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ERLANGEN-NÜRNBERG

EBAM 2020

3rd International Conference on Electron Beam Additive Manufacturing

5 – 7 October 2020 · Erlangen, Germany

ENGINEERING
OF ADVANCED
MATERIALS

www.ebam.fau.de

Welcome

It is our pleasure to welcome you to the third **International Conference on Electron Beam Additive Manufacturing EBAM 2020**, which is organized by the Chair of Materials Science and Engineering for Metals (WTM) in cooperation with the Cluster of Excellence - Engineering of Advanced Materials (EAM) at the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU).

The conference aims to discuss specific challenges and opportunities offered by the electron beam. EBAM 2020 will bring together researchers and industrial users to accomplish improvements in this technology. Invited presentations from academics as well as industry will give high-level insight into this fabrication technology.

In the hope of a live event, we decided to postpone the conference from March 2020 to October 2020 because of the world wide spread of the new coronavirus. Due to the unchanged circumstances today, we came to the conclusion, that hosting a digital EBAM 2020 with pre-recorded presentations is the only responsible decision.

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

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

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

Carolin Körner

Conference Coordinator

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Invited Speakers

Paolo Gennaro	Precicast Additive, Switzerland
Matthias Gieseke	Baker Hughes, Germany
Timothy Horn	North Carolina State University, US
Michael Kirka	Oak Ridge National Laboratory, US
Guilhem Martin	Science et Ingéniere des Matériaux et Procédés, France
Colin Ribton	The Welding Institute, UK
Xipeng Tan	Nanyang Technological University, Singapore
Julia Ureña	AIDIMME Instituto Technológico, Spain
Wentao Yan	National University of Singapore, Singapore

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Thomas Niendorf	University of Kassel, Germany
Lars-Erik Rännar	Mid Sweden University, Sweden
Anders Snis	GE Additive - Arcam EBM, Sweden
Iain Todd	University of Sheffield, UK

Conference Coordinator

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Matthias Markl	WTM, FAU Erlangen-Nürnberg

Technical Organization

Ina Viebach	EAM, FAU Erlangen-Nürnberg
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Local Organization Committee

Christoph Breuning	WTM, FAU Erlangen-Nürnberg
Julian Pistor	ZMP, FAU Erlangen-Nürnberg
Maximilian Wormser	ZMP, FAU Erlangen-Nürnberg

9^{00} - 9^{15} **Welcome**
Carolin Körner · FAU Erlangen-Nürnberg, Germany

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Chair: Matthias Markl · FAU Erlangen-Nürnberg, Germany

A1: Electron Beam

Electron beam guns and optics for additive manufacture
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EBMPerform – a H2020 project for developing high-quality, high-speed EBM 3D printing by the integration of high-performance electron sources
Joakim Ålgårdh · GE Additive - Arcam EBM, Sweden

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Robin Stephansen · Freemelt AB, Sweden

Modelling of electron beam absorption in powders
Benjamin Seznec · Laboratoire de Physique des Gaz et des Plasmas, France

Technological flexibility in additive manufacturing and related processes provided by low voltage profile electron beam
Dmytro Kovalchukc · JSC NVO Chervona Hvily, Ukraine

M1: Titanium

Titanium aluminide, 4 manufacturing processes for 1 blade
Paolo Gennaro · GF Precicast Additive SA, Switzerland

A study on the chemical and microstructural optimization of the Ti48-2-2 alloy processed by electron beam melting
Cristian Ghibaudo · Politecnico di Torino, Italy

Process stability and microstructural uniformity of additively manufactured Gamma TiAl alloy using electron beam melting
Johnson Jacob · The University of Melbourne, Australia

Anelastic phenomena in Ti6Al4V additivley manufactured by EBM
Yaron Ganor · Ben Gurion University, Israel

On the improvement of geometrical outcomes of EBM parts with a novel design approach
Umut Gövez · Gazi University, Turkey

Fatigue crack growth rate of electron beam powder bed fusion (EB-PBF) titanium alloy (Ti-6Al-4V): Effects of crystallographic texture
Nik Hrabe · National Institute of Standards and Technology, United States

M2: Aluminum

Electron beam-based additive manufacturing of periodic open cellular Raney-Copper-Catalysts
Zongwen Fu · FAU Erlangen-Nürnberg, Germany

Microstructure refinement for superior ductility of Al-Si alloy by electron beam melting
Huakang Bian · Tohoku University, Japan

Selective electron beam melting of Al-Cu-Mg alloy: Processability, microstructure characterization, and mechanical performance
Mohammad Saleh Kenevisi · Tsinghua University, China

P1: Poster Material

Please find the corresponding poster abstracts starting from page 58.

Impression: Poster Session at EBAM 2018

9^{00} - 11^{00} **Discussion on sessions A2, A3, M3, M4 and P2**
Chair: Matthias Markl · FAU Erlangen-Nürnberg, Germany

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Karin Ratschbacher · GfE Metals and Materials GmbH, Germany

Electron beam melting of alloy 718 - Powder recycling and its effect on defect formation
Hans Gruber · Chalmers University of Technology, Sweden

Influence of powder deterioration on the risk of smoke in EB-PBF processes using IN718 powder
Jan Drendel · Siemens AG, Germany

Formation mechanism, microstructure and composition of the spatter formed during EBM processing of IN718
Ahmad Raza · Chalmers University of Technology, Sweden

Modeling single-particle and powder bed absorption in CM247LC superalloy for electron beam melting additive manufacturing
Guglielmo Vastola · A*STAR Institute of High Performance Computing, Singapore

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Breaking the link between build temperature and powder electrical characteristics allows optimizing the processing window of EB additive
Ralf Edinger · CANMORA TECH Inc., Canada

Avoiding “smoke” with a ball milling in air for alloy powder in powder bed fusion type electron beam additive manufacturing
Akihiko Chiba · Tohoku University, Japan

Multi-physics modeling of the electron beam additive manufacturing processes: powder spreading, pre-heating, and melting
Wentao Yan · National University of Singapore, Singapore

On the Use of Inherent Strain Method for Modelling Electron Beam Melting
Evren Tan · ASELSAN Inc., Turkey

Development of a thermo-mechanical model of electron beam additive manufacturing process for repair purposes
Fatih Sikan · McGill University Montreal, Canada

Explore the applications of electron beam melting for industrial components
Pan Wang · A*STAR Singapore Institute of Manufacturing Technology, Singapore

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Alexander Kirchner · Fraunhofer IFAM, Germany

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Carlos Botero · Mid Sweden University, Sweden

SEBM of wear-resistant materials
Burghardt Klöden · Fraunhofer IFAM, Germany

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Kenta Aoyagi · Tohoku University, Japan

Predictive modeling and validation of electron beam powder bed fusion additive manufacturing of metals at the mesoscale
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Dechen Zhao · Tsinghua University, China

In situ optical/near infrared process monitoring of selective electron beam melting
Guillaume Croset · Université Grenoble Alpes, France

Video imaging methods for in-situ detection of irregular powder bed recoating and hot-spots in EBM
Marco Luigi Giuseppe Grasso · Politecnico di Milano, Italy

Combining in-situ monitoring and X-ray computed tomography to assess the quality of parts by electron beam melting
Philip Sperling · Volume Graphics GmbH, Germany

In-situ quality inspection in Ebeam machine based on fringe projection profilometry
Liam Blunt · University of Huddersfield, United Kingdom

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The role of atom probe tomography in additive manufacturing of engineering alloys by electron beam melting
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Nano-structured NiAl-Cr(Mo) in-situ composites processed by additive manufacturing
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Michael Kirka · Oak Ridge National Laboratory, United States

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Guilhem Martin · Université Grenoble Alpes, France

Production and properties of the single crystalline nickelbase superalloy CMSX-4 processed by SEBM
Julian Pistor · FAU Erlangen-Nürnberg, Germany

Modelling materials with tailored grain structures - combining grain growth models and crystal plasticity
Andreas Kergaßner · FAU Erlangen-Nürnberg, Germany

Tailoring thermal post-treatment for EBM produced Alloy 718
Sneha Goel · University West, Sweden

P3: Poster Process

Please find the corresponding poster abstracts starting from page 69.

Electron beam guns and optics for additive manufacture

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e-mail: colin.ribton@twi.co.uk

Electron beams (EBs) are being deployed for two types of additive manufacturing systems – powder bed and wire fed. In powder bed systems the EB is electromagnetically deflected to selectively melt a powder layer. In wire fed systems the beam melts a wire to build the part.

The requirements for EBs deployed for powder bed additive manufacturing systems present some equipment design challenges. Many systems require the EB to be run for over 100 hours continuously, with the additional requirement that the beam characteristics remain unchanged and manufacturing remains consistent. Compared to EB welding machines, widely established in industry, this represents a 10 fold increase in the gun life time. To deflect the beam across wider powder beds, allowing larger components to be additively manufactured, a combination of high deflection angle and long working distance is required. However, both of these features cause beam spot aberration and can limit the resolution of the manufacturing process.

Wire fed systems may also require long beam on times when applied to larger components. For most systems, the beam, wire feed direction, the wire position relative to the beam and substrate and direction of movement must be orientated consistently to maintain build performance. One EB wire fed system uses a novel electron gun design approach to overcome these requirements.

The first additive manufacturing systems used conventional EB generators – similar to the majority of EB welders and melters. The cathodes comprised a thin tungsten ribbon, heated to the electron emission temperature (some 2500 °C) by a current passed through it. Distortion and surface evaporation, despite changing the cathode dimensions by only a few microns, can give rise to changes in beam intensity, and ultimately degradation of additive manufacturing quality.

For powder bed machines, lanthanum hexaboride cathodes have been developed which offer some distinct advantages. They are indirectly heated, using a low power laser, and consequently can be button shaped and are more mechanically stable so little distortion occurs. Lanthanum hexaboride emits at a much lower temperature (1500 °C) so surface regression, for this material due to sublimation, is minimal.

EBMPerform – a H2020 project for developing high-quality, high-speed EBM 3D printing by the integration of high-performance electron sources

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The aim of the EBMPerform project has been to overcome key obstacles concerning future requirements for EBM 3D printing for production of complex parts through the integration of new technologies [1]. The work has been focused on developing novel electron beam units and integrate them with an EBM machine focusing on realising the enhanced capabilities of consistent manufacturing performance and higher productivity. Also, the development and integration of a new beam calibration procedure will provide quantified quality assurance of machine manufacturing readiness. The key research challenges have been the design of the electron source and optics, and the development of new software for improved build procedures making best use of the new sources.

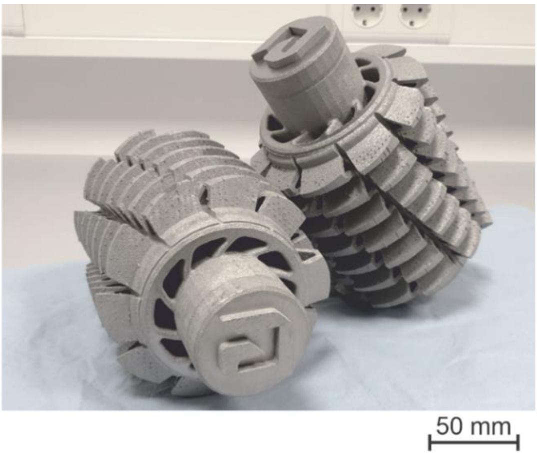

Figure 1: Parts in tool steel M4 built with the EB unit developed in EBMPerform.

[1] https://cordis.europa.eu/project/rcn/196409/brief/en?WT.mc_id=exp

Open data format for beam scanning in Electron Beam Powder Bed Fusion (E-PBF)

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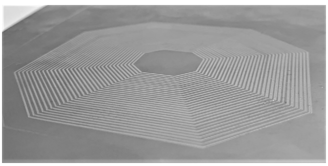
A cornerstone of the worldwide R&D community is the willingness to openly exchange data and results with peers. We introduce a modern data format for beam scanning, Open Beam Path (OBP), designed for the specific needs of E-PBF and free for everyone to use. With OBP, a beam scan pattern is described down to individual lines or dots. OBP provides full freedom to define beam paths, layer by layer, and the results can easily be shared and reused by others. OBP is free to implement with any research equipment or software, regardless of supplier, and potentially both advanced heat simulation software and 3D-printers can work from the same OBP file. OBP is designed for the extremely high throughput of data needed for E-PBF, where scan speeds can reach kilometers per second, but also for direct readability and editability desired in R&D. To accomplish this, the OBP data format comes in two formats, one binary for machine control and one editable text based, that are identical in respect of the data that they can hold. A scan pattern can easily be converted between the two formats. To generate OBP data, we have implemented a design library in Python, but as the specifications are open, everyone is free to implement OBP into other applications. The OBP data format will be described in detail in this presentation. We will show examples of how to create OBP beam scan patterns and illustrate the results by videos of beam patterns recorded in a Freemelt ONE E-PBF system [1].



```
def get_contour(radius, theta, speed, spotsize, beampower):
        cont = []
        for k in range(8):
            p = Point(radius*math.cos(theta + k*math.pi/4), radius*math.sin(theta + k*math.pi/4))
            q = Point(radius*math.cos(theta + (k+1)*math.pi/4), radius*math.sin(theta + (k+1)*math.pi/4))
            cont.append(Line(p, q, speed, Beamparameters(spotsize, beampower)))
        return cont

pattern = []
for i in range(30):
    pattern.extend(get_contour(10000 + i*1000, 0, 100000, 100, 500))

FileHandler.WriteObp(Transformations.Rotate(pattern, math.pi/8), "Octagon.obp")
```

Figure 1: An example of a beam scan pattern (left) and its corresponding code (right).

[1] U. Ljungblad, U. Ackelid, P. Ohldin, R. Stephansen, M. Wildheim, EBAM 2018, Nuremberg.

Modelling of electron beam absorption in powders

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Among the processes used for additive manufacturing, Electron Beam Melting (EBM) is an interesting method to produce metallic structures layer by layer from metal powder because due to the higher available power of the electron beam (10 kW) compared to CW lasers (< 1 kW). In addition, while the penetration distance of the laser into a powder particle is limited by the skin effect (maximum 100 nm), the electron beam can penetrate deeper (ten micrometers) into the powder particle, depending of its kinetic energy, and hence heating it uniformly and more efficient. However, the powders accumulate electrons (depending of its electrical conductivity) and cause them to repel each other. Under several conditions, the electrostatics forces can become so strong as the powder particles are ejected from the powder bed — phenomenon called smokes. It is therefore necessary to understand electron transport to optimize powder heating and minimize powder charging effects due to electron penetration into metal powders. The energy transferred to the metal and inelastically loss by other mechanisms is an important issue.

A model describing the trajectory of electrons inside one powder particle has been developed by LPGP. Electron collisions are treated using Monte Carlo method and the energy loss of the electrons can be deduced from the stopping power of the electron into the metal. It consider also the generation of secondary electrons, especially at the border of the particles. In addition this model, deals with the electron backscattering in the case of a powder bed layer and allows the estimation of the volumic density of power released by electrons to the powder.

This presentation will figure out the general behavior of electron absorption giving the parametric trends in relation to with the powders radius, energy of the electron beam, beam shape etc. The aim is to quantify the deposited energy on the powder bed and estimate the heating and the charging of the powder particles.

Technological Flexibility in Additive Manufacturing and Related Processes Provided by Low Voltage Profile Electron Beam

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For a long time the electron beam is considered as the most flexible heating source in metallurgy, allowing precise control of both power and power concentration over a wide range. In additive manufacturing – both in PBF and DED processes – EB guns developed for welding are mainly used, often with only minor changes in the design and in the beam control methods. The electron beam generated by such EB guns has a relatively low total power, but a very small focal spot, which results in quite high energy concentration - up to 10^6 W/cm^2. At the same time, during layer-by-layer formation of a three-dimensional object the energy of the heating source should be released in a very small volume of the processed material, and the melting depth should be minimized to avoid damaging the previously deposited layers. In DED-wire processes, typical parameters of the welding EB gun make it even more difficult to control the energy distribution between the substrate and additive material, resulting in low accuracy and coarse metal structure of the produced parts. Gas-discharge electron beam guns are able to solve most of these problems thanks to their capability to generate low voltage (<30kV) electron beam with high total power but moderate power concentration within the range of 10^3 ... 10^4 W/cm^2, in addition the profile electron beam can be directly generated without any transformation means. For example, the xBeam3D Metal Prirnting technology of DED-wire type is based on the application of hollow conical electron beam both for formation melt pool on the substrate and melting of the additive wire which can be fed coaxically with the said electron beam. Such configuration provides very good capabilities to control heat distribution resulting in good accuracy and in good metal structure of produced three dimensional objects. In addition, profile electron beam opens a number of other technological opportunities in post-processing and other processes related to additive manufacturing. Results and prospects of applications of the low voltage profile electron beam sources in additive manufacturing will be demonstrated and discussed.

