as-built samples 32 times higher compared to the average Ra for machined samples. Porosity analysis shows how the majority of internal defects are gas pores, with a small quantity of flat elongated lack of fusion flaws.

The stronger dependency of σ limit is correlated to the surface characteristics rather than HIPping, for as-built samples. However, HIPping raises fatigue performances on machined samples (+240 %), since roughness becomes a less critical parameter. Here a major influence of internal defects in fatigue resistance has been found. The presence of a TT® lattice ring doesn't play a structural role positioning the fatigue results close to as-built condition. Those results are strongly dependent on the process parameters (internally developed in LimaCorporate). Further projects will be performed in order to extend fatigue testing to L-PBF technology and to develop analytic tools to predict the fatigue limit leveraging surface and volumetric data.

[1] A.H. Chern, P. Nandwana, C.E. Duty, 2019, *International Journal of Fatigue* **119**, 173-184.

[2] L. Sheng-Li, L. Young-Li, L. Ming-Wei, 2001, *International Journal of Fatigue* **119**, 75-83.

Additive manufacturing of high-entropy alloys with EBM

A. Chiba*, K. Yamanaka, K. Aoyagi, Y. Cui, C. Yang

Institute for Materials Research, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan

e-mail: akihiko.chiba.d3@tohoku.ac.jp

"High Entropy Alloys" (HEAs) have been attracting much attentions because of their potential exceptional mechanical properties, such as high strength, good ductility, and superior fracture toughness at cryogenic temperatures. However, HEAs are not always ductile and some of these alloys show poor deformability due to the formation of brittle intermetallic compounds. From the viewpoint of manufacturing HEAs, since they are composed of many elements, conventional processing methods such as melting and casting cause elemental segregation and microscopic and/or macroscopic solidification defects. The problem is that it tends to be a heterogeneous microstructure including coarse grains and solidification defects. Therefore, the current situation is that processing methods based on existing technologies have problems such as restrictions on the selection of alloy compositions when developing new HEAs. Therefore, there is a limit to the selection of alloy composition in developing new HEAs in processing methods based on existing technology.

Electron beam additive manufacturing (EBAM) can manufacture parts with complex shapes regardless of the melting point of metal alloys. Moreover, the obtained microstructure can be expected to have a uniform and fine structure because the ultra-rapid melting and solidification effect peculiar to metal additive manufacturing especially with the powder bed fusion type can be exhibited. The EBAM, a powder-bed-fusion additive manufacturing technology is considered to have a high possibility as a processing method that can avoid the above-mentioned problems inherent to HEAs (segregation, coarse microstructure, solidification defects, etc.).

In this talk, microstructures, mechanical properties, and corrosion behavior of an equiatomic AlCoCrFeNi HEA will be presented as an typical example of HEA fabricated by using EBAM and will be compared with those of a conventionally cast specimen. Microstructural observations revealed that both cast and EBM specimens consisted of a nano-lamellar mixture of disordered body-centered-cubic (BCC) and B2 (ordered BCC) phases. Notably, the EBM process realized rapid solidification during fabrication, resulting in finer grains than those in the cast counterparts.

Refractory high-entropy alloys (RHEAs) composed of high-melting-point elements with a body-centered cubic solid solution structure are attracting attention as next-gene-ration high-temperature structural materials due to their excellent performance. However, the low ductility characteristic of RHEA makes it difficult to further fabricate complex-shaped components for RHEA using conventional processing methods. In addition, since RHEA has a strong tendency of elemental segregation, it is difficult to remove the elemental segregation generated in the casting process only by post heat treatment. Therefore, by effectively utilizing the ultra-high-rate solidification process of EBAM, it is possible to produce parts without elemental segregation by exerting the solute trapping effect. The present talk introduces the possibility of EBAM technology as a manufacturing process for the HfMoNbTaTi RHEA, which is expected to be an ultra-high temperature heat resistant material.

Functional properties of as-built electron beam-based powder bed fusion NiTi

A. Fink[1,*], Z. Fu[1], C. Körner[1,2]

(1) Advanced Materials and Processes, Friedrich-Alexander-Universität Erlangen-Nürnberg, Dr.-Mack-Str. 77, 90762 Fürth, Germany

(2) Chair of Materials Science and Technology for Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

e-mail: alexander.fink@fau.de

Nitinol (NiTi) is characterized by its unique functional properties. The alloy is able to restore the original shape after deformation when the temperature rises. Besides the shape memory effect, superelastic properties as well as a two-way shape memory effect can be found in NiTi. These functional properties are adjustable when varying the Ni-content and controlling the microstructure of the alloy [1] The combination of NiTi with Additive Manufacturing (AM) opens up a new field allowing near-net shape manufacturing. The commonly used AM process for NiTi is Laser Powder Bed Fusion. However, problems of crack formation due to residual stresses or embrittlement due to the oxygen pickup were observed. [2] The high preheating temperatures during Electron Beam Powder Bed Fusion (PBF-EB) can suppress this crack formation [3]. This study displays the progress of producing Ti-rich NiTi on a freely programmable EB-PBF machine Freemelt One. Moreover, it covers the generation of a process map using Electron-optical observation (ELO) and conventional methods (see Figure 1) as well as an analysis of the thermo-mechanical and functional properties using a Gleeble 3500. The aim is to understand the interaction between process parameters, microstructure, and functional properties of PBF-EB as-built NiTi.

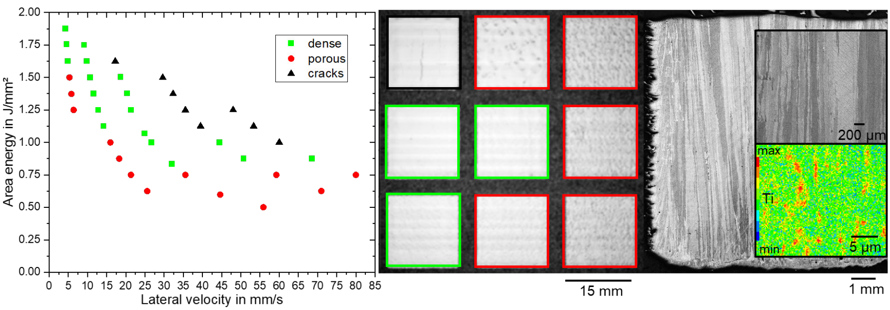


Figure 1: Generation of a PBF-EB NiTi process map using ELO-imaging and metallographic analysis.

This project is funded by the DFG (German Research Foundation) - 432515505.

[1] JV. Humbeeck, 2001, *Adv. Eng. Mater.* **11**, 837-850.

[2] M. Elahinia, NS.Moghaddam, RF. Hamilton, 2016, *Prog. Mater. Sci* **83**, 630-663.

[3] Q. Zhou, MD. Hayat, P. Cao, 2019, *Mater. Sci. Eng. A* **744**, 290-298.

Wire-based electron beam additive manufacturing of copper

A. Zamorano Reichold*, B. Baufeld

pro-beam additive GmbH, Gilching, Germany

e-mail: alejandro.zamorano@pro-beam.com

Additive manufacturing of pure copper is facing challenges due to high thermal conductivity, reflectivity and oxide formation. The electron beam as an energy source is superior to the laser beam to overcome these challenges due to a high energy input with high efficiency and operating in high vacuum.

Pro-beam additive GmbH researches various applications demanded by different markets providing Wire Electron Beam Additive Manufacturing (WEBAM) to achieve non-porous copper components with high deposition rates of up to 2 kg/h. Examples for achieved geometries are walls, cylinders/ half-shell with cylinder, hemispheres, and cones with wall thicknesses between 3 and 8 mm. A 22 kg rocket propulsion mockup with a height of 650 mm and a maximum diameter of 295 mm was built with a deposition rate of 2 kg/h, resulting in a perfect surface quality so that machining is not absolutely necessary. For this, the average power was 2 kW.

WEBAM has been successfully used to produce bimetallic components with an excellent bonding, such as steel bowl with outer copper rings or a copper overlay on a prefab steel ring. The team has also succeeded in producing copper geometries such as walls or tubes on a copper baseplate.

It has been proved that components made of pure copper 99.99 % have excellent electrical conductivity with values comparable to the international standard for annealed copper (IACS). Here, the Vickers hardness depends on the local grain size and ranges from 60 HV to 90 HV, which corresponds to traditionally manufactured copper components. Tensile strengths of up to 220 MPa and a high elongation at break of more than 35 % have been demonstrated.

Together, high mechanical properties and high electrical conductivity indicate the high quality of WEBAM components and their successful industrial use.

Modeling and simulation of in-situ alloying during electron beam powder bed fusion using elemental powders of Cu and Cr

R. Scherr*, M. Markl, C. Körner

Chair of Materials Science and Engineering for Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

e-mail: robert.scherr@fau.de

Electron beam powder bed fusion (PBF-EB) is a highly complex manufacturing method due to the stochastic influence of the powder bed and an interplay of physical phenomena like beam absorption, phase changes, fluid dynamics and heat conduction. This work adds a new degree of freedom to the process by addressing the transition from processing a single alloy powder to a mixture of different elemental powders, which is termed as in-situ alloying.

For a better understanding, especially in terms of consolidation and liquid phase mixing, simulations are powerful tools. Therefore, we extended the in-house developed simulation software SAMPLE2D (Simulation of Additive Manufacturing on the Powder scale using a Laser or Electron beam) [1] by additional physical effects like diffusion [2], enthalpy of mixing and the concentration-dependent Marangoni convection.

Numerical predictions for the processing of elemental powder mixtures were validated using PBF-EB experiments with a powder blend of 25 wt.-% Cr and 75 wt.-% Cu (see fig. 1). The simulation software was then used to analyze process strategies for the optimization of the compositional homogeneity. Selected numerical and experimental results will be presented in this talk.

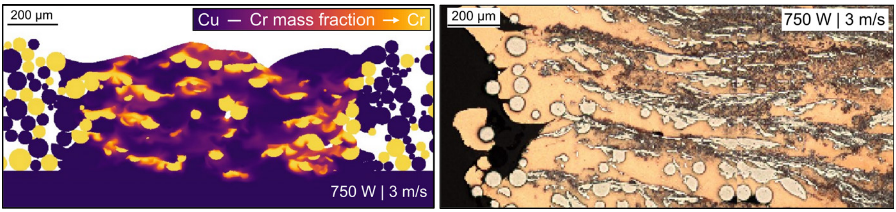


Figure 1: Comparison between the numerical and experimental composition distribution of CuCr25 after processing the respective elemental powder mixture via PBF-EB.

[1] M. Markl, A. Rausch, V. Küng, C. Körner, 2019, *Adv. Eng. Mater.* **22**, 1901270.

[2] V. Küng, R. Scherr, M. Markl, C. Körner, 2021, *Comput. Mater. Sci* **194**, 110415.

High-power E-PBF processing of dense and crack-free tungsten

A. Balachandramurthi*, U. Ackelid

Freemelt AB, Bergfotsgatan 5A, 43135 Mölndal, Sweden

e-mail: arun.balachandramurthi@freemelt.com

Tungsten finds many demanding applications thanks to its unique physical and chemical properties, such as high melting point, high density, high X-ray absorption, high tensile strength, etc. Due to the poor machinability of tungsten, there is an increasing interest to fabricate tungsten parts from powder, using additive manufacturing. However, Laser Powder Bed Fusion (L-PBF) has proven difficult due to the high ductile-to-brittle transition temperature of tungsten. Tungsten built with L-PBF is prone to cracking [1,2].

Electron Beam Powder Bed Fusion (E-PBF) has two distinct advantages useful for tungsten: elevated powder bed temperatures and a high vacuum environment preventing oxygen pickup [2,3]. In this study, we demonstrate crack-free tungsten processing above 1000 °C, and explore innovative E-PBF melting beyond the traditional hatch strategy. We show how microstructure, porosity and material properties are affected by various e-beam scanning patterns, and we discuss how to reach maximum build rate. Video material recorded in a Freemelt ONE system will be used for illustration.

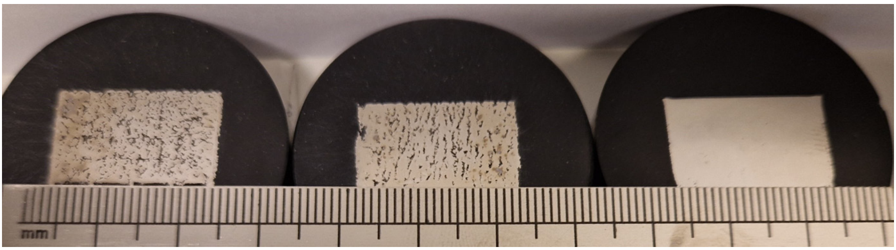


Figure 1: Tungsten cross-section specimens built in Freemelt ONE, showing random porosity (left), chimney porosity (middle), and full density (right).

