FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

EBAM 2016

1st International Conference on Electron Beam Additive Manufacturing

27 – 29 April 2016 · Nürnberger Akademie, Nuremberg, Germany

www.eam.fau.de/EBAM2016

WELCOME

It is my pleasure to welcome you at Nuremberg for the first **International Conference on Electron Beam Additive Manufacturing EBAM 2016** organized as cooperation of the Chair of Metals Science and Technology (WTM) and 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. It is thought to bring together researchers and industrial users to accomplish improvements in this technology. Keynote presentations will be held by well-known researchers and industrial users of this technology.

Although EBAM 2016 is the first international conference on this very specific topic, we got an enormous number of submissions from around the world. The number of participants (from 19 countries, 77 from foreign countries) had to be limited to 130 due to lack of space.

We hope that the wide range of inspiring talks including the invited presentations in combination with high-quality poster presentations initiates various fruitful discussions and future cooperation.

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

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

Carolin Körner
Conference Coordinator

TABLE OF CONTENTS

INVITED SPEAKERS/ INTERNATIONAL ADVISORY BOARD

Ulf Ackelid	Arcam AB, Sweden
Tadashi Fujieda	Hitachi Ltd., Japan
Paolo Gennaro	GE Avio, Italy
Ola Harrysson	North Carolina State University, US
Ulric Ljungblad	Arcam AB, Sweden
Thomas Niendorf	University of Kassel, Germany
Lars-Erik Rännar	Mid Sweden University, Sweden
Chris Ryall	Manufacturing Technology Centre, UK
Iain Todd	University of Sheffield, UK

ORGANIZATION

Carolin Körner
Matthias Markl
Thomas Bögelein
Matthias Schwankl

www.wtm.fau.de

Aline Looschen
Annette Tyrach

www.eam.fau.de

GENERAL INFORMATION

Conference Venue

Nürnberger Akademie, Marmorsaal
Gewerbemuseumsplatz 2
90403 Nuremberg

The Marmorsaal is located on the second floor of the Nürnberger Akademie, which is marked on the map on page 6.

Registration & Help Desk

The registration desk will be located in the foyer of the Marmorsaal. It will be in service on 27 April 2016 from 9:00 to 11:00. Late registration is possible during the whole conference at the help desk at the entrance to the Marmorsaal. During registration the whole conference material is handed over.

The conference fee includes entrance to all sessions, coffee breaks, lunches, the social event including the conference dinner and the conference material. Please indicate during registration if you will take part at the social event and the conference dinner. Outstanding payments will be directly sorted at the registration or help desk.

Instructions for Oral Presentation

Oral presentations are limited to a total of 20 minutes; invited speakers will have 30 minutes. This time includes a short discussion about 5 minutes to the presented topic. Speakers are requested to respect the schedule, to keep the time of their presentation and to present themselves to their session chairman directly before the session.

Speakers are requested to provide their presentation at least 15 minutes before the beginning of the session. The Marmorsaal is equipped with a data projector connected to a local computer operating under Windows. MS PowerPoint and PDF presentations are appreciated; CD reader, USB Port and laser pointers are available. If it is necessary, speakers can use their own laptops for their presentation. Although, adapters for many video output formats are available, please provide a suitable adapter to VGA if possible.

Instructions for Poster Presentation

The posters will be displayed in the Marmorsaal surrounding the presentation area. Boards and mounting material for posters will be ready for poster installation on 27 April 2016 from 9:00 to 15:00. The poster session will be held on 27 April 2016 from 16:30 to 18:30 with some light refreshments. Posters should be displayed until 14:00 on 28 April 2016. They must be removed until 18:00 on 28 April 2016.

Lunches, Coffee Breaks & Light Refreshment

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

Social Event & Conference Dinner

The social event will start on 28 April 2016 from 18:00 with a guided city tour in front of the Nürnberger Akademie. The city tours are available in German and English. They end in front of the conference dinner venue:

Alte Küch'n / Im Keller
Albrecht Dürer Str. 3
90403 Nuremberg

The conference dinner will take place from 19:00 to 22:00. The location is marked on the map on page 6.

Accommodation

Contact information to Motel One Nürnberg – Plärrer, marked on the map on page 6, for participants who made use of our room contingent.

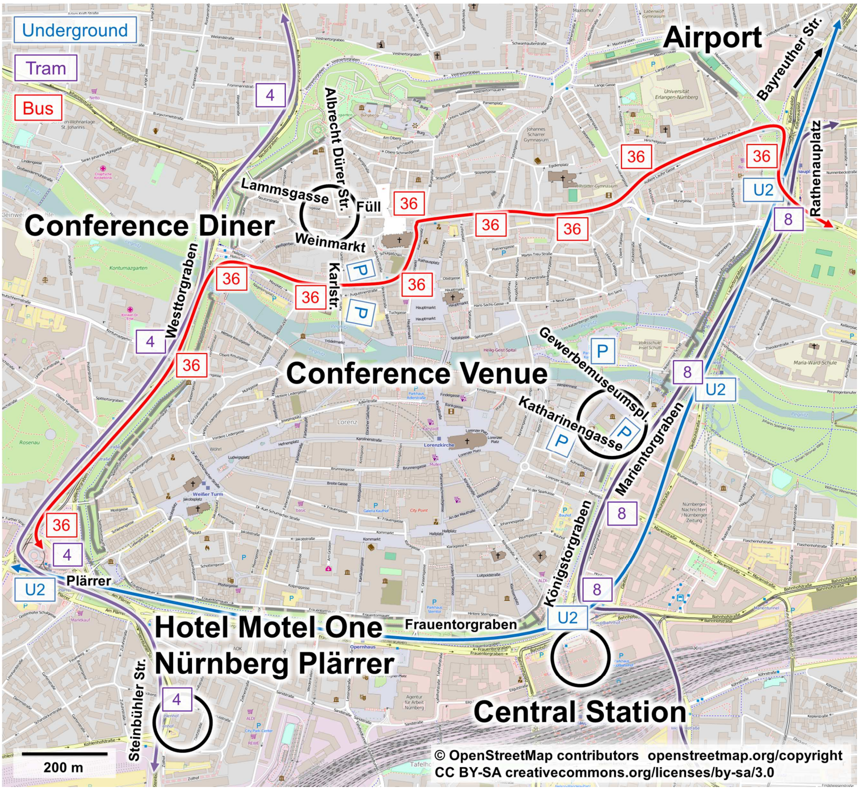
Motel One Nürnberg Plärrer	+49 911 235 626 0
Steinbühler Str. 13	nuernberg-plaerrer@motel-one.com
90443 Nuremberg	

Important Phone Numbers

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

Map

Please find detailed maps of Nuremberg including its city center and the public transportation in your conference material folder.



WEDNESDAY · 27 APRIL 2016

9^{00}–10^{00} **Registration**

10^{00}–10^{20} **Welcome & General Information**
Carolin Körner · Chair of Metals Science and Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

10^{20}–10^{50} **History and Future of EBM** — Invited
Ulric Ljungblad · Arcam AB, Sweden

PROCESS AND PROCESS OBSERVATION I
Chair: Chris Ryall

10^{50}–11^{20} **The Influence of Process Parameters on Build Outcome in EBM: Can We Rewrite the Rule Book?** — Invited
Iain Todd · Department of Materials Science and Engineering, University of Sheffield, UK

11^{20}–11^{40} **The AM Process Cycle with EBM Technology**
Francisco Medina · Buffalo Manufacturing Works, US

11^{40}–12^{00} **Multi-Scale Modeling of EBM Process**
Wentao Yan · Department of Mechanical Engineering, Tsinghua University, China

12^{00}–13^{00} **Lunch**

PROCESS AND PROCESS OBSERVATION II
Chair: Iain Todd

13^{00}–13^{20} **Development and Evaluation of an Optimal Ad-Hoc Reduced Chamber for an A2XX Electron Beam Selective Melting System**
Riccardo Tosi · Manufacturing Technology Centre, University of Birmingham, UK

13^{20}–13^{40} **The Development of Dual-Material Electron Beam Selective Melting System and its Application in Gradient Material Fabrication**
Wenjun Ge · Korea Advanced Institute of Science and Technology, South Korea

13^{40}–14^{00} **Quality Monitoring of the EBM Process**
Stephan Janson · iwb Anwenderzentrum Augsburg der TU München, Germany

14^{00}–14^{20} **Simulation of Temperature Distribution and Mechanical Material Behavior in the EBM Process**
Daniel Riedlbauer · Chair of Applied Mechanics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

14^{20}–15^{00} **Coffee Break**

WEDNESDAY · 27 APRIL 2016

TITANIUM ALLOYS
Chair: Ulric Ljungblad

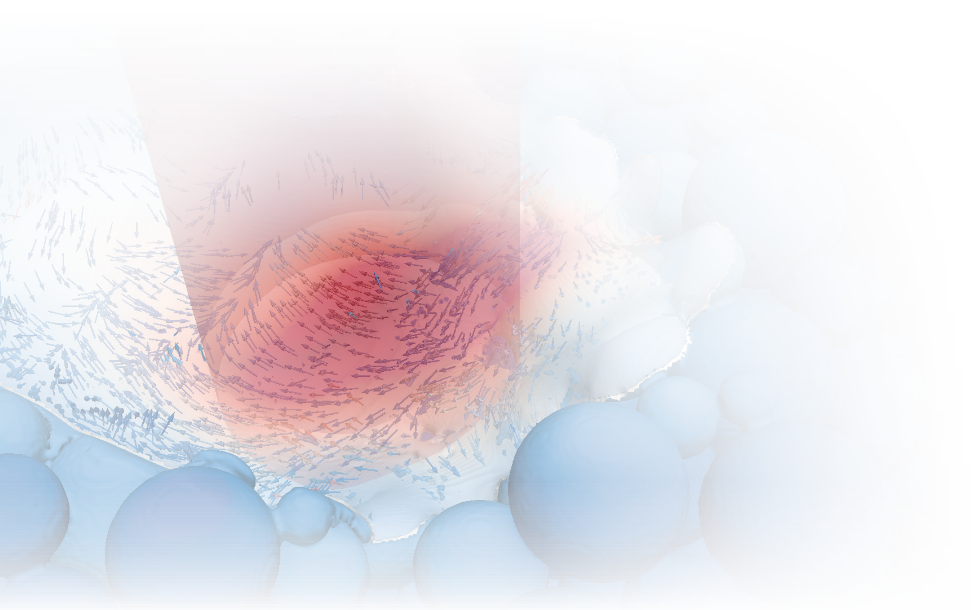
15^{00} – 15^{30} **Fatigue Properties of Ti-6Al-4V Processed by SEBM** Invited
Thomas Niendorf · Institut für Werkstofftechnik – Metallische Werkstoffe, University of Kassel, Germany

15^{30} – 15^{50} **Influence of Building Parameters on Microstructures and Mechanical Properties of EBM of Ti-6Al-4V alloy**
Xiaoli Shui · Institute for Materials Research, Tohoku University, Japan

15^{50} – 16^{10} **The Influence of Temperature on Mechanical Properties of Electron Beam Melted Ti-6Al-4V Alloy**
Rosario Borelli · Italian Aerospace Research Center CIRA, Italy

16^{10} – 16^{30} **Elemental Vaporization and Mechanical Property Control of Electron Beam Rapid Manufacturing Ti-6Al-4V Alloy**
Jianrong Liu · The Institute of Metal Research – Titanium Alloy Division, China

POSTER SESSION
16^{30} – 18^{30} **Poster Presentation and Light Refreshment**



THURSDAY · 28 APRIL 2016

POWDER FEEDSTOCK Chair: Thomas Niendorf

9^{00} – 9^{30} **Ti-6Al-4V Powder Feedstock Characterization and Testing for EBM** — Invited
Ola Harrysson · Industrial and Systems Engineering, North Carolina State University, US

9^{30} – 9^{50} **The Experimental Studies on the Powder Collapse in Electron Beam Selective Melting Processing**
Bin Zhou · Department of Mechanical Engineering, Tsinghua University, China

9^{50} – 10^{10} **Induction Plasma Technology Applied to Development and Mass Production of Spherical Powders Manufacturing for EBM Applications**
Romain Vert · Tekna, France

10^{10} – 10^{30} **Microstructure of Nickel-Titanium Powder by Plasma Rotation Electrode Process**
Meng-Hsiu Tsai · Metal Industrial Research & Development Centre, Taiwan

10^{30} – 11^{00} **Coffee Break**

HIGH TEMPERATURE ALLOYS Chair: Tadashi Fujieda

11^{00} – 11^{30} **Numerical Modelling of SEBM for Ni-based Superalloys** — Invited
Matthias Markl · Chair of Metals Science and Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

11^{30} – 11^{50} **Powder Characterizations and Processing Window for Ni-based Superalloy IN625 Produced by EBM**
Edouard Chauvet · Laboratoire de Science et Ingénierie des Matériaux et Procédés SIMAP, Grenoble University, France

11^{50} – 12^{10} **Melt Pool Characterization and Modelling of EBM for IN718**
Xiao Ding · Institute for Materials Research, Tohoku University, Japan

12^{10} – 12^{30} **Processing the Precipitation Hardened Ni-based Superalloy IN738LC with EBM**
Simon Eichler · Neue Materialien Fürth GmbH, Germany

12^{30} – 12^{50} **Selective Electron Beam Melting of the Single Crystal Ni-base Superalloy CMSX-4**
Markus Ramsperger · Chair of Metals Science and Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

13^{00} – 14^{00} **Lunch**

THURSDAY · 28 APRIL 2016

POST-PROCESSING Chair: Ola Harrysson

14^{00} – 14^{30} Improved Parameters for Hot Isostatic Pressing of Ti-6Al-4V Additively Manufactured by EBM — Invited
Ulf Ackelid · Arcam AB, Sweden