Titanium Aluminide, 4 Manufacturing Processes for 1 Blade

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TiAl manufacturing is one of the most challenging operations in the additive world, and the EBM process is today the only practical way to do. The LPT blade is probably the most important industrial application using TiAl and the EBM process. The aim of the presentation is to explain why the EBM additive process represent the most cost-effective solution compared with Casting, Forging and Milling from a block.

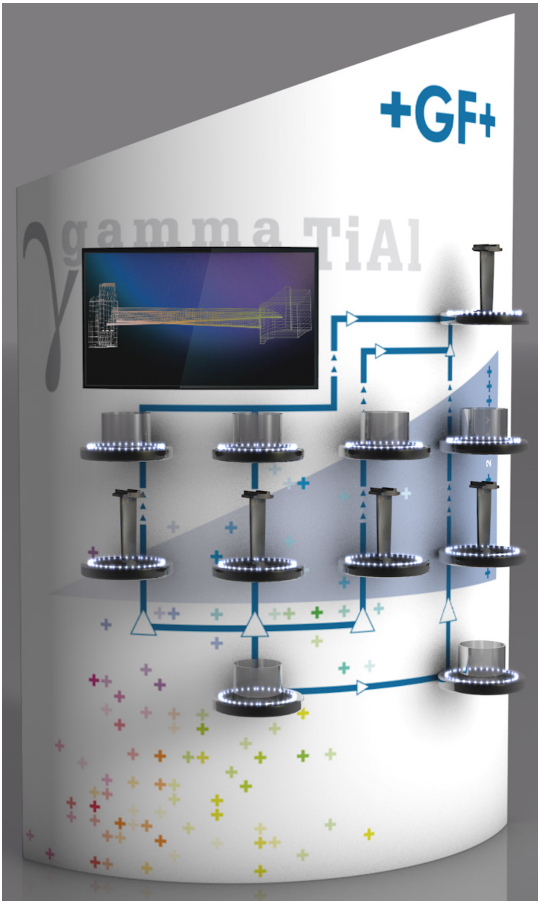

Figure 1: 4 Manufacturing Processes for TiAl blades.

A study on the chemical and microstructural optimization of the Ti48-2-2 alloy processed by Electron Beam Melting

M. Galati[1,3,*], C. Ghibaudo[2,3], G. Rizza[1], R. Wartbichler[4], S. Mayer[4], L. Iuliano[1,3], H. Clemens[4], D. Ugues[2,3], S. Biamino[2,3]

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Engineering titanium aluminide (TiAl) alloys are a family of intermetallic materials that, thanks to their outstanding specific mechanical properties, attracted significant attention for high-temperature automotive and aerospace applications. One of the key-points for the introduction of TiAl alloys as jet turbines for the next generation of aircraft engines is related to the sustainable weight reduction. Electron Beam Melting (EBM) already proved to be a promising process for TiAl alloys production, however further efforts are necessary in the comprehension of the role of the process parameters in order to better understand their relationship with residual porosity, Al loss and homogeneity of the microstructure. In order to improve the final properties, in this work a study of the EBM process as well as the subsequent heat treatment has been carried out on Ti-48Al-2Cr-2Nb (at. %) alloy and two slight modified chemical compositions. Theoretical-experimental analysis has been combined with the use of simulation tools to speed up the optimisation of both chemical composition and process parameters for EBM production. Such a combined approach was conducted regarding the influence of Al loss during the EBM process on phase fraction and phase transition temperatures. Additionally, heat treatment studies were carried out to further optimize the microstructure.

The presented work summarizes the preliminary results obtained in the NEWTEAM project "Next gEneration loW pressure TurbinE Airfoils by aM" funded by the EU's Horizon 2020 programme in the framework of Clean Sky 2.

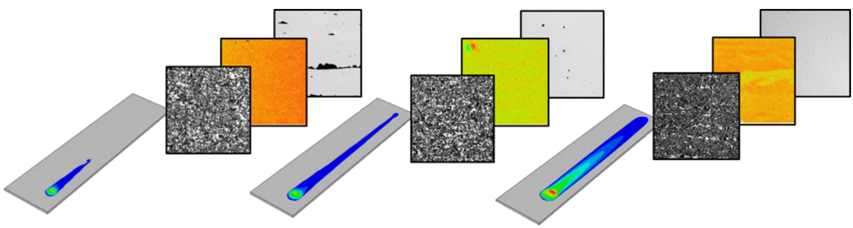

Figure 1: Microstructure and process parameter optimisation by process simulation tool: Effects of the process parameters on the aluminum loss and porosity.

Process stability and microstructural uniformity of additively manufactured Gamma TiAl alloy using Electron Beam Melting

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Ti–48Al–2Cr–2Nb alloy was manufactured by the electron beam melting (EBM) process, microstructural development and process stability were investigated. The requirement of high build temperatures 1000 °C for crack free TiAl printing is a challenge for a stable process, primarily due to the electron beam nature of the heat input and the electrical overcharging of the powder bed. Preheating and printing strategy using pins were helpful for adequate sintering of the powder bed, thereby reduced the occurrence of charge build-up and powder smoke. It is generally recognised that as-EBM TiAl samples exhibit a microstructural banding along the build direction, which can be attributed to the cyclic heat input and local Heat Affected Zones (HAZ) during layer by layer deposition in EBM [1]. Nearly fully dense Ti-48Al-2Cr-2Nb samples with minimum defects were printed. Detailed microstructural characterization along the build direction of samples printed by EBM showed that Energy Density (ED) has considerable influence on the as-EBM microstructure and final build quality in the EBM process. The microstructural uniformity along the build direction has been studied under different energy input conditions. Higher energy input, ED 6 J/mm 2 or more, showed better uniformity. Higher energy samples were near lamellar but medium and low energy samples were duplex or featureless massive gamma structure. 30% increase in colony size was observed with an increase of ED from 4 J/mm^2 to 6 J/mm^2. The study provides a valuable reference for fabricating gamma TiAl parts by EBM and control of microstructural uniformity.

[1] Todai, Mitsuharu, et al. (2017) *Additive Manufacturing*, **13**, 61-70.

Anelastic Phenomena in Ti6Al4V Additivley Manufactured by Electron Beam Melting

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Additive Manufacturing (AM) of metals is becoming a widespread method for fabricating parts in many industries. As a relatively new method, AM parts and methods are constantly being tested and improved. Mechanical properties are the focus of intensive studies, along with optimization of printing parameters and processes. Under certain service conditions, mechanical properties may be altered (i.e. cyclic loading), raising concern to their applicatibility. Therefore, while designing an engineering part for prolonged service, aspects such as anelastic phenomena (relaxation, hysteresis or creep for instance), should be considered.

This study is focused on anelastic phenomena and their implications on the mechanical properties of the Ti6Al4V additively manufactured products *via* electron beam melting. Printed specimens were subjected to symmetric cyclic tension/compression loading in the elastic regime and relaxation tests were also performed. Post processes on printed specimen were compared with commercially available extruded specimens. Results showed that the AM specimens exhibit different anelastic properties compared to extruded specimens, most likely as a result of the unique microstructure of AM parts, including hysteresis. It was also shown that specimen groups, differing by the post processing treatment had different stress coping mechanisims, resulting in changes in the material and mechanical properties.

On The Improvement of Geometrical Outcomes of EBM Parts with a Novel Design Approach

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Additive Manufacturing (AM) recently presents an increasing growth regarding the production of mechanical parts, due to its outstanding characteristics in comparison to conventional processes. AM methods facilitate the production of parts with unique and complex geometries without requiring subsequent operations or processes [1]. Electron beam melting (EBM) is considered as one of the effective AM methods to production of metallic parts. Designers are mostly unaware of the capabilities of EBM method and they face many challenges to utilize the EBM process because of the lack of design rules and guidelines [2]. Geometrical tolerances are very critical for a functional component and the manufacturing process plays an important role to determine the tolerances. Therefore this study aims to investigate the relationship between neighbouring features and productability of parts with improved geometric tolerance by using EBM. The goal was to propose specific design rules for these features. Hence, an experimental artifact (Figure 1) including different feature groups mainly composed of holes with / without dummy cylinders has been designed The holes and cylinders were modelled with different interspacing from 130 to 500 µm to examine the effect of geometric tolerances. The artifact from Ti6Al4V powders was produced with an ARCAM A2X machine and investigated.
The results have shown that by using EBM method with dummy cylinders; geometrical tolerances were improved, surface roughness (Ra) were decreased down to 17 µm, dimensional accuracies were improved by more than 50 % compared to EBM catalogue capability and 30 % better cylindiricity-circularity was obtained.

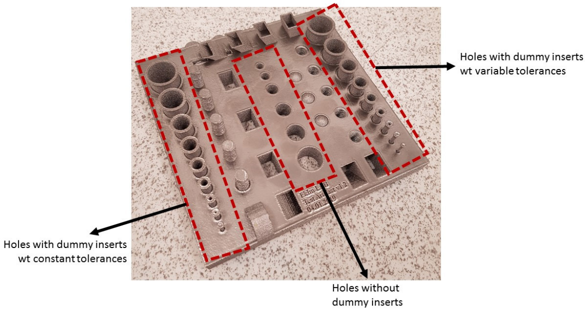

Figure 1: EBM Test Artifact.

[1] Umaras, Eduardo, and Marcos SG Tsuzuki (2017) *IFAC-PapersOnLine*, **50(1)**, 14940-14945.
[2] Ameen, Wadea, Abdulrahman Al-Ahmari, and Osama Abdulhameed (2019) *"Design for Metal Additive Manufacturing: An Investigation of Key Design Application on Electron Beam Melting"*.

Fatigue Crack Growth Rate of Electron Beam Powder Bed Fusion (EB-PBF) Titanium Alloy (Ti-6Al-4V): Effects of Crystallographic Texture

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The effects of crystallographic texture and internal pores on ASTM E647 fatigue crack growth rate (R = 0.1) of electron beam powder bed fusion (EB-PBF, Arcam A1) titanium alloy (Ti-6Al-4V) were investigated by studying material in the as-built and hot isostatically pressed (HIPed) conditions as well as in two orthogonal crack growth directions with respect to the build direction. HIPing sufficiently reduced porosity (x-ray CT), and unexpected texture variation (EBSD) was observed for this material (i.e. NOT $\langle 100 \rangle_\beta$-fiber in the build direction). It is hypothesized that the Arcam scan length function (at scan lengths shorter than the lack-of-fusion formation limit) unintentionally leads to variations in melt pool aspect ratio and gives rise to significant texture variation, possibly for identical parts adjacent to each other in the same build. Significant effect on the onset of unstable crack growth was observed due to internal porosity and texture variation.

Electron Beam-Based Additive Manufacturing of Periodic Open Cellular Raney-Copper Catalysts

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The powder bed-based selective electron beam melting (SEBM) is so far considered the optimal approach to fabricate periodic open cellular structures (POCS) for applications in chemical reaction engineering. In this work, Raney-Copper POCS with dense struts composed of a highly brittle Al-Cu alloy containing 29.4 at.% copper are successfully processed via SEBM (Figure 1 (a)). After selective leaching of aluminum in a NaOH solution, catalytic active periodic open cellular structures (CAPOCS) containing core-shell structured struts with a nanoporous copper surface layer and a solid core are derived (Figure 1 (b)). The SEBM-processed and selectively leached Raney-copper CAPOCS show a high catalytic activity in methanol synthesis. The nanoporous skin layer exhibits a high reaction surface area, while the unreacted core ensures sufficient mechanical stability for the reactor application and improves heat transfer.

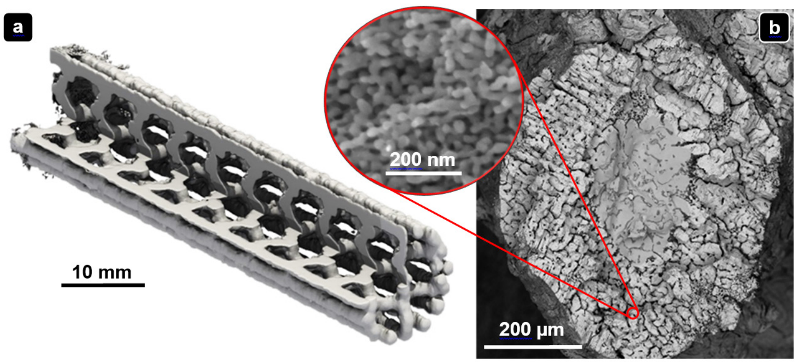

Figure 1: (a): CT-cutaway reconstruction of a SEBM-processed POCS with dense struts in the as-build state; (b): microstructure of the cross section of a leached strut with a nanoporous copper skin layer and a solid core; the inset shows copper ligaments and channels in the nanoporous skin area.

Microstructure refinement for superior ductility of Al–Si alloy by electron beam melting

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Refining the Si phase in Al–Si alloy has been a research interest for decades. Previous studies suggested many Al- and Si-enriched nano-segments (approximately 100 nm) can coexist in a melted Al–Si liquid solution when they were reheated to a temperature between 1080 and 1290 °C. These nano-segments could be retained to become crystal nuclei and grew into fine grains under a very fast cooling rate. Thus, this provides a novel approach of refining the microstructure of Al–Si alloy using electron beam melting (EBM) technology because the temperature exceeds 1500 °C in the melting pool with a cooling rate higher than 103 $°C\,s^{-1}$ during EBM building process. In this study, EBM is used to refine the microstructure of AlSi10Mg alloy to enhance the ductility. The formation mechanism of the microstructure during EBM build process was discussed. An argon gas-atomized AlSi10Mg (wt %) powder was used to fabricate as-built specimens using an Arcam A2X EBM system (Arcam AB, Mölndal, Sweden). AlSi10Mg alloys with well surface finish were fabricated using EBM. The microstructure observation shows mixed fine island-like and scattered granular Si phase particles (approximately 2 µm) having rounded corners and edges were embedded in the Al matrix. Fine Al sub-grains with size of 0.5 to 2 µm formed during EBM building process. A maximum ductility of approximately 32.7 % with a tensile strength of approximately 136 MPa were achieved for the as-EBM-built AlSi10Mg alloy [1]. The improved ductility compared with cast ones was attributed to the fine Si phase and the bimodal Al grains (large and fine sub-grains). A novel pathway of refining the Al–Si alloy microstructure to improve the tensile ductility without adding any modification element was developed in this study.

[1] H. Bian et al. Additive Manufacturing (2019) *in press.*

Selective electron beam melting of Al-Cu-Mg alloy: Processability, Microstructure Characterization, and Mechanical Performance

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Additive manufacturing of meal parts has been widely considered in different industries recently. To date, the most commonly used Al alloys for AM are eutectic/near-eutectic alloys. However, fabricating high strength aluminum parts have not yet fully investigated due to their susceptibility to solidification cracking and porosity formation. Compared with the selective laser melting, electron beam selective melting (EBSM) provides high potential for fabrication of aluminum alloys as is not affected by reflectivity of metal powders along with the advantage of oxidation inhibition in vacuum.

Gas atomized Al2024 powder was used in this study. Different sets of processing parameters such as beam current, scanning speed, hatch spacing, and scan strategy were used to investigate their effect on the parts' performance. Samples with relative densities ranges from 95 % to full-dense were built and results showed high relative densities can be achieved by increasing the input energy to an optimum value, however by further increasing the energy the relative density decreases as a result of porosity formation. As shown in Figure 1, crack-free, equiaxed and fine-grained microstructure mainly having eutectic Al2Cu and AlCuMnFe phases distributed in α phase matrix was obtained.

Microhardness results showed an almost uniform change of hardness values in both horizontal and vertical sections, ranges from 100 HV to 110 HV for as-built samples. Moreover, tensile and yield strengths of as-built samples reached 314 MPa and 192 MPa, respectively.

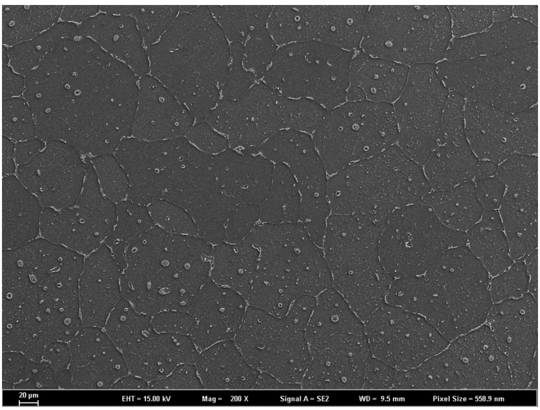

Figure 1: SEM micrograph of an as-built sample displaying defect-free microstructure.