[1] J. Li, Y. Wu, B. Zhou and Z. Wei, 2021, *Materials* **14**, 165.

[2] J. Wright, 2020, "Additive Manufacturing of Tungsten via Selective Laser Melting and Electron Beam Melting", PhD thesis, Univ. of Sheffield.

[3] G. Yang, P. Yang, K. Yang, N. Liu, L. Jia, J. Wang, H. Tang, 2019, *Int. J. Refract. Hard. Met.* **84**, 105040.

Zero-waste additive manufacturing via big data mining, modeling and monitoring: opportunities and challenges

B. M. Colosimo*, M. Grasso

Department of Mechanical Engineering, Politecnico di Milano, Italy

e-mail: biancamaria.colosimo@polimi.it

In the last years, a wide and rapidly growing literature has been devoted to in-situ sensing, monitoring and control of metal additive manufacturing (AM) processes, especially in the field of powder bed fusion technologies. However, the range of methods and solutions available for electron beam powder bed fusion (EB-PBF) is still quite limited compared to the large number of studies and industrial toolkits in laser powder bed fusion (L-PBF) [1]. Indeed, the EB-PBF process imposes some additional challenges in terms of in-process measurements (e.g. the need of protection from metalization and x-ray emissions, the very high chamber temperatures, etc.), although it also enables process signatures that are not available in other processes (e.g., back-scattered electron imaging). This study explores the current state of the art on in-situ and in-line monitoring of the EB-PBF process. It provides examples of solutions that combine statistical and machine learning techniques with different in-situ sensing architectures for a fast, automated and robust detection of anomalies while the part is being built [2, 3].

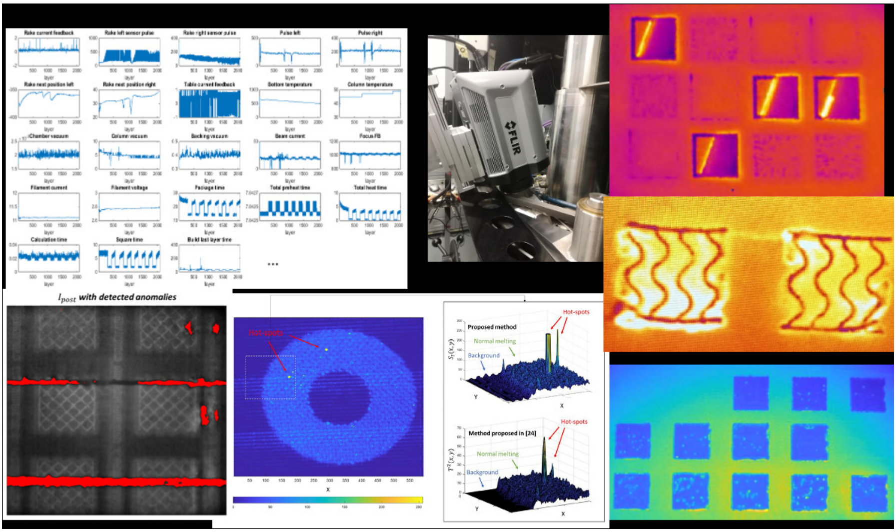


Figure 1: An overview of in-situ monitoring methods in EB-PBF.

[1] Grasso, M., Remani, A., Dickins, A., Colosimo, B.M., Leach, R.K., 2021, *Meas. Sc. & Tech.* **32(11)**, 112001.

[2] Grasso, M., 2021, *Materials* **14(22)**, 7015.

[3] Grasso, M., Valsecchi, G., Colosimo, B.M., 2020, *Manuf. Letters* **24**, 47-51.

Electron optical imaging with multi-detector systems for process monitoring and control applications

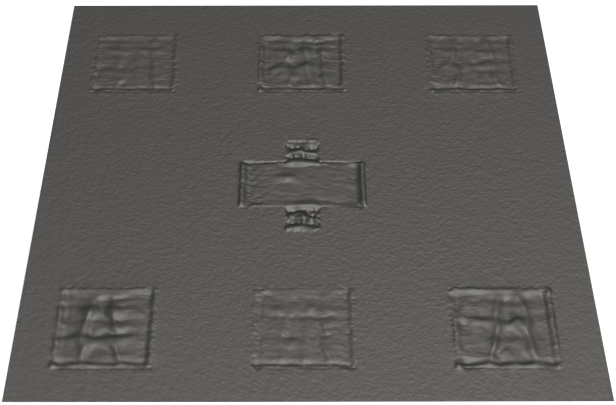
J. Renner*, M. Markl, C. Körner

Chair of Materials Science and Engineering for Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

e-mail: jakob.renner@fau.de

Electron Optical (ELO) imaging is a prominent process monitoring method in Electron Beam Powder Bed Fusion (PBF-EB). The build surface is imaged with a focused, low-power electron beam by scanning the build surface. Single detectors systems can assess porosity reliable, but local surface bulging can be determined only qualitatively [1]. Multi-detector ELO systems view the build surface from several directions. We present an algorithm which allows to reconstruct the surface topography of the build surface by building on the work of the Scanning Electron Microscope community. The algorithm is tailored to the geometrical conditions in PBF-EB machines [2]. We show that it is possible to obtain a quantitative measurement of the local height of the build surface for every layer during a build process. In addition, the locally varying material contrast can be computed by the sum of ELO images of opposite detector pairs. First applications of surface topography and material contrast in PBF-EB processes are presented in the context of process monitoring and control.

Surface topography



This work is funded by CRC-814, Project B2, German Research Foundation

[1] C. Pobel, C. Arnold, F. Osmanlic, Z. Fu, C. Körner, 2019, *Materials Letters* **249**, 70-72.

[2] J. Renner, C. Breuning, M. Markl, C. Körner, 2022, *Additive Manufacturing* **60**, 103172.

In-situ inclusion detection, with material characterization, using backscattered electron imaging in an electron beam powder bed fusion process

M. Gardfjell[1], M. Reith[1,*], M. Franke[1], C. Körner[2]

(1) Neue Materialien Fürth GmbH, Dr.-Mack-Str. 81, 90762 Fürth, Germany
(2) Chair of Material Science and Engineering for Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

e-mail: marcel.reith@nmfgmbh.de

Electron Beam Powder Bed Fusion (PBF-EB) is an AM method that utilizes an electron beam to melt and consolidate metal powder. The beam, combined with a backscattered electron detector, enables advanced processes monitoring, a method termed Electron Optical Imaging (ELO). ELO is already known to provide great topographical contrast, but its capabilities regarding material contrast are less studied. In this article the extents of material contrast in ELO are investigated, focusing mainly on identifying powder contamination. It will be shown that an ELO detector is capable of distinguishing a single 100 µm foreign powder particle, during an PBF-EB process. Additionally, it is investigated how the material contrast can be used to infer material characterization. This article provides the mathematical framework required to describe the relationship between the signal intensity in the detector and the effective atomic number of the alloy. The approach is verified with empirical data from ten different materials, demonstrating that the effective atomic number of an alloy can be predicted within 0.878 atomic numbers, for specimen with polished surfaces and sufficient size. For inclusions, with as-built surface roughness and small dimensions (< beam diameter), the same approach is found to be less accurate. Nevertheless, merely detecting a single foreign powder particle in an PBF-EB process is remarkable and serves as an indicative of the potential of ELO as a process monitoring tool.

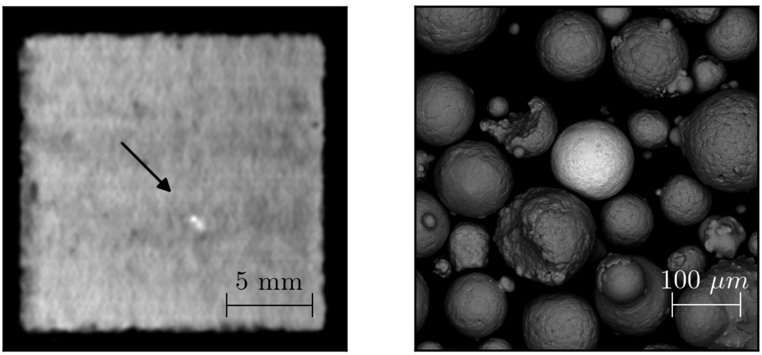


Figure 1: An ELO image of a cube with an inclusion and a SEM image of a contaminated powder particle.

Real-time EBeam printing defects classification using deep learning analyses of electron optical monitoring images

L. Le Roux*, S. Bigot

School of Engineering, Cardiff University, Cardiff CF24 3AA, UK

e-mail: lerouxl@cardiff.ac.uk

Metal Additive manufacturing (AM) processes, such as EBeam, are prone to defects that can be hidden in the created parts due to a certain lack of maturity. Although online monitoring techniques that rely on the evaluation of each printed layer can be used to detect some of these defects during fabrication.

This research work focused on the development of a deep learning model capable of assessing real-time the quality of parts produced by EBeam printing, using Electron Optical (ELO) monitoring images of each layer, thus providing useful feedback to a printer operator and allowing decision-making during the printing process.

In a precedent paper, a deep learning model was proven effective for the classification of large areas (15 mm by 15 mm) of ELO monitoring images into 3 categories (porous, bulging, and ideal), achieving a classification accuracy of more than 95 %. The research work presented in here expands this previous achievement by making it capable of classifying smaller areas of powder bed images (5 mm by 5 mm) into 5 categories (porous, bulging, ideal, edges and powder bed), thus enabling a finer classification of parts with complex shapes. The classification results for all powder bed areas can be presented in a single view, as shown in Figure 1, providing a machine user with a clear view of each printed layer quality prediction.

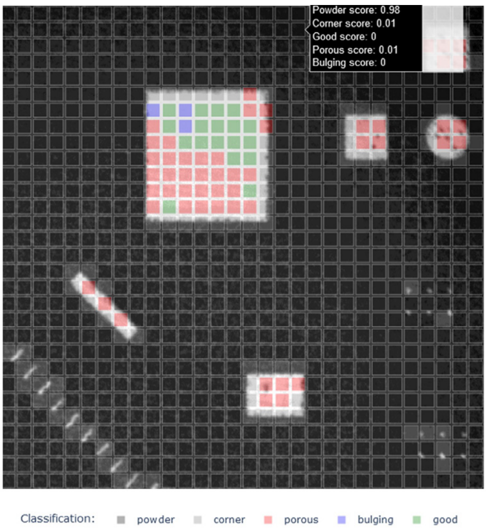


Figure 1: Image classification.

Defect detection using near-infrared images in Ti-6Al-4V manufactured by electron beam powder bed fusion

K. Thalavai Pandian[1,*], E. Lindgren[1], M. Neikter[1], A. Ganvir[2], C. Brochs[3], T. Hansson[1,2], R. Pederson[1]

(1) University West, Department of Production Technology, SE-461 86 Trollhättan, Sweden
(2) GKN Aerospace Engine Systems, SE-461 38 Trollhättan, Sweden
(3) AIM SWEDEN AB, SE-832 56 Frösön, Sweden

e-mail: karthikeyan.thalavai-pandian@hv.se

Electron beam powder bed fusion (PBF-EB) is one of the well-established additive manufacturing processes to manufacture Ti-6Al-4V components. Still, there are several challenges in the PBF-EB process to build defect-free complex components for fatigue-critical applications. To identify potential defects in PBF-EB built components, one can employ different techniques to capture information from the build. Obtaining in-situ near-infrared (NIR) images from the build is one such technique broadly used to potentially assess the quality of the build. The images taken at each layer are then stacked to form a 3D model of the intensity variation and further analyzed (e.g. segmented) to reveal potential defects. In this study, samples were manufactured with pre-designed defects in the size range of natural defects and embedded in the build geometry. Later, the NIR image intensity variation between unmelted powder and solid geometry was analyzed using image processing algorithms to identify the spatial distribution and morphology of pre-designed defects. In addition, X-ray computed tomography (XCT) was employed post-build to obtain the position and shape of the pre-designed defects. A qualitative and quantitative comparison between the two datasets was conducted, and a scaling factor between the two measurement methods was derived with the XCT data as the calibration dataset. The scaling factor was then utilized to explore the potential of utilizing the NIR image data to also detect potential naturally occurring process defects.