14^{30} – 14^{50} Effect of Heat Treatments on the Mechanical Properties of Ti-6Al-4V Additively Manufactured by EBM
Alexander Kirchner · Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Germany

14^{50} – 15^{10} Towards an Innovated Methodology for Manufacturing Homogeneous Metallic Alloys by the EBM Technology
Akram Alhussein · Université de Technologie de Troyes, France

15^{10} – 15^{30} A Critical Review of Surface Finishing Methods for Additive Manufactured Parts
Anita Buxton · The Welding Institute TWI Ltd., UK

15^{30} – 15^{50} Characterizing the Surface Texture of AM Parts Upon Surface Finishing: Alternative Methods of Evaluating the Surface Quality of AM Parts
Augustin Diaz · REM Surface Engineering, US

15^{50} – 16^{20} **Coffee Break**

MATERIALS Chair: Ulf Ackelid

16^{20} – 16^{50} Mechanical and Corrosion Properties of High-Entropy Alloys Additive Manufactured using SEBM — Invited
Tadashi Fujieda · Hitachi Ltd., Japan

16^{50} – 17^{10} Microstructure and Mechanical Properties Evolution of Biomedical Co-Cr-Mo Alloys Produced by Electron Beam Additive Manufacturing
Akihiko Chiba · Institute for Materials Research, Tohoku University, Japan

17^{10} – 17^{30} Microstructure and Mechanical Properties of WCp Reinforced IN625 Composite Produced by EBM
Hui Peng · Material Science and Engineering, Beihang University, China

17^{30} – 17^{50} Process Development and Properties of Copper Components Fabricated via SEBM
Matthias Lodes · Joint Institute of Advanced Materials and Processes ZMP, Germany

18^{00} – 19^{00} **Social Event**
Guided City Tour from the Conference Venue to the Dinner Location

19^{00} – 22^{00} **Conference Dinner**
Alte Küch’n/Im Keller, Albrecht-Dürer-Straße 3, 90403 Nürnberg

FRIDAY · 29 APRIL 2016

INTERMETALLICS Chair: Lars-Erik Rännar

9:00 – 9:30 **Additive Opportunities** Paolo Gennaro · GE Avio, Italy — Invited

9:30 – 9:50 **Processing of Titanium Aluminides by SEBM**
Vera Jüchter · Chair of Metals Science and Technology,
Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

9:50 – 10:10 **Ti-48Al-2Nb-0.7Cr-0.3Si Titanium Aluminide for Automotive Applications Processed by EBM**
Giorgio Baudana · Department of Applied Science and Technology,
Politecnico di Torino, Italy

10:10 – 10:30 **Finite Element Thermal Model of EBM Process to Investigate Different Experimental Microstructures for TiAl**
Manuela Galati · Department of Management and Production
Engineering, Politecnico di Torino, Italy

10:30 – 10:50 **Fabrication of NiTi Porous Scaffolds using μEBM**
Saeed Khademzadeh · Metallurgy Engineering,
Amirkabir University of Technology, Iran

10:50 – 11:20 **Coffee Break**

COMPONENTS Chair: Paolo Gennaro

11:20 – 11:50 **The Potential of EBM for a Multi-Disciplinary Research** — Invited
Lars-Erik Rännar · Department of Quality Technology, Mechanical
Engineering and Mathematics, Mid Sweden University, Sweden

11:50 – 12:10 **Dental Implant Manufacturing using EBM – Geometry Deviation from Intraoral Scanning and from Cone Beam Computed Tomography**
Per-Erik Legrell · Oral and Maxillofacial Radiology,
School of Dentistry, Umea University, Sweden

12:10 – 12:30 **Lattice Structures made by EBM: Mechanically Efficient Matter**
Rémy Dendievel · Laboratoire de Science et Ingénierie
des Matériaux et Procédés SIMAP, Grenoble University, France

12:30 – 12:50 **Microstructure and Mechanical Properties of Beta-type Ti-24Nb-4Zr-8Sn Porous Structure Fabricated by EBM**
Shujun Li · The Institute of Metal Research –
Chinese Academy of Sciences, China

12:50 – 13:10 **Optimization of EBM Build Processes by Localized Preheat Strategies**
Phillipp Drescher · Fluid Technology and Microfluidics, University of Rostock, Germany

13:10 – 13:20 **Concluding Remarks**
Carolin Körner · Chair of Metals Science and Technology,
Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

13:20 – 14:30 **Lunch**

Invited

History and Future of Electron Beam Melting

U. Ljungblad
Arcam AB, Krokslätts Fabriker 27A, 43138 Mölndal, Sweden
Email: ulric.ljungblad@arcam.com

Additive manufacturing (AM) of metals is developing in a significant manufacturing method for several applications. A couple of decades ago AM of metals was very inmature compared with AM of plastic materials and very much still a technology in it's cradle. In that landscape Arcam was started in 1997 and formed into a small company set out to develop machines for Free Form Fabrication as the term was in those days. An initial arc welding process was quickly abandoned in favour of a whole new technology branch of AM using an electron beam instead of a laser beam for additive formation of components from powder. In the first years a new AM system, the S12 machine, was developed and the first of these systems was sold and delivered to a customer in 2003. 13 years later Arcam has developed two more generations of EBM systems, the A-series and the Q-series, and delivered hundreds of machines for various applications. Large scale industrial manufacturing applications for EBM started in late 2006 when the first system was sold for manufacturing of medical implants. This was also the motivation for the focus on titanium as the main material for EBM since then. Today EBM is a well-established manufacturing technology for a wide variety of orthopaedic implants with integrated net structure for osseointegration. Beside medical implants, over the more recent years focus has been to develop EBM into a manufacturing technology also for aerospace applications. The Arcam A2X system was specifically developed to cope with very high manufacturing temperatures to make it possible to use the technology to build parts in titanium aluminide. This was developed together with the Italian company Avio to develop production of turbine blades for commercial aero engines. Arcam has also developed titanium applications for aerospace such as static vanes which was done in collaboration with Rolls Royce. In this presentation we will show how Arcam has over the years step by step raised the level of the technology to the matureness level of industrial production with the help of several innovative steps such as “pre-sintering”, “controlled vacuum” and “multi-beam”. We will also show the recently developed LayerQam and XQam technologies incorporated with EBM for process surveillance and system autocalibration as a view into the future of EBM.

Invited

The Influence of Process Parameters on Build Outcome in Electron Beam Melting: Can We Rewrite the Rule Book?

I. Todd

GKN/Royal Academy of Engineering Research Chair,
Department of Materials Science and Engineering, University of Sheffield,
Mappin Street, Sheffield, S1 3JD, UK

Email: i.todd@sheffield.ac.uk

Standard melting strategies often yield very good results but can sometimes be less than optimal for the geometries or microstructures we seek to manufacture. We may wish to manufacture with no support structures, or to build at much higher rates or we may just simply wish to experiment with alternative building conditions to gain a deeper understanding of the limits of the process. Here we present the results of our research into the development of alternative processing parameters using a modified Arcam EBMS12 - initially addressing questions of melt strategy, defect incidence and defect distribution - but ultimately delivering faster process themes and more consistent products.

The Additive Manufacturing Process Cycle with Electron Beam Melting Technology

F. Medina
Buffalo Manufacturing Works, 847 Main St, Buffalo, NY 14203, USA
Email: fmedina@ewi.org

The EBM technology has many advantages such as build speed, process stability, hanging supports and part nesting. The Additive Manufacturing process is not just the production of an EBM part, it includes a full series of steps to get the AM parts production ready. The cycle for production ready parts may include part redesign, material selection, process optimization, post processing, quality control and inspection. We will show samples on how different tools and equipment interact and play an important role on the final production ready part.

The majority of the parts currently being manufactured with traditional process are not AM friendly and must be redesigned to take advantage of the AM processes. New software is being created to optimize and help design for AM. Creating production parts in the EBM machine is not just filling the start plate with parts, but optimizing the part orientation and support structures in 3D space and understanding the effects of part volume interaction with part nesting, to fully take advantage of the EBM technology.

Post processing may include powder removal, support removal, surface improvement, and machining. Different inexpensive and rapid techniques have been tested and proven to produce successful surface improvements such as bead blasting and tumbling. Quality Control and Inspection include Computer Tomography that has demonstrated to be a powerful tool in defect detection on AM parts.

All the different process come together to produce an acceptable and functional AM part for production from the EBM systems.

Multi-Scale Modeling of Electron Beam Melting Process

W. Yan[1,2,*], W. Ge[2], J. Smith[1], F. Lin[2] and W. K. Liu[1]

(1) Department of Mechanical Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, United States

(2) Department of Mechanical Engineering, Tsinghua University, Beijing, China

Email: wentao.yan@northwestern.edu

Electron Beam Melting process consists of multiple complex physical phenomena at multiple temporal and spatial scales, which remain to be thoroughly understood. In this study, we developed multi-scale models of EBM process. At the nano-scale, we employed Monte Carlo method to simulate the electron-atom interactions to establish the realistic heat source model [1]. The heat source model is capable of taking into account the influence of the acceleration voltage, incidence angle, and the material. At the meso-scale, the heating process of single powder particle was investigated [2]. At the macro-scale, the porous powder bed was simplified into an effective continuum material model based on the results of the meso-scale models, which we incorporated into the heat transfer model based on Finite Element Method (FEM) [3]. The FEM model greatly simplified the element activation procedures. The model was primarily validated by the gradient material fabrication experiments.

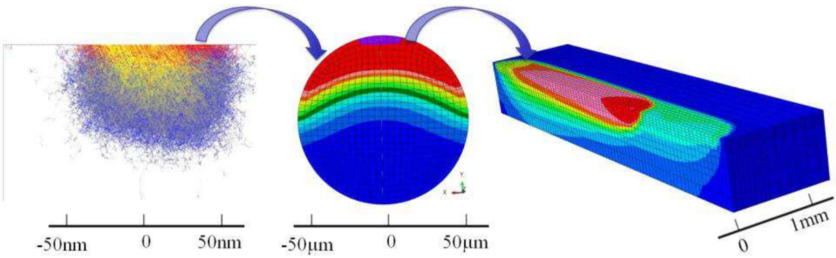


Fig. 1: Multi-scale models of EBM process

[1] W. Yan et al., *Comp. Mech*. **56**, 2, 265-276 (2015)

[2] W. Yan et al., *Advances in Materials & Processing Technologies Conference*. Madrid, Spain (2015)

[3] W. Yan et al., *Annual International Solid Freeform Fabrication Symposium*. Austin, U.S. (2015)

Development and Evaluation of an Optimal Ad-Hoc Reduced Chamber for an A2XX Electron Beam Selective Melting System

R. Tosi[1,2,*], Y. Liu[2], M. Attallah[1], E. Muzangaza[2], C. Ryall[2] and D. Wimpenny[2]

(1) University of Birmingham, Metallurgy & Materials, Edgbaston, Birmingham, B15 2TT, United Kingdom

(2) The Manufacturing Technology Centre, Ansty Park, Coventry, CV7 9JU, United Kingdom

Email: riccardo.tosi@the-mtc.org

Time and cost are becoming important drivers for the additive manufacturing market. An investigation of an ad-hoc chamber was manufactured to optimise the bed configuration of an A2XX Electron Beam Selective Melting (EBSM) system. Existing (A2XX) machines require 200 kg of Ti-6Al-4V to fill for a build height of 380 mm. The reduced size of the chamber and powder hoppers decreased the amount of powder needed by over 70% for a full build as well as the time taken to setup the machine. Cost and building time were analysed to understand the impact of the compacted “adaptronic” unit on the conventional Arcam chamber. The quality of the Ti-6Al-4V samples built with the newly reduced adaptronic chamber and the original large chamber was compared in terms of the variations in microstructure and mechanical properties. The advantages and disadvantages using a customised chamber were discussed.

The Development of Dual-Material Electron Beam Selective Melting System and its Application in Gradient Material Fabrication

W. Ge[1,2,3,*], C. Guo[1,2,3] and F. Lin[1,2,3]

(1) Department of Mechanical Engineering, Tsinghua University, Beijing, China

(2) Key Laboratory for Advanced Materials Processing Technology, Ministry of Education of China, Tsinghua University, Beijing, China

(3) Biomanufacturing and Rapid Forming Technology Key Laboratory of Beijing, Tsinghua University, Beijing, China

Email: gewj11@mails.tsinghua.edu.cn

Electron Beam Selective Melting (EBSM) is an additive manufacturing technique that directly fabricates three dimensional parts in a layer-wise fashion by using an electron beam to scan and melt the metal powder. In this study, a novel EBSM system capable of building gradient structure with dual metal materials was developed. In this novel system, a powder supplying method based on vibration was put forward. Two different powders can be supplied individually and then mixed homogeneously. the Ti6Al4V powder and Ti47Al2Cr2Nb powder were used in this study, in which Ti6Al4V has excellent strength and plasticity at room temperature, while Ti47Al2Cr2Nb has excellent performance at high temperature, yet very brittle in room temperature. Ti6Al4V-TiAl gradient material was successfully fabricated by the developed system. Results showed that the thickness of the gradient zone and chemical composition were affected by process parameters. The interface was free of cracks and the chemical compositions exhibit a staircase-like change within the interface. The microstructures and chemical compositions were characterized by optical microscopy, scanning microscopy and electron microprobe analysis.