Production and Properties of Gas Atomized TiAl and Ti-alloy EBM-Powders

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EBM-technology (Electron beam melting) has lead to an increased demand of TiAl- and Ti-powders. Among the applicable atomization technologies, the EIGA processing (Electrode Induction Gas Atomization) provides a reasonable set of melting and atomizing parameters for adjusting the resulting particle size distributions to the different AM technology needs.

TiAl based as well as tailor made Ti-alloy EIGA electrodes are being produced via single step VAR processing (Vaccum Arc Remelting) and subsequent VAR Skull Melting followed by centrifugal casting [1] or gravity casting [2] in permanent moulds. Typical diameters are in the range of 80 to 120 mm. EIGA processing principle shown in Figure 2 offers a crucible free melting procedure which saves energy and prevents very effectively the pick-up of metallic or ceramic impurities. Controlled Ar-atmosphere throughout all post-atomization powder handling steps minimizes pick-up of impurities during sieving and packaging.

Physical powder properties such as sphericity, Ar porosity, particle size distribution, apparent density and flowability depend on gas atomization parameters namely the nozzle diameter, the Ar flow rate, the melt rate and the corresponding shape of the induction coil. Within a given frame it is possible to adjust the atomizing parameters to different requirements on the particle size distribution in order to optimize specific powder yields to subsequent processing via EBM.

The fast-growing demand for spherical TiAl powders requires further efforts for technology improvements. One of the key steps to increase the efficiency is to maximize powder yields for the target grain size distribution, while not compromising key physical powder properties.

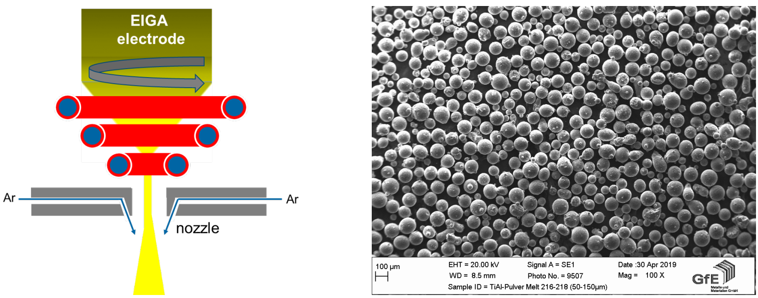

Figure 1: Sketch of EIGA process and resulting TiAl48-2-2 powder for EBM.

[1] V. Güther, M. Allen, J. Klose, H. Clemens (2018) *Intermetallics*, **103**, 12-22.
[2] K. Ratschbacher, J. Lindemann, M. Allen, V. Güther (2019) *Intermetallics, **104**.*
[3] V. Güther, K. Ratschbacher, J. Lindemann (2019) Manufacturing of TiAl Powders Based on Electrode Induction Gas Atomization, presentation at the Titanium Europe 2019, Vienna, Austria.

Electron Beam Melting of Alloy 718 - Powder Recycling and its Effect on Defect Formation

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This study addresses the connection between powder recycling, powder chemistry and presence of defects in EBM processed Alloy 718. First, virgin and recycled powder was studied to detect differences in surface morphology, surface chemical composition as well as bulk chemistry as a consequence of powder recycling. Significant oxidation of the powder surface is observed to occur during long-time exposure at the conditions in the EBM build chamber, leading to a steady gain in oxygen level of the progressively re-used powder [1]. Following this, analysis of the EBM material processed from recycled powder shows that the amount of oxide inclusions is clearly higher than in the virgin powder counterpart. In addition, large lack of fusion defects (LOFDs) form more easily when using the recycled powder, owing to accumulation of oxide in the hatch-contour interface region, as well as due to the reduced conductivity of the oxidized powder. Based on the defect morphologies, it is shown that most defects originate from Al-rich oxide particulates from the surface of the recycled powder, as well as titanium nitride from inside the powder, see Fig. 1. Clustering of oxide and nitride in the liquid metal often results in large inclusion defects. Elimination of porosity and LOFDs through hot isostatic pressing (HIP) of the as-printed specimens clearly reduces the defect density. However, as compared the virgin powder counterpart, the samples produced from recycled powder have a higher defect density after HIP treatment due to the higher amount of oxide inclusions [2].

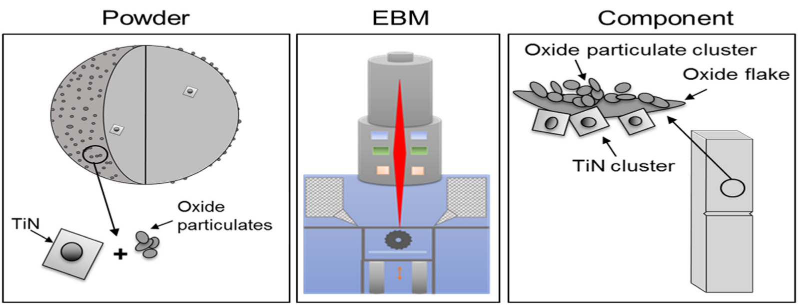

Figure 1: Transfer of non-metallic inclusions from the powder to the component in EBM processing.

[1] H. Gruber, M. Henriksson, E. Hryha, L. Nyborg (2019) *MMTA*, **50**, 4410-4422.
[2] H. Gruber (2019) *Electron beam melting of Alloy 718 – Powder recycling and its effect on defect formation, Licentiate Thesis, Chalmers University of Technology.*

Influence of powder deterioration on the risk of smoke in EB-PBF processes using IN718 powder

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Using electrons as energy source in powder bed fusion additive manufacturing brings a number of advantages, but also leads to charging of the powder particles. Due to the high electric resistivity of powder beds the electrostatic forces can reach the magnitude of the particles gravitational forces and lift the particles out of the build plane. This event, often referred to as "smoke" or "powder spreading", destroys the current powder layer and may lead to process termination. In this work, a procedure was developed to determine smoke free process windows for electron beam current and scan velocity, including the influence of a repeating scan pattern. Investigations have been conducted using Inconel 718 powder. It has been shown, that for an arbitrary scan pattern and a fixed beam current, the scan velocity not only has a lower limit but also an upper limit. Exceeding either leads to smoke. While the reason for the lower limit is obvious, the upper limit is counter-intuitive as a higher scan velocity leads to a more even charge deposition across the powder bed. Investigations were repeated for three different levels of powder aging. With increasing powder age, the velocity window decreases. For unaged powder, the velocity limits did not show a significant dependence on the electron beam current, which cannot be explained using prevailing models for powder bed charging.

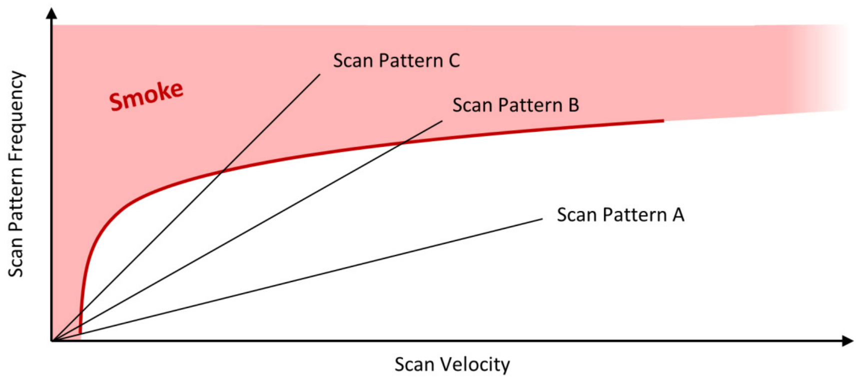

Figure 1: Determination of the process window for different scan patterns.

Formation mechanism, microstructure and composition of the spatter formed during EBM processing of IN718

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Considering the recyclability of the powder, there are two major factors which can immensely deteriorate the properties of the final product that include powder surface oxidation and spatters formation. The powder oxidation of IN718 has been studied already presented [1-2]. However, the spatters analysis did not attract enough attention. The current study is focused on the investigation of the spatter formation during EBM processing of IN718. For the analysis of the spatters, heat shields from Arcam A2X machine were used which contains a large density of the condensate with presence of spatter particles, see Fig.1. Hence, the evaporation and condensation of the elements with high vapor pressure were also studied. Microstructural and chemical analysis have been done by using HRSEM, EDS, XPS and AES techniques. The spatter distribution analysis on the sheet shows that most of the spatter is located at the bottom of the heat shields, assuming high fraction of the spatter present in the powder bed. Spatter observed on the heat shields is covered by layer of condensate, deposited after spatter deposition. The chemical analysis of the powder surface and corss-section by EDS and XPS have shown that the surface of the spatters on the heat shield mainly covered by the oxides of Al and Cr, corresponding to the higher thermodynamic stability of the mentioned oxides.

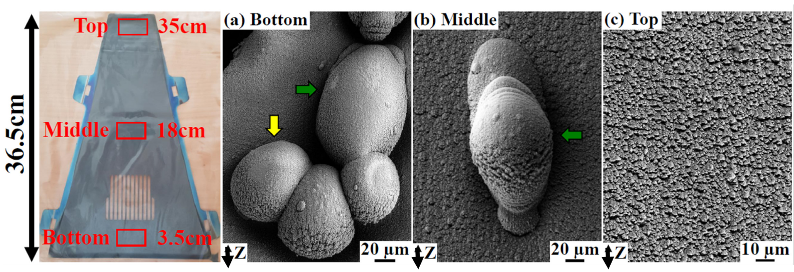

Figure 1: The illustration of spatter distribution on the heat shields.

[1] H. Gruber, M. Henriksson, E. Hryha and L. Nyborg (2019) *MMTA*, **50**, 4410-4422.
[2] H. Gruber (2019) Licentiate Thesis, Chalmers University of Technology.

Modeling single-particle and powder bed absorption in CM247LC superalloy for electron beam melting additive manufacturing

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Precise representation of electron-matter interaction is crucial to accurate modeling of the electron beam melting process, especially given the high energies at play compared to laser processing. For industrially-relevant alloys such as CM247LC, electron beam melting is a promising candidate to tackle the significant challenge of building a crack-free component. With this long-term goal in mind and starting with established semi-empirical models for pure metals, we study electron beam absorption for the actual alloy composition of CM247LC. Using the model, we then simulate absorption in one particle and in a powder bed. Single-particle absorption profile is consistent with validated single-element profiles. Absorption in powder bed clearly shows the front particles shadowing the buried ones, thus providing a complex absorption landscape. In turn, energy absorption profile is a key ingredient for a reasonable model of heat source for the electron beam process.

Breaking the Link Between Build Temperature and Powder Electrical Characteristics Allows Optimizing the Processing Window of EB Additive

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Developing the LEAM powder feeder allows us to decouple the typical electron beam additive process sequence (see Figure 1) by including a powder in situ processing step. This powder treatment targets various aspects of the material such as humidity, oxides and electrical parameters.
Experiments show that materials such as water atomized particles can be dispensed with this advanced method in a very controlled way. In addition, the powders can be de-oxidised with various techniques before dispensing onto the build platform. As such the electrical charge of powder, or smoking effect, can be better controlled and part melting at lower temperatures with thicker layers can be achieved. The various powder preparation techniques will be discussed, and solutions shown. The commercial impact of optimizing the electron beam melting will be outlined targeting the reduction of material costs, shorten the build time, improving process stability and therefore reducing overall production costs.

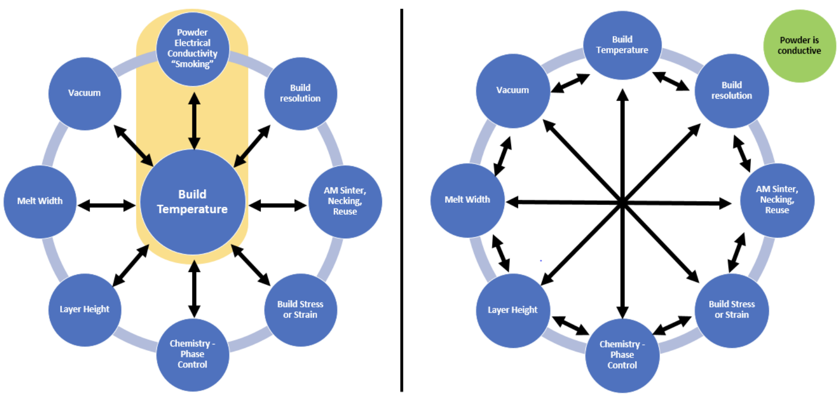

Figure 1: Left shows the current EB Additive process, the right shows the decoupled process flow.

Avoiding "smoke" with a ball milling in air for alloy powder in powder bed fusion type electron beam additive manufacturing

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Powder bed fusion type electron beam additive manufacturing (PBF-EBAM) is a technology that irradiates an alloy powder bed (PB) with a high-power electron beam to produce parts as per 3D design. Unlike the laser beam irradiation, the electron beam has a negative charge, so that the individual metal powders are negatively charged by the irradiation, and the PB is scattered in the form of smoke by a process called "smoke" due to the Coulomb repulsive force. When smoke occurs, PBF-EBAM processing becomes virtually impossible. For this reason, one of the most important issues in the PBF-EBAM processing is the development of technology that suppresses smoke.
As a method of suppressing smoke, the current process has been developed through optimization, guided by qualitative rules of thumb through experimentation. Specifically, the fact that increasing the temperature of the PB often makes it insusceptible for the powder to be smoked; in the case of Inconel 718, for example, the preheating temperature has to be set at approximately 1273 to 1323 K to suppress the smoke. However, this empirical smoke suppression method lacks physical explanation and is not necessarily useful in predicting whether smoke can be suppressed under a given building condition. Therefore, a basic understanding of the charging behavior of the alloy powder is necessary to accurately predict these building conditions that cause smoke, and is an extremely important research issue for further development of PBF-EBAM technology. However, there is currently little research and development related to alloy powders from this viewpoint. The purpose of this study is to clarify the relationship between electrical impedance and smoke generation ability and finally to find a way to prevent smoke without preheating the PB.
Different kind of alloy powders were mechanically treated with a ball mill in air to strain the nm-ordered thickness oxide film covering the powder surfaces. The electrical resistivity and AC impedance of various powders (Inconel 718, Ti alloy, Fe-C steel, Cu, etc.) with and without straining were systematically measured. Furthermore, the Inconel 718 powder was irradiated at temperatures from RT to 973 K with an electron beam in order to verify the smoke generation ability.
In this study, it has been substantiated for the first time that mechanically straining the powder surface with a ball milling in air is an effective methodology to suppress the smoke without a preheating the powder bed in PBF-EBAM process.

Multi-physics modeling of the electron beam additive manufacturing processes: powder spreading, pre-heating, and melting

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The electron beam additive manufacturing processes consist of three major procedures: 1) spreading a powder layer; 2) preheating to slightly sinter the powder to prevent powder "smoke"; 3) selective melting. To comprehensively understand the processes, we developed multi-physics models to resemble the actual fabrication procedures [1-3]: 1) a powder-spreading model using the discrete element method (DEM); 2) a phase field (PF) model of powder sintering (solid-state sintering); 3) a powder-melting (liquid-state sintering) model using the finite volume method (FVM). Experimental validation demonstrates the capability of these models to shed light on the physical mechanisms and to guide the parameter selection and optimization.

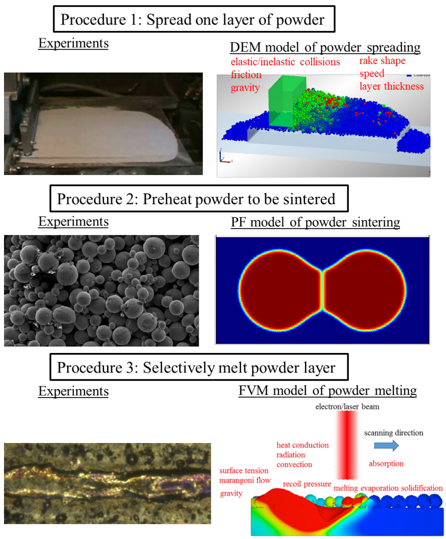

Figure 1: Multi-physics modeling of the electron beam additive manufacturing processes [1]

[1] W. Yan, Y. Qian, W. Ma, B. Zhou, Y. Shen, F. Lin (2017) *Engineering*, **3(5)**, 701-707.
[2] W. Yan, W. Ge, Y. Qian, S. Lin, B. Zhou, W.K. Liu, F. Lin, G.J. Wagner (2017) *Acta Materialia*, **134**, 324-333.
[3] W. Yan, Y. Lian, C. Yu, O.L. Kafka, Z. Liu, W.K. Liu, G.J. Wagner (2018) *Computer Methods in Applied Mechanics and Engineering*, **339**, 184-204.