This research work is funded by VINNOVA, through the "Nationella flygtekniska forskningsprogrammet 7" (NFFP) (project #: 2019-02741).

Abstracts for Poster Presentations

The interplay between process parameters and solidification structures of a Cu-Cr hypereutectic alloy using electron beam re-melting experiments

L. Varoto[1,2,*], J-J. Blandin[2], S. Roure[1], A. Papillon[1], M. Chosson[1], G. Martin[2]

(1) Schneider Electric Industries, F-38000 Grenoble, France

(2) Univ. Grenoble Alpes, CNRS, Grenoble INP, SIMaP, F-38000 Grenoble, France

e-mail: lucas.varoto@grenoble-inp.fr

Cu-Cr-based alloys with Cr content from 5 to 50 wt.% are widely used as electrical contacts for vacuum interrupters for medium voltage applications because of their excellent combination of mechanical, thermal, and electrical conductivity. Cu-Cr electrical contacts are usually processed by sintering or casting processes such as VC (Vacuum Casting) or VAR (Vacuum Arc Remelting). The microstructure of such components is subjected to various evolutions during its lifecycle due to severe thermal constraints caused by the generation of an electrical arc during an electrical breakdown. These thermal constraints result in complex local melting and solidification conditions. Such microstructural evolutions are expected to affect the electrical, thermal, and mechanical properties of the electrical contacts. However, to date, few studies have been devoted to the investigation of the microstructures resulting from local melting caused by a local heat source such as an electrical arc. In this study, electron beam re-melting experiments are conducted to mimic the microstructural evolutions induced by the electrical arc. By varying the processing parameters (scanning speed, beam power, and scanning strategy), different microstructures are produced. Based on a multi-scale microstructural characterization, we emphasize the main differences as a function of the processing conditions. The mechanical and electrical properties are also evaluated. We show that similar microstructures can be obtained with electron beam re-melting experiments to those resulting from an electrical arc.

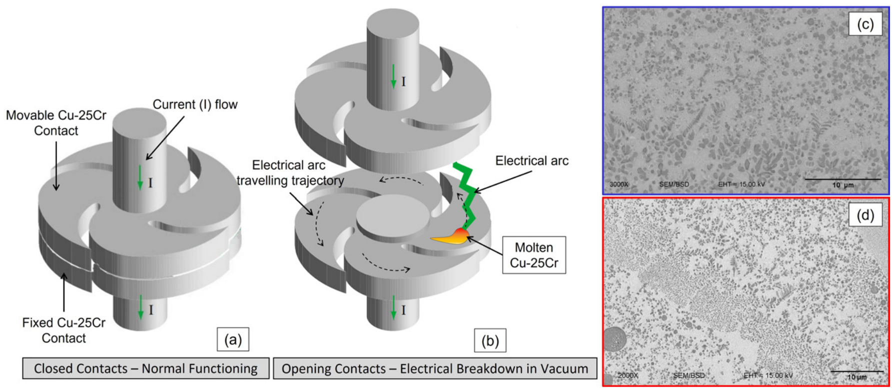


Figure 1: Schematic illustration of (a) closed electrical contacts under standard operating conditions. (b) opening contacts with the establishment of a vacuum electrical arc traveling onto the Cu-25Cr surfaces (electrical breakdown). SEM-BSD of microstructure in cross-section (c) affected by the electrical arc (d) remelted by electron beam remelting.

Building of Si/SiC composite materials by electron beam additive manufacturing

T. Ishii[1,2,*], K. Aoyagi[1], A. Chiba[1]

(1) Institute for Materials Research, Tohoku University, 2-1-1 Katahira, Aobaku, Sendai 980-8577, Japan
(2) TOKYO ELECTRON MIYAGI LIMITED, 1 Techno-Hills, Taiwa-cho, Kurokawa-gun, Miyagi 981-3629, Japan

e-mail: takayuki.ishii.q4@dc.tohoku.ac.jp

The electron beam additive manufacturing method has excellent features such as high energy absorption rate and high temperature vacuum process. However, there is a problem that "smoke" is generated in which the powder bed scatters due to the charging of the powder by the negative charge of the electron beam. Therefore, it is considered that ceramic materials, which are insulators, cannot be built. Sublimation materials such as SiC, in particular, cannot theoretically be built because it is impossible to form a melt pool.

We focused on Si/SiC, which is a composite material of SiC and Si. SiC alone cannot be built due to its insulating properties and sublimation properties, but adding silicon that can be builder can provide both conductivity and melting properties. In this study, we investigated the electrical properties of SiSiC and verified the feasibility of building. Si-48 wt.% SiC powder was used in the experiment. By AC impedance measurement, it was confirmed that the electrical properties of Si+SiC powder were almost the same as those of Si powder.

An electron beam additive manufacturing machine A2X manufactured by Arcam was used for building. "Fireworks", in which the powder scatters due to the vapor pressure of SiC sublimation during building, occurred, and the phenomenon that the object did not remain. In order to suppress fireworks, a double irradiation process was performed in which the powder was bound by the first electron beam and melted by the second electron beam. Fireworks can be suppressed by the double irradiation process, so we were able to obtain a high-density object. This object has a structure in which SiC is uniformly dispersed in silicon crystals, confirming that the building of Si/SiC was successful.

This is the first example in the world, and is considered to be the result of expanding the possibilities of electron beam additive manufacturing technology.

Enhancement of a quasi-analytical solution for modeling the electron beam additive manufacturing process

S. Cooke*, C. Sinclair, D. Maijer

Department of Materials Engineering, University of British Columbia, Vancouver, V6T 1Z4, Canada

e-mail: src@student.ubc.ca

Typically, numerical modeling methods such as finite element (FE) can provide accurate descriptions of laser or electron beam melting processes, however the high computational costs at part-scale make them unsuitable for process modeling in additive manufacturing (AM) [1-3]. Alternative methods such as semi-analytical solutions based on a moving heat source have been applied to AM in the past, although the underlying assumptions are unrealistic. Additional heat transfer mechanisms such as radiation, temperature-dependent physical properties and latent heat are not considered in the semi-analytical approach but can have a significant effect on the thermal history [1-3] . In this study, the error associated by each of these contributions are assessed against the conduction-only solution for a range of processing parameters. The semi-analytical model is then “enhanced” with FE results for single melt track training data to better encompass the heat transfer mechanisms in the electron beam AM process. The model is then validated experimentally with different beam trajectories using k-type thermocouples for selective melting on a solid Ti-6Al-4V substrate.

[1] J. C. Steuben, A. J. Birnbaum, J. G. Michopoulos, and A. P. Iliopoulos, 2019, *Additive Manufacturing* **25**, 437–447.

[2] B. Stump, A. Plotkowski, 2019, *Applied Mathematical Modelling* **75**, 787–805.

[3] S. Imani Shahabad, G. Karimi, E. Toyserkani, 2021, *Lasers in Manufacturing and Materials Processing* **8**, 288–311.

ProHeat® - a new heating method for electron beam powder bed fusion, opening a wider range of processable feedstocks

C. Medina Viramontes, U. Ljungblad, U. Ackelid*

Freemelt AB, Bergfotsgatan 5A, 43135 Molndal, Sweden

e-mail: camilo.medina@freemelt.com, ulf.ackelid@freemelt.com

To our knowledge, the evolution of Electron Beam Powder Bed Fusion started in 1991, when it was discovered at KU Leuven that an e-beam directed towards a metal powder bed is prone to scatter powder particles into a powder cloud [1]. This phenomenon, later termed "smoke" within the E-PBF community, usually disrupts the E-PBF process.

Preheating with a fast-scanning e-beam was later developed by Arcam to prevent smoke. The e-beam energy semi-sinters every powder layer and increases its electrical conductivity prior to melting. This laid the basis of the commercial E-PBF process successfully used today for e.g. titanium alloys. However, e-beam preheating is not a universal cure. Anyone who has experimented with various powders in E-PBF knows the effort of finding smoke-safe preheating parameters, particularly for fine powders and materials of low electrical conductivity.

This poster introduces ProHeat®, a alternative heating method converting the e-beam energy to infrared radiation [2]. ProHeat® consists of a conductive plate that can be positioned above the powder bed. The plate is heated to a red-hot temperature by the e-beam (or by other heating devices) and IR radiation from the plate heats the powder. In this way, the powder layer semi-sinters without being exposed to electric charge. ProHeat® gives 100 % smoke suppression and opens a wider range of powder feedstocks for E-PBF. We will show how ProHeat® has been implemented in a Freemelt ONE system and give some examples of its use.

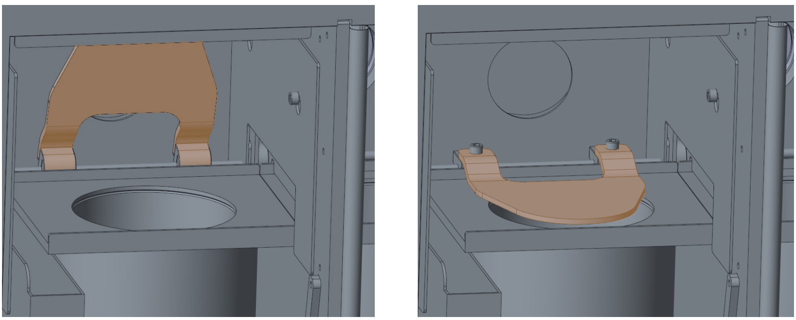


Figure 1: ProHeat® as installed in Freemelt ONE

[1] B. van der Schueren, 1991, documented in PhD thesis "Basic Contributions to the Development of the Selective Metal Powder Sintering Process", KU Leuven, Belgium.
[2] U. Ackelid, 2021, SE2050445A1, Swedish Patent and Registration Office.

On the processability of pure copper by electron beam powder bed fusion process

M. Vanzetti[1,2,*], E. Padovano[1], G. Marchese[1], S. Biamino[1], F. Bondioli[1,2,3]

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

(2) Istituto Italiano di Tecnologia, Center for Sustainable Future Technologies IIT@Polito,
Via Livorno 60, 10124, Torino, Italia

(3) Consorzio Interuniversitario Nazionale per la Scienza e Tecnologia dei Materiali (INSTM),
Via G. Giusti 9, 50121, Firenze, Italia

e-mail: matteo.vanzetti@polito.it

Copper and its alloys are widely studied thanks to their excellent physical and chemical properties, such as their high electrical and thermal conductivity, and good corrosion resistance. These outstanding properties make copper and its alloys suitable for a wide range of applications such as in the aerospace industry, for electrical and electronic components, in heat exchangers, and heat sinks.

These materials have been normally processed by casting, wrought, machined, and welded; however, in the last decades, there has been a growing interest in their processability by Additive Manufacturing (AM). Electron Beam Powder Bed fusion (EB-PBF) is one of the most used and studied AM technology to process pure copper and copper alloys because it is not influenced by the optical reflectivity of these materials, and it works under vacuum avoiding their oxidation [1]–[3].

In this study, a pure copper has been processed by EB-PBF, investigating the main process parameters and their impact on the porosity, the microstructure and the surface finishing (Figure 1). Moreover, the mechanical and electrical properties have been investigated.

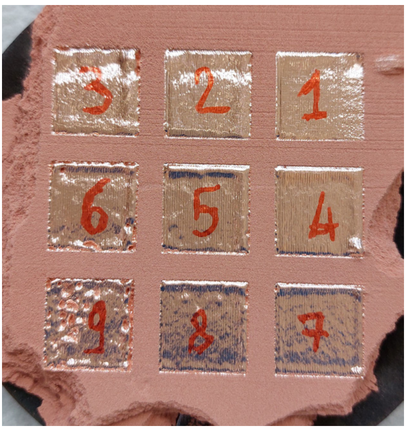


Figure 1: Top view printed samples.

This work was performed within the project "IMplementazione della Produzione Additiva CompetiTiva, IMPACT" co-financed by POR-FESR Piemonte 2014-2020, Azione I.1b.2.2 Bando PiTeF, Piedmont Region.

[1] C. Körner, 2016, *Int. Mater. Rev.* **61**, 361–377, doi: 10.1080/09506608.2016.1176289.

[2] Q. Jiang et al., 2021, *Coatings* **11**, 740, doi: 10.3390/coatings11060740.

[3] T. Q. Tran et al., 2019, *Metals* **9**, 756, doi: 10.3390/met9070756.