Quality Monitoring of the Electron Beam Melting Process

S. Janson[1,*], F. Bayerlein[1] and M. F. Zäh[2]

(1) *iwb* Anwenderzentrum Augsburg der TU München, Beim Glaspalast 5, 86153 Augsburg, Germany

(2) *iwb* Technische Universität München, Boltzmannstr.15 85748 Garching, Germany

Email: stephan.janson@iwb.tum.de

In metal-powder-bed-based additive manufacturing technologies two energy sources for the selective melting of the powder, namely laser and electron beam (EBM), are competing for market share. Currently the machines relying on a laser beam are more widely spread, however the electron beam possesses advantages like the higher possible deflection speed, the higher level of electrical efficiency and the higher energy output [1]. The laser process is usually carried out in an inert gas atmosphere while the EBM process uses high vacuum to reduce defocussing of the beam as well as oxidation of the powder. Due to the x-radiation emerging from the EBM process and the necessary vacuum, the respective machines need to be sealed from the surrounding, limiting the possibilities of monitoring the process.

To assess their ability to detect defects in the selectively solidified layers during the build-up, different imaging technologies using visible (VIS) and near infrared (NIR) light (see Fig. 1) as well as backscattered electrons in a so called electron-optical-system (ELO) are tested. The layer-images are analysed using a software tool and compared to the initial job data. This enables the detection of distortions and potential defects such as pores. Additionally, the stack of images can be assembled to a 3D model for quick evaluation of defect severity. Finally, the results of the different process monitoring tools are compared to those of post-process computer tomography scans and an out-look of the handling and further use of the acquired data for inline process control is given.

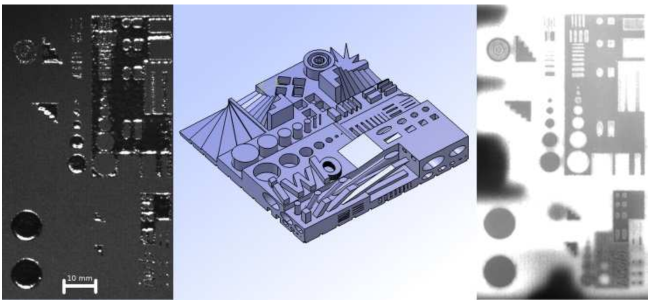


Fig. 1: Layer images in the visible (left) an NIR range (right) of the iwb testing platform (mid).

[1] M. F. Zäh et al. *Prod. Engineer.* **4,** 1, 15-23 (2010)

Simulation of Temperature Distribution and Mechanical Material Behavior in the Electron Beam Melting Process

D. Riedlbauer*, D. Soldner, A. Kergaßner, P. Steinmann and J. Mergheim

Chair of Applied Mechanics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Egerlandstr. 5, 91058 Erlangen, Germany

Email: daniel.riedlbauer@ltm.uni-erlangen.de

The selective electron beam melting (SEBM) of metals is an additive manufacturing process. It is used to additively build geometrical complex parts from thin layers of powder material. In the SEBM process the energy of the electron beam fuses the powder in defined, locally-restricted points in the current layer. Due to the high energy of the beam extreme temperatures and temperature gradients occur. These result in residual stress and distortion of the produced part, which should be avoided.

The goal of this contribution is to predict the transient temperature distribution in the SEBM process and to simulate the residual stresses and distortion of the produced part. For this purpose a simulation tool is developed. The basis of the tool is a continuous, nonlinear thermomechanical model to simulate the process from a macroscopic point of view. In the model the powder material is not described as single powder particles, but as a continuum. The model is able to capture temperature-dependent material parameters, the effect of latent heat and to distinguish between powder, molten and solid material. Since the material behavior of the solidified material, e.g. TiAl6V4, in the SEBM process is not only elastic but also plastic and rate- and temperature-dependent, a thermo-visco-plastic material model is applied. The finite element method is adopted for the spatial discretization of the model and the implementation is done by using the open-source finite element library deal.II [1]. The energy input of the electron beam is computed by using the electron beam model from [2]. An adaptive mesh refinement strategy is adopted to capture the extreme temperature gradients in the area of the beam.

The developed tool is used to simulate the SEBM process for TiAl6V4. In this context not only the processing of multiple powder layers is simulated, but also the deposition of new powder layers. The numerical results for temperature, residual stress and deformation are discussed in detail and partly compared with experimental data.

[1] W. Bangerth et al. *ACM Trans. Math. Softw.* **33**, 24, 1-7 (2007)

[2] A. Klassen et al. *J. Phys. D Appl. Phys.* **47**, 065307 (2014)

Invited

Fatigue Properties of Ti-6Al-4V Processed by Selective Electron Beam Melting

T. Niendorf[1,2,]*, J. Günther[1], D. Krewerth[1], A. Weidner[1] and H. Biermann[1]

(1) TU Bergakademie Freiberg, Institut für Werkstofftechnik,
09599 Freiberg, Germany

(2) Universität Kassel, Institut für Werkstofftechnik – Metallische Werkstoffe,
34125 Kassel, Germany

Email: niendorf@uni-kassel.de

Additive manufacturing techniques like selective laser melting and selective electron beam melting allow fabrication of highly complex components that can be directly employed in applications without excessive mechanical finishing. For robust use, solid process-microstructure-property relationships have to be established. Particularly, fatigue properties have to be evaluated. Current literature clearly reveals that process induced issues, i.e. porosity, anisotropy and residual stress, are extremely detrimental with respect to damage evolution under cyclic loading (Fig. 1 and Refs. [1-2]). The present study has been conducted in order to evaluate fatigue properties of Ti-6Al-4V processed by selective electron beam melting.

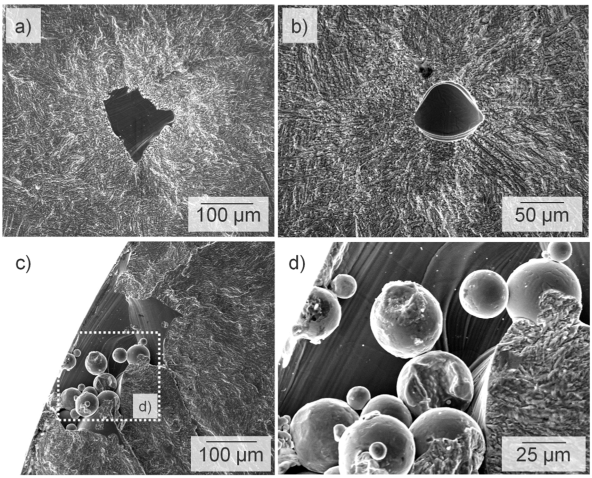


Fig. 1: Representative defects in additively manufactured specimens. Defects differ in size, morphology and defect position and either are induced by lack of fusion (a,c,d) or entrapped gas inside initial alloy powder (b). Most detrimental with respect to mechanical properties are large defects in direct vicinity of the sample surface (c,d).

[1] S. Leuders et al. *Int. J. Fatigue.* **48**, 300-307 (2013)

[2] S. Leuders et al. *Metall. Mater. Trans.* **A46**, 3816-3823 (2015)

Influence of Building Parameters on Microstructures and Mechanical Properties of Electron Beam Melting of Ti-6Al-4V alloy

X. Shui[1,*], K. Yamanaka[1], M. Mori[2], Y. Nagata[3], K. Kurita[3] and A. Chiba[1]

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

(2) Department of Materials and Environmental Engineering, National Institute of Technology, Sendai College, 48 Nodayama, Medeshima-Shiote, Natori 981-1239, Japan

(3) Koiwai Co., Ltd., 244-6 Haneo, Odawara 256-0804, Japan

Email: lilyshui@imr.tohoku.ac.jp

Electron beam melting (EBM) is a process that produces components by selectively melting layers of metal powder from 3D data. Careful attention should be paid to EBM processing parameters because they have significant influences on fabricated parts' microstructure and mechanical properties. In this work, Ti–6Al–4V alloy samples were produced by EBM under various building parameters. The resulting microstructures and corresponding mechanical properties were studied. Crystallographic textures and elemental distributions of the samples were also investigated.

Ti–6Al–4V alloy samples with a square base of 10 × 10 mm^2 and a height of 30 mm were built using an Arcam A2X system. Scanning speed and ling energy were varied between 0.2 to 6.4 m/s and 0.15 to 1.0 J/mm, respectively. Process window was determined based on the top surface morphologies of the samples. Microstructures of each sample were examined by electron backscatter diffraction (EBSD) and scanning electron microscopy (SEM). The texture evolution during EBM fabrication was measured by X-ray diffraction (XRD). Tensile tests with a strain rate of 1.5 × 10^{-4} s^{-1} were carried out at room temperature.

The ultimate tensile strength obtained by tensile testing is shown in Fig. 1. The samples prepared with line energy below 0.15 J/mm showed relative lower strength. In contrast, when line energy exceeded 0.15 J/mm, the samples had higher strength similar to each other. The variation of tensile strength can be explained in terms of the relative density of the samples. The process window for obtaining fully dense products was also determined.

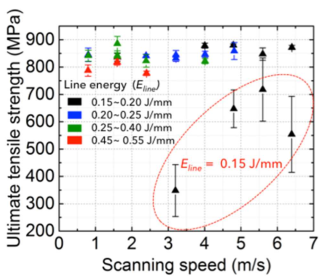


Fig. 1: Ultimate tensile strength for EBM-produced Ti–6Al–4V samples.

The Influence of Temperature on Mechanical Properties of Electron Beam Melted Ti-6Al-4V Alloy

S. Franchitti, C. Pirozzi and R. Borrelli*

CIRA – Italian Aerospace Research Centre, Manufacturing Processes for Metallic Materials Laboratory, Via Maiorise snc, Capua (Ce), Italy

Email: r.borrelli@cira.it

Powder based layered manufacturing methods are relatively novel additive manufacturing technologies that can build parts from powdered material via layer-by-layer melting induced by a directed electron or laser beam. Among the powder base manufacturing techniques, the EBM process produces a physical component from digital CAD models by building the component in a series of layers. Ti6Al4V powder is selectively melted by an electron beam inside a vacuum chamber preheated up to 700°C. The ability to additively manufacture fully melted metal components starting from high-end engineering alloys, such as Ti6Al4V, is a powerful tool but the obtained microstructural and mechanical performance needs to be further evaluated keeping in mind that such additive manufactured components are typically used in extreme environments and for critical applications in the aerospace industry.

In particular for aerospace propulsion applications, mechanical systems are subjected to very strict temperature conditions therefore a thermo-mechanical test campaign, in order to get a better characterization of the Ti6Al4V material processed via EBM, was needed.

In this study a mechanical characterization has been performed on EBM built Ti6Al4V tensile samples at two different temperatures: the first set of specimens has been tested at environmental condition, the second set of specimens has been tested at 190°C. Moreover the two sets of tensile specimens have been manufactured with different growth orientations (0°, 45°, 90°) with respect to the start plate (x-y plane) in order to investigate orientation effects (anisotropy).

Elemental Vaporization and Mechanical Property Control of EBRM Ti-6Al-4V Alloy

J. Liu[1,*], Q. Wang[1], L. Wang[1], S. Zhu[1], H. Suo[2] and S. Gong[2]

(1) Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, China

(2) Beijing Aeronautical Manufacturing Technology Research Institute, Beijing, China

Email: jrliu@imr.ac.cn

Electron beam rapid manufacturing (EBRM) technique characterized by wire feeding is a high-efficiency additive manufacturing method to make large size parts and realize in-orbit construction of space component and structures. However selective elemental vaporization in a vacuum atmosphere and coarse columnar structure made the EBRM deposit exhibited a relatively poorer matching between strength and ductility compared with its forging counterpart. For this reason, relations among elemental vaporization, microstructure characteristics and mechanical properties were carried out on Ti-6Al-4V alloy in this article. The results indicated that apparent vaporization (0.6~1.0%) of Al was found, while vaporization of V was negligible. Simple compensating of Al to feeding wire material to ensure an equivalent chemical of EBRM deposit with that of forging could not results in equivalent matching of mechanical properties. For recovery of properties, chemical composition needs to be redesigned, and depositing and especially heat treating parameters need to be properly controlled.

Invited

Ti6Al4V Powder Feedstock Characterization and Testing for Electron Beam Melting

O. Harrysson[1,*], T. Horn[1], H. West[1], H. Gu[1], and J. Beuth[2]

(1) Center for Additive Manufacturing and Logistics, North Carolina State University, Raleigh, NC 27695, USA

(2) Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA

Email: harrysson@ncsu.edu

The users of EBM have been limited to acquiring powder feedstock from the OEM to guarantee that the provided process parameters will work. Further, the users are limited to the powder particle size distribution as well as the prescribed layer thicknesses mandated by the OEM. In an ongoing project we are evaluating how the powder characteristics and the powder particle size distribution will affect the process. Batches of powders from different manufacturers are characterized and the process parameters are adjusted until acceptable builds can be achieved regarding the microstructure as well as the dimensional accuracy. Powder batches with different distributions are tested as well as different layer thicknesses ranging from 25-200 µm. The characteristics of the powders will be correlated to the process parameter adjustments necessary to achieve a stable process and a model will be developed to help make such adjustments. The goal of the project is to facilitate for EBM users to more easily acquire powder feedstock from other powder vendors and to be able to use custom powder size distributions that will allow for a greater variability in layer thickness and build speed.

The Experimental Studies on the Powder Collapse in Electron Beam Selective Melting Processing

B. Zhou*, H. Li and F. Lin

Department of Mechanical Engineering, Tsinghua University, Beijing, China

Email: zhoubin13@mails.tsinghua.edu.cn

Powder collapse is a special phenomenon in electron beam selective melting (EBSM) processing, in which the powder flies away from the spot of electron beam when the electron beam hits the powder bed and the subsequent forming process is interrupted. There are three causes may lead to this phenomenon, which are electrical repulsion, evaporative thrust and electronic impact. In order to investigate the effects of these three causes, comparative experiments are designed and carried out in self developed EBSM machine. The design and phenomenon of these experiments will be presented, based on which the effects of each causes will be discussed. By the above experimental studies, it is expected that the valid cause of the powder collapse in EBSM could be discovered and the interactions between the powder and EB could be comprehended more.