On the Use of Inherent Strain Method for Modelling Electron Beam Melting

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Electron Beam Melting (EBM) is an additive manufacturing (AM) method suitable to process a wide range of alloys in an effective manner due to its high power density and considerably high scan rates in comparison to other metal AM processes. However, a significant level of expertise is necessary to establish this process for demanding industrial applications. By means of fact and accurate process simulation to predict the residual stress/distortion in EBM parts, it is possible to ensure manufacturability and improve the component quality. Most of the commercial software available in the market utilize different variants of inherent strain method to simulate Selective Laser Melting (SLM), to estimate the residual stresses and resulting distortions at part-scale. Some software packages such as MSC Simufact employ experimental calibration to determine the applied inherent strain components. Thus, this study addresses the feasibility of using MSC Simufact to simulate the residual stresses and distortions in EBM parts utilizing inherent strain method and calibration. The calibration parts shown in Figure 1 did not show significant deformations, yet a wavy surface profile depending on the periodic support beneath, which is a phenomenon not encountered in the SLM process. The preliminary evaluations which will be detailed in the presentation lead to the conclusion that EBM process simulation at part-scale without taking into account several mechanisms inherent to the process is not achievable for the moment.

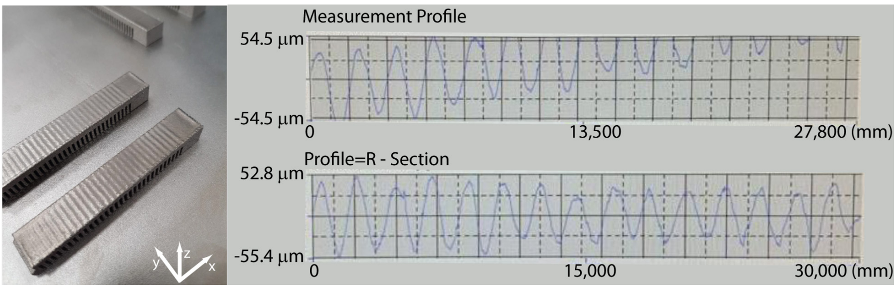

Figure 1: Calibration parts produced along X and Y directions (a) leading to wavy surfaces with their (b) profiles measured.

Development of a Thermo-mechanical Model of Electron Beam Additive Manufacturing Process for Repair Purposes

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Repair through electron beam additive manufacturing (AM) deposition on aerospace components proves to be promising, especially if replacements of expensive materials and manufacturing costs are considered. However, high residual stresses, distortion and heterogeneous microstructures induced on parts due to complex thermal cycles are the major challenge for development of AM based repair techniques to meet performance criteria and extend the service life of these components. In this study, a thermo-mechanical finite element model (FEM) to predict residual stresses and distortion during repair process was developed. FEM simulated results were validated using electron beam wire AM experiments with aerospace alloy, Ti-6Al-4V. Thin wall plates are used to replicate repairing procedure of turbine blade geometry. Microstructural and mechanical property characterization of the repaired parts was undertaken to allow comprehensive understanding of the inter-relationships between the process, structure and performance.

Explore the Applications of Electron Beam Melting for Industrial Components

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Although early adopters electron beam melting (EBM) has shown that the better-designed components offer substantial performance improvements over current designs, some inherent drawbacks such as rough surface, and relatively small in the size of the built part, limited its adoption. We'd like to share the efforts done by our group to overcome the drawbacks. It covers our three newly proposed approaches, (i) hybrid fabrication to reduce the total cost and realization of bimetal components [1], (ii) in-situ welding to realize the full-volume fabrication [2] of different alloys, and (iii) ex-situ welding [3] to fabricate large volume components, to suit for various applications such as aerospace and compliant mechanism. Some case studies by using our proposed approaches will also be shared.

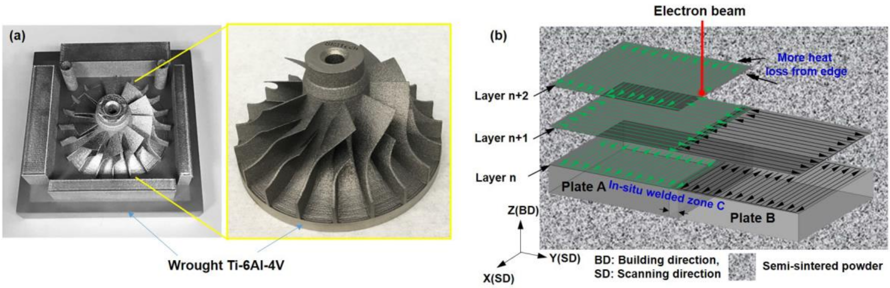

Figure 1: Illustration for (a) hybrid fabrication and (b) in situ welding.

[1] Y.Y. Sun, P. Wang, S.L. Lu, L.Q. Li, M. L. S. Nai, and J. Wei (2019) *J. Alloy Comp.*, **782**, 967-97.
[2] P. Wang, M.L.S. Nai, W.J. Sin, S. Lu, B. Zhang, J. Bai, J. Song, and J. Wei (2018) *Additive Manufacturing*, **22**, 375-380.
[3] P. Wang, M.L.S. Nai, S. Lu, J. Bai, B. Zhang, and J. Wei (2017) *JOM*, **69(12)**, 2738-2744.

SEBM Processing of Water Atomized Iron Powder

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In the present state of the art, highly spherical alloy powders are employed as feedstock in powder bed fusion processes. These powders are characterized by high flowability and apparent density. Their elaborate fabrication process is reflected in high powder price, adding a significant fraction to the cost of additively manufactured parts. Thus, the use of non-spherical powders such as water atomized material can lower costs significantly. Here, the selective electron beam melting (SEBM) of water atomized iron powder is studied. Important powder properties of the feedstock are characterized. In a further step alloying elements were added. Samples were characterized by metallographic cross-section, EDX mapping and mechanical testing. Despite raking problems using the coating mechanism in standard configuration samples with densities exceeding 99.5 % were fabricated. After SEBM processing of the powder mixtures chemical homogeneity and mechanical properties were characterized. Beside the low cost this approach of using water atomized powder mixed with master alloy offers the advantage of high flexibility for potential application.

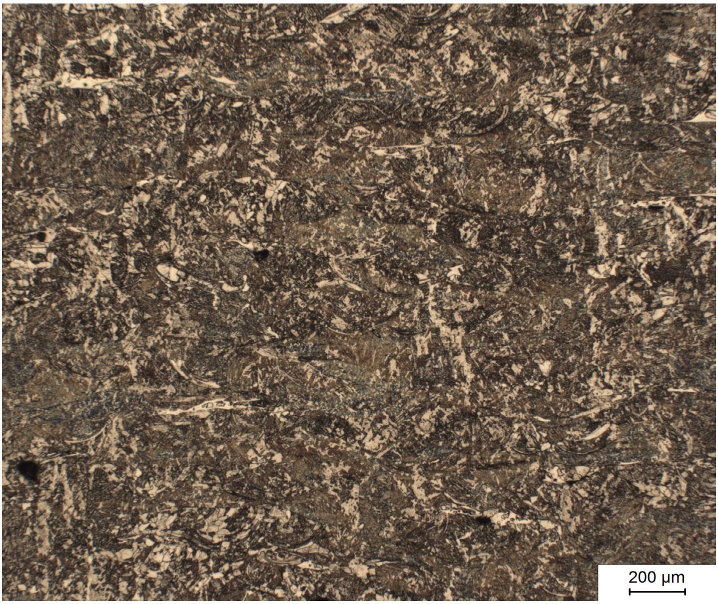

Figure 1: Optical micrograph of SEBM processed water atomized iron powder blended with 10 % 316L and 0.25 % graphite. Polished sample etched with Nital. Build direction is vertical.

Microstructural and Mechanical Evaluation of Cr-Mo-V Cold-Work Tool Steel Produced via Electron Beam Melting (EBM)

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As one of the Additive Manufacturing (AM) techniques, Electron Beam Melting (EBM) has been successfully used for the manufacturing of high performance components for the aerospace and medical industries. As a consequence, that research has also mainly been focused on material systems relevant for the aforementioned industries, and other alloying systems such as tool steels are only recently receiving attention.
In this study, martensitic highly alloyed (Cr-Mo-V) cold-work tool steel processed by EBM has been examined. Based on the as-built microstructure obtained, a modified heat treatment was devised in order to optimize it, which was studied by means of light optical (LOM) and scanning-electron microscopy (SEM) techniques. Phase analyses were also conducted by X-ray diffraction (XRD). Effect of hot isostatic pressing (HIP) on the mechanical properties of EBM produced parts was also investigated. Compressive strength, impact toughness, abrasive wear properties were also evaluated to assess its performance for intended tooling applications. The results were compared with those obtained from the conventionally processed material through the powder metallurgy route.

SEBM of wear resistant materials

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Due to the small diversity of materials, the areas of application of additive manufacturing in the toolmaking industry are currently still limited. In order to meet these challenges, AM material development for high carbon containing iron based materials, which are characterized by high strength and hardness as well as high corrosion or wear resistance, must be intensified. However, these materials are often susceptible to crack formation or lacks of fusion during processing. Therefore, these materials are preferentially suited for SEBM.

In this paper different material examples will be presented, namely the MMC Ferro Titanit® and the material system FeCrV. Ferro Titanit® consists of titanium carbide (TiC) embedded in a corrosion resistant soft martensitic metal matrix. Investigations on different powders were carried out on the EBM system Arcam A2X. These powders varied with respect to e.g. flowability, because this material cannot be produced by gas atomization. The material system FeCrV is characterized by a two phase microstructure with an Fe rich matrix and VC reinforcements. Investigations using gas atomized powder were done on the EBM system Arcam A2X as well.

The resulting microstructures were characterized by scanning electron microscopy (SEM), energy dispersive spectrometry (EDX), and optical image analysis. Furthermore, mechanical properties (e.g. hardness) were measured in the as built as well as heat treated state.

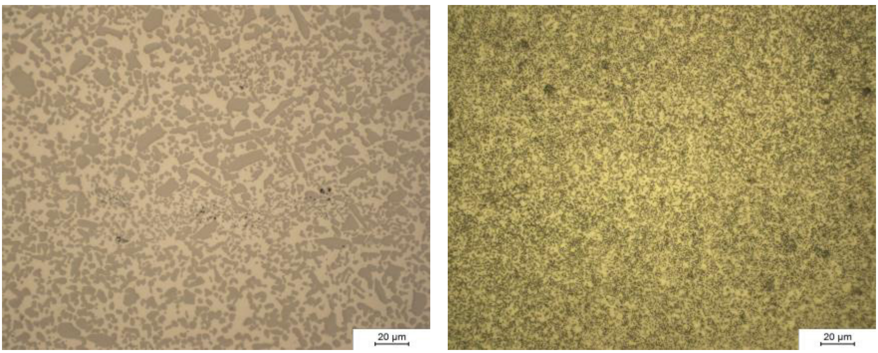

Figure 1: Microstructure of EBM built Ferro Titanit® (left) and FeCr10V (right).

Square celled TRIP-steel honeycomb structures produced by electron beam melting

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The powder-bed additive manufacturing technology Electron Beam Melting (EBM) is suitable to produce metallic components with complex geometries. Therefore, it is an appropriate method to generate lightweight structures in order to save material and energy in fields of transportation. Usually the microstructure of additive manufactured metals is governed by columnar grains in build direction. Hence the mechanical properties are affected by strong anisotropy. Recently, Günther et al. [1] showed the microstructure of a metastable austenitic CrMnNi steel produced by EBM. Due to primary ferritic solidification and multiple phase transformation induced by intrinsic heat-treatment in the layer-wise EBM process the material develops a fine-grained microstructure. In the present study the microstructure evolution of this particular alloy is investigated for square-celled honeycomb structures with varying geometrical features produced by EBM. Quasi-static out-of-plane compression tests on these honeycomb structures show, that the strength rises with increasing energy input during additive manufacturing. A high energy input on cell structure struts leads to an enhanced mechanical energy absorption capacity due to less porosity.

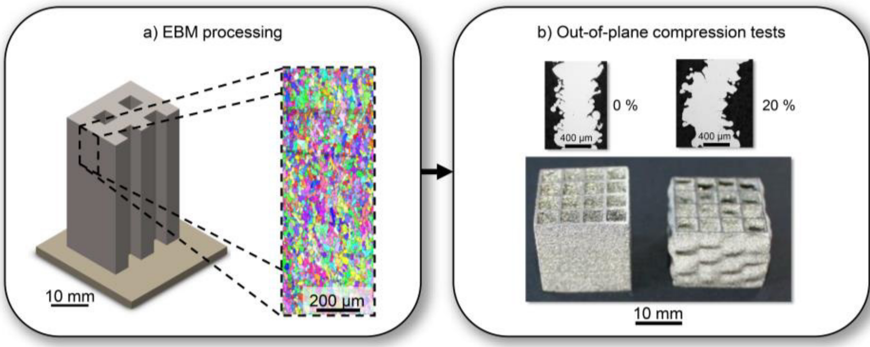

Figure 1: a) 3D model of square celled honeycomb structure and EBSD scan of microstructure, b) condition before and after out of plane compression test.

[1] J. Günther, F. Brenne, M. Droste, M. Wendler, O. Volkova, H. Biermann and T. Niendorf (2018) *Scientific Reports*, **8**, 1-14.

Characteristics, Processing and Process Monitoring of High Purity Copper Powders for EB-PBF Additive Manufacturing

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Despite recent progress, achieving the high purity requirements for copper using EBM has remained a significant challenge. Applications including particle accelerators and microwave vacuum electronic devices (VEDS) require the highest electrical and thermal conductivity as well as ultra-high vacuum compatibility. Copper used in these applications approaches the theoretical maximum achievable quality in terms of both purity and density, as well as tightly controlled crystallographic texture and grain size ($0.15176\,\Omega\,\mathrm{g\,m^{-2}}$ at 20 °C and max 0.0005 wt.-% Oxygen). The negative influence of oxygen contamination on the electrical, thermal and mechanical properties of copper is well-documented. Perhaps more significant is the adverse effect of embrittlement caused by excessive oxygen content during subsequent hydrogen brazing processes. Of chief concern is the powder feedstock purity. Copper powders for AM typically exceed 100 - 300 wt.-ppm oxygen or more. The powder feedstock commonly used in AM is subject to oxygen contamination during handling, screening, loading and transport. The characteristics of AM powders that contribute to the rapid kinetics of oxidation, also suggest that correspondingly rapid reduction processes may be employed to improve feedstock purity for AM processing. Hydrogen, carbon monoxide and ethanol are commonly employed reducing agents of Cu_2O and CuO in thin films and powders. Hydrogen for instance reduces grain boundary oxides forming H_2O gas. The later H_2O molecules do not diffuse, and the resulting pressure forms steam pores along grain boundaries. This well-known mechanism is considered deleterious for most traditional copper powder processing techniques causing swelling, porosity and embrittlement through plastic deformation, work hardening, the reduction of grain boundary area, and material failure at elevated temperatures. However, a unique feature of EBM compared to bulk powder metallurgy approaches is that melting, and solidification occurs locally on a micro scale. In the present work, we demonstrate that the localized control of thermal inputs can be leveraged to liberate retained H_2O from copper powder exposed to hydrogen during EBM on a layer-by-layer basis, resulting in significantly higher copper purity without the detrimental effect of embrittlement observed in traditional powder metal processes.