An algorithm for detection of powder cleanability on parts designed for electron beam melting

A. Öztaşkın[1,*], E.B. Yasa[2]

(1) AddPark Advanced Engineering Inc., ODTÜ Teknokent Silikon Blok, 06800 Çankaya/Ankara, Türkiye
(2) Department of Mechanical Engineering, Eskişehir Osmangazi University, 26480 Eskisehir, Türkiye

e-mail: alptug.oztaskin@addpark.co

Electron Beam Melting (EBM) results in semi-sintering of non-used powder. This causes difficulty for powder removal, making sandblasting necessary on post processing which hinders some design advantages of AM, such as availability of complex inner structures or concave geometries where machinning would be difficult.

To reduce manual design evaluation, automatic detection of unaccessible regions is proposed. Poisson Disk Sampling is performed on given mesh. For each point obtained, a parametric, pen shaped filter volume (representing the blasting gun) is placed along the normal of the points on the surface. If a filter volume intersects the mesh, finite number of filter volume rotations are performed around the Poisson point. If there exists a rotation that does not intersect the mesh, given point is considered "cleanable". To reduce running time, filter volumes are simplified to line segments, allowing the use of ray tracing algorithms. Output of the proposed algorithm may be used for directing designers to problematic regions. Moreover, it can also be integrated on automated design processes (such as topology optimization) as an in-loop feedback mechanism.

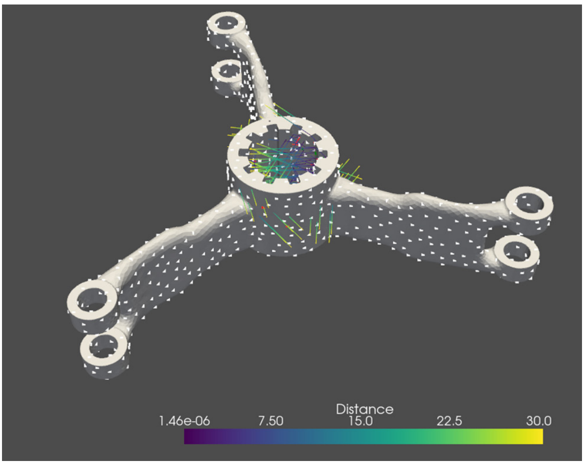


Figure 1: A mesh file with sample points, where uncleanable points on the center of the part are marked with filter volume line segments.

This study is part of EBM-PRO project, funded by TÜBİTAK on the scope of ARDEB 1003 call.

Coating as a methodology to increase processability of Al_2O_3 in electron beam powder bed fusion

W. Sjöström[1,+,*], C. Botero[1,+], E. Jimenez-Pique[2]
+ Authors contributed equally to the work.

(1) Sports Tech Research Centre, Department of Quality Management and Mechanical Engineering, Mid Sweden University, Akademigatan 1, SE-83125 Östersund, Sweden
(2) Department of Materials Science and Engineering, EEBE, Universitat Politècnica de Catalunya-BarcelonaTECH. Avda. Eduard Maristany 16, 08019 Barcelona, Spain

e-mail: william.sjostrom@miun.se

Additive manufacturing (AM) by electron beam powder bed fusion (E-PBF) is available for a growing number of metal alloys. So far, processing ceramic powders by E-PBF is problematic due to limited flowability, powder charging and beam instability. However, metal coating has recently been found to increase the processability of such powders. This work investigates the feasibility to create Al_2O_3 parts by electroless Ni coating and E-PBF. Resulting powder properties and morphology as well as melted powder was studied by microscopy, nanoindentation and energy dispersive X-ray analysis. By the suggested approach angular Al_2O_3 powder particles could be fully melted under the electron beam, although there is still development needed to attain a stable layer environment. The results disclose that coating can be a feasible method for increasing the processability of Al_2O_3 and how process settings affect residual metal elements after melting.

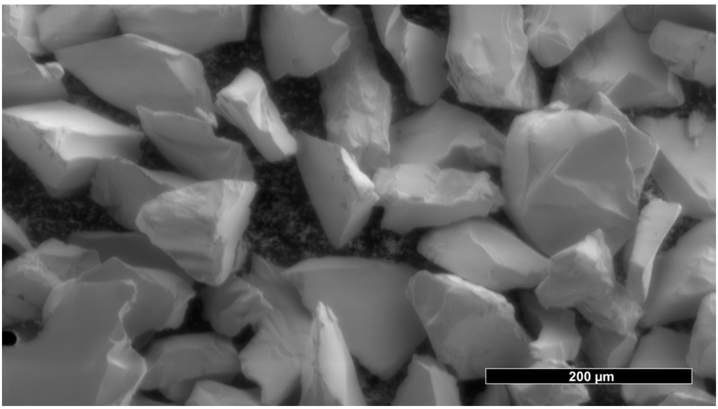


Figure 1: Angular Al_2O_3 ceramic powder before coating.

Microstructure prediction and tailoring in electron beam powder bed fusion of a medium-C hot work tool steel

E. Sullivan[1,*], C. Oikonomou[2], G. Lindwall[1]

(1) KTH Royal Institute of Technology, Brinellvägen 23, 100 44 Stockholm, Sweden
(2) Uddeholms AB, Uvedsvägen, 683 85 Hagfors, Sweden

e-mail: ethans@kth.se

This work examined the ability of electron beam powder bed fusion (EPBF) to create tailored microstructures in a medium-C hot work tool steel by alteration of printing parameters (including build temperature) and post-print cooling rate. Machine learning (Ferritico) informed by CALPHAD calculations and experimental continuous cooling dilatometry measurements was used to predict the as-printed microstructure. Printing was carried out at temperatures in fully austenitic, fully ferritic, and two phase regimes. Inert gas was used after printing to achieve varying final cooling rates. SEM/EBSD and XRD were used to validate the neural network predictions.

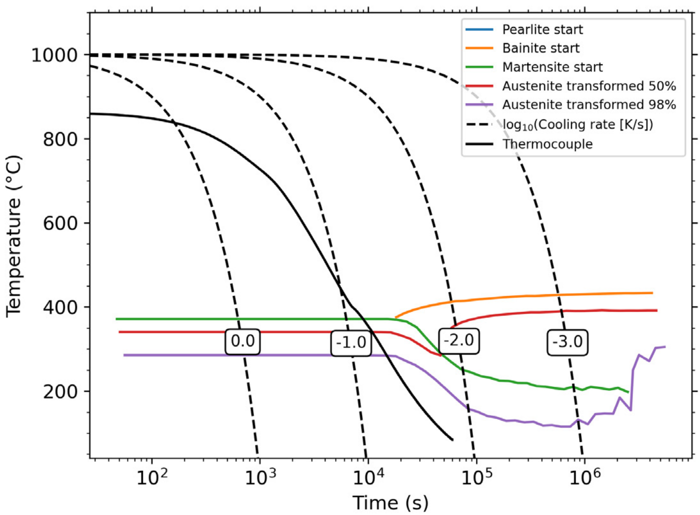


Figure 1: CALPHAD-produced continuous cooling transformation (CCT) prediction with actual post-print cooling curve overlaid.

This work was funded by the Research Initiative on Sustainable Industry and Society (IRIS) at KTH. Uddeholms AB provided in-kind support.

Powder electrical and thermal properties in relation to electron beam additive manufacturing

C. W. Sinclair*, W. Sparling, S. Cooke, D. M. Maijer

Department of Materials Engineering, The University of British Columbia, 6350 Stores Road, Vancouver British Columbia, Canada

e-mail: chad.sinclair@ubc.ca

The electrical and thermal properties of the powders used in powder bed electron beam additive manufacturing (EBAM) remains vexing for a number of reasons. Pre-heating, used (generally) to avoid smoking, constrains the optimization of the process. To overcome this it is necessary to decouple build temperature from smoking. New results point toward opportunities for improved electrical properties of powders and thus the decoupling of build temperature from smoking elimination; the recent work of Chiba and co-workers [1-4] is particularly notable. Similarly, the pre-heating and melting processes impact on thermal properties. These continue to evolve over time as the powder sinters in-situ. This means that the degree of sintering and thus thermal properties are a function of position within the bed, but the effect of this on melt geometries is only weakly understood [5-7].

In this contribution, I will present our recent work on the electrical and thermal properties of EBAM powder beds. I will focus on the properties of Ti-6Al-4V, with the aim of developing a generic understanding. We follow on the work of Chiba by examining ball milling as a way of modifying electrical properties of gas atomized powder. We then compare results to a variety of expected behaviours based on the electrical response of granular materials and use both discrete and mean-field models to help better understand our observations. I will also show results on the thermal conductivity of powders sintered ex-situ to allow for controlled structure-property relationships to be developed. Again, we compare our measured thermal properties with those expected from both mean field [5] and discrete particle based models.

[1] A. Chiba, Y. Daino, K. Aoyagi, and K. Yamanaka, 2021, *Materials* **14**, 4662.

[2] S. Yim, H. Bian, K. Aoyagi, K. Yanagihara, S.I. Kitamura, H. Manabe, Y. Daino, Y. Hayasaka, K. Yamanaka, A. Chiba, 2022, *Additive Manuf.* **52**, 102634.

[3] S. Yim, K. Aoyagi, H. Bian, Y. Cui,A. Chiba, 2022, *Powder Tech.* **412**, 117996.

[4] S. Yim, K. Aoyagi, K. Yanagihara, H. Bian,A. Chiba, 2023, *J. Mater. Sci. Tech.* **137**, 36-55.

[5] A. V. Gusarov, T. Laoui, L. Froyen,V. I. Titov, 2003, *Intern. J. Heat Mass Trans.* **46**, 1103–1109.

[6] W. Yan, W. Ma, Y. Shen, 2020, *Mater. Today Comm.* **25**, 101579.

[7] C. J. Smith, S. Tammas-Williams, E. Hernandez-Nava, I. Todd, 2017, *Sci. Rep.* **7**, 1-8.

Structure-property relationship for heat treated electron beam melted Ti-6Al-4V alloy above and below β transus temperature

A. K. Singh*, A. Ranjan, S. Mishra

Department of Mechanical Engineering Indian Institute of Technology Bombay

e-mail: akp2930@gmail.com

As built additively manufactured Ti-6Al-4V using electron beam melting (EBM) possess better ductility and ultimate tensile strength than laser additive manufacturing. Samples were heated below and above beta transus temperature for one hour residence time followed by water and furnace cooling to observe the changes in microstructure, tensile and fatigue crack growth rates. The heat treatment at 950 °C and 1050 °C with furnace cooling results in coarsening of the α+β phase in the build and transverse directions confirmed by inverse pole figure maps. Epitaxial growth during re-melting of subsequent layers in EBM is prevalent after heat treatment below beta transus temperature. Whereas, the heat treatment above β transus temperature erase the footprint of additive manufacturing and epitaxial columnar grain growth of prior β grans is converted into coarse α+β phase and the structure is homogeneous normal to building and transverse directions and hence the structure is similar to conventional Ti-6Al-4V. The mechanical properties in as build and heat treated samples are systematically discussed in the context of structural property relationship. Relatively fine grains decorated with nano size β phase in as build microstructure leads to better strength and fatigue crack growth resistance than heat treated samples.

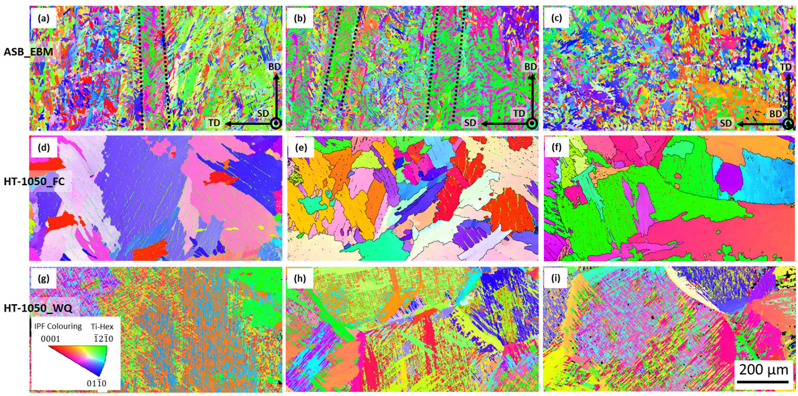


Figure 1: Microstructure in EBM fabricated Ti-6Al-4V alloy before and after heat treatment at different cooling rates. (ASB_EBM – As build in EBM, HT-1050_FC – Heat treatment at 1050 °C followed by furnace cooling, HT-1050_WQ - Heat treatment at 1050 °C followed by water quenching).