Fig. 1: Case 3 remaining powder

[1] Guo C et al. *J. Mater. Process. Tech.* **217**, 148-157 (2015)

Induction Plasma Technology Applied to Development and Mass Production of Spherical Powders Manufacturing for Electron Beam Melting Applications

R. Vert*, A. Vassa and R. Pontone

Tekna Group, 200 boulevard de la résistance, 71 000 Mâcon, France

Email: romain.vert@tekna.com

Metal-based Additive Manufacturing (AM) technologies, in particular EBM technology, requires satellites-free powders having a spherical shape ensuring the highest packing density achievable, a specific particles size distribution, high flow ability as well as an internal particle structure which is free of pores. Despite the various advantages that commercially available powders can offer in terms of affordability and/or ease of availability, they rarely meet all the requirements listed above.

The Inductively-Coupled Plasma (ICP) process is based on the in-flight heating and melting of the individual particles of the feed material, followed by their gradual cooling and solidification before reaching the bottom of the powder processing chamber. A wide range of plasma gas mixtures could be used allowing accurate control of material chemistry. These plasma conditions allow to treat a wide range of materials including oxygen sensitive metals.

The Tekna plasma spheroidization process allows for the industrial scale manufacturing of spherical powders which exhibit controlled chemistry, controlled oxygen level, high flow ability and high density. As the feed material is heated and melted in the plasma they form perfectly spherical dense molten metal droplets which cool and solidify as they drop by gravity to the bottom of the processing chamber.

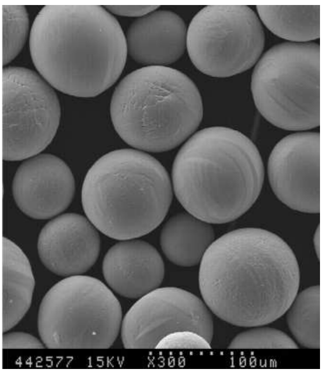


Fig. 1: Example of Ti6Al4V powder produced by ICP for EBM applications

Microstructure of Nickel-Titanium Powder by Plasma Rotation Electrode Process

M. H. Tsai[1,*], C. N. Kuo[1], A. Chiba[3], C. C. Wang[1] and C.-M. Wei[1]

(1) Metal Process R&D Department, Metal Industries Research & Development Centre (MIRDC), Kaohsiung, Taiwan

(2) Institute for Materials Research, Tohoku University, Sendai 980-0812, Japan

Email: kennytsai@mail.mirdc.org.tw

NiTi alloy contains many significant characteristics, such as super-elasticity, shape-memory, and so on. However, major drawbacks in machining NiTi alloys such as high tool wear; undesired chip formation; formation of burrs after turning and grinding may also limit its applications. Additive manufacture is one of solution for making nitinol products. The key factor is how to obtain NiTi alloy powder. Therefore, Plasma Rotation Electrode Process (PREP) is studied in this article to discuss the microstructure of NiTi powder by PREP, including composition and phase transformation, and microstructure. Experimental results shows composition changes in different powder size and segregation also be discussed.

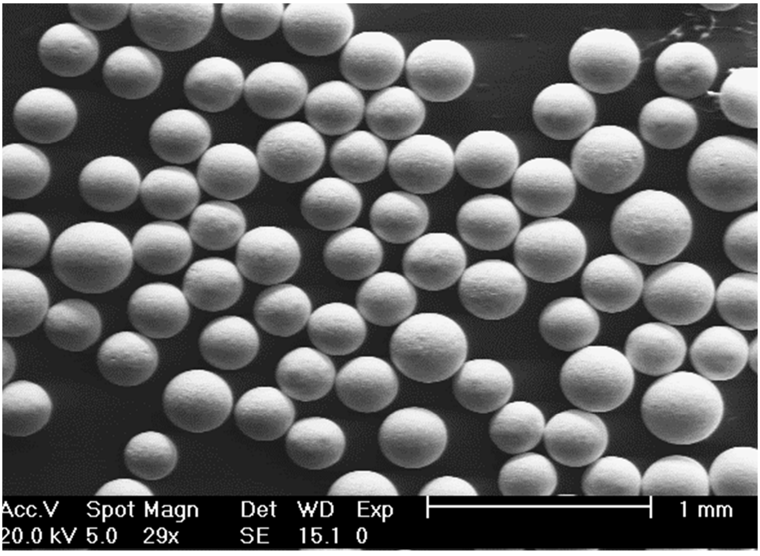


Fig. 1: Morphology of nickel titanium powder produced by PREP.

Invited

Numerical Modelling of Selective Electron Beam Melting of Ni-based Superalloys

M. Markl[1,*], A. Bauereiß[1], V. Forster[1], H. Helmer[2], A. Klassen[3], J. Köpf[2], A. Rai[1] and C. Körner[1,2]

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

(2) Joint Institute of Advanced Materials and Processes, Friedrich-Alexander-Universität Erlangen-Nürnberg, Dr.-Mack-Str. 81, 90762 Fürth, Germany

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

Email: matthias.markl@fau.de

Selective electron beam melting is a powder-bed-based additive manufacturing technology to produce metallic parts layer upon layer. The resulting material properties are complex functions of the material, powder and process parameters. Until today, the exact interplay between these parameters is not fully understood and hardly predictable. We employ a 2D thermal free surface lattice Boltzmann (LB) method, which models the process on the powder scale. In contrast to a continuum approach, this numerical method addresses physical phenomena, like capillary forces, wetting conditions and the local stochastics of individual powder layers. Additionally, the grain structure evolution during melt pool solidification is taken into account by a cellular automaton (CA) approach. Comparisons of numerical results with experimental findings for Ni-based superalloys demonstrate the successful prediction of the key characteristics during selective electron beam melting and elucidate fundamental mechanisms of the underlying physical phenomena, whereby the grain structure evolution during solidification is highlighted.

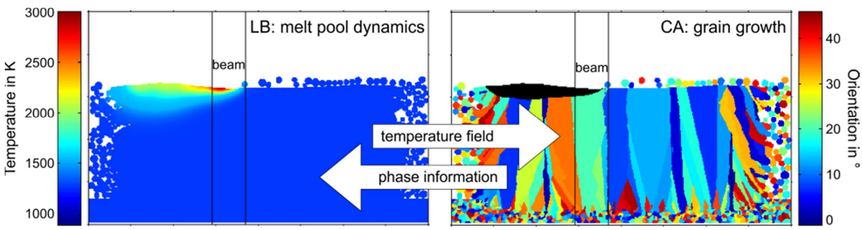


Fig. 1: Coupling Scheme of the LB and CA methods. Both methods interchange the temperature field and the phase information of the material. Temperature distribution in the vicinity of the beam is shown for the LB approach (left) and the grain misorientation to the build direction for the CA approach.

Powder Characterizations and Processing Window for Ni-based Superalloy IN625 Produced by Electron Beam Melting

E. Chauvet[1,2,*], G. Martin[1,2], B. Vayre[3],
S. Abed[3], R. Dendievel[1,2] and J.-J. Blandin[1,2]

(1) Université Grenoble Alpes, SIMAP-F-38000 Grenoble, France

(2) CNRS, SIMAP, F-38000 Grenoble, France

(3) Poly-Shape, 13300 Salon de Provence, France

Email: edouard.chauvet@simap.grenoble-inp.fr

The EBM technology is nowadays considered as an efficient process to produce parts made of Ti6Al4V alloy and Cr-Co alloy. An increasing demand has recently emerged from the automotive and aerospace industries to investigate the possibility to produce Ni-base superalloys parts using the EBM technology. Several Ni-base superalloys such as Inconel 718 [1], Inconel 625, and Rene 142 [2] have been tested. In the present contribution, we confirm that Inconel 625 is a good candidate to be manufactured by EBM.

The as-received Inconel 625 powder has been characterized in terms of chemical composition, morphology, size distribution, internal porosity, and flowability. The smoke sensitivity as well as the sintering behavior have been evaluated. These preliminary results have shown that this powder is EBM-compatible. The melting parameters have then been optimized using a design of experiment approach based on beam current, spot size (focus offset) and scanning speed. It has been shown that the process parameters have an impact on the processing time, the microstructure, the chemical composition, the surface finish as well as on the porosity. A set of parameters leading to near fully dense parts (~ 99,5%) with a relatively good surface finish has been identified. The powder main characteristics have also been studied after 10 builds to estimate their recyclability.

Furthermore, a comparison between Inconel 625 parts made by EBM and LBM was established. Microstructural differences have already been highlighted in the literature (e.g. [3]). Here we focus on differences in terms of rate productivity and powder recyclability.

[1] H.E. Helmer et al., *J. Mater. Res.* **29**, 29, 1987- 1996 (2014)

[2] L.E. Murr, *Additive Manufacturing*. **5**, 40-53 (2014)

[3] K.N. Amato et al., *J. Mater. Sci. Res.***1**, 2, 3-41 (2012)

Melt Pool Characterization and Modelling of Electron Beam Melting for IN718

X. Ding[1,*], Y. Koizumi[2] and A. Chiba[2]

(1) Department of Materials Processing, Graduate School of Engineering, Tohoku University, 6-6-11, Aramaki, Aoba-ku, Sendai 980-8579, Japan

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

Email: x.ding@imr.tohoku.ac.jp

The electron beam meting (EBM) technology has attracted increasing attention in automotive and aerospace industry, due to its amazing advantages compared with traditional processing method. In EBM, process parameters determine thermal history and temperature distribution as well as melt pool geometry, resulting in the occurrence of ultrahigh temperature gradients and cooling rates. And solidification process and microstructures are controlled by temperature gradients and cooling rates [1]. Therefore microstructures can be controlled by optimization of process parameters. In order to obtain the desired microstructures, melting and solidification process during EBM need to be investigated.

In the present study both experiment and simulation were conducted to clarify the relationship between process parameters and melt pool geometry based on melt pool characterization in IN718, which is one of the most common materials that EBM is applied to.

An A2X EBM system (Arcam AB) was used to perform single bead experiments. Single scans of electron beam with various combinations of beam power and scan speeds were conducted on IN718 base plate for the following three cases, Case A: with neither preheating nor powder, Case B: with preheating at 850 °C without powder, and Case C: with preheat of 850 °C and with 5 layers of IN718 powders (layer thickness was 50 µm). The beam conditions were same for all the cases.

FEM simulation of the single bead formation was also conducted by using surface heat source model with Gaussian distribution, which had been modified according to experimental results. History of temperature distribution were analyzed to estimate temperature gradients, solidification rate and cooling rate. Temperature gradients and solidification rate were then plotted on solidification map of IN718 to predict microstructures.

With increasing energy density (i.e. beam power/scan speed), the surface of beads changed from (i) hardly recognized to (ii) distinguishable but with defects and then to (iii) continuous with good quality. With increasing beam power, width and depth of melt pool increased almost linearly. A reciprocal relationship existed between width/depth ratio and line energy for all the three cases. Fully columnar grains were observed on the cross-section of the bead for all the cases with different process parameters examined.

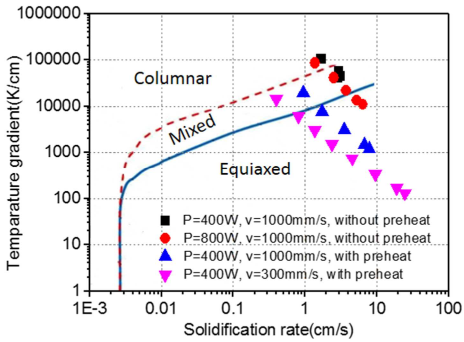


Fig. 1: Microstructure prediction by G and R on solidification map [2].

The simulated melt pool shape and size were consistent with the experimental results. However, equiaxed and mixed grains were predicted from the temperature gradient and solidification rate in the simulated melt pool, plotted on a solidification map (Fig.1). The solidification map for EBM need to be modified. Simulation results also show that process parameters have profound influence on temperature gradient, solidification rate and cooling rate of melt pool.

[1] W. Yan et al. *Comput. Mech.* **56**, 265–276 (2015)

[2] J. R. Thompson. Relating microstructure to process variables in beam-based additive manufacturing of Inconel 718. Master thesis, Wright State University (2014)

Processing the Precipitation Hardened Ni-based Superalloy IN738LC with Electron Beam Melting

S. Eichler[1,*], C. Körner[2], R. F. Singer[1], M. Franke[1], M. Hoebel[3] and T. Etter[3]

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

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

(3) GE (Switzerland) GmbH, Zentralstr.40 CH-5242 Birr, Switzerland

Email: simon.eichler@nmfgmbh.de

Precipitation hardened nickel-based superalloys, such as IN738LC, are well established for power generation turbine blades and aerospace engine components. This is above all due to their good high-temperature strength and corrosion resistance. Selective electron beam melting (SEBM) represents an entirely new manufacturing process for these alloys compared to the conventional investment casting process. SEBM reduces design limitations and it can also enable a local optimization of the microstructure. Furthermore SEBM can be used for repair applications by rebuilding worn-down areas from turbine blades. Compared to IN718, which is already qualified for SEBM, IN738LC shows new challenges due to its high-temperature corrosion resistance, the alloy's high amount of γ'-phase and the corresponding poor weldability. This contribution reveals the influence of the process temperature during the SEBM processing on crack initiation mechanisms. The resultant process window for crack-free IN738LC samples, the as build microstructure and corresponding mechanical properties are shown and compared to literature data.