Effect of surface coating for pure-Cu powders on electron beam melting process

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Additive manufacturing of pure-Cu has attracted much attention owing to the possibility of fabricating complexed-shaped pure-Cu parts, which enable high-efficient heat radiator. Because of high absorptivity of pure-Cu for electron beam, electron beam melting (EBM) is one of the prospective candidates for fabrication complex-shaped pure-Cu parts. On the other hand, EBM process needs preheating sequence in order to avoid smoke phenomena, which is powder spreading due to electrostatic charge of powders by electron beam. This preheating sequence elevated the temperature of powder bed, and Cu powders are easy to be sintered, indicating that a strongly-sintered powder bed forms during EBM process of pure-Cu. The strongly-sintered powder bed prevents the removal of powders around the fabricated parts, especially in the case of removing powders from the flow channel in the parts. In order to weaken the sintering of pure-Cu powder bed around fabricated parts, in this study, we have prepared pure-Cu powders with surface coating and have investigated the effect of the surface coating on the sintering of powder bed and properties of the EBM-fabricated parts.
Pure-Cu blocks were fabricated by ARCAM A2X EBM system using surface-coated Cu powders as raw material. Process parameters were optimized by a machine learning approach. Powders, sampled from powder bed near the fabricated parts and base plate, were screened by using a sieve with the mesh size of 150 µm in order to investigate the sinterability of powders. The microstructure, chemical composition, mechanical properties, and electron conductivity were also analyzed in order to investigate the effect of the surface coating for powders on the properties.
The dense pure-Cu blocks with high relative density over 99 % can be successfully fabricated. The fabricated blocks showed same electron conductivity as pure-Cu, indicating that the surface coating for the raw material powders does not have detrimental effect on the thermal conductivity of EBM-fabricated parts. The powders, sampled from powder bed after EBM process, could be easily screened by using the sieve with the mesh size of 150 µm without blast treatment, indicating that the surface coating can prevent powders from being sintered with each other.

Predictive Modeling and Validation of Electron Beam Powder Bed Fusion Additive Manufacturing of Metals at the Mesoscale

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Parameter development and consistent quality control for new materials, part geometries and next generation machines can be challenging in powder bed fusion (PBF) additive manufacturing, in part due to insufficient in-depth understanding of the connection between the process parameters, melt-pool behavior and the resulting part properties.
We present the results of 3D modeling of the electron beam PBF process at the mesoscale level, with high-fidelity numerical tool that includes physics of the electron beam and the laser interaction with the powder bed, phase transitions, and detailed liquid dynamics of the molten metal. The model captures in detail the fundamental differences in the heat deposition between the electron beam (volumetric heat source) and the laser (surface heat source) PBF. Examples of the resulting differences in the melt pool behavior and potential advantages of EBM for high productivity PBF are described.
The model has been applied to a number of materials of interest for additive manufacturing; comparison with experimentally measured morphology of single tracks on plate and powder as well as results of modeling of the entire layer formation are given for Ti-6Al-4V and Cu cases. Model applications to the process parameter development, training of reduced order thermal models, guidance for the design of the electron beam properties for next generation EBM PBF AM machines are discussed.

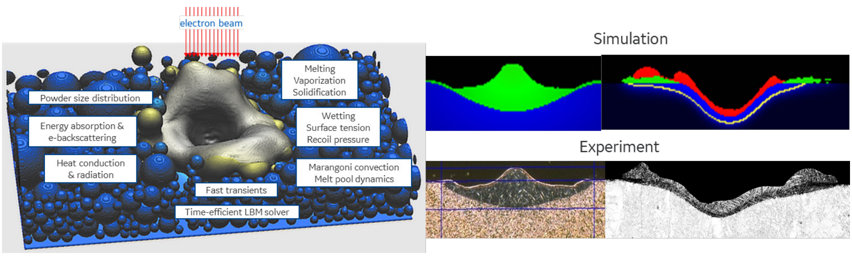

Figure 1: Electron beam powder bed fusion model illustration and single track validation examples.

Development of CuCrZr Components by Electron Beam Melting (EBM) Technology

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Precipitation hardened CuCrZr alloy is the reference point as heat sink material for the water cooled W divertor concept of DEMO because of its excellent mechanical properties and high thermal conductivity. CuCrZr traditionally processed by forging, casting or hot rolling involves quite a lot of challenges such us coarsening of Cr precipitates, microstructures highly heterogeneous as well as troubles in obtaining complex geometries. However, this point can be solved by Additive Manufacturing which allows creating innovative solutions with complex structures for heat exchangers and heat sinks.
Cu and Cu alloys are the main metal choice for these applications. However, these materials present limited process ability by laser-based technologies such us Laser Melting due to their high reflectivity and thermal conductivity which leads to difficulties in obtaining highly dense components by promoting the presence of defects like cracks or delamination.
In the present work the Electron Beam Melting (EBM) technology is proposed to process the CuCrZr alloy since EBM is not influenced by the reflectivity of the materials and it allows obtaining highly dense Cu-based components. Additionally, EBM works under high vacuum, which prevents oxidation of powders with high affinity to oxygen such us pure Cu and Cu alloys.
In this work the study of a CuCrZr alloy with nominal composition 0.6-0.9 Cr, 0.07-0.15 Zr (wt. %) has been carried out by Electron Beam Melting. A detailed process parameters study has been performed in order to obtain a process window which allows processing dense materials free of defects. The process parameters, including post-built heat treatments like HIP, solution annealing and age hardening have been correlated according to microstructure and mechanical properties. Microstructure was characterized by Optical Microscopy (OM) and Scanning Electron Microscopy (SEM). Thermal conductivity, hardness and the mechanical behaviour obtained were compared to values obtained in CuCrZr alloys processed by casting and forging or hot rolling, and by HIP of gas atomized powders.

Process Monitoring by Evaluation of Backscattered Electrons during Electron Beam Melting

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Additive manufacturing (AM) by Electron Beam Melting (EBM) arouses increasing interest among industrial users, especially for medical and aerospace applications. The successful integration of AM processes into the production chain of these industries is based upon the fulfillment of high requirements regarding process control and the compliance with well defined quality standards. During EBM, arduous processing conditions, i.e. extreme temperature, high vacuum and X ray radiation, impede the continuous operation of standard process monitoring devices like light optical camera systems. To overcome this deficit, detection of backscattered electrons is a highly promising approach. It delivers a signal, which is sensitive to variations during processing while the detector is insusceptible to the harsh environmental conditions. A detection system for backscattered electrons is implemented in an in house EBM system and used for the acquisition of electron optical images of the molten surfaces as well as for the record of the in operando signal during melting. The data is correlated afterwards to the as built specimens to demonstrate the high usability for process monitoring challenges during EBM.

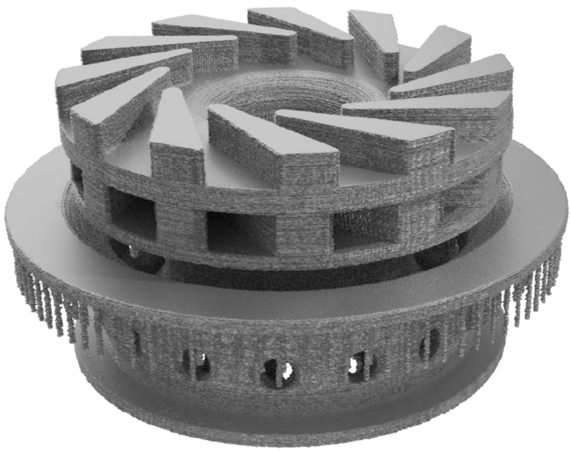

Figure 1: Reconstruction of as built component by evaluation of electron optical images during electron beam melting.

Bilateral Detector Electronic Imaging Technique for in-situ Monitoring of Electron Beam Selective Melting

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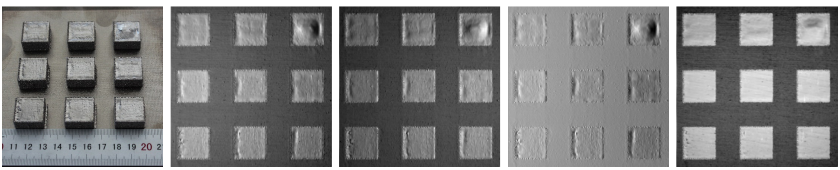
Electron Beam Selective Melting (EBSM) is a promising additive manufacturing technique while lack of process monitoring and quality control are restricting its industrial application. Major studies concentrated on the thermographic monitoring of layerwise deposition with near-infrared or infrared thermal sensors. These thermal sensors are largely restricted by the intensive radiation, elevated temperature and strong evaporation. Electronic imaging, which is insensitive to metal evaporation and also suffers little from radiation and high temperature, was introduced into EBSM process. As an active monitoring method, electronic imaging is expected to detect and identify various defects such as surface fluctuation and pores, which are usually caused by excessive energy input or insufficient energy input in EBSM process.
In this presentation, a novel bilateral detector electronic imaging technique for in-situ monitoring of EBSM process will be presented, including the system configuration and signal process. A verification experiment, as shown in Fig.1, will be presented as well to explore its sensitivity on surface morphology. The image of difference signal of left detector to right detector enhanced the depressions and bulges features, as shown in Fig.1(d). On the contrary, the image of summary signal of both lateral detectors enhanced the porous features, as shown in Fig.1(e), while neutralized the depressions or bulges features. Furthermore, the altitude of the surface could be reconstructed through the signals from bilateral detectors, which could provide 3D geometric data for defects identification. Recent studies illustrated that the in-situ monitoring by the bilateral detector electronic imaging technique would be expanded to intelligent process parametric optimization and online quality control.



a) b) c) d) e)

Figure 1: Optical image and electronic images of the CoCrMo specimens.

In situ optical/near infrared process monitoring of Selective Electron Beam Melting

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Electron Beam Melting (EBM) is becoming a mature additive manufacturing process. However, EBM can generate defects which can be detrimental for the final performances of the fabricated components. In order to increase the process reliability and to anticipate the quality of the built parts, *in situ* imaging is a requirement. Our strategy is to monitor the EBM process (EBM A1 Arcam machine) using an "optical/near infrared" high resolution camera which allows to observe the layer-by-layer process when building test parts made of Ti-6Al-4V alloy. The developed device enables to acquire images either at key processing steps (typically after completing each layer) or continuously so as to produce movies. Images contain information about part geometry but can also provide qualitative thermal information. Thanks to in-house image analysis routines, our monitoring device reveals, layer-by-layer, the occurrence of defects created throughout the EBM process such as lack-of-fusion defect, "channel-like" pores or geometric distorsions. In order to validate this detection, images taken at every layer during the build and reconstructed to obtain a 3D image are compared with the 3D volume obtained by X-ray microtomography once the build is completed (see Figure 1). Furthermore, fine qualitative analysis of the images grey levels allow to point out some thermal issues such as a bad energy input or a defective energy dissipation.

Work supported by the FUI21 PALOMA project.

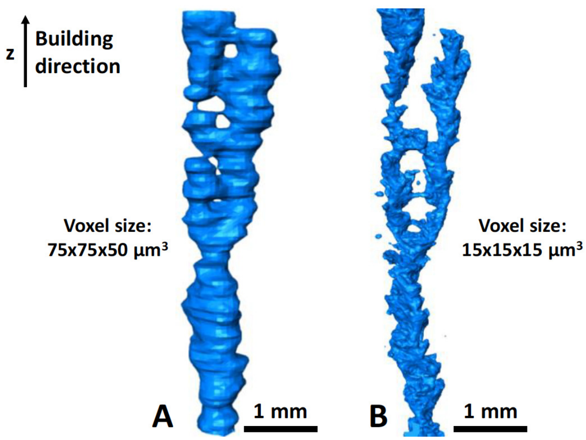

Figure 1: Same "channel-like" pore obtained from A) in situ optical images, B) X-ray microtomography.

Video imaging methods for in-situ detection of irregular powder bed recoating and hot-spots in EBM

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An increasing attention has been devoted in the recent years to in-situ sensing and monitoring of the Electron Beam Melting (EBM) technology ranging from first seminal methods based on infrared imaging [1] to novel methods based on back-scattered electron detection [2]. However the in-situ monitoring capabilities in EBM are still more limited than in laser powder bed fusion (LPBF). Some methods that are already industrially available in LPBF systems, like in-situ detection of recoating errors, together with other methods whose feasibility has been demonstrated in the LPBF-related literature, have not been investigated and tested in EBM so far. Motivated by the attempt to fill this gap, we present two novel in-situ monitoring methodologies in EBM that can be easily implemented in industrial machines as they are based on high-spatial and high-temporal video imaging in the visible range. The first approach (Figure 1a) is aimed at identifying inhomogeneities and local irregularities in the powder bed by means of layerwise image acquisition synchronized with the powder recoating operation. The second approach (Figure 1b) focuses on the automated detection of so called "hot spots" [3], i.e., regions of the powder bed where anomalous heat accumulation occurs, leading to possible in-plane and out-of-plane geometrical distortions and/or local peaks of material evaporation. We present the benefits and open issues related to the proposed methods with different motivating case studies, and we discuss the correlation between in-situ detected anomalies and actual defects in the part to deepen the potential role of proposed methods for in-situ and in-line qualification of EBM.

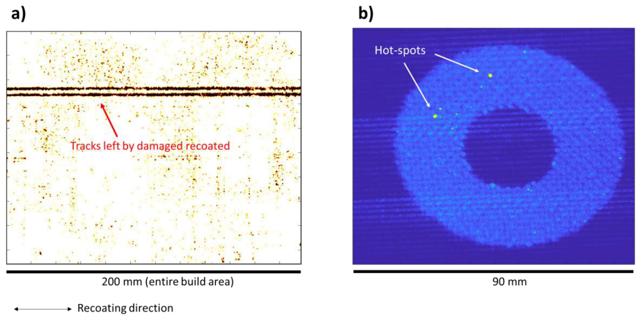

Figure 1: Examples of proposed methods for in-situ defect detection in EBM : a) detection of a recoating error caused by a damaged recoated, based on layerwise high-spatial resolution imaging; b) detection of hot-spots during the EBM of a lattice component, based on statistical analysis of high-temporal resolution video image data.

[1] Dehoff, R. R., Kirka, M. M., Ellis, B., Paquit, V. C., Nandwana, P., & Plotkowski, A. J. (2018) *Electron Beam MeltingTechnology Improvements (No. ORNL/TM 2019/1092). Oak Ridge National Lab.(ORNL), Oak Ridge, TN, USA.*
[2] Pobel, C. R., Arnold, C., Osmanlic, F., Fu, Z., Körner, C. (2019) *Mater. Lett.*, **249**, 70-72.
[3] Colosimo, B.M., Grasso, M. (2018) *Journal of Quality Technology*, **50(4)**, 391-417.

Combining In-situ Monitoring and X-Ray Computed Tomography to Assess the Quality of Parts Manufactured by Electron Beam Melting

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In the most recent metal powder bed fusion technologies for additive manufacturing different in-situ monitoring sensors are available. These monitoring technologies generate a huge amount of data directly during the production process. In the future, this data could be used to avoid, reduce or precisely target following destructive or non-destructive testing methods or even stop the production of this build job in an early stage.
In the current state of in-situ monitoring solutions the indications and process instabilities shown are very hard to interpret. Further investigations and correlations with post-process testing measures are necessary. In our paper, we show how to correlate in-situ monitoring data with computed tomography results. For this, we use a test specimen which was produced on an Arcam Q20+ with monitoring functionalities. Further, we show different approaches of analyzing the in-situ data for process instabilities and how to use modern machine learning methods [1] to correlate process signatures with part quality metrics.

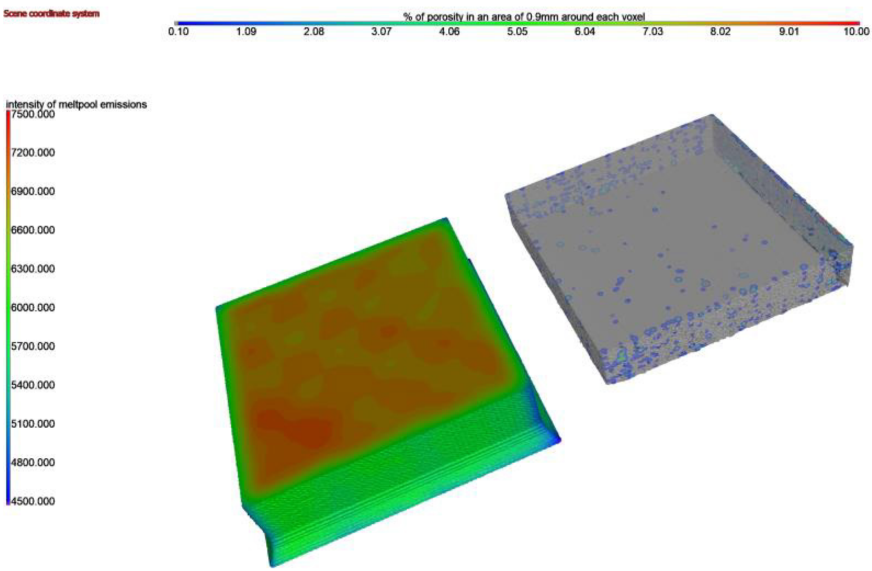

Figure 1: Correlation investigation between meltpool emissions (left side) and CT porosity analysis (right side).