[1] R. Sabban, S. Bahl, K. Chatterjee, S. Suwas, 2019, *Acta Mater.* **162**, 239-254.

[2] A.K. Singh, B. Kumar, K. Jha, A. Astarita, A. Squillace, S. Franchitti, Amit Arora, 2020, *J. Mater. Process. Technol.* **277**, 116433.

A sample environment for in-situ synchrotron X-ray studies on electron beam powder bed fusion (E-PBF) of metals and its application for alloy design

H.-H. König[1], C. Ioannidou[1], N. Semjatov[2], G. Spartacus[1], E. Sullivan[1,*], M. Wildheim[3], A. Lindahl[3], U. Ackelid[3], C. Zenk[2], C. Körner[2], P. Hedström[1], G.Lindwall[1], M. Ishikawa[1]

(1) Department of Materials Science and Engineering, KTH Royal Institute of Technology, Brinellvägen 23, SE-100 44 Stockholm, Sweden

(2) Chair of Materials Science and Engineering for Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Martensstr. 5, 91058 Erlangen, Germany

(3) Freemelt AB, Bergfotsgatan 5A, SE-431 35 Mölndal, Sweden

e-mail: hhkonig@kth.se

Powder bed fusion (PBF) technologies are successfully implemented processes in additive manufacturing (AM) of metal components. While Laser-PBF (L-PBF) has a larger share of production capacities, Electron beam-PBF (E-PBF) is particularly promising for manufacturing of high-performance alloys that require high process temperatures. To foster the development of E-PBF, essential understanding of the physics behind the complex and rapid phenomena occurring during the repeated heating, melting and solidification cycles of E-PBF is necessary.

Synchrotron X-ray characterization techniques (e.g. imaging, diffraction and small-angle X-ray scattering) offer in-situ observations with high spatial and temporal resolution, and have led to profound insights on solidification and microstructure evolution, as well as melt pool- and powder dynamics during the L-PBF process.

E-PBF has not yet been studied in such experiments, probably due to the high equipment demands compared to L-PBF. Although L-PBF and E-PBF are conceptually similar, there are significant differences between both techniques, mainly related to the nature of the energy sources, the process steps and the different processing environment, thus, knowledge by synchrotron studies on L-PBF are not transferable to E-PBF.

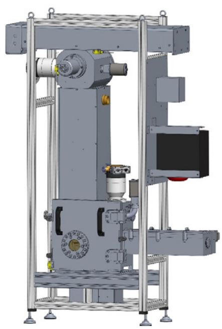


Figure 1: Schematic of the E-PBF sample environment for synchrotron studies.

In this work, we present the development of an environment that enables in-situ synchrotron X-ray measurements during E-PBF, allowing for studies of electron beam-matter interactions under realistic E-PBF processing conditions. The design is based on an industrial E-PBF system, Freemelt ONE, but includes a custom-built process chamber optimized for synchrotron measurements. Those measurements aim for a better understanding of phase transformation kinetics under various printing parameters, and ultimately, to facilitate the alloy design for E-PBF.

Design of 60-90 kV beamline for electron beam melting additive manufacturing

M.G. Sanal*, P. Uslu Kiceci

Aselsan Inc., Ankara 06830, Turkiye

e-mail: mgsanal@aselsan.com.tr

Additive manufacturing (AM) is the advanced technology for manufacturing of the structures directly from the CAD model using feedstock material. It has advantages over traditional methods such as reduced material waste, better lead times and ability to manufacture complex structures with reduced process steps [1]. Electron Beam Melting (EBM) is one of the additive manufacturing techniques and it is highly used due to its superior properties such as high building temperature, high beam power and fast scan speed. Current EBM machines provide acceleration voltage at a single point for all manufacturing processes [2]. This experimental design enables using various acceleration voltages in the range of 60-90 kV for the different materials and manufacturing options to observe the effects of acceleration voltage and its penetration ability on materials. Therefore, it provides opportunity to conduct experiments with various scenarios for best results. To be able to work with various voltages, design is focused on beam control mechanisms and beamline. Beamline consists of electron gun and a series of electromagnetic lenses. Those lenses are used to adjust the electron beam that has different parameters with changing voltages and currents. Calibration tables and interpolated transfer functions are integrated into the control system. The beamline was designed using semi-linear beam optics code and CST Particle Studio. Measurements and calibrations were performed using off the shelf and novelly designed beam diagnostic devices. Also, a thermocouple and a FIR thermal camera were used to monitor the melt pool and measure the temperature. In the scope of this study, concept of the machine design and results of various electron beam-material interaction will be presented.

This study is funded by Aselsan Inc. and The Scientific and Technological Research Council of Turkey (TUBITAK)

[1] W. E. Frazier, 2014, *Journal of Materials Engineering and Performance* **23**, 1917-1928.

[2] Zhang, L. C., Liu, Y., Li, S., Hao, Y., 2018, *Advanced Engineering Materials* **20**, 1700842.

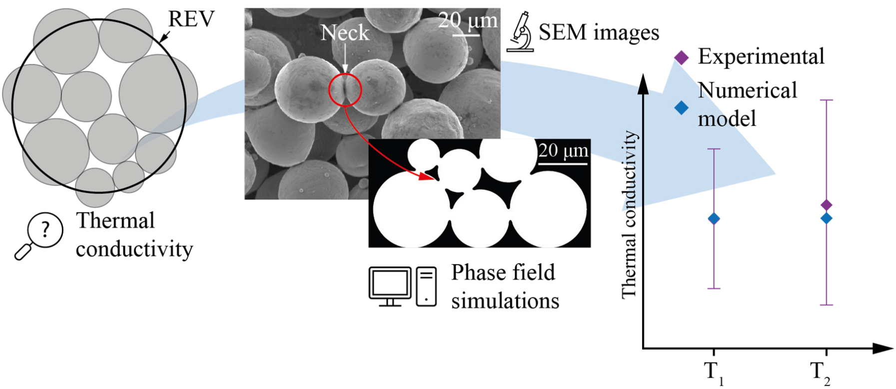
Thermal conductivity evaluation at PBF-EB conditions

G. Rizza*, M. Galati, P. Antonioni, M. Giordano, L. Iuliano

Department of Management and Production Engineering (DIGEP), Integrated Additive Manufacturing center (IAM@PoliTo), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

e-mail: giovanni.rizza@polito.it

The thermal conductivity of a powder bed is a crucial property in the additive powder bed fusion (PBF) processes to guarantee its stability [1]. In particular, for PBF with electron beam (PBF-EB/M), this is the main parameter that controls the interaction between the EB and the powder material, the heat transfer during the whole process, the cooling rate [2] and, consequently, the final component microstructure. Since the powder usually has poor thermal conductivity, sintering between particles during the EB-PBF is the only way to promote the formation of necks between the particles and achieve the desired level of conductivity [3]. However, this process is usually uncontrolled, calibrated only via a trial and error approach, and therefore the real value of the thermal conductivity of the powder remains unknown. This work presents a novel numerical framework to evaluate the powder bed's thermal conductivity. The approach adapts the tortuosity factor concept to characterize the powder bed's geometric complexity, including neck generation and its evolution with temperature and time. The model was validated against experimental results for Ti6Al4V processed with an Arcam A2X, a PBF-EB system. An innovative experimental/analytical method has been introduced to measure the actual thermal conductivity of sintered powder bed, capable of accounting for the specific temperatures and vacuum conditions during a PBF-EB. The measurements were conducted at different temperatures and different thicknesses of the sintered powder bed, up to 800 °C, the common processing temperature of Ti6Al4V.



[1] M. Galati, L. Iuliano, 2018, *Addit. Manuf.* **19**, 1-20.

[2] M. Galati, G. Rizza, S. Defanti, L. Denti, 2021, *Precis. Eng.* **69**, 19-28.

[3] G.Rizza, M.Galati, L.Iuliano, 2022, *Int. J. Adv. Manuf. Technol.* **123**, 855-873.

Influence of powder wetting on the construction quality of the EBM-printed thin wall structures studied by a multilayer mesoscopic simulation

S. Belousov, M. Bordanova, I. Iskandarova, B. Korneev, A. Perepelkina, B. Potapkin*, A. Zakirov

Kintech Lab Ltd., 123298, Moscow, 3rd Khoroshevskaya st., 12, Russia

e-mail: potapkin@kintechlab.com

There is a known set of parameters that have a significant impact on the morphology of a single track, e.g. scan speed, beam width and power, preheating temperature. The characteristics of substrate and powder wetting also can be a parameter of special importance [1]. Being known as one of the reasons causing the balling effect for a single track [2], mesoscopic wetting effects and in particular poor wetting of the powder by the melt may greatly affect the roughness and irregularities of AM parts. Due to poor ability to control the wetting conditions during the AM process, it becomes even more important to understand the degree of influence of this effect. Here we are applying the numerical simulation for that.

To correctly describe the wetting effects, the particles in the powder bed are directly resolved in the mesoscopic simulation. The solver is based on the free surface temperature lattice Boltzmann method, taking into account the surface tension and wetting, the evaporation, the electrons propagation including back-scattering in a three-dimensional simulation [3]. Powder feeding process before the selective melting on each layer is simulated using the discrete element method.

Simulations show strong sensitivity of surface profile roughness to wetting parameters, i.e. equilibrium wetting angle between the powder particles and the melt. This effect is especially emphasized for the thin wall builds. Proposed approach can be applied to a process parameter optimization for the additive manufacturing of thin-wall and other fine structures.

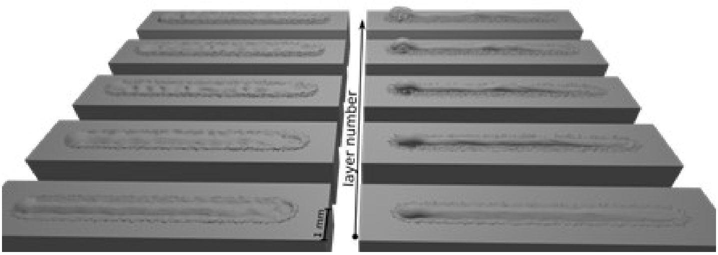


Figure 1: 3D rendering of two Ti6Al4V thin wall build simulation runs (first 5 layers). On the left: simulation with 30°, on the right: θ=90°. θ denotes the equilibrium wetting angle between the melt and the powder. Other manufacturing parameters are the same: electron beam with the power P=1680 W, speed S=4.27 m/s, Gaussian beam D4S=880 μm, powder size is 45 to 100 μm, platform step is 50 μm, preheating temperature is T=1000 K.

[1] C. Körner, E. Attar, P. Heinl, 2011, *J. Mater. Process. Technol.* **211**, 978-987.

[2] L. Li J. Li, T. Fan, 2021, *Phys. Fluids* **33**, 042116.

[3] A. Zakirov et al., 2020, *Addit. Manuf.* **35**, 101236.

Use case hip stem (Ti-6Al-4V)

M. Franke-Jurisch[1,*], A. Kirchner[1], B. Klöden[1], T. Weißgärber[1,2], L. Detmering[3]

(1) Fraunhofer IFAM Dresden, Dresden, Germany
(2) Institute of Material Science, Technical University Dresden, Dresden, Germany
(3) ARISTOTECH Industries GmbH, Luckenwalde, Germany

e-mail: marie.franke-jurisch@ifam-dd.fraunhofer.de

Additive manufacturing by electron beam melting (PBF-EB) is already commercially established for some implants made of Ti-6Al-4V. However, cementless hip stems (long stems) present a particular challenge due to the required fatigue strength, which is strongly influenced by material and surface engineering aspects. On the other hand, e.g. our own studies show that sufficient fatigue strength can be achieved by machining and thermal or thermomechanical post-treatment of components manufactured by EBM processes [1]. Unfortunately, neither reliable feasibility studies nor accessible knowledge about corresponding production steps for additive manufacturing of these medical devices are available.

With this focus, investigations of the PBF-EB process and post-treatment (hot isostatic pressing (HIP)) for balanced mechanical properties were carried out.