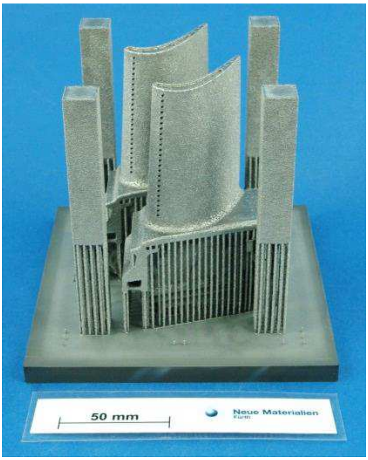


Fig. 1: Turbine blades made of IN738LC manufactured by EBM

Selective Electron Beam Melting of the Single Crystal Ni-base Superalloy CMSX-4

M. Ramsperger* and C. Körner

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

Email: markus.ramsperger@fau.de

Selective electron beam melting (SEBM) belongs to the powder bed based additive manufacturing processes and is especially interesting to manufacture high performance materials like titanium, titanium aluminides or nickel-base superalloys. SEBM works under vacuum conditions, which results in good (oxidation) protection of the metal during processing. Beneficial for manufacturing is the high available beam energy. In addition, the beam is used for heating resulting in high process temperatures (~ 950 °C) to minimize/prevent warpage.

Apart from generating dense and crack free materials it is essential to understand the correlation between geometry, process parameters and process strategy on the occurring microstructure. The flexibility of the electron beam, which can be moved with very high velocities, allows unique beam movement strategies. Therefore building time can be reduced on the one hand and on the other hand this technique opens the possibility to tailor the microstructure for specific requirements of parts.

In this contribution selective electron beam melting of the single crystalline nickel-base superalloy CMSX-4 is investigated. It is shown how crack formation problems can be avoided by an appropriate process strategy. The correlation between process strategy and resulting microstructure is discussed. The microstructure is evaluated and compared with investment casted single crystal CMSX-4 by conventional light microscopy, electron microscopy, electron backscatter diffraction and micro probe analysis.

Invited

Improved Parameters for Hot Isostatic Pressing of Ti-6Al-4V Additively Manufactured by Electron Beam Melting

F. Bahbou and U. Ackelid*

Arcam AB, Krokslätts fabriker 27 A, SE-43137 Molndal, Sweden

Email: ulf.ackelid@arcam.com

It is known that hot isostatic pressing (HIP) closes microporosity and improves the fatigue performance of AM Ti-6Al-4V. The ASTM standards F2924 and F3001 define the following HIP parameters: Argon pressure >100 MPa, temperature 895-955°C and time 2-4 hours. These parameters originate from experience with Ti-6Al-4V castings and PM material, and to our knowledge, few attempts have been made to optimize HIP parameters for AM material.

In this work, we have tested HIP parameters for Ti-6Al-4V made by Electron Beam Melting (EBM). Test specimens were built with intentional porosity and investigated before and after HIP. Full densification was observed at HIP temperatures as low as 800°C, with improved retainment of the fine microstructure and the high tensile strength observed in as-built Ti-6Al-4V material. This is attributed to the EBM vacuum environment. In contrast to AM processes operating at atmospheric pressure, porosity created under vacuum will not contain gas, resulting in better HIP efficiency.

Effect of Heat Treatments on the Mechanical Properties of Ti-6Al-4V Additively Manufactured by Electron Beam Melting

A. Kirchner[1,*], B. Klöden[1], T. Weißgärber[1], B. Kieback[1], A. Schoberth[2], S. Bagehorn[2] and D. Greitemeier[2]

(1) Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Branch Lab Dresden, Winterbergstrasse 28, 01277 Dresden, Germany

(2) Airbus Group Innovations, 81663 Munich, Germany

Email: alexander.kirchner@ifam-dd.fraunhofer.de

The additive manufacturing of titanium components offers attractive benefits such as high freedom of design, low production time, customized production and improved utilization of material. However, the relative lack of understanding the mechanical properties compared to conventionally fabricated material is hampering a widespread application.

In this work standardized Ti-6Al-4V test specimen fabricated by selective electron beam melting are subjected to heat treatments between 650 °C and 1050 °C. The microstructural evolution is analyzed on metallographic cross-sections. Significant coarsening is observed only at temperatures above beta-transus. Correspondingly, the heat treatments below beta-transus affect the static tensile strength only slightly. In contrast significant improvements can be achieved for the fatigue performance. Suitable heat treatments result in high-cycle fatigue strength exceeding 600 MPa (Fig. 1). The crack propagation rates of the specimen are discussed in terms of their fracture surface. Marked differences to Ti-6Al-4V manufactured by selective laser melting are found and an explanation is attempted.

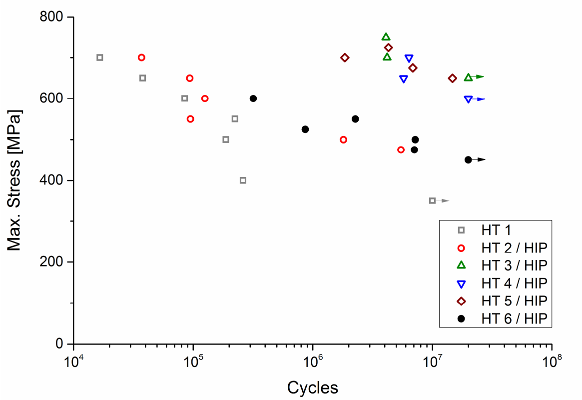


Fig. 1: High-cycle fatigue behavior of heat treated specimen built by EBM.

Towards an innovated methodology for manufacturing homogeneous metallic alloys by the EBM technology

A. Alhussein[1,2,]*, F. Boisselier [3] and P. Vannerot[3]

(1) ICD-LASMIS, Université de Technologie de Troyes, UMR 6281, CNRS

(2) Nogent International Center for CVD Innovation, LRC CEA-ICD-LASMIS, UTT Antenne de Nogent, Pôle Technologique de Haute-Champagne, 52800 Nogent, France

(3) 3A - Applications Additives Avancées, Pôle Technologique de Haute-Champagne, Rue Lavoisier, 52800 Nogent, France

Email: akram.alhussein@utt.fr

The main goal of all companies is to decrease the manufacturing cost and improving quality and properties of product. We present a new methodology innovated recently by the 3A company [1] to manufacture homogenous titanium alloys by the EBM technology. The production cycle of a metallic part made in a vacuum chamber: preheating of powder, melting and construction of layers and then cooling of manufactured part causes naturally its aging. Indeed, the construction of part layers is performed with expending an important energy and scanning a wide area. Outside of the parts, the unmelted powder grains badly joined are considered very poor heat conductors. These induce deformations and defects in parts such as swelling, delamination…etc.

The main question was: Is it possible to reduce the area scanned by the electron beam? One of the solutions proposed and investigated is the production of hybrid components whose envelope fused by EBM. Thus the obtained pieces are completely closed hermetically and filled with agglomerated titanium powder and then compacted with applying a heat isostatic pressing. This process eliminates the material porosity without spending a lot of energy.

Mechanical tests and microstructure analysis were carried out by manufacturing two types of cylindrical specimens: with or without adding lattice structures in the core of these parts. The thickness of specimen envelope fused by the EBM is enough to be closed. The core of specimens is different: "V" for test pieces containing only the agglomerated powder, and "P" for pieces having internal lattice structures (3 to 10% of the core volume).

It has been shown that the grains of both envelop and core areas are different in form and size: lamellars (15-50µm) and round particles (10-15µm), respectively. We noted that the homogeneously of compacted powder leads to excellent mechanical properties.

[1] P. Vannerot, Procédé de fabrication additive, 3A - Applications Additives Avancées, patent reference: 9A195BT1FR, deposited on October 23th, 2015.

A Critical Review of Surface Finishing Methods for Additive Manufactured Parts

A. L. Buxton* and C. S. Punshon

TWI Ltd, Granta Park, Great Abington, Cambridge, CB21 6AL, UK

Email: anita.buxton@twi.co.uk

Powder based additive manufacturing (AM) techniques allow complex geometries to be fabricated (some of which cannot be manufactured by other means). However, the surface finish and dimensional accuracy of the as-AM components is not always fit for purpose. Thus a surface finishing step is necessary. This paper addresses the complex challenge of selecting a surface finishing process for AM parts and reviews the available processes.

Methods are critically assessed by means of a case study focusing on an automotive turbocharger rotor wheel, which arose from the EU project, TiAlCharger. It was accepted that a surface finishing step would be required to improve the as-EBM surfaces of the rotor (Ra ~30μm) to a level acceptable for turbocharger usage (Ra <4μm). Ten surface finishing methods with potential suitability for EBM surface improvement were investigated in terms of:

- Achievable surface condition (through trials) – See Fig.1
- Practical implementation in production
- Process economics
- Process speed
- Potential to retain critical dimensional tolerances of the components.

Results were assessed and the most promising techniques for turbocharger wheel finishing and other potential AM applications have been identified.

Fig. 1: A photograph of a rotor wheel showing the effect of surface finishing on one blade segment

Characterizing the Surface Texture of Additive Manufactured (AM) Parts Upon Surface Finishing: Alternative Methods of Evaluating the Surface Quality of AM Parts

A. Diaz*, L. Winkelmann and J. Michaud

REM Surface Engineering, 2107 Longwood Dr, Brenham, TX 77833

Email: adiaz@remchem.com

Additive Manufactured (AM) technology using powder bed technologies has advanced in the last decade significantly. Nevertheless, the parts surfaces are still significantly rougher than those formed by conventional machining processes. The complex surface texture of an AM produced part can be described as the combination of the inherent waviness from the layer-by-layer build-up, the roughness associated to the partially melted/sintered powder particles (secondary roughness), and the roughness associated with the melted pool solidification (primary roughness).[1-3] In order to achieve the dynamic properties and biocompatibility that approximates conventionally machined parts, a secondary process and post printing operation is a must.

It is accustomed in the machining field to use the roughness average (Ra) parameter to measure the integrity of the surface. However, the surface of an AM produced part shows a unique and complex texture that the Ra parameter by itself cannot describe. Nevertheless, due to common practices, the Ra recommended settings of ISO 4288-1996 is almost mandatory to quantify improvements in surface integrity. This paper will suggest alternative methods to characterize the complex surface obtained by AM. The surface texture characteristics of an EBM as-built part will be discussed and compared to those of parts which were surface finished by the ISF® (isotropic superfinishing) and the Extreme ISF® Processes, two proprietary surfaces finishing process developed by REM Surface Engineering. We will discuss what the improved surface quality looks like, and how to characterize such a surface from a practical and straight-forward point of view. The waviness and roughness will be quantified using well known, but non-traditional surface characterization parameters, including aereal hybrids parameters and fractal analysis. In addition, we will examine the mechanical performance of the treated parts as a result of the significant surface quality improvement created by the elimination of surface defects, cracks and notches. Special attention will be given to the improvement of the surface quality for mechanical and biomedical applications.

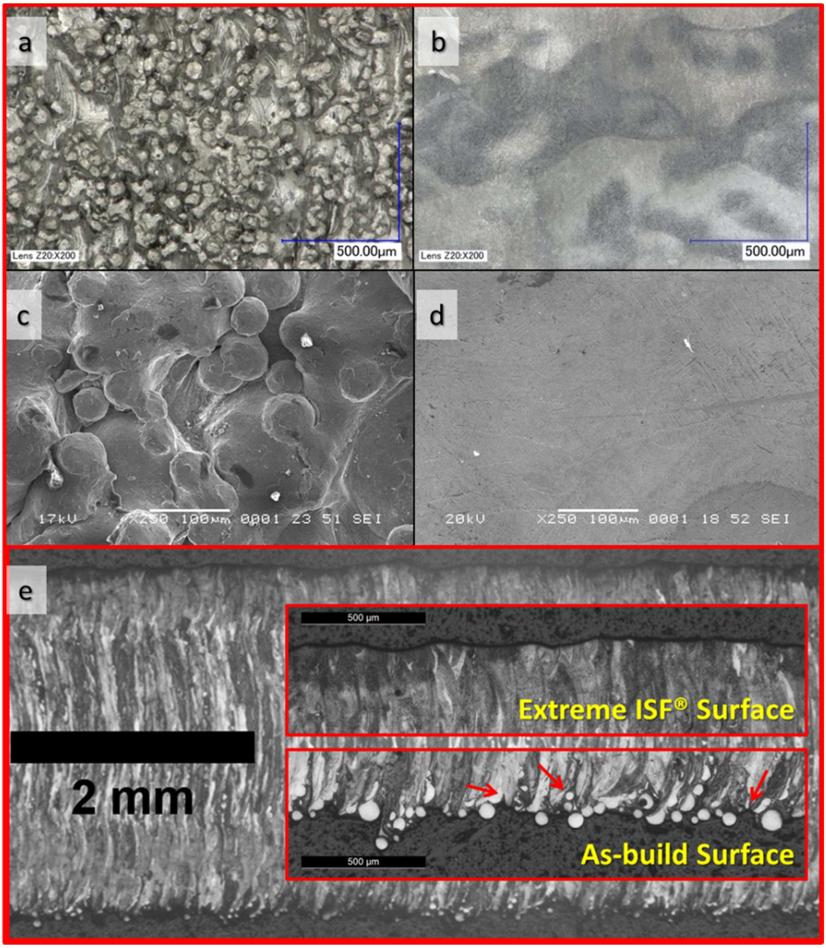


Fig. 1: Optical images (a and b) and SEM images (c and d) of an as-built EBM produced part before (a and c) and after (b and d) the Extreme ISF® Process. Micrograph image (e) of the sectioned part with the upper part finished by the Extreme ISF® Process and the bottom part as-built (inset shows a magnification of each surface section, with red arrows pointing out areas of concerns).