[1] P. Fuchs et al. (2019) *iCT.*

In-situ quality inspection in Ebeam machine based on fringe projection profilometry

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In recent years, additive manufacturing (AM), primarily metal AM has developed rapidly in many areas. AM has emerged as a flexible process with its primary advantage in the area of facilitating the manufacture of complex geometry parts. AM has added advantages of using less material and allowing economic production of small batch size or one-off parts. Electron-beam (Ebeam) AM systems have proved particularly useful in the manufacture of medical implants and aerospace components. However there remains issues with the part dimensional metrology and process stability during the build process. In-situ dimensional metrology inspection is an important tool that can monitor the development of the part geometry over the part build cycle. It has the potential to provide information that can allow for "on the fly" process optimization and hence improvement of part quality and process yield. This paper presents the development and implementation of a layer by layer in-situ optical inspection system embedded within a commercial Ebeam machine. The inspection system is based on fringe projection profimometry, it has an acquisition time of 2s and allows for testing of the powder bed surfaces before melting and the solidified metal surfaces post layer processing, figure 1. A new optical calibration method and exemplar measurement data are reported.

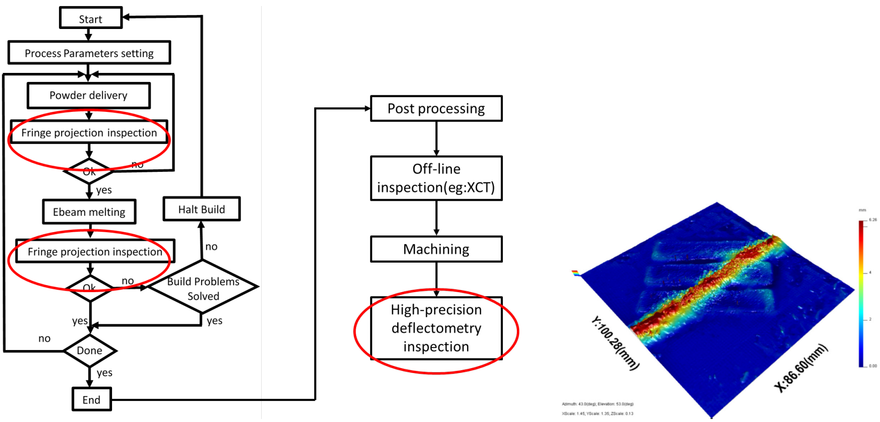

Figure 1: EBAM processing flow chart and example measurement (left) exemplar data capture (right).

[1] Y. Liu, L.A. Blunt, Z. Zhang, H.A. Rahman, F. Gao, X. Jiang (2020) *Additive Manufacturing*, **31**, 10

The role of atom probe tomography in additive manufacturing of engineering alloys by electron beam melting

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Selective electron beam melting (SEBM) presents a state-of-the-art electron beam additive manufacturing technology capable of printing fully dense, near-net-shape metallic parts with complex geometries and superior mechanical properties. However, EBM-built metals and alloys are typically subject to anisotropic and heterogeneous properties in terms of build geometry and orientation. In addition, some unprecedented material behavior and phenomenon are acquired via the cyclically rapid solidification and cooling processes together with annealing effects that are involved in SEBM process, leading to interesting microstructures for a wide variety of engineering alloys. Therefore, microstructural evolution at atomic and nanometer scales is becoming increasingly concerned in SEBM-processed alloys. Atom probe tomography (APT) is known to be a unique characterization technique mapping volumetric elemental distribution in 3D and at atomic scale. In this talk, the role of APT in phase evolution and interface properties for a couple of engineering alloys processed by SEBM is discussed. It paves the way to high-performance metal additive manufacturing by using the atomic-scale microstructural engineering method.

[1] X.P. Tan, Y.H. Kok, Y.J. Tan, M. Descoins, D. Mangelinck, S.B. Tor, K.F. Leong and C.K. Chua (2015) *Acta Mater.*, **97**, 1-16.

[2] X.P. Tan, Y.H. Kok, W.Q. Toh, Y.J. Tan, M. Descoins, D. Mangelinck, S.B. Tor, K.F. Leong and C.K. Chua (2016) *Sci. Rep.*, **6**, 26039.

[3] X.P. Tan, P. Wang, Y. Kok, W.Q. Toh, Z. Sun, M.L.S. Nai, M. Descoins, D. Mangelinck, E. Liu, and S.B. Tor (2018) *Scripta Mater.*, **143**, 117-121.

Nano-structured NiAl-Cr(Mo) in-situ composites processed by additive manufacturing

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NiAl-Cr and NiAl-Cr(Mo) eutectic in-situ composites are promising high temperature materials due to their high melting point, excellent oxidation behavior and low density. To enhance the poor room temperature fracture toughness of these composites, high cooling rates are beneficial to obtain fine cellular-lamellar structures, which can be achieved by additive manufacturing. The influence of SEBM process parameters on the microstructure and their effect on mechanical properties of NiAlCr(Mo) were analyzed in this study. The investigations reveal a very high hardness of the composites due to the fine microstructure according to Hall-Petch strengthening. The eutectic microstructure results also in good high temperature strength and creep properties. Fracture surfaces where analysed and promising fracture toughness increasing mechanisms like crack bridging, renucleation or crack deflection at NiAl-Cr(Mo) interfaces were formed. The study shows that SEBM is suitable to process NiAl-Cr(Mo) in-situ composites with promising mechanical properties.

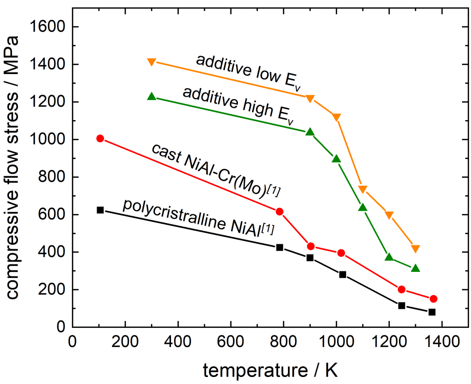

Figure 1: Compressive flow stress of selected electron beam melted NiAl-28Cr(6Mo) with different volume energy in comparison with cast NiAl-28Cr(6Mo) and polycrystalline NiAl. Data of NiAl and cast NiAlCr(Mo) from [1].

[1] Tang et al. (2010) *Trans. Nonferrous Met. Soc. China*, **20**, 212-216.

Processing refractory metals by electron beam melting: Challenges and Potentials

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The limitations of conventional methods hinder the exploration the full potential of refractory metals. Additive manufacturing is a revolutionary process extending the possibilities of powder metallurgy to produce complex parts. Therefore, the possibilities of the additive manufacturing to process refractory metals to overcome problems like high melting temperature, sensitivity to atmosphere and brittle behavior must be explored. Powder bed based AM, like electron beam melting, delivers the tools to optimize the process conditions for refractory metals as processing temperature, cooling rate and atmosphere conditions. Due to their extraordinary properties, materials like tungsten, niobium or molybdenum are of most interest for applications with high demands.
However, there is lack of understanding of the processing of these materials by electron beam melting and the resulting properties. Therefore, the basic feasibility of the manufacturing of refractory metals as tungsten and niobium is explored and the challenges and potentials are deducted. Furthermore, mechanical properties and pick up of impurities are discussed.

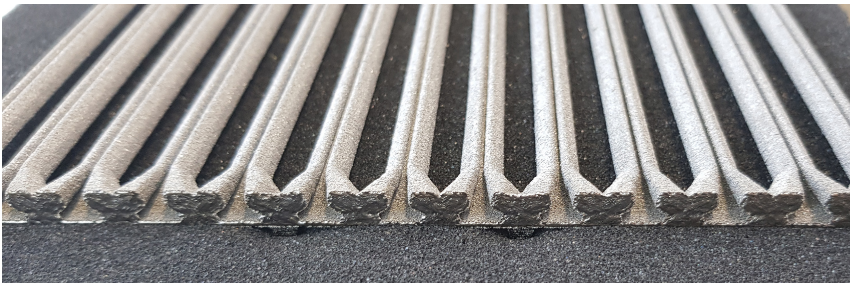

Figure 1: Pure tungsten demonstrator manufactured by electron beam melting.

From Research to Production: Selective Electron Beam Melting of a High Wear Resistant CoCrW Alloy for Industrial Applications

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High strength materials like cobalt chromium alloys with high abrasion, erosion, and corrosion resistance are of major interest because tools in the oil and gas industry often operate in highly corrosive and abrasive environments. To enhance the lifetime of specific components the cobalt chromium tungsten alloy CoCr6, also know under the brand name Stellite®6, was identified to be a promising candidate to fulfil these demands. In contrast to the established ASTM F75 cobalt chromium molybdenum alloys, CoCr6 offers an enhanced wear resistance and hardness.

For the future production of CoCr6 parts, the lead time as well as freedom of design plays an important role for the CoCr6 products. Therefore, additive manufacturing (AM) was chosen as the manufacturing technology.

CoCr6 is a typical cladding material [1] but has never been processed using powder bed based AM technologies. Therefore, a feasibility study has been carried out first. The Selective Electron Beam Melting (SEBM) technology was chosen to minimize the risk of thermal cracking during processing. The feasibility study has been carried out on an Arcam Q10 using industrial CoCr6 powder material. With this, a large processing window has been found where fully dense and crack free parts could be produced. The mechanical properties exceeded the cast material properties and the wear properties also met the requirement.

Due to this great success SEBM of CoCr6 was implemented into the industrial production. Therefore several challenges like occupational safety, industrial SEBM as well as the transfer from the Arcam Q10 to the Arcam Spectra H production system needed to be faced. The first direct transfer of the parameters worked well and parts could successfully be produced on the Q10 and Spectra H with the same theme file. However, the Spectra H showed an elevated build temperature towards the Q10 when using the same theme file. Therefore, further adjustments were made to the parameters and further optimizations have been undertaken in order to increase build speed and to meet geometrical accuracy. By this, the machine and the CoCr6 material can be qualified in order to set up an industrial manufacturing process.

[1] F.C. Campbell (2008) *Elements of Metallurgy and Engineering Alloys,* 557-561.

Data Driven Scan Strategies for Microstructure Development in EBM

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Additive manufacturing processes traditionally utilize scan strategies to melt the powder in a given layer based on various space filling algorithms that are concerned about melt time or path efficiency. As a result, most processes do not consider the critical implications of microstructure and texture or the potential for site-specific textures to influence the overall mechanical performance of AM parts. In this work, we will present data driven scan strategies not for beam path for time or vector length optimization, but for developing a desired microstructure and texture within a given region. An examples of these scan patterns includes manipulation of the texture within parts through conductive pathways (Figure 1a) that are melted in a given order before other areas to result in an alternating columnar structure normal to the build plane and a randomized grain morhophology and size between the alternating columnar rows. Additional advanced space filling techniques for voxel-by-voxel beam movement for texture control will be discussed.

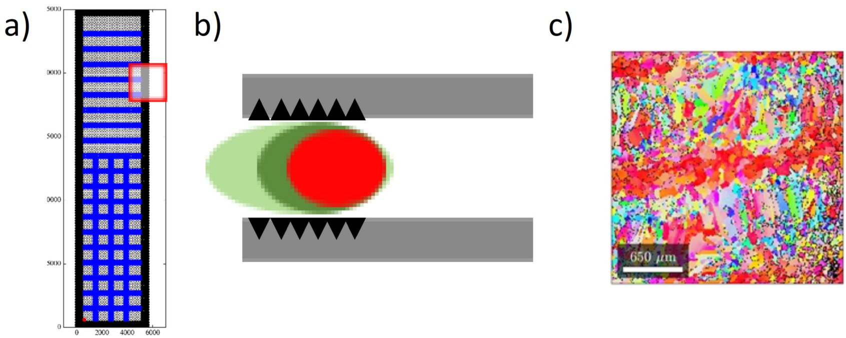

Figure 1: Localized conductive solidification manipulation based on melting mask structures a) Areas first melted (blue lines) within a larger structure b) Movement of e-beam between conductive walls first melted and unmelted areas during second stage of melting c) Representative EBSD micrograph showing the effect of different melting steps on the texture of the part with the build direction coming out of the plane of the image.

From atoms to hot cracks in AM Ni-based superalloys: a fundamental study

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The mechanisms that lead to hot cracking in parts build by additive manufacturing (AM) of non-weldable nickel-based superalloys are still under debate. This lack of in-depth understanding of the root causes of hot cracking is an impediment to designing engineering parts for safety-critical applications.
A non-weldable Ni-based superalloy was fabricated by selective electron beam melting. A coarse-columnar grain microstructure was obtained and hot cracks were found to develop only along high angle grain boundaries [1]. A near-atomic-scale approach was deployed to investigate the details of the compositional decoration of those cracked grain boundaries [2]. The progressive enrichment in Cr, Mo and B at grain boundaries over the course of the AM-typical successive solidification and remelting events, accompanied by solid-state diffusion, causes grain boundary segregation induced liquation.
From our fundamental understanding of the cracking mechanism, guidelines to achieve crack-free microstructures are suggested. Based on those guidelines, we demonstrate that by adjusting build parameters to obtain (i) a microstructure free of HAGB [3], or (ii) a fine-grained equiaxed [2] or (iii) a columnar microstructure with grain width smaller than 100 µm enables to avoid cracking [2], see Figure 1. The fabrication of crack-free microstructures is finally discussed at the light of our fundamental understanding of the cracking mechanism.

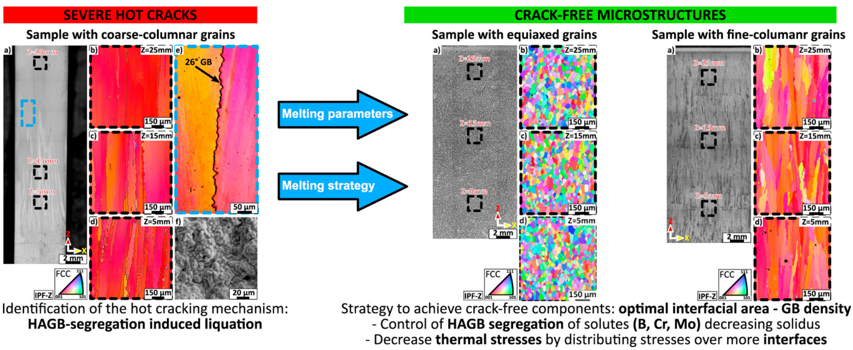

Figure 1: Strategies to overcome hot cracking issue in a non-weldable Ni-based superalloy built by EBM.

[1] E. Chauvet, P. Kontis, E. Jagle, B. Gault, D. Raabe, C. Tassin, J-J. Balndin, R. Dendievel, B. Vayre, S. Abed and G. Martin (2018) *Acta Mater*, **142**, 82-94.
[2] P. Kontis, E. Chauvet, Z. Peng, J. He, A. Kwiatkowski Da Silva, D. Raabe, C. Tassin, J-J. Blandin, S. Abed, R. Dendievel, B. Gault and G. Martin (2019) *Acta Mater*, **177**, 209-221.
[3] E. Chauvet, C. Tassin, J-J. Balndin, R. Dendievel, G. Martin (2018) *Scripta Mater*, **152**, 15-19.

Production and properties of the single crystalline nickelbase superalloy CMSX-4 processed by SEBM

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Single crystal Ni-Base superalloys are the state of the art material in applications with both high temperature and high mechanical loads. Being able to withstand temperatures up to 1100 °C in long term exposure this material class is the dominating material for turbine blades in aerospace or powerplant gas turbines. The conventional production is done according to Bridgman casting method facing problems like a high degree of residual elemental segregation and restrictions in geometry. Being extremely prone to cracking, this type of alloy is considered as non-weldable thus making additive manufacturing challenging. Nevertheless, we showed that with SEBM single crystalline production of a CMSX-4 type single crystal alloy is possible [1]. The crucial material properties in this high temperature application field have been determined. In comparison to the cast material, improvements in creep strength, low-cycle fatigue (LCF) lifetime and phase stability have been achieved, making SEBM a very promising alternative production route for single crystals [2,3].

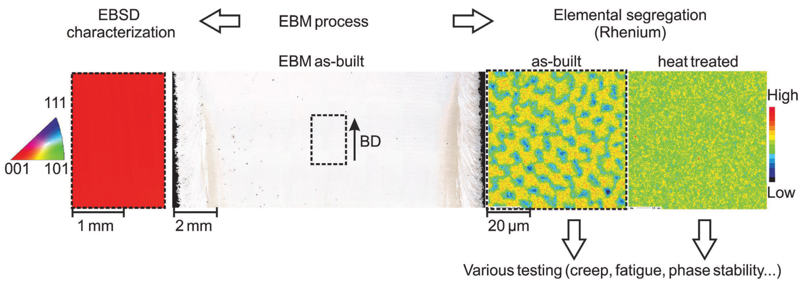

Figure 1: The CMSX-4 SEBM SX specimens are characterized with regard to microstructure and tested in as-built and heat treated condition afterwards.