Processing was done on an Arcam Q20+ system. A parameter study for a layer thickness of 75 µm was done, in which the parameters speed function, hatch distance and focus offset were varied. Three parameter sets were found, from which the final set was chosen based on mechanical properties of R_m=1011 MPa, A=10 %. After that the focus was on establishing a processing window for the HIP process, from which two parameter sets ((i) 800 °C, 180 MPa, 2 h and (ii) 920 °C, 100 MPa, 2 h) were chosen for tests of fatigue strength. In the final stage, prototype hip stems were fabricated and machined. Their fatigue strength was measured according to ISO 7206-4.

Results of the PBF-EB processing window, fatigue strength tests and processing-property correlations will be presented.

The study was funded by the BMBF.

[1] A. Kirchner et al., 2016, *Key Engineering Materials* **704**, 235-240.

Effect of E-PBF processing parameters on the producibility of revolute joints with close tolerances

E. Tan*, U. Gövez, P. Korkmaz Tilki

ASELSAN Inc., Ankara, 06830 ,Türkiye

e-mail: evrentan@aselsan.com.tr

Electron Powder Bed Fusion (E-PBF) is one of the metal powder bed fusion techniques with its unique hot processing capability leading to less deflections of supportless products. This advantage enables the design and manufacture of consolidated parts involving revolute joints with close tolerances. The effect of geometric tolerances has been previously worked [1] and the relationship between neighboring features and producibility of parts with improved geometric tolerance was shown.

During manufacturing of revolute joints, surface roughness is one of the important factors that should be kept under control. For the additive manufacturing case where post processing of contacting surfaces of consolidated joints is limited; one should take precautions during the manufacturing step. Parameters of contouring & hatching stage seems to affect the surface roughness for E-PBF of Ti6Al4V [2, 3].

The aim of this study is to enhance our previous study by implementing the processing factors. Different scanning strategies namely "just hatch" and "n contours + hatch" have been used to produce the test artifact (Fig 1). Holes with inserts having different interspacing from 130 μm to 500 μm have been remanufactured with the new strategies. The initial results showed that having two sets of contour lines in the contact surface might not be required to preserve the geometric tolerance.

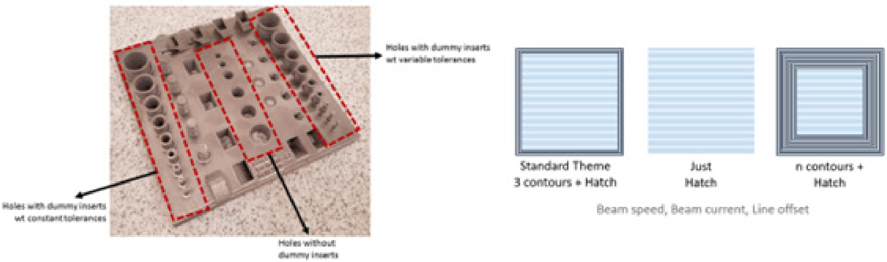


Figure 1: Test Artifact and Melting Themes.

[1] U. Gövez, O. Yılmaz, E. Tan, B. Gumus, 2020, *The 3rd Int Conf for Electron Beam Additive Manufacturing*.

[2] C.A. Biffi, J.Fiocchi, A.Tuissi, 2020, *Int. J. Adv. Manuf. Technol.* **107**, 4913–4924.

[3] D. Mallipeddi, T. Hajali, P.Krajnik, 2020, *Procedia CIRP* **87**, 327-332.

Optimization of electron beam melting parameter for high melting point metal ingot

H. Kim[1,2], N. Kwon[1,2], Y. Lee[1,2], J. Kim[1,2], J. Sim[1,2], S.-J. Seo[1], K.-T. Park[1,*]

(1) Korea Institute for Rare Metals, Korea Institute of Industrial Technology, 194, Hogupo-ro, Namdog-gu, Incheon, Republic of Korea

(2) Department of materials science and engineering, Korea University, Anam-Dong, Seongbuk-gu, Seoul, Republic of korea

e-mail: ktpark@kitech.re.kr

Manufacturing production of high-purity rare metals requires high energy densities and uniform heating methods. Electron beam melting (EBM) is one of the dry refining processes is essential for the commercialization of rare metal ingot manufacturing. Considering the high quality and productivity of the ingot, it is necessary to calculate the electron beam (EB) energy density by the DC voltage and the magnetic field of coil with a numerical approach to explain the correlation of the ingot growth rate of rare metals according to the EB energy for optimized output parameters [1].

In this study, the beam trajectory and EB energy were calculated by controlling the state of the beam focusing coil current and output power of the electron beam gun through finite element analysis (FEA). In the EB gun system, the output parameters for efficient irradiation of the EB are obtained through the prediction of energy loss due to electron escape by the magnetic density of the coil current, and through this, the temperature distribution and the heat-affected-zone (HAZ) are analyzed. In addition, the HAZ was calculated by the EB irradiation pattern, such as the beam rotation parameter for large-area melting of the ingot surface, which is and important parameter for high-quality ingot growth. For this simulation result, compared with the experimental results.

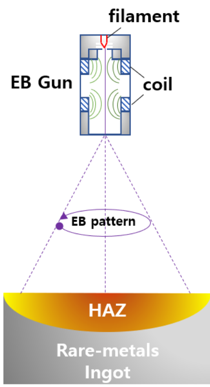


Figure 1: Schematics of electron beam melting to product of rare metal ingot.

[1] Manuela G.,Oscar Di M., Luca I., 2020, *Crystals.* **10**, 532.

Microstructure and mechanical properties of additively manufactured γ-TiAl with dual microstructure

J. Knörlein[1,*], M. Franke[1], M. Schloffer[2], T. Berger[3], C. Körner[1,3]

(1) Neue Materialien Fürth GmbH, Dr.-Mack-Str. 81, 90762 Fürth, Germany
(2) MTU Aero Engines AG, Dachauer Str. 665, 80995 München, Germany
(3) Chair of Materials Science and Engineering for Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

e-mail: julia.knoerlein@fau.de

The latest research on electron beam powder bed fusion (PBF-EB) reveals the possibility of establishing a dual microstructure and differing mechanical properties inside a complex-shaped component made of titanium aluminides (TiAl). The dual microstructure part is processed with two different, well-adjusted AM process parameter sets leading to a significant change in localized aluminum (Al) loss via evaporation during PBF-EB melting. After heat treatment, the as-built microstructure, containing two different levels of Al, is transformed into customized microstructures: fully lamellar (FL) and nearly lamellar (NL + γ). Microstructural and mechanical characteristics of 4th generation TiAl alloy TNM will be presented. Tensile and creep tests are performed for single and dual microstructure specimens. The Al distribution is determined and the microstructures and defects are characterized. The presented new processing route is a groundbreaking benefit from the PBF-EB process and necessary for superior mechanical performance. The stress-strain and the creep curves of the dual microstructure specimens are situated between the single microstructure specimens. The mechanical characterization shows that the interface between FL and NL + γ microstructure does not cause any weakening. The failure always takes place in the weaker microstructure (tensile: FL; creep: NL + γ). For the first time, AM components such as TiAl turbine blades can consist of creep-resistant airfoil sections and high-strength root sections [1].

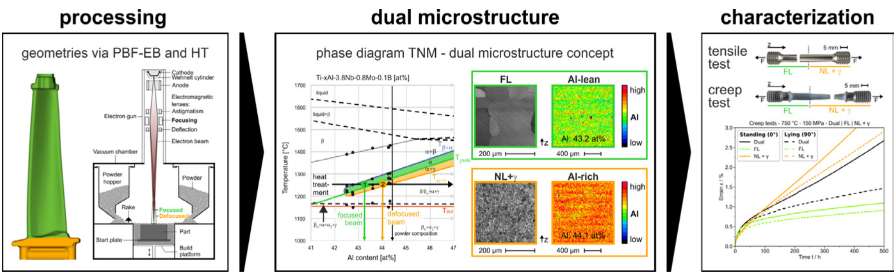


Figure 1: Procedure for the manufacturing and characterization of TiAl parts with dual microstructure.

[1] J. Knörlein, M. Franke, M. Schloffer, C. Körner, 2022, *Addit. Manuf.* **59**, 103132.

How a high acceleration voltage enables the next generation of electron beam powder bed fusion machines?

M. Reith[1], M. Franke[1,*], C. Körner[1,2]

(1) Neue Materialien Fürth GmbH, Dr.-Mack-Str. 81, 90762 Fürth, Germany

(2) Chair of Materials Science and Engineering for Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

e-mail: martin.franke@nmfgmbh.de

Theoretical background

The penetration depth of the electron beam depends on the material properties and the kinetic energy of the electrons, which is determined by the acceleration voltage [1]. Consequently, a higher acceleration voltage enables a deeper and more homogeneous energy absorption during electron-based powder bed fusion (PBF-EB). In addition, for a given beam current I higher beam powers P are accessible by a higher acceleration voltage U (P = U*I).

Pre-Heating

This study demonstrates the feasibility of processing Ti-based alloys (Ti-43Al-4Nb-1Mo and Ti-6Al-4V) without process gas. The deeper penetration depth together with the lower beam current leads to a homogeneous charge distribution in the powder bed, effectively avoiding smokes. Further, a reduction in pre-heating time is achieved, which is also reported by [2].

Melting

A higher acceleration voltage also benefits the melting during PBF-EB. It is demonstrated for several alloys, that the increase in acceleration voltage from 60 kV to 150 kV is widening the usable parameter range necessary for applying advanced scanning strategies to the PBF-EB process. For instance, the aluminum content in a titanium aluminide alloy can be adjusted over a wider range, increasing the flexibility for locally optimized microstructures.

Outlook – What´s next

The high acceleration voltage enables larger beam powers and hence larger pre-heating areas. Larger parts can be built and the productivity of manufacturing small parts increases. The available beam power makes advanced scanning strategies like point melting or return time compensation possible. Acceleration voltages up to 150 kV are the basis for next generation PBF-EB machines.

This work is funded by the Bavarian Research Foundation (project ID AZ-1421-20).

[1] K. Kanaya, S. Okayama, 1972, *J. Phys. D: Appl. Phys* **5**, 43.

[2] H. Li, Y. Yu, Y.Li, F. Lin, 2022, *Addit. Manuf.* **50**, 102579.

Development of high-speed modulation electron source (HSES) for next generation EBM

K. Higuchi[1,*], R. Sato[1], K. Yano[1], A. Yamada[1], T. Goto[1], K. Abe[1], N. Iijima[1], K. Shimada[1], K. Takahashi[1], Y. Naramoto[1], J. Matsui[1], B. Poorganji[2], M. Ishikawa[1]

(1) Nikon Corp., Shinagawa Intercity Tower C, 2-15-3, Konan, Minato-ku, Tokyo 108-6290, Japan

(2) Morf3D Inc., 821 N Nash St., El Segundo, CA 90245, USA

e-mail: Kota.Higuchi@nikon.com

Electron beam melting (EBM) has achieved rapid development such as high power, large build volume, and visualization of the molding process. On the other hand, there are many difficult issues such as handling difficult-to-process materials, handling complicated shapes including cavities with improved surface precision. Our group has developed a prototype which has the concept of a high-speed electron source that enables delicate heat input control to resolve these issues.

The most important feature of the prototype is a high-speed modulating electron gun which is capable of high-speed ON-OFF switching of the power and emission half-angle modulation of the electron beam. Conventional electron guns for EB3DP generally have 2 or 3 electrodes[1], but our electron gun has 6 electrodes (hexode) because of increasing modulating parameters in order to achieve the future which is written below. And the prototype has an electron gun performance measurement tool which is composed of apertures and aligners to monitor gun performance change in manufacturing. We can measure the gun performance in just 4 ms using the tool. We can achieve less than 100 μm spot size in every emission region, using the hexode electron gun, the electron gun performance measurement tool, a magnetic lens and an aligner which has small aberration coefficients.

Another feature of the prototype is high-speed deflection and high-speed spot size modulation of the electron beam using an electrostatic lens and an aligner system which reduce eddy currents. The beam tubes in the deflector system is made of ceramic which have a carbon coating on the inner diameter. This carbon coating suppresses the attenuation of the magnetic field in the beam tube due to eddy currents and deflects the beam at a higher operating frequency (>20 kHz). We can achieve high-speed beam scanning and beam size modulating and expand the parameter region which is used for manufacturing using previously mentioned elements.

[1] Z. Fu, C. Körner, 22022, *Eur. J. Mater.* **1:2**, 54-117.