[1] D. Greitemeier et al. *Mater. Sci. Technol.* **00**, 0, 1743284715Y.000 (2015)

[2] T. Grimm et al. *Surf. Topogr. Metrol. Prop.*, **3**, 1, 014001 (2015)

[3] A. Triantaphyllou et al. *Proc. ASPE Spring Top. Meet. Dimens. Accuracy Surf. Finish Additive Manuf.*, **3**, 2, 127–130 (2014)

Invited

Mechanical and Corrosion Properties of High-Entropy Alloys Additive Manufactured using Selective Electron Beam Melting

T. Fujieda[1,*], H. Shiratori[2], K. Kuwabara[1], M. Hirota[1], T. Kato[1,3], K. Yamanaka[2], Y. Koizumi[2], A. Chiba[2] and S. Watanabe[3]

(1) Center for Technology Innovation - Materials, Research & Development Group, Hitachi, Ltd., Hitachi 319-1292, Japan.

(2) Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

(3) Faculty of Engineering, Hokkaido University, N13, W8, Kita-ku, Sapporo 060-8628, Japan.

Email: tadashi.fujieda.yv@hitachi.com

High-entropy alloys (HEAs) are equiatomic, multi-element systems that contain five or more principal elements and that have unique and excellent properties. However, the inherent complexity and high levels of control required to produce homogeneous alloys industrially are difficult to overcome using a conventional casting method. We succeeded in demonstrating for the first time that selective electron beam melting (SEBM) is a promising manufacturing process for utilizing HEAs as engineering materials [1]. We could produce high density and homogeneous AlCoCrFeNi HEA [2] and CoCrFeNiTi-based HEA using SEBM and investigated the mechanical and corrosion properties compared with those of the casting specimens. The mechanical properties of SEBM specimens were superior to those of the casting specimens. We attribute these superior mechanical properties to the fine homogeneous microstructure. In particular, the CoCrFeNiTi-based HEA fabricated by SEBM exhibited much higher strength and ductility at room temperature and much higher corrosion resistance in a chloride solution than conventional engineering materials like stainless steels.

[1] T. Fujieda et al., *Mater. Lett.* **159,** 12–15 (2015)

[2] H. Shiratori et al., *Mater. Sci. Eng.* **A 656** 38-46 (2016)

Microstructure and Mechanical Properties Evolution of Biomedical Co-Cr-Mo Alloys Produced by Electron Beam Additive Manufacturing

A. Chiba*, S. Kurosu, K. Yamanaka, K. Aoyagi and Y. Koizumi

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

Email: a.chiba@imr.tohoku.ac.jp

Recently, electron beam melting (EBM) has become an established additive manufacturing technology to produce any three-dimensional (3D) complex structures from precursor powders of advanced metal alloys. The purpose in this work is to investigate the effect of the build direction on the microstructure of CCM alloy fabricated EBM. In addition, the precipitation behavior of carbides in CCM alloys with different amount of carbon content is investigated to improve the strength and hardness of the CCM alloys.

The samples were fabricated on an Arcam A2X EBM system (Arcam AB, Mölndal, Sweden). The powder used in the experiment consisted of spherical particles and attached small satellite particles, with an average particle size of 64 µm. The chemical composition of the Co–28Cr–6Mo–0.23C–0.17N alloy powder was used, which was within the range of ASTM F75 standards. Additionally, CCM alloys with excess amount of carbon contents were prepared to study the precipitation behavior of the carbides under rapid cooling condition typically obtained in the powder bed fusion type additive manufacturing. The carbon and nitrogen contents are relatively high within the range of the standard. Higher carbon and nitrogen contents are known to provide a large amount of precipitates and stabilize γ-phase. The Co–28Cr–6Mo–0.23C–0.17N alloy rods fabricated in the directions of 0°, 45°, 55°, and 90° from the *z* axis are designated as the 0°-sample, 45°-sample, and so on. The rods were 15 mm in the diameter, and 85 mm in the height. Microstructures of each portion were investigated by electron backscatter diffraction (EBSD). The microstructure on the top part (67 mm from the bottom) of rod for each orientation was investigated by scanning electron microscopy (SEM), EBSD, and X-ray diffraction (XRD) on the longitudinal cross section consisting of the cylinder and *z* axes.

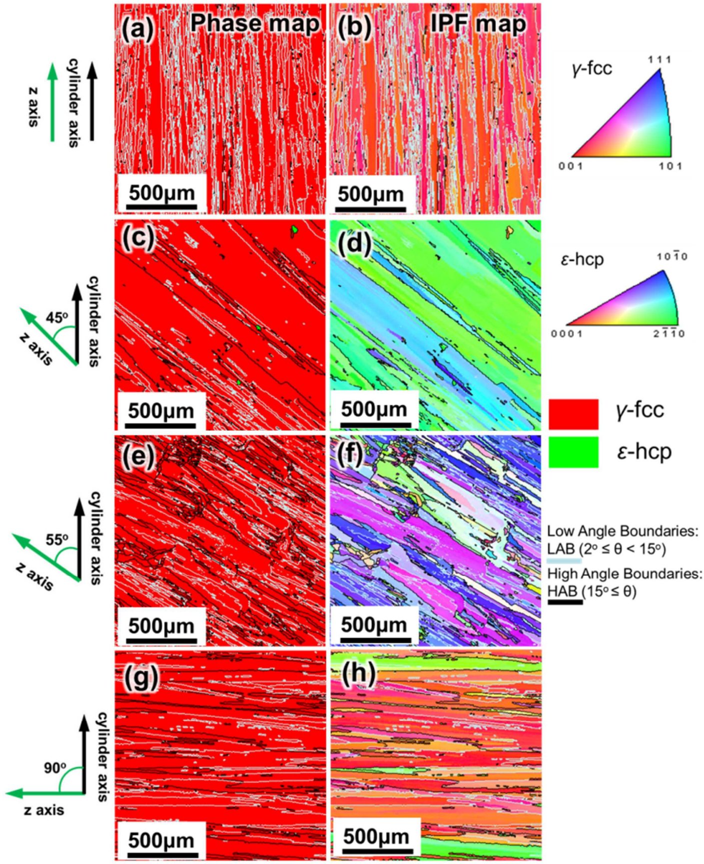


Fig. 1: EBSD phase maps (a, c , e, g) and IPF maps (b, d, f, h) on vertical cross section of top part of as-EBM-built samples, (a, b) 0°-sample, (c, d) 45°-sample, (e, f) 55°-sample and (g, h) 90°-sample.

Fig. 1 shows the EBSD analysis results of top part of as-EBM-built samples. The high-angle and low-angle grain boundaries are indicated by black and light blue lines, respectively, on the inverse pole figure (IPF) maps and phase maps. From Fig. 1 it can be seen that the boundaries basically aligned along *z* axis. The IPF maps showed the orientations in the direction of the cylindrical axis, it indicates that that the preferential orientations of the *γ* phase in the as-EBM-built samples along the cylindrical axial directions were near [001], [110], [111], and [100] in the 0°-, 45°-, 55°-, and 90°-samples, respectively, which are believed to be a result of oriented crystal growth of the *γ*-fcc phase along the <001> direction.

Microstructure and Mechanical Properties of WCp Reinforced IN625 Composite Produced by Electron Beam Melting

H. Peng[1,]*, C. Liu[2] and H. Guo[1,2]

(1) School of Materials Science and Engineering, Beihang University, No. 37 Xueyuan Road, Beijing, China

(2) Beijing Key Laboratory for Advanced Functional Material and Thin Film Technology, Beihang University, No. 37 Xueyuan Road, Beijing, China

Email: penghui@buaa.edu.cn

Ni-based metal matrix composites (MMC) have been widely used in industry for tribocorrosion applications. The superior performance offered by such materials relies on the combination of the hardness of the carbide reinforcement and the toughness of the Ni-based matrix. In this work, a Ni-based MMC will be produced by electron beam melting (EBM) with a pre-blended powder containing Inconel 625 and cast WC. Different amount of addition of WC reinforcements will be tested. The relationship between the processing parameters and the microstructure of the MMC will be discussed. Then, the mechanical properties of the MMC will be also investigated. Finally, crack free components with complex geometries made of MMC will be shown.

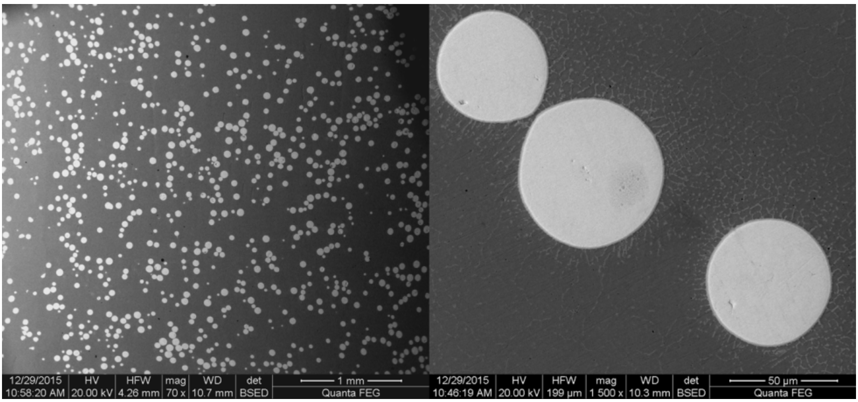


Fig. 1: Cross-section of as-fabricated WCp reinforced Inconel 625 composite (X-Y plane)

Process Development and Properties of Copper Components Fabricated via Selective Electron Beam Melting

M. A. Lodes[1,*], R. Guschlbauer[1] and C. Körner[1,2]

(1) Joint Institute of Advanced Materials and Processes, Friedrich-Alexander-Universität Erlangen-Nürnberg, Dr.-Mack-Str. 81, 90762 Fürth, Germany

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

Email: matthias.lodes@fau.de

Selective electron beam Meeting (SEBM) shows its strengths particularly in the fabrication of "difficult" materials. Difficult here usually means materials which are either prone to atmospheric gases (e.g. Titanium alloys) or need high melting and preheating temperatures (intermetallics, superalloys etc.). Although copper does not fit into that common scheme, selective electron beam melting has proven to be the only powder based AM method to be able to process pure copper. Challenges that need to be overcome are the high conductivity and especially high reflectivity. This talk presents the pathway to manufacture dense copper components with focus on sustaining the high electrical and thermal conductivity of the base material. Defects deteriorating the conductivities are discussed. Furthermore it is shown that oxide dispersion strengthening is no feasible way to improve strength of copper components if they are fabricated via SEBM.

Invited

Additive Opportunities

Paolo Gennaro*

GE Avio S.r.l., Strada Giuseppe Gabrielli, 28062 Cameri (NO), Italy

Email: paolo.gennaro@avioaero.it

Users of additive manufacturing are increasingly applying the technology for production applications rather than simple prototypes. This change is driving the supply chain to respond, resulting in the delivery of greater competiveness, quality, standardization, and innovation. This presentation will look at how these changes are affecting the supply chain and how AvioAero is working to meet current and future needs. One of the world's most challenging applications is the production of turbine blades made in titanium aluminide (TiAl) for jet engines.

Processing of Titanium Aluminides by Selective Electron Beam Melting

V. Jüchter[1,*], M. Franke[2] and C. Körner[1]

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

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

Email: vera.juechter@fau.de

Processing of titanium aluminides by selective electron beam melting is very promising as it offers various advantages for this material class. Besides the vacuum condition, which prevents the material from oxygen pickup, also high building temperatures hinder cracks to occur. Choosing suitable parameter settings to gain good material properties is a key knowledge to produce high end parts like turbine blades. In this contribution general aspects of processing titanium aluminides and various important scanning strategies to influence the material properties are discussed. Here especially the process parameters like energy input, line offset and scanning speed show a high influence on properties like chemical distribution, microstructure and therefore mechanical properties. Furthermore the possibilities to produce complex parts are shown by giving an application example.

Fig. 1: Titanium aluminide turbine blade produced by selective electron beam melting

Ti-48Al-2Nb-0.7Cr-0.3Si Titanium Aluminide for Automotive Applications Processed by Electron Beam Melting

G. Baudana[1,*], S. Biamino[1], B. Klöden[2], A. Kirchner[2], A. Buxton[3], P. Fino[1] and C. Badini[1]

(1) Politecnico di Torino (DISAT), C.so Duca degli Abruzzi 24, Torino, Italy

(2) Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Winterbergstr. 28, Dresden, Germany

(3) TWI Ltd, Granta Park, Great Abington CB21 6AL Cambridge, United Kingdom

Email: giorgio.baudana@polito.it

γ-TiAl alloys are a family of intermetallic compounds that thanks to their unique properties represent an attractive alternative to Ni-based superalloys for high temperature automotive structural applications [1]. The Electron Beam Melting (EBM) additive manufacturing technology is well known and considered for the processing of TiAl alloys, in particular for the aerospace application [2].

In this work, carried out within the European project TIALCHARGER, TiAl-based powders of Ti-48Al-2Nb-0.7Cr-0.3Si for automotive application, were used to fabricate specimens and prototypes of turbocharger turbines by Electron Beam Melting [3]. Thanks to the freedom in design given by EBM, hollow turbine wheels were produced bringing to a further reduction of the component weight. The produced components were characterized in terms of chemical composition, residual defects and microstructure. Furthermore, heat treatments were set up in order to obtain the desired microstructure for the application. After all, some brazed joints between the steel shaft and TiAl wheel processed by EBM were produced and characterized in order to verify the feasibility of the component.