[1] C. Körner, M. Ramsperger, C. Meid, D. Bürger, P. Wollgramm, M. Bartsch and G. Eggeler (2018) *Metall and Mat Trans A*, **49**, 3781-3792.
[2] J. Pistor and C. Körner (2019) *Mater. Lett. X*, **1**, 100003.
[3] C. Meid, A. Dennstedt, M. Ramsperger, J. Pistor, B. Ruttert, I. Lopez-Galilea, W. Theisen, C. Körner and M. Bartsch (2019) *Scr. Mater.*, **168**, 124-128.

Modelling materials with tailored grain structures - combining grain growth models and crystal plasticity

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In selective electron beam melting an electron beam, guided by electromagnetic fields, is used to locally melt metal powder and build parts in a layer-wise manner. The electron beam allows for very fast deflections and various scan strategies. By using these scan strategies it is possible to tailor the resulting grainstructure of the material, which may range from a columnar to an equiaxed texture. For various grain structures different macroscopic mechanical properties are expected. Long and similarly oriented grains cause highly anisotropic behavior. In contrast, a uniform grain structure results in isotropic mechanical behavior. The different orientations, the grain sizes and grain boundaries strongly influence the macroscopic mechanical properties.
In this contribution, the material behavior is simulated by means of Finite Element simulations. On the mesoscale, a gradient enhanced crystal plasticity model [1], accounting for relative misorientations on the grain boundaries with a formulation as given in [2] is applied. Mesostructures and textures from cellular automaton based grain growth simulations of the process [3] are used. Computational homogenization and macroscopic experimental data are utilized to inversely identify elastic and plastic mesoscopic mechanical parameters. With this approach at hand, the macroscopic mechanical properties, such as the yield locus, are modeled for varying grain structures.

[1] A. Kergaßner, J. Mergheim, and P. Steinmann (2019) *CAMWA*, **78(7)**, 2338-2350.
[2] M. E Gurtin, L. Anand, and S. P Lele (2007) *JMPS*, **55(9)**, 1853–1878.
[3] J. Köpf et al. (2018) *Acta Materialia*, **152**, 119-126.

Development of a Thermo-mechanical Model of Electron Beam Additive Manufacturing Process for Repair Purposes

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Electron beam melting (EBM) route is particularly attractive for part manufacture with difficult-to-machine materials such as Alloy 718. EBM Alloy 718 build has to be subjected to suitable post-treatments involving hot isostatic pressing (HIPing) and heat treatment (HT) to reduce inevitable defects present in the as-built material as well as to alleviate concerns related to phase inhomogeneity, anisotropy, etc. The limited previously reported efforts on post-treatment of EBM-built Alloy 718 have typically involved long HT schedules, which are traditionally applied to wrought Alloy 718. However, these may not be either ideal or necessary because the starting microstructures of wrought and EBM-built Alloy 718 are vastly different. The presentation will focus on tailoring post-treatment protocol for EBM material. This would involve identification of appropriate processing window for defect closure via HIPing without causing grain coarsening and shortened HT via study of microstructural evolution during the treatment. The results will be substantiated by in-depth material characterization to reveal the influence of various post-treatments, with and without prior HIP, on grain morphology, grain size, phase constitution and mechanical behavior of the material compared to the as-built condition. Moreover, the response of varied starting microstructures to the post-treatments will be presented, such as material with tailored grain structure (columnar, equiaxed, and combinations thereof) or tailored defect content.

EBM of Pure Copper – From Research to Industrialisation

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As electron beam absorption in pure Copper is far superior to laser, work on printing pure Copper with EBM started several years ago [1,2] and, while research has progressed, industrialization has so far been rather limited with only a few companies going into production. Seeing the interest in this material, GE Additive has invested in developing parameter sets for pure Copper to serve as a basis for large-scale industrialisation.
Using the Arcam EBM Q10plus platform (EBM Control 5.3), a constant current scan strategy parameters set for pure Copper has been developed. The powder used was pure Copper >99.95 wt % with low Phosporous and Oxygen content. Using the developed parameters, high relative densities were obtained, with resulting electrical conductivities of >57 MS/m (>98.36 % IACS) as well as good tensile properties. Tensile properties has furthermore been investigated in X, Y and Z-directions to determine the impact of the microstructure on the mechanical properties. Cracking issues were encountered and overcome during the project.
Industrialisation topics such as compensation function optimization, e.g. thickness function on overhangs, contour melting, supports and stacking, as well as powder handling and reuse will be discussed, along with other factors affecting the business case for industrialisation, such as build rates. Challenges for moving forward into full industrialisation will be discussed.

[1] D.A. Ramirez, L.E. Murr, S.J. Li, Y.X. Tian, E. Martinez, J.L. Martinez, B.I. Machado, S.M. Gaytan, F. Medina, R.B. Wicker (2011) *Mat. Sc. Eng. A*, **528**, 5379-5386.
[2] D.A. Ramirez, L.E. Murr, E. Martinez, D.H. Hernandez, J.L. Martinez, B.I. Machado, F. Medina, P. Frigola, R.B. Wicker (2011) *Acta Mater.*, **59**, 4088-4099.

Isotropic mechanical properties of a TiAl alloy processed via electron beam melting

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Titanium aluminides are implemented in more and more applications like low-pressure turbine blades or turbocharger wheels. Their high strength, good creep and oxidation resistance combined with the low density makes them a very promising high temperature material. Unfortunately, Titanium aluminides are very brittle at room temperature and therefore difficult to manufacture by conventional technologies like centrifugal casting or isothermal forging. [1]
Electron beam melting (EBM) can provide an easier and cheaper way to manufacture titanium aluminides [2]. However, the EBM process has some challenges of its own. Due to the layer wise manufacturing, TiAl processed via EBM often show anisotropic mechanical properties [3]. The anisotropy is mainly caused by misconnections due to inferior process parameter and a heterogeneous and layered microstructure, which can develop during the EBM process [3].
It is shown that isotropic mechanical properties of TiAl can be achieved (see Figure 1) by minimizing defects and controlling the microstructure during the EBM process.

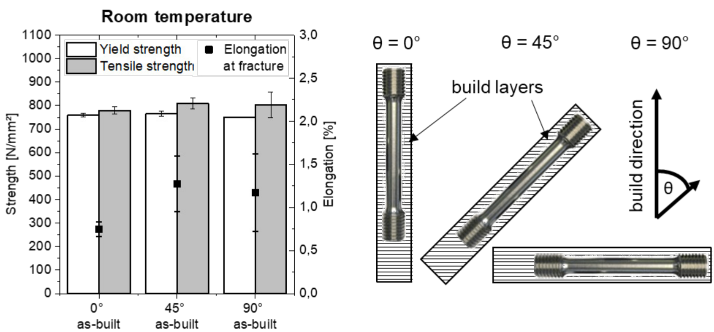

Figure 1: Isotropic mechanical properties of the TiAl alloy at room temperature processed via EBM.

[1] B. P. Bewlay, S. Nag, A. Suzuki, M. J. Weimer (2016) *Materials at High Temperatures*, **33**, 549-559.
[2] P. Gennaro (2019) *Titanium Aluminides – 4 Manufacturing processes for 1 Blade, Arcam UGM.*
[3] M. Todai, et al. (2017) *Additive Manufacturing*, **13**, 61-70.

Exploring the Use of Water Atomized Powders in Electron Beam Based AM

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Reducing the cost of the feed material in powder based additive manufacturing would significantly broaden the domain of application towards lower cost components where, presently, the financial concerns outweigh the benefits. There is evidence that water atomized metallic powders, which are significantly cheaper than gas or plasma atomized powders, maybe suitable for binder jet printing and selective laser melting but, to date, the number of published reports on powder bed melting AM studies have been limited. To our knowledge, there are no published reports on the particular challenges of using water atomized powder in electron beam additive manufacturing. In this study we have used water atomized Fe based powders, these powders conventionally used in powder metallurgy, to study different combinations of sintering, melting and feeding conditions on the microstructure of parts produced in our LEAM system at UBC. The relationship between the various process parameters and the structure (porosity, surface) of test samples will be discussed.

Processing of copper electrical conductors by Electron Beam Melting

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Electrical conductors are usually made of pure copper because it shows outstanding electrical conductivity (from 95 to 100 % IACS, depending on work hardening rate). Additive manufacturing can be used to further improve the performances of electrical conductors because it enables to consider sophisticated geometries impossible to be fabricated by conventional processing routes such as casting, machining or hot forming. Processing pure copper by laser-assisted additive manufacturing is very challenging since conventional laser sources used in standard LBM machines are highly reflected. As a result, the Electron Beam Melting (EBM) process turns out to be a good candidate to additively manufacture pure copper components. The EBM process has been developed by ARCAM AB and is widely used to make components made of Ti-6Al-4V. Physical properties of this Ti-alloy differ significantly from those of pure copper. In particular, copper thermal and electrical conductivities are respectively 30 and 25 times higher than the ones of the Ti-6Al-4V grade, which requires very specific conditions to be melted.
A preliminary study consisting in identifying the conditions to achieve the required degree of powder consolidation to process pure copper has been conducted, to adjust the preheating conditions. A miniaturized building chamber that fits into A1-ARCAM EBM machine has been custom-designed and used to limit the amount of powder required for a build (typically 10 kg of powders whereas the standard EBM chamber requires at least 60 kg).
A design of experiment is carried out using our custom-designed building chamber on high purity copper powder to identify the processing window. It allows to build samples with a density higher than 99.9 % and without cracks. Specific specimens with different orientations are built in order to perform volumetric electrical conductivity measurements using the 4 probes method as well as to determine the mechanical properties. The volumetric electrical conductivity of 100 % IACS is successfully achieved with EBM pure copper.

This work was carried out as part of the FUI AMbition project, supported by the BPI and the regions of Auvergne-Rhône-Alpes and Ile-de-France.

Phononic Band Gap Metamaterials

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Additive manufacturing technology enables the realization of complex cellular structures with innovative and non-intuitive properties such as phononic band gaps (PBG). Materials with PBGs are capable of blocking the propagation of mechanical waves in certain frequency ranges. We use a strut-based cellular material design to generate a PBG material out of metal (Ti-Al6-V4) printed via selective electron beam melting (SEBM). The experimentally tested 3D structures verify the phononic band gaps previously calculated by two types of FEM simulations, i.e., dispersion relation and transmission simulation. By applying knowledge about the behavior of the strut-based system in regards to stiffness and rotational centers we can tune the position and frequency range of the band gap.

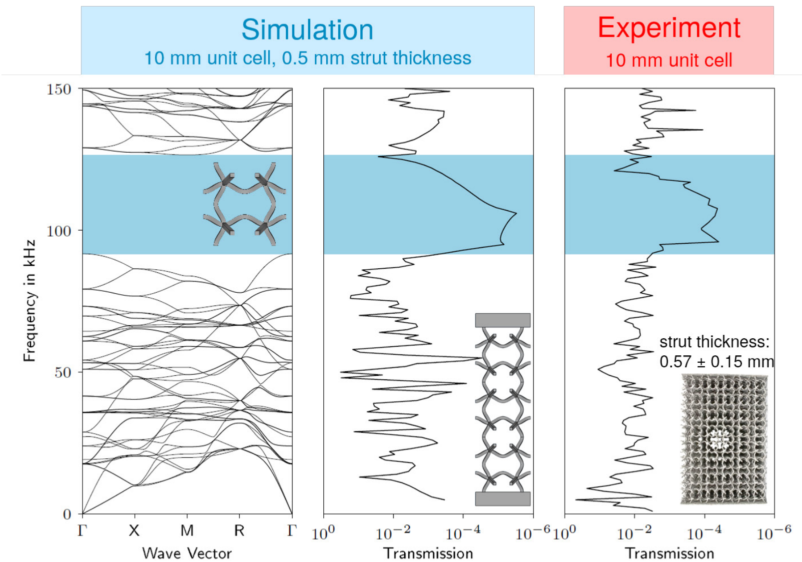

Figure 1: Comparison of numerical and experimental results. PBGs are marked in blue. A Transmission of 1 indicates lossless transmission. Lower values indicate a loss in transmission amplitude.

[1] F. Warmuth, M. Wormser and C. Körner (2017) *Sci. Rep.*, **7**, 3843.

Investigation of mechanical modelling assumptions in the context of additive manufacturing

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Additive manufacturing offers the ability to design and build components without manufacturing restrictions. In selective electron beam melting components are built layer by layer by applying and fusing metallic powder. During exposure, locally high temperatures arise, leading to large temperature gradients within the component. As a result, distortion and residual stresses within the part are observed. In order to reliably predict these undesired effects at component level, thermo-mechanical simulations are used. In this contribution the influence of different modelling approaches for the mechanical simulation, which in literature vary widely, are investigated with regard to the resulting stresses and plastic strains [1,2]. The validity of the small strain assumption in the context of selective beam melting processes is analyzed. The influence of the temperature dependence of material parameters is evaluated. Another aspect to be investigated is the relaxation of stress and plastic strain during melting. The hard reset of these quantities at a certain relaxation temperature while using a thermo-elasto-plastic material model is compared to the relaxation using a thermo-elasto-visco-plastic material model [2,3].

[1] L-E. Lindgren (2001) *Therm. Stresses*, **24**, 141-192.
[2] E. Denlinger, J. Irwin, P. Michaleris (2014) *Manuf. Sci. Eng.*, **136.**
[3] R.K. Ganeriwala, M. Strantza, W.E. King, B. Clausen, T.Q. Phan, L.E. Levine, D.W. Brown, N.E. Hodge (2019) *ADDMA*, **27**, 489-502.

Monte Carlo Simulations of electron's beam energy deposition during EBM AM processes

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Electron Beam Melting (EBM) is a metal powder bed fusion Additive Manufacturing (AM) technology that allows the fabrication of three-dimensional near-net-shaped parts by spreading successive layers of metal powder on powder bed-chamber and fusing them selectively. Previous works have reviewed some of the physical transient effects which occur during the AM process [1]. They have assisted to outline certain process procedures, mainly preheating the powder bed in order to reduce the "black smoke" (the effect of sudden powder spreading during beam material interaction) which is the most infamous transient effect caused by the electrostatic charge of the powder particles. In this study, we tried to further improve the AM process. We examined the mutual influence of the different gas pressures on the energy deposition to the powder in an AM process. Experiments were conducted utilizing the Arcam Q20 machine. The process takes place in 10-3 mbar pressure of Helium. The use of Helium in the process improves the electrical conductivity of the powder. Furthermore, high vapor pressure of some elements in the printed alloy evolved during the high temperature built processes. Increasing the pressure to the low vacuum regime could reduce these effect. An optimum pressure regime ensures that electrons will not be attenuated significantly along their path to the powder. This study aims to calculate the electrons' energy deposition to the powder using the EGS5 (Electron-Gamma Shower) Monte Carlo code[2]. The simulations results led to obtain the optimal gas pressure and were supported by an experimental study in which optimization was elucidated.

[1] Cordero, Z. C., Meyer, H. M., Nandwana, P., Dehoff, R. R. (2017) *Acta Materialia*, **124(C)**, 437-445.
[2] Hirayama, Hideo, Namito, Yoshihito, /KEK, Tsukuba, Bielajew, Alex F, Wilderman, Scott J, U, Michigan, Nelson, Walter R, and /SLAC. (2005). The EGS5 code system. United States: doi:10.2172/877459.

Optimizing the resulting microstructure of additively built lattice structures by predictive crystal growth simulation (SEBM)

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Revenue with additive manufactured parts is rising constantly for years [1]. Increasing sale rates are accompanied by growing demands in the properties of the resulting parts. With the feasibility of tailoring the microstructure for application-specific requirements, additive manufacturing can fulfill these sophisticated demands, albeit with limitations. Because the underlying coherencies are not yet fully understood, a multitude of trial-and-error experiments are needed in order to benefit from this possibility.
Numerical simulations can aid the development process by significantly reducing the amount of necessary experiments. The use of microstructure simulations is not limited to finding the best initial guess of process parameter resulting in a desired microstructure though. The possibility of scrutinizing the thermal conditions during melting and solidification of each layer is prerequisite for understanding the underlying principles leading to the specific grain structure.
In this work we present a three-dimensional microstructure simulation software for use with powder bed fusion additive manufacturing. The predictive capabilities of the software were already shown both for the bulk [2] as well as the shell [3] of additively build parts using nickel-base superalloys. Implementation of a new thermal solver enabled the calculation of more complex geometries with less computational efforts. The capabilities of the new compound are demonstrated by the predictive simulation of the microstructures resulting from different scanning strategies.