Macro- and microstructure design of soft magnetic materials using electron beam-based additive manufacturing

J. Yang[1,2,*], Z. Fu[1], C. Körner[1,2]

(1) Advanced Materials and Processes, Friedrich-Alexander-Universität Erlangen-Nürnberg, Dr.-Mack-Str. 77, 90762 Fürth, Germany

(2) Chair of Materials Science and Technology for Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

e-mail: jing.jy.yang@fau.de

Fe93.5Si6.5 (wt.%), exhibiting excellent soft magnetic properties, is hard to be processed through conventional fabrication methods due to its brittle nature. In this work, Fe93.5Si6.5 (wt.%) toroidal specimens are additively manufactured by means of Electron Beam Powder Bed Fusion (PBF-EB) using novel hatching strategies ("radial hatching" and "circle hatching"). The specimens produced using different hatching strategies show identical relative densities but various macro- and microstructural features, resulting in different magnetic properties. The Fe93.5Si6.5 (wt.%) specimens fabricated using the circle hatching strategy show a structure with circles being concentric with the center of the toroidal specimen, which can benefit the flow of the magnetic flux, leading to superior soft magnetic properties (e.g., low power losses and high maximum magnetic flux density, see Figure 1 e).

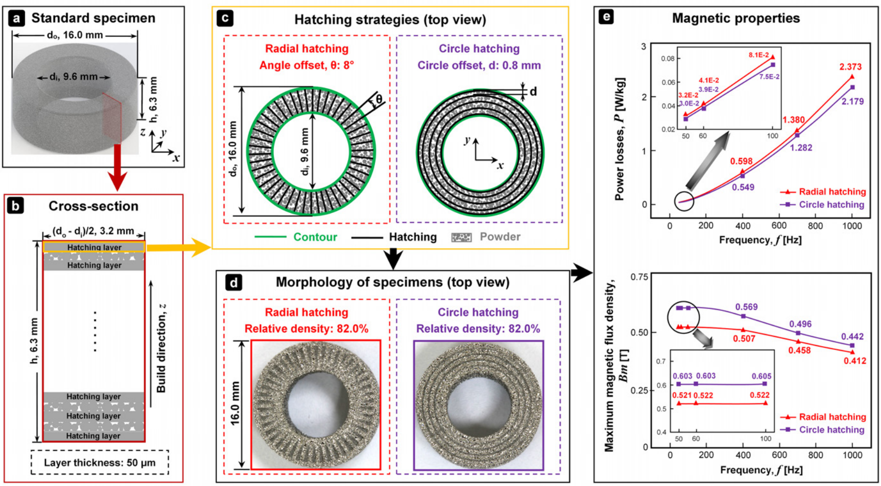


Figure 1: Fe93.5Si6.5 (wt.%) with promising magnetic performance fabricated by PBF-EB using novel hatching strategies ("radial hatching" and "circle hatching").

The project, "Electron beam-based additive manufacturing Fe-Si soft magnetic material", is funded by China Scholarship Council (CSC).

Alloy development for additive manufacturing

B. Wahlmann*, M. Markl, C. Körner

Chair of Materials Science and Engineering for Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

e-mail: benjamin.wahlmann@fau.de

To this date, most alloys that are processed by additive manufacturing (AM) have originally been developed for forging or investment casting. Contrary to these processes, the material undergoes multiple fast heating and cooling cycles during AM. This poses a problem, especially for alloys that are considered non-weldable such as Ni-base superalloys, which are prone to cracking. As AM-built superalloy parts may offer superior mechanical properties compared to cast ones [1], there is great interest in developing crack-free Ni-base superalloys.

Crack-resistant alloys with a low solvus temperature of the γ' phase, which is crucial for high-temperature performance, have been developed for laser powder bed fusion [2]. However, higher γ' solvus temperatures and phase fractions, such as in casting alloys, are necessary for optimal mechanical properties. As these alloys require high building temperatures, electron beam powder bed fusion (PBF-EB) is required for processing. In this work, we attempt to understand the principal reason for cracking of high-γ' superalloys during AM and to design Ni-base superalloys that are less susceptible to cracking. We investigated the effectiveness of various cracking models found in the literature for describing the actual cracking sensitivity in PBF-EB. Furthermore, we simulated the thermally induced stresses during processing using a custom finite element framework. Finally, we identify the material parameters that influence cracking the most.

[1] C.Körner, M. Ramsperger, G. Eggeler, 2018, *Metall. Mater. Trans. A.* **49**, 3781-3792.

[2] Y.T. Tang, C. Panwisawas, R.C. Reed, 2021, *Acta Matr.* **202**, 417-436.

What's the point of single-spot melting?

A. Klassen*, S. Pohl

pro-beam additive GmbH, Zeppelinstr. 26, 82205 Gilching, Germany

e-mail: alexander.klassen@pro-beam.com

Metal powder bed fusion by electron beam melting (EBM) offers great potential for manufacturing near net shape products of various metals and alloys that are otherwise difficult to process. Increasing demands for reproducibility and as-built product quality at high productivity levels impose increasing demands on the additive manufacturing (AM) system, printing strategy and monitoring. In regard of the printing strategy, since the advent of EBM more than 20 yrs ago, line-wise scanning ("hatching") has been state of the art albeit with known limitations related to part geometry as well as size or homogeneity of material properties. Recent years, however, have seen the rise of a new printing strategy that utilizes the full capacity of EB deflection: Single-spot melting. This contribution addresses the question of how the single-spot strategy can play to its strength, or even whether it can serve as an all-purpose tool for powder heating and melting.

Study on electron beam powder bed fusion process for high strength Al2024 alloy

M. Jiao[1,*], Y. Li[1], Iijima[1], M. S. Kenevisi[1], G. Peng[2], F. Lin[1]

(1) Department of Mechanical Engineering, Tsinghua University, Beijing, 100084, China
(2) Department of Mechanical Engineering, National University of Singapore, Singapore, 119077, Singapore

e-mail: linfeng@tsinghua.edu.cn

The high strength aluminum alloy such as 2xxx series and 7xxx series has been wildly used in aerospace and automobile area due to its high strength to weight ratio. However, fabricating large-scale high strength aluminum parts by powder bed fusion additive manufacturing has still been a challenge due to the defects such as the cracks and porosity formation being present [1]. In addition, there are few investigations on the loss of elements such as Al and Mg during the EB-PBF fabrication process currently, which would result the chemical composition change from standard of Al2024 and the reduction of its strength [2].

The EB-PBF process to build the crack-free full-dense Al2024 parts is developed, including the hot crack restrain, the chemical composition control and the strength property regulation. The ultimate tensile strength of as-built and heat-treated Al2024 sample are 328 MPa and 475 MPa respectively. Based on the developed EB-PBF process, a large-scaled crack-free Al2024 part with the dimension of 150 mm × 150 mm × 200 mm was successfully fabricated and will be presented.

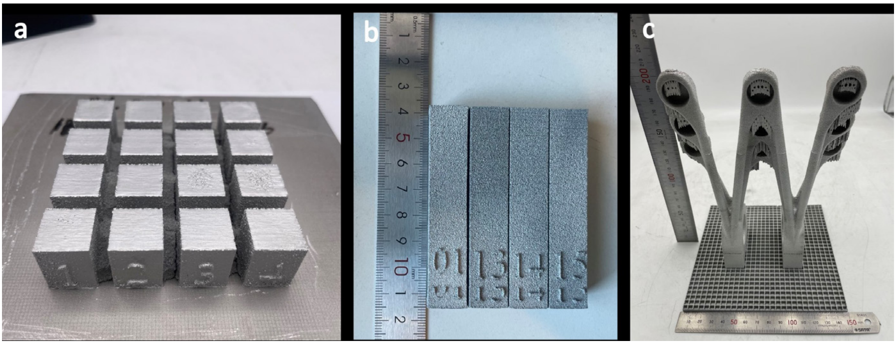


Figure 1: (a) Al2024 parts with the dimension of 15mm×15mm×15mm for process development. (b) Al2024 parts with the dimension of 15 mm × 15 mm × 75 mm for mechanical testing. (c) large-scaled crack-free Al2024 part with the dimension of 150 mm × 150 mm × 200 mm.

The is research is supported by the Science and Technology Innovation Project of COMAC (Y19GS12).

[1] M. Kenevisi, Y. Yu, F. Lin, 2021, *Mater. Sci. & Tech.* **37**, 805-829.

[2] M. Kenevis, F. Lin, 2020, *J. of Alloys and Compounds* **843**, 155866.

A novel simultaneous preheating process using dual-electron-gun to achieve the high and steady powder bed temperature

Y. Li[1,*], X. Liang[1], W. Kan[1,2], D. Zhao[1,2], F. Lin[1]

(1) Department of Mechanical Engineering, Tsinghua University, Beijing, China
(2) Beijing QuickBeam Technology Co., Ltd., Beijing, China

e-mail: linfeng@tsinghua.edu.cn

In current electron beam powder bed fusion (EB-PBF) process, preheating scan and melting scan execute subsequently to fabricate parts with powder bed temperature over 600 °C to restrain the smoking phenomenon and reduce the thermal stress [1,2]. However, fabricating non-weldable superalloys through EB-PBF technology is still difficult, especially controlling cracking and thermal stress. One of the reasons might be that, when the temperature of powder bed is above 1000 °C, it's maintenance is very dependent on the energy input. But in conventional EB-PBF system, the preheating scan is terminated during printing scan, which leads to a sharp decline of the powder bed temperature, causes the thermal stress and induces the hot cracking.

In order to inhibit the cracking and improve preheating efficiency, the simultaneous preheating electron beam powder bed fusion (SPEB-PBF) with dual-electron-gun is proposed. Compared with the conventional EB-PBF process, the SPEB-PBF makes the synchronization of both preheating scan and printing scan and the nonstop preheating energy input available to ensure a stable fabricated temperature even above 1100 °C. The crack-free parts were fabricated including nickel-based superalloys and Nb-Si superalloys. The comparison of the powder bed temperature between conventional EB-PBF and SPEB-PBF will be presented, and the mechanism of the cracks inhibition by the SPEB-PBF process will be discussed as well.

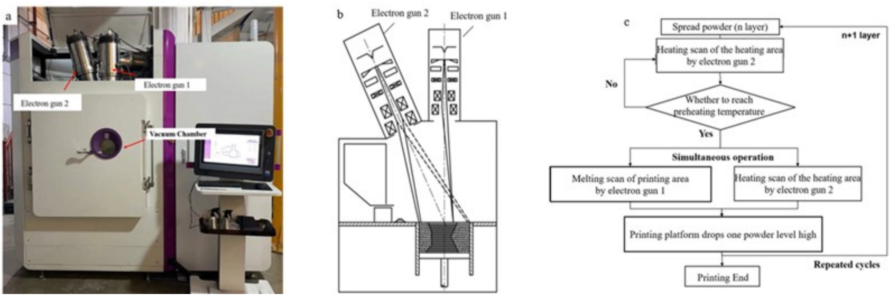


Figure 1: (a) SPEB-PBF equipment, (b) Schematic diagram of SPEB-PBF, (c) Process flow chart of SPEB-PBF equipment.

[1] Y. Li, W. Kan, Y. Zhang, M. Li, X. Liang, Y. Yu, et al, 2021, *Addit Manuf.* **47**, 102371.

[2] Y. Li, Y. Yu, Z. Wang, X. Liang, W. Kan, F. Lin, 2022, *Acta Metall Sin (English Lett)* **35**, 353.

[3] Authors, 2022, *Mater. Charact.* **190**, 112043.

Dashed-scan strategy for contour scan to reduce the surface roughness of the TC4 and TiAl4822 parts fabricated by EB-PBF

F. Wang[1,*], C. Wu[2], W. Kan[3], F. Lin[4], Y. Liang[1], J. Lin[1]

(1) State Key Laboratory for Advanced Metals and Materials, University of Science and Technology Beijing, Beijing 100083, China

(2) School of Mechanical Engineering and Automation, Fuzhou University, Fuzhou 350108, China

(3) Beijing QuickBeam Technology Co., Ltd., Beijing, China

(4) Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China

e-mail: linjunpin@ustb.edu.cn, linfeng@tsinghua.edu.cn

For electron beam powder bed fusion (EB-PBF), the shortage of its surface quality, caused by electron beam spotting effect and instability of the melting pool, has restricted its development [1]. In the EB-PBF process, the morphology of the melting pool and the strategy of contour scan has an important impact on the surface quality of printed parts. In this study, a dashed-scan strategy is proposed to limit the melting pool size and control its morphology by the use of high-frequency beam hopping of electron beam. Additionally, the remelting of the overlap of the adjacent dashed-scan segment is optimized carefully to retain the contour quality, which is investigated through validated high-fidelity multi-physics modeling simulations [2]. The above initiatives guide the experiment to obtain flat and less fluctuant contours, and reduce the roughness of the vertical thin-walled side surface of TC4 from Ra25 μm to under Ra12.5 μm. Moreover, by controlling the dashed-scan parameters and the overlap length of the adjacent dashed-scan segment, the downward surface roughness of the 45° inclined TC4 thin-walled overhang can be improved from Ra>60 μm to Ra15 μm, and the 75° inclined TC4 thin-walled overhang can reach Ra10 μm. The dashed-scan strategy is adapted to Ti-48Al-2Cr-2Nb (TiAl4822) powder as well, of which the vertical thin-walled side surface roughness is improved from Ra30 μm to around Ra15 μm.