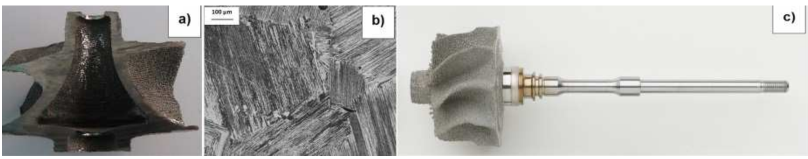


Figure 1: a) Cross-section of an hollow turbine; b) NL microstructure after heat treatment; c) joining trial.

[1] X. Wu, *Intermetallics*. **14**, 1114-1122, (2006)

[2] S. Biamino et al., *Intermetallics.* **19,** 776-781 (2011)

[3] T. Tetsui, *Mat. Sci. Eng.* **A329-331** 582-588 (2002)

FE Thermal Model of Electron Beam Melting Process to Investigate Different Experimental Microstructures for TiAl

M. Galati[1,*], G. Baudana[2], A. Salmi[1], E. Atzeni[1],
S. Biamino[2], P. Fino[2] and L. Iuliano[1]

(1) Politecnico di Torino, DIGEP, C.so Duca degli Abruzzi 24, Torino, Italy

(2) Politecnico di Torino, DISAT, C.so Duca degli Abruzzi 24, Torino, Italy

Email: manuela.galati@polito.it

γ-TiAl materials represent an important class of structural materials which already proved to be extremely promising for both automotive and aerospace applications. At present, the EBM is the most attractive additive manufacturing process for the production of TiAl components [1,2]. In this study several samples of the alloy Ti-48Al-2Cr-2Nb (at%) were produced varying EBM process parameters such as line offset, speed function, max beam current and focus offset according to a DoE matrix exhibiting differences in terms of residual defects, microstructure, aluminum evaporation, etc. Within this work an FE thermal model of the EBM process [3] was used in order to investigate and explain the above mentioned differences obtained during the process.

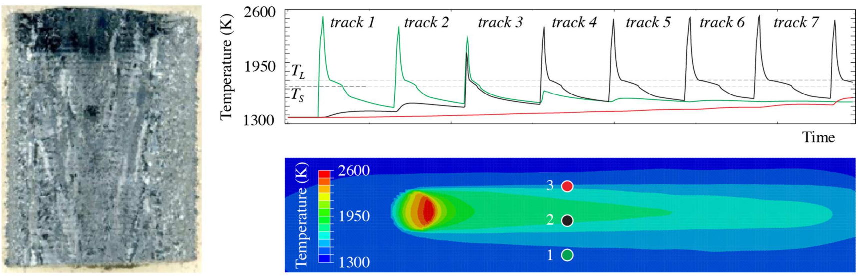


Figure 2: Temperature map and distribution on the top layer and cross section of the specimen.

The FE thermal model of the EBM process gives an idea of the reached temperature and showed that material is subjected to numerous thermal cycles before and after the EB scan, which lead to a first temperature raise before the EB scan, and then several remelting events of the same tracks.

[1] S. Biamino et al., *Intermetallics.* **19,** 776-781 (2011)

[2] M. Terner et al., *Intermetallics*. **37**, 7-10 (2013)

[3] M. Galati et al., *Proc. 5th International Conference on Additive Technologies - iCAT2014.* 109-118 (2014)

Fabrication of NiTi Porous Scaffolds using Micro Electron Beam Melting

S. Khademzaeh* and N. Parvin

Metallurgy Engineering Department, Amirkabir University of Technology, Hafez Ave, Tehran, Iran

Email: khademzadeh@aut.ac.ir

For fabrication of porous scaffolds with complicated geometry and internal architecture, it’s required to develop new and modern manufacturing processes to design micro and macro pores in such scaffolds. Additive manufacturing needs each layer to be fabricated according to an exact geometry defined by a 3D CAD model. This concept is suitable for production of porous parts with complicated geometries. This work covers development of micro electron beam melting (µEBM) as a micro additive manufacturing process. µEBM is a promising method for fabrication of parts with micro-features and complicated geometry. In this study, the combination of high energy mechanical alloying and µEBM techniques is experimented with the aim of assessing the feasibility of synthesizing near single phase NiTi from elemental Nickel and Titanium powders. The results showed that B2-NiTi phase with small quantity of NiTi2 can be obtained by micro electron beam melting of mechanically alloyed Ni50.8Ti49.2 powder. The effects of process parameters on surface quality of products were investigated using scanning electron microscope (SEM) and optical profilometer. Also, the effect of process parameters on formation and distribution of micro pores was analysed using micro computed tomography (µCT) and SEM.

Invited

The Potential of Electron Beam Melting for a Multi-Disciplinary Research

L.-E. Rännar*, M. Bäckström and A. Koptioug

Mid Sweden University, Sports Tech Research Centre, Department of Quality Technology and Management, Mechanichal Engineering and Mathematics, Akademigatan 1, SE-832 25 Östersund, Sweden

Email: lars-erik.rannar@miun.se

In present paper we would like to share some experiences of building a new research centre in Sports Technology at Mid Sweden University and in particular how additive manufacturing and Electron Beam Melting (EBM) fits into the different application areas. The disciplines involved in the centre spans from physiology and biomechanics with emphasis on winter sports over to additive manufacturing and new materials where the research mostly is targeting industrial and biomedical applications, with the projects done in close collaboration with companies and clinicians, see Fig. 1.

The additive manufacturing laboratory within the centre was established in 2003, when the first plastic material extrusion machine was installed, followed by an Arcam EBM A2 machine in 2007. The group is now well established in the national and international research society and a range of successful projects have been carried out where the EBM method have had an important role. Especially noteworthy in the context of this conference is the progress within the development of the EBM process for materials such as bulk metallic glasses, stainless steel and high carbide tooling steel.

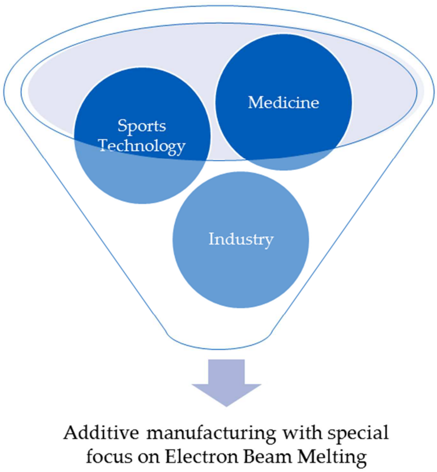


Fig. 1: The three different application areas addressed in the research.

Other spectacular projects in Ti64 like the design and manufacturing of a unique roller-ski designated for a unique test environment within cross-country skiing and individualised durable prosthetic socket will also be presented.

Dental Implant Manufacturing using Electron Beam Melting – Geometry Deviation from Intraoral Scanning and from Cone Beam Computed Tomography

M. Cronskär[1,3], P. E. Legrell[2,*], P. Tidehag[2,], L.-E. Rännar[3]

(1) Additive Innovation and Manufacturing Sweden AB, Akademigatan 3, SE-831 40, Östersund, Sweden

(2) Umeå University and Västerbottens Läns Landsting, Umeå Dental School, SE-901 85, Umeå, Sweden

(3) Mid Sweden University, Sports Tech Research Centre, Akademigatan 1, SE-832 25 Östersund

Email: pererik.legrell@vll.se

Titanium dental implants have revolutionised reconstructive dentistry since the first experimental studies in the beginning of the 1960´s to the 1980:s when they were introduced as accepted treatment modalities [1]. Today, several different brands and types of implants are used but restrictions in available dimensions and overall geometries may hamper the surgical outcome, especially in cases with sub-optimal bone conditions due to infections and/or physiologic bone resorption after tooth extraction. Optimising implant size by customisation of the implant to the remaining bone dimensions in the intended implant area could however increase the chances for a successful treatment in these cases.

The research questions addressed in this study are to investigate if dental implants manufactured using electron beam melting (EBM) have the same physical dimensions as the original model, i.e. a tooth, and if the method could be used to manufacture customised dental implants for direct replacement of removed teeth.

The extracted human premolar was scanned with an intraoral scanning (IOS) device (3M™ True Defintion Scanner) and also radiographically examined with Cone Beam Computed Tomography (CBCT, J Morita, Jpn). The CBCT-examination was saved as DICOM-files and then transferred to STL-files using segmentation with three different threshold values in the Mimics software (Materialise, BE) and these 3D reconstructions were then compared with the scanned human premolar. EBM samples were then manufactured using STL files from both IOS and CBCT and geometry deviations from 3D reconstruction and manufacturing was then analysed using digital volume measurement and digital surface deviation. The results show that the volume for the 3D reconstructions are smaller than for the scanned original while the surface deviation of the reconstruction is mainly negative in the root and positive in the crown. The volume deviations originating form manufacturing are also mainly negative and one conclusion is that it is viable to manufacture dental implants using EBM but such small components need special attention when it comes to scaling the models properly before manufacturing.

[1] R. M. Sullivan. *J Calif Dent Assoc.***29**:737–745.F (2001)

Lattice Structures made by Electron Beam Melting: Mechanically Efficient Matter

M. Suard[1], R. Dendievel[1,*], J.J. Blandin[1],
G. Martin[1], F. Vignat[2] and F. Villeneuve[2]

(1) Univ. Grenoble Alpes, SIMAP, F-38000 Grenoble, France

(2) Univ. Grenoble Alpes, G-SCOP, F-38000 Grenoble, France

Email: remy.dendievel@grenoble-inp.fr

This work focuses on the structural and mechanical characterization of lattice structures produced by Electron Beam Melting. The unit cell is a regular octet-truss. Structures consist in five unit cells (fig.1 left). The structural characterization mainly relies on X-ray tomography on single struts whereas mechanical properties are assessed by uni-axial compression on structures. For small strut size, the difference between the designed structure and the produced one is large enough to impact the desired mechanical properties. In particular, matters corresponding to strut roughness or irregularities is not useful from a mechanical point of view. For purpose of simulation, this concept of mechanical efficient matter is taken into account by replacing the struts by a cylinder with a *mechanical equivalent diameter* (Fig.1 right). This diameter depends in particular on strut size, strut orientation and melting strategies. After validation with the compression results, it has been used into "realistic" simulations and optimization procedures, thus taking into account the inherited EBM process constraints.

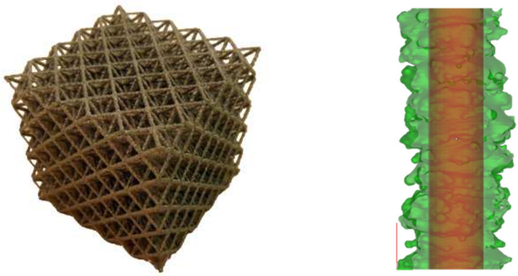


Fig. 1: *left* : structure composed of 5x5 octet-truss unit cells -- *right* : X-ray view of a 1mm vertical single strut and its related mechanical equivalent diameter in brown

Microstructure and Mechanical Properties of Beta-type Ti-24Nb-4Zr-8Sn Porous Structure Fabricated by Electron Beam Melting

S. J. Li[1,*], Y. J. Liu[1,2], W. T. Hou[1], Y. L. Hao[1], L. C. Zhang[2] and R. Yang[1]

(1) Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, China

(2) School of Engineering, Edith Cowan University, 270 Joondalup Drive, Joondalup, Perth, WA 6027, Australia

Email: shjli@imr.ac.cn

Porous titanium and its alloys have been considered as promising replacement for dense implants, considering they possess low elastic modulus matching to that of human bone and are capable of providing space for in-growth of bony tissue to achieve a better fixation. Recently, additive manufacturing (AM) using the electron beam melting (EBM) method has been successfully applied to fabrication of Ti-6Al-4V cellular meshes and foams. However, the toxicity of elements (i.e. Al, V) and low fatigue strength of EBM-produced Ti-6Al-4V components has been pointed out. To avoid these shortcomings, fabrication of low-modulus non-toxic β-type titanium alloy cellular structures is good choice. In this talk, electron beam melting (EBM) is applied to manufacture β-type Ti-24Nb-4Zr-8Sn porous components with 60-90% porosity. Microstructures, defects and mechanical properties of EBM-produced components are investigated. The processing-microstructure-property relationship and deformation behavior of EBM-produced components are detailed discussed.

Optimization of Electron Beam Melting Build Processes by Localized Preheat Strategies

P. Drescher* and H. Seitz

Fluid Technology and Microfluidics, Justus-von-Liebig Weg 6,
18059 Rostock, Germany

Email: philipp.drescher@uni-rostock.de

Post-processing of parts produced by SEBM typically involves the removal of semi-sintered powder through the use of a powder blasting system. Furthermore, the sintering of large areas before melting decreases productivity. Current investigations are subject to improve the melting process in order to achieve better productivity, geometric accuracy and resolution. In this study, the focus lies on the sintering process in regard to building highly porous titanium components as well as test specimens and increasing the productivity by only sintering the area in which the melt pool is created. The aim of this study is to decrease build time, possibly improve mechanical properties of components and to remove the residual powder more easily after a build.

Improving Part Quality Thanks to Additive Features

N. Beraud[1,2,*], F. Vignat[1,2], R. Denvievel[3,4] and F. Villeneuve[1,2]

(1) Univ. Grenoble Alpes, G-SCOP, F-38000 Grenoble, France

(2) CNRS, G-SCOP, F-38000 Grenoble, France

(3) Univ. Grenoble Alpes, SIMAP, F-38000 Grenoble, France

(4) CNRS, SIMAP, F-38000 Grenoble, France

Email: Nicolas.beraud@grenoble-inp.fr

Improving the dimensional accuracy of parts produced by Electron Beam Melting process is a real challenge to produce functional parts. The part design is completely change due to the process capability. Thus, different kind geometry topologies can be used as lattice structure, thin wall or massive volume.