[1] T.T. Wohlers, I. Campbell, O. Diegel (2019) *Wohlers Report 2019, Wohlers Associates.*
[2] J. Koepf, M. Gotterbarm, M. Markl, C. Körner (2018) *Acta Materialia*, **152**, 119-126.
[3] J.A. Koepf, D. Soldner, M. Ramsperger, J. Mergheim, M. Markl, C. Körner (2019) *Computational Materials Science*, **162**, 148-155.

Simulation of multi-material powder bed fusion

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Electron beam melting is a highly complex manufacturing process 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 powder compositions, which is termed as *multi-material powder bed fusion*.
For a better understanding, especially in terms of consolidation and liquid phase mixing, simulations are powerful tools. Therefore, we extend the in-house simulation software SAMPLE^{2D} Simulation of Additive Manufacturing on the Powder scale using a Laser or Electron beam) [1] by additional physical effects like diffusion, enthalpy of mixing and the concentration dependency of material parameters. This method can be applied to a variety of alloys, e.g., CuCr used for switching contacts to achieve small, uniformly distributed Cr precipitates and reduce production costs.
Preliminary results show that the most import influence on the melting behavior and thus on the defect generation is the difference of melting temperatures of the two powders. Additionally, new challenges like locally varying depths of fusion or improvable liquid phase mixing (see Fig. 1) can be identified which indicate the need for novel process strategies.

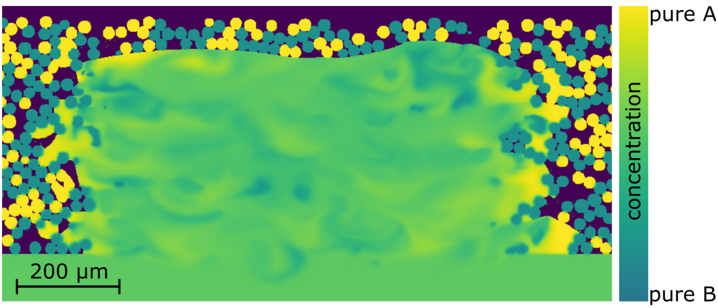

Figure 1: 2D concentration distribution after an EBM process, simulated using the SAMPLE^{2D} software. Ten layers were processed using two different arbitrary pure metal powders with a melting temperature of about 1200 K (pure A) and 1800 K (pure B), respectively. All other material parameters were identical.

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

Modeling microstructure evolution during Electron Beam Selective Melting (EBSM) with a CA-based model

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Although try-and-error experimentation is successfully used to link process to microstructure and the mechanical performance for EBSM, the lack of effective observation method makes it almost impossible to get an insight into the physical processes, which, however, could be reproduced with numerical modeling. In this work, we developed a coupled Cellular Automaton-Finite Volume Method (CAFVM) model to simulate melting and grain growth in EBSM process. The simulated grain structure in single tracks is validated by experiments. Furthermore, relationships between scan strategies, thermal field and grain growth are investigated with multi-layer and multi-track simulations. The results show: it is more likely to obtain equiaxial microstructure using scan strategies which can lead to uncontinuous or unstable thermal field. What's more, to consider the influence of high-temperature powder bed, this work also incorporates model for solid-state phase transformation.

The influence of melt pool flow dynamics on the formation of grain structure

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One of the advantages of the numerical modeling of the additive manufacturing processes is the ability to track the formation of the grains in detail. Thus, a full 3D microstructure that is obtained in the simulation may be visualized, and its qualitative characteristics may be computed. During multiple simulation runs, the parameters may be varied, and the influence of the material and laser parameters on the grain shape, size, elongation, and orientation can be studied.

We have implemented the grain formation model described in [1,2]. The grain formation is influenced by the temperature history of a propagating electron beam. The temperature history may be simulated by a prescribed movement of the heated zone, or with a heat transfer simulation in the melt pool.

At the same time, convection in the fluid influences the solidification processes, and the account for the fluid dynamics may significantly change the grain orientation and shape in the modeling output. The simulation of the flow dynamics in the melt pool is available in the high performance code FaSTLaB [3]. The model includes phase transitions, thermal conductivity, volume heat generation, liquid dynamics of molten metal, evaporation of metal and recoil pressure, surface tension, Marangoni convection, wettability of a surface with melt, and movement of powder particles under the surface tension and vapor flux forces. The temperature history, as well as the dynamics of the melted zone geometry, is among the outputs of the model. The interactive visualization in FaSTLaB allows to investigate the influence of the complex physical phenomena in the melt pool fluid flow on the microstructure in the resulting material.

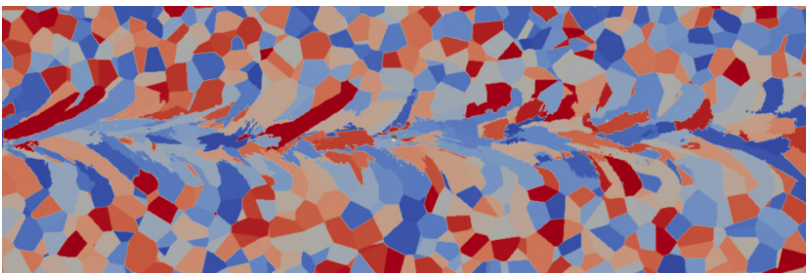

Figure 1: Grain formation in the substrate in the electron beam melting process.

[1] Gandin, Ch-A., and Michel Rappaz. 1994 *Acta metallurgica et materialia*, **42(7)**, 2233-2246.
[2] M. Markl and C. Körner 2016 *Annu. Rev. Mater. Res*, **46**, 93-123.
[2] D. Nakapkin, A. Zakirov, S. Belousov, M. Bogdanova, B. Korneev, A. Stepanov, A. Perepelkina, V. Levchenko, B. Potapkin, and A. Meshkov, *II International Conference on Simulation for Additive Manufacturing Sim-AM* (2019), Conference Materials E-Book 304-315.

An Investigation of Wire-Feed Electron Beam Additive Manufacturing of Metals and Metallic Multimaterials

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Recently, additive technologies have increasingly been adopted in various scientific and technological fields around the world, thus expanding opportunities for the design and manufacture of various complex-shaped components, particularly those made of metallic materials. The wire-based technologies remain almost non-alternative for obtaining the large-sized metal products. Because of the close cooperation with the leading Russian industrial enterprises in the transport and aerospace industries, the Institute of Strength Physics and Materials Science SB RAS (Tomsk, Russia) is conducting a number of complex studies aimed at developing the wire-feed electron beam technology. The investigations were carried out on experimental laboratory equipments for EBAM self-developed by ISPMS SB RAS.
The main results achieved through the research undertaken. Corrosion studies were carried out on additively manufactured samples from AISI 304 wire feedstock [1]. The studies show that when heat inputs increase from 0.25 to 0.27 $\mathrm{kJ\,mm^{-1}}$ the content of δ-ferrite decreases and also a cubic texture is formed. This leads to improving the corrosion resistance of samples. Also, the studies of the wire-feed geometry influence on the process of complex-shaped product formation were conducted on samples of Ti-6Al-4V alloy [2]. The results showed that the use of three-axis water-cooled table for the complex-shaped rotation bodies printing leads to formation of so-called geometry affected zones, which results in formation of external distortions and interferes with the manufacturing process. The addition of a fourth (rotary) axis allows getting rid of such zones, but it is necessary to control the temperature conditions to obtain the required properties. Another important result is the data on the gradient zone formation in copper-steel multimaterials. In these studies, the main stages of gradient zone formation with simultaneous double wire feeding into the molten bath were identified and the particles formed in the process of bimetal manufacturing were studied and classified. This work was performed within the frame of the Fundamental Research Program of the State Academies of Sciences for 2013-2020, line of research III.23.

[1] S. Yu. Tarasov, A. V. Filippov, N. N. Shamarin, S. V. Fortuna, G. G. Maier and E.A. Kolubaev (2018) *J. Alloys Compd.*, **753**, 247-255.
[2] K. N. Kalashnikov, V. E. Rubtsov, N. L. Savchenko, T. A. Kalashnikova, K. S. Osipovich, A. A. Eliseev and A. V. Chumaevskii (2019) *Int. J. Adv. Manuf. Tech.*, **105**, 3147-3156.

Manufacturing constraints of Electron Beam Melting (EBM) and Laser Powder Bed Fusion (LPBF) and their effects on final component quality

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Metal powder bed-based Additive Manufacturing (AM) technologies such as Electron Beam Melting (EBM) and Laser Powder Bed Fusion (LPBF) have been established in several industries due to the high design freedom and achievable mechanical properties, such as high hardness. Both AM processes are similar in terms of general working principles. However, process specific manufacturing constraints influence component design and orientation regarding the need and design of support structures and post-processing to achieve the desired component quality. The differences in energy coupling, electron beam or laser, with the powder bed leads to differences in solidification conditions and thus differences in microstructure. Other differences in the process chains affect achievable surface finish and geometrical accuracy. As opposed to LPBF, during Electron Beam Melting (EBM) every powder layer is preheated and consequently sintered prior to selectively melting the powder. Sintered powder layers withstand loads reducing the need for support structures (see Figure 1). Heat dispersion in sintered (EBM) powder is more uniform than in loose powder (LPBF) resulting in differing cooling rates and microstructures, which are compared in terms of grain size and orientation. This work focuses on the manufacturing constraints of each powder bed process and their effects on final part quality, i.e. microstructure, surface roughness and mechanical properties.

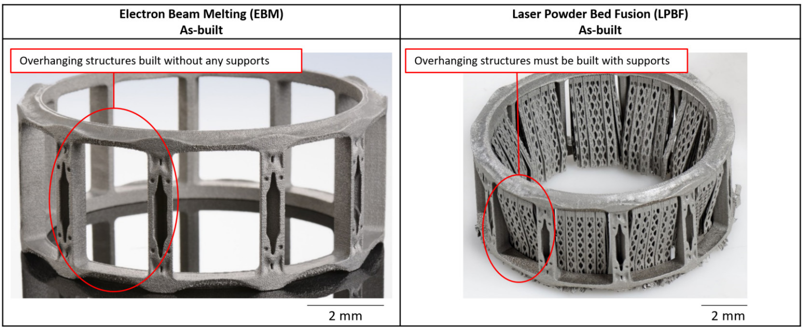

Figure 1: Comparison of component printed via EBM and LPBF highlighting the influence of process constraints on required support structure (manufactured in collaboration with Cerobear GmbH).

Electrostatic Charging of the Powder Particles during Electron Beam Interaction

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Powder-bed *Electron Beam Additive Manufacturing* (EBAM) is disruptive due to its high energy efficiency, scanning speed, part integrity (purity and minimal residual stresses), and material versatility. However, there are several issues related to charged particles [1,2]. The electrons kept in focus by the high accelerating voltage and impacted the powder-bed thus converting kinetic energy into heat to melt the particles. Also, the electrons lodged on them cause them to fly away due to electrostatic charging, which is called as smoking. In this paper, several aspects of the smoking and its remedies are presented in detail.

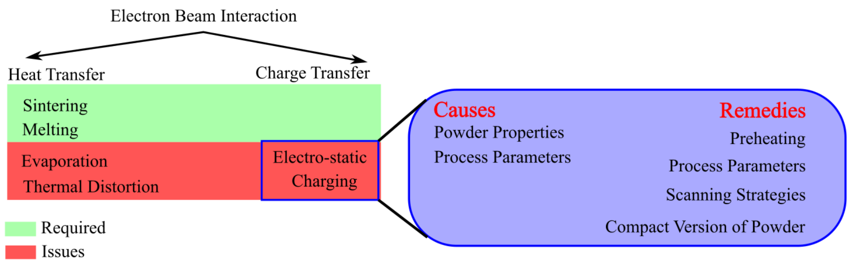

Figure 1: Interaction of Electron-Beam with Powder.

[1] Cordero, Z. C., Meyer III, H. M., Nandwana, P., Dehoff, R. R. (2017) *Acta Materialia*, **124**, 437-445.
[2] Körner, C. (2016) *International Materials Reviews*, **61(5)**, 361-377.

Using a stereo camera module and AI methods for process monitoring of powder-based 3D printers

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Components manufactured using powder-based 3D printing have high rejection rates caused by various types of defects occurring during the build process. Thus, a monitoring system is needed that is capable of detecting these defects during the build process. Such a system enables closed-loop feedback, which leads to improved uniformity of manufactured parts across different printers operating on the same principle [1]. Therefore, we present a new topography measuring device small enough to fit into the build chamber and capable of determining quantitative measurement data with high lateral and vertical resolution. To monitor the process, a stereo line scan camera with its own illumination system is mounted to the recoater of the printer. With the movement of the recoater the system captures each point of both the fused layer and the freshly applied powder layer. The fused layer consists of the fused powder and the loose powder that has not been exposed to the laser. In order to derive the topography of the surfaces from the captured 2D images, the surfaces are observed from two different perspectives and the height of each point is calculated by a stereo algorithm. To enable a closed-loop feedback, it is mandatory to evaluate the last printed layer before the building process of the next layer is started. Due to the large amount of data and the need for fast evaluation, artificial intelligence is used in combination with conventional algorithms running on a Graphics Processing Unit (GPU).

[1] T. G. Spears, S. A. Gold (2016) *Integr. Mater. Manuf. Innov.*, **5**, 16-40.

Thermal Response Materials in UBC's LEAM System: Experiments, Simulations and Process Monitoring

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Predicting and measuring the temperature distribution during EBAM production is central to better understanding the processing of parts. With this focus, we have been working in parallel to develop in-situ thermography in our LEAM system and process models for predicting thermal histories at time and length-scales consistent with builds. In this presentation we will illustrate our work on in-situ thermography and its interpretation as well as its comparison with a 'fast-to-run' thermal model developed for predicting part scale thermal histories. We will also illustrate our ongoing work to better understand the relationship between metal powder bed characteristics and their associated thermal properties.

A Comparative Study Between Gas-atomized and Plasma Rotating Electrode Processed Powders on Forming Quality of IN718 in Electron Beam Powder-bed Fusion

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The quality of powder applied in powder bed-type additive manufacturing, including electron beam powder-bed fusion (EB-PBF), plays a vital role in process stability and final part performance [1]. There are two types of IN718 alloy powders, namely, one fabricated by gas atomization (GA) and one fabricated by the plasma-rotating electrode process (PREP). They are different in geometry and inherent defect. In this study, the forming qualities of the EB-PBF-built IN718 samples concerning surface profile, density, and internal defect were evaluated and compared between two kinds of powders under the same process regime. Especially, the forming quality was further compared between the samples using the optimal process condition obtained by a machine learning method [2] for each kind of powder. Notably, different powder shapes with different surface features would possess variation in heat transfer during melting. Therefore, the effect of powder geometry on the fusion process in EB-PBF was also investigated, which was elucidated by the numerical simulation.
Besides experimental characterizations, numerical simulations that consist of discrete element method (DEM) and computational thermo-fluid dynamics (CtFD) were performed for analyzing melting behaviors using different powders. DEM simulations were utilized for the generation of the powder bed. The packing structure of the powder bed from DEM was set as the initial geometrical data for the CtFD simulations of the heat transfer and fluid flow. The results revealed that as almost without inner gas pore in PREP-powders, the PREP samples possessed a higher density than that of GA samples (Fig. 1), even under the optimal process condition. In simulations, as with the different surface features, the amount of heat radiation was different for two kinds of powder beds. PREP-powder with high sphericity and small surface area was relatively appropriate for EB-PBF, which was favorable for melt stability and enlarging the process window.

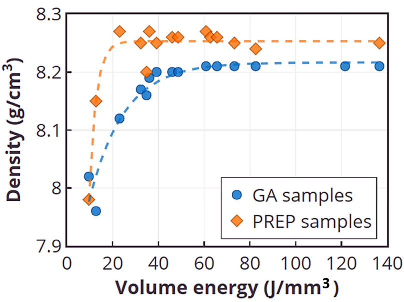

Figure 1: Density evaluation for the samples fabricated by GA- and PREP-powders.

[1] Vock. S, Klöden. B, Kirchner. A, et al. (2019) *Progress in Additive Manufacturing*, **4(4)**, 1-15.
[2] Aoyagi K, Wang H, Sudo H, et al. (2019) *Additive Manufacturing*, **27**, 353-362.

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