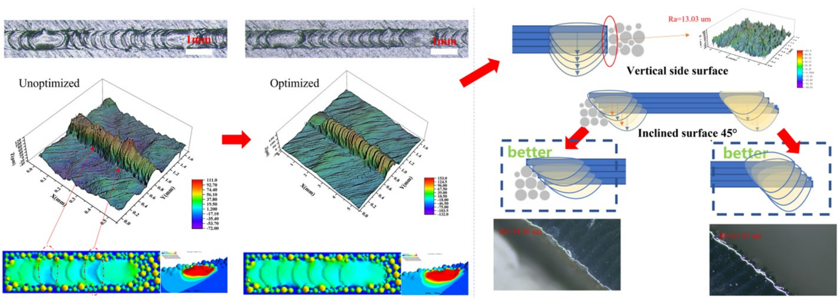


Figure 1: Research on side surface quality optimization based on smoothing of melting track.

[1] Lucas C. B. Carolo, Robert E. Cooper O, 2022, *Addit. Manuf.* **59**, 103103.

[2] C C Wu, M. Q. Zafar, H.Zhao, 2021, *Addit. Manuf.* **47**, 102204.

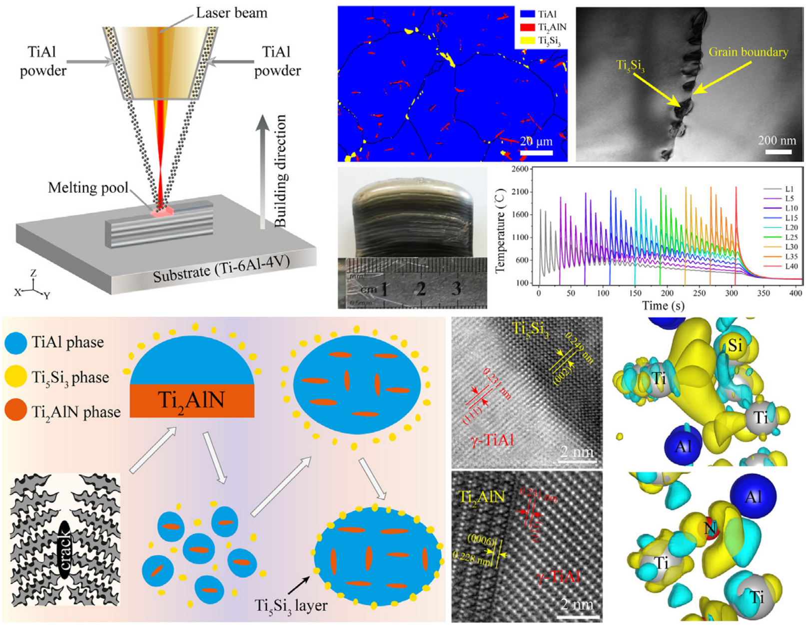
Additive manufacturing of micro/nano multiphase synergistically reinforced Ti-55Al-7.5Nb alloy

H. Xue[1,*], Y. Liang, F. Wang, J. Lin

State Key Laboratory for Advanced Metals and Materials, University of Science and Technology Beijing, Beijing 100083, China

e-mail: xueh67@126.com

Novel γ-based TiAl alloys are a promising alternative to conventional dual-phase TiAl alloys, which suffer from microstructural degradation and solid-state phase transformations at high temperatures. However, monolithic intermetallic γ phases exhibit poor plasticity, and they are incompatible with conventional manufacturing techniques. A microstructural modification was used to enable the preparation of a single-phase matrix from an Nb-rich TiAl metal matrix composite using via direct laser deposition technique. Micro/ nano-precipitates of Ti_5Si_3 and Ti_2AlN were produced by adding Si_3N_4 precursors to the pre-alloy powder. The Ti5Si3 and Ti_2AlN precipitates refined the grains in the metal and Ti_5Si_3 strengthened the grain boundaries.



This work was funded by the National Natural Science Foundation of China (51831001), the National Key R&D Program of China (2021YFB3700501), the Funds for Creative Research Groups of China (51921001), and the National Science and Technology Major Project (J2019-VII-0016-0156).

[1] H. Xue, Y. Liang, H. Peng, Y. Wang and J. Lin, 2022, *Addit. Manuf.* **58**, 102989.

[2] H. Xue, Y. Liang, H. Peng, Y. Wang, S.-L. Shang, Z.-K. Liu and J. Lin, 2023, *Scripta Mater.* **223**, 115102.

Exploiting the potential of electron optical imaging for powder bed characterization

M. R. Azadi Tinat*, J. Renner, M. Markl, C. Körner

Chair of Materials Science and Engineering of Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

e-mail: mohammad.reza.azadi@fau.de

Electron optical (ELO) imaging is on the way to get the gold standard of process observation during electron beam powder bed fusion (PBF-EB). Today, almost all machines provide a single ELO detector, while mutli-detector setups are under research. Up to now, first algorithms to extract information of the surface like porosity, material transport or topography from post-melting ELO images are available. However, ELO imaging can provide much more like pre-melting powder bed images or in situ melting measurements.

In order to understand the measured signals, numerical simulation of the ELO measurement is beneficial. This contribution presents a ray tracing approach and its application on numerically generated powder beds before melting. The numerical results are interpreted and compared to experimental results from two different PBF-EB machines with different acceleration voltages resulting in different beam diameters. We show how to extract information on, e.g., the powder size distribution or the layer thickness depending on the beam shape (see Figure 1).

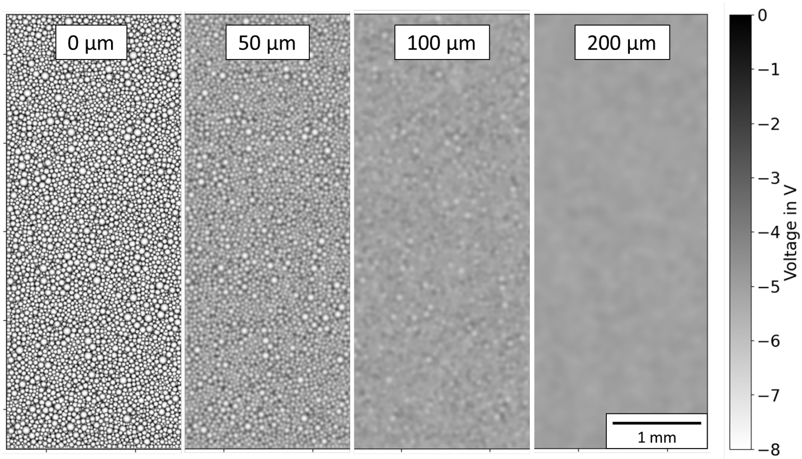


Figure 1: Simulated ELO images of a powder bed with a mean powder size distribution of 50 µm for different beam diameters from 0 µm to 200 µm.

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No 101018634)

Electron-optical observation of smoke evolution during electron beam powder bed fusion

J. Ye[1,*], J. Renner[1], Z. Fu[2], C. Körner[1,2]

(1) Chair of Materials Science and Technology for Metals, Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstr. 5, 91058 Erlangen, Germany

(2) Advanced Materials and Processes, Friedrich-Alexander-Universität Erlangen-Nürnberg, Dr.-Mack-Str. 77, 90762 Fürth, Germany

e-mail: jihui.ye@fau.de

During Electron Beam Powder Bed Fusion (PBF-EB), a so-called smoke phenomenon might occur during the process, leading to an explosion-like powder spreading in the vacuum chamber, which is catastrophic for the build process. This phenomenon happens rapidly and it is hard to be observed from its initial stage. In this study, the powder smoke phenomenon and its development are investigated using an ELectron-Optical (ELO) monitoring system as well as an optical process monitoring tool based on high-speed camera. According to high-speed camera capture, the smoke development can be separated into a stable stage , a meta stable powder fume development stage as well as a catastrophic powder avalanche stage. The ELO system is capable of capturing all these three stages. This opens up the possible application for ELO system as a very robust smoke monitoring tool at the initial stage.

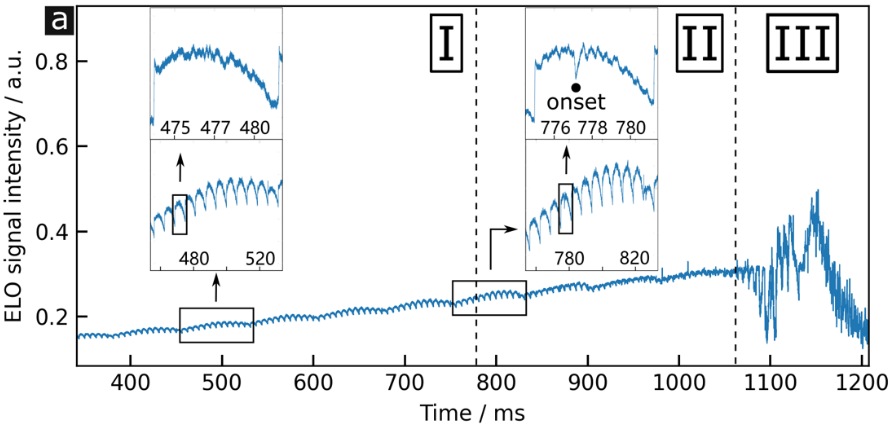
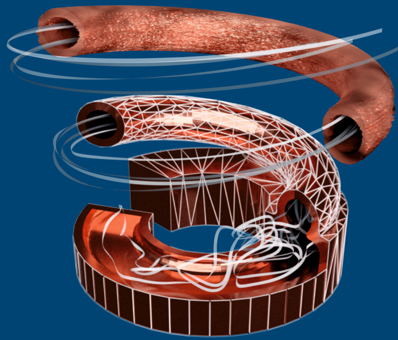


Figure 1: ELO signal development during a smoke event. It consists of three characteristic stages based on the noise level. Stage I: stable period without noticeable abnormal signal fluctuation; stage II: unstable period, in which small local powder fumes and abnormal fluctuations of the ELO signal are observed; stage III: a catastrophic smoke event leading to chaotic ELO signal. Four insets show more details about the signal evolution.

Key Visual | **Watercooled Induction Coil**

Key Visual	**Watercooled Induction Coil**
Manufacturing	PBF-EB of pure copper
Top Spiral	Rendered ELO measurements
Bottom Part	Wireframed CAD model
Streamlines	Simulated cooling water flow



KEY VISUAL TEAM

Christopher Arnold, Christoph Breuning, Alexander Fink, Zongwen Fu, Yannic Westrich

CONFERENCE COORDINATOR

Prof. Carolin Körner

Chair of Materials Science
and Engineering for Metals (WTM)
Friedrich-Alexander-Universität
Erlangen-Nürnberg (FAU)

Martensstraße 5 · 91058 Erlangen
Phone: +49 9131 85-27528
Email: carolin.koerner@fau.de

CONTACT

EBAM Conference Office
Email: conference-ebam@fau.de

Dr. Matthias Markl
Scientific Organization

Chair of Materials Science and
Engineering for Metals (WTM)
Friedrich-Alexander-Universität
Erlangen-Nürnberg (FAU)

Martensstraße 5 · 91058 Erlangen
Phone: +49 9131 85-28748
Email: matthias.markl@fau.de

Angelika Mach
Technical Organization

FAU Competence Unit
Engineering of Advanced Materials (EAM)
Friedrich-Alexander-Universität
Erlangen-Nürnberg (FAU)

Cauerstraße 3 · 91058 Erlangen
Phone: +49 9131 85-70477
Email: angelika.mach@fau.de

ENGINEERING
OF ADVANCED
MATERIALS
COMPETENCE UNIT