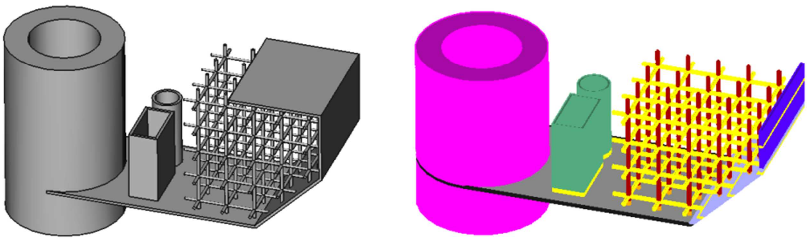


Fig. 1: Example of feature decomposition

In electron beam melting the melting strategy is composed by the beam trajectory and the beam parameters (beam voltage, beam current, beam diameter, beam speed). The melting strategy has a large influence on the part quality. Study shows that use appropriated strategy for specific features (overhanging surface for example) allows to wildly improve the part quality [1]. The study developed defines the concept of feature in additive manufacturing and shows the quality improvement of multi-feature part.

[1] N. Béraud et al. *Procedia CIRP*, *17*, 738-743 (2014)

[2] N. Béraudet al. Evaluation de la chaine numérique en fabrication par Electron Beam Melting. In *14ème Colloque National AIP PRIMECA* (2015)

Selective Evaporation during Selective Electron Beam Melting – Numerical Simulation

V. Forster[1,*], A. Klassen[2] and C. Körner[1]

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

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

Email: vera.forster@fau.de

During selective electron beam melting intense evaporation is a common problem, especially if the vapour pressures of the main alloying elements differ by several orders of magnitude. This is the case, for example, in titanium aluminide based alloys, where aluminium is considerably more volatile than titanium and the other constituents in the system. Selective evaporation is known to cause local changes in the chemistry of the processed alloy and thus of the final product fabricated using SEBM. In order to understand how evaporation affects the concentration distribution during the SEBM process, the local heating and fusion of powder particles is studied by means of numerical simulations. Key value is the evaporating mass flux that depends on both the surface temperature and the concentration distribution of the melt pool. The heat and mass losses as well as the recoil pressure resulting from this mass flux are coupled back into the thermal and hydrodynamic fields which are calculated via the lattice Boltzmann method.

Comparison of experimental data with numerical results shows that the multi-component evaporation model is capable of accurately predicting melt pool shapes, evaporative losses and concentration distributions over a wide range of SEBM process parameters. With this tool it is now possible to analyse the time-resolved evolution of the concentration distribution within the molten region. Furthermore, we can identify factors that impact evaporation rates and investigate how changes in alloy composition can be avoided.

Effect of Building Position on Phase Distribution in Co–Cr–Mo Alloy Fabricated by Electron-Beam Additive Manufacturing

Y. Koizumi[1,*], T. Takashima[1,2], K. Yamanaka[1],
K. Aoyagi[1], T. Saito[1] and A. Chiba[2]

(1) Department of Materials Processing, Graduate School of Engineering, Tohoku University, 6-6-11, Aramaki, Aoba-ku, Sendai 980-8579, Japan

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

Email: koizumi@imr.tohoku.ac.jp

We fabricated 20 rods of biomedical Co–Cr–Mo alloy with height of 160 mm arranged in a 4 × 5 matrix by EBAM, and observed the phase constitution in the middle part (at a height of 80 mm) of the rods by scanning electron microscopy–electron backscatter diffraction. It was found that the rods in the center of the matrix consisted of more of the fcc (γ) phase and less of the hcp (ε) phase than those in the outer. This suggests that the rods in the center had been exposed to higher temperature than those in the outer, and less thermal dissipation took place because the neighboring rods were also heated by the electron beam. Hence, we need to take into consideration the heterogeneity of microstructure due to the difference in the thermal histories depending on the horizontal position be in addition to the heterogeneity depending on the vertical position [1-3] when many objects are fabricated simultaneously.

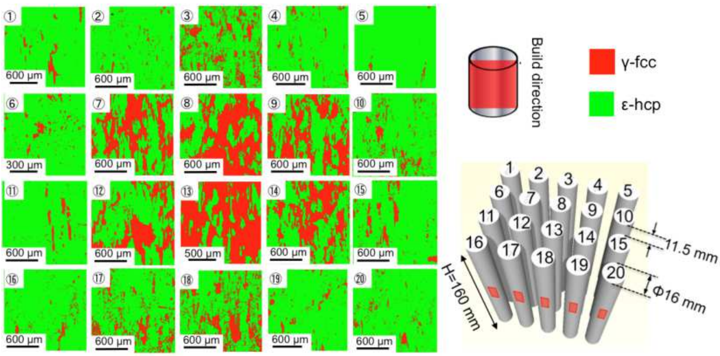


Fig. 1: EBSD phase maps of Co-Cr-Mo alloy rods fabricated at different horizontal positions.

[1] S. H. Sun et al. *Acta Mater.* **64**, 154-168 (2014)

[2] S. H. Sun et al. *Acta Mater.* **86**, 305-318 (2015)

[3] S. H. Sun et al. *J. Jpn. Soc. Powd. Powd. Metall.* **61**, 234-242 (2014)

Thermal Field Simulation and Microstructure Predict of Ti-6Al-4V by Electron Beam Melting Process

C. N. Kuo*, M. H. Tsai, Y. L. Su, and C. T. Kuo

Metal Industries Research & Development Centre, Kaohsiung 811, Taiwan

Email: cnkuo@mail.mirdc.org.tw

Electron beam additive manufacturing process is widely used to directly manufacture products such as medical devices and aerospace parts. Due to the high power of electron beam and resulting high temperature and big melting pool, the densification is close to 99 % and thus the mechanical properties are promised. However, the microstructure is hard to control during the solidification of the melting pool. To control the microstructure during the EBM process is a global issue since it is the key point to control the EBM product performance. In this study, thermal field simulation prototype model is built. The microstructure of EBM Ti-6Al-4V was predicted by simulation results and verified by EBM experiments. The relation between simulation results, EBM parameter, and microstructure of EBM samples are compared and discussed in this study.

Process and Quality Supervision with LayerQam and X-ray Sensors

J. Backlund and U. Ljungblad*

Arcam AB, Krokslätts Fabriker 27A, 43137 Mölndal, Sweden

Email: johan.backlund@arcam.com

The orthopedic implant industry has used the EBM (Electron Beam Melting) technology for series production since 2007, and the aerospace industry is now about to do the same. This focus on production has brought an increasing demand for process and quality supervision, e g defect detection, and we describe some of the technical solutions that have been developed and is under development to meet these industry requirements. A high resolution camera has been integrated with the newest line of EBM systems. The camera is able to take one or several high resolution images of the entire powder bed build area after the melting to evaluate build quality of each manufactured layer. The high build temperature in the EBM-process enables heat sensitive functionality also in the visible and near infrared wavelength region. This enables defect detection and post build quality evaluation of the built parts. This function can be used for process surveillance and serves as a complement to other non-destructive testing (NDT) methods. A new X-ray sensor is also being integrated in the newest line of EBM systems. With this sensor it is possible to determine beam parameters such as position, focus and beam shape with very high accuracy. Future development of applications for the X-ray sensor will have the possibility to include in-process monitoring of build accuracy and further improve process robustness.

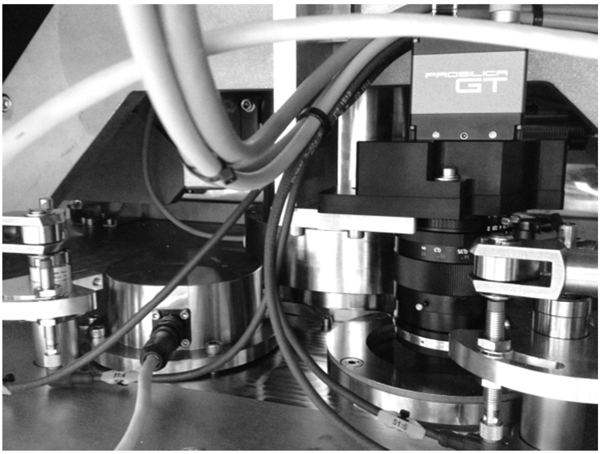


Fig. 1: LayerQam camera (right) and the new X-ray sensor (left) on the chamber of an Arcam Q20.

Influence of Specimen Dimensions on the Mechanical Behavior of EBM Produced Ti-6Al-4V Alloys

M. Madeja*, R. Dziedzic, and E. Chlebus

Wroclaw University of Technology, Mechanical Department, CAMT-FPC, Wroclaw Lukasiewicza 5, Poland

Email: marcin.madeja@pwe.edu.pl

Electron beam melting (EBM) is a powder based additive manufacturing technique where metal parts are built layer by layer. It is common used in industries such as the medical, automotive and aerospace because it enhances the ability to fabricate complex and functional component parts.

In process of development of complex and lightweight parts there is needed to know material properties. In most cases mechanical characteristics of specific material is made i.e. in static uniaxial tensile test. Geometry of specimen is taken according to i.e. ASTM E-8 standard. Test samples are usually cut from large slabs of material made in EBM process.

Results obtained based on such samples may not by fully suitable for lightweight parts or complex, tuss-like structures especially when components cross-sections are smaller than a cross-section of standard specimen.

The studies included production and testing of tensile test samples with different shapes and cross-sections area. In this research EBM samples made of Ti6Al4V have been manufactured with similar to its final geometry. Only small amount of material was added to perform finishing machining. Result of this experiment show influence of different geometry and cross section on mechanical properties of samples produced with EBM technology.

Process Window for Ti-6Al-4V on the Arcam Q10

C. R. Pobel[1,*], M. A. Lodes[1] and C. Körner[1,2]

(1) Joint Institute of Advanced Materials and Processes, Friedrich-Alexander-Universität Erlangen-Nürnberg, Dr.-Mack-Str. 81, 90762 Fürth, Germany

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

Email: christoph.pobel@fau.de

Selective electron beam melting (SEBM) of metal powders allows a nearly inertia free and rapid beam deflection (up to 10.000 m/s) offering the potential to realize novel scanning strategies. For the Arcam S12, A2 and A2x machines, the power of the electron beam cannot be fully used for the melting step due to a strong increase of the beam diameter at beam powers higher than 1 kW. In the Arcam Q10 system, the standard tungsten filament cathode is replaced by a single crystalline CeB_6 cathode leading to a much better beam quality also at higher beam power opening the possibility to exploit the limits of the machine.

In this contribution, a processing map for Ti-6Al-4V on an Arcam Q10 machine is determined. The focus is on extremely high deflection speeds and high build rates. It is shown that the process window enlarges due to the better beam quality of the Q10 compared to the other machines.

Expanding Powder Capabilities through Hot Gas Atomization

C. Schmetter*, G. Wolf and P. Masset

Fraunhofer UMSICHT, Sulzbach-Rosenberg, Germany

Email: clemens.schmetter@umsicht.fraunhofer.de

Modern additive manufacturing processes (AM) such as electron beam melting impose specific requirements on the applied powder materials, because their properties significantly influence the manufacturing processes and quality of the manufactured components. Currently, there is a trend towards the application of powder materials < 10 µm in AM processes in order to realize finer structures and to decrease the surface roughness.

The majority of powders used in AM are produced through inert gas atomization, which delivers spherical particles ideally suited for AM with a high yield in the range of 40-50 µm. However, the yield significantly decreases for finer fractions < 10 µm which results in a high material throughput in order to reach required quantities and consequently in higher costs.

Hot gas atomization allows increasing the yield in the fine particle range and simultaneously reducing the gas consumption. Special developments made at our plant enable the operation at atomization gas temperatures above 1000 °C, which exceeds standard hot gas atomization techniques. A fourfold efficiency increase in plant operation can thus be achieved compared to conventional inert gas atomization. Furthermore, the processing of highly viscous melts (which normally results in the formation of fibers) and the use of reactive hot gases (e.g. for metal / ceramic compounds) is possible.

Mechanical Property Comparison of Electron Beam Melting Samples with Different Porous Structure

Y. L. Su[1,*], C. N. Kuo[1*], M. H. Tsai[1], Y. C. Wu[2] and J. C. Huang[2]

(1) Metal Industries Research & Development Centre, Kaohsiung 811, Taiwan

(2) Department of Materials and Optoelectronic Science,
National Sun Yat-Sen University, Kaohsiung 804, Taiwan

Email: allansu@mail.mirdc.org.tw

Titanium alloy is the material that has been developed for a long time. Due to its excellent characteristic of resistant to corrosion and the highest strength-weight ratio, it’s extensive used in medical implant and aerospace. Nowadays, Electron Beam Melting (EBM) process has been proved that it could manufacture the products which exhibit excellent mechanical properties similar to forging products. In addition, the designed light-weighting and bionic porous structure can be manufactured by EBM technology. However, different porous structure will lead different mechanical properties. In this research, EBM process is utilized to produce several Ti-6Al-4V samples with different porous structure. The mechanical properties were tested and discussed in this study.

Estimation and Simple Modelling of Elastic Strain Generated in Process Using 3D Finite Element Approach

S. Tadano*, T. Hino, Y. Nakatani, A. Tanaka and M. Takahashi

Toshiba Co.Ltd. Power and Industrial Systems R&D Center 2-4 Suehiro-cho, Tsurumi-ku, Yokohama 230-0045, Japan

Email: satoshi.tadano@toshiba.co.jp

For process stability during manufacturing and reliability of assembled components, it is challenging issue to control residual strain (stress) distribution in EBAM process. The powder preheating step is one of factors influencing on residual stresses of components [1], and it is required to facilitate thermo-mechanical simulations in order to determine reasonable condition for decreasing residual strains. The objective of this research is to estimate residual elastic strains induced by preheat temperature deference using 3D finite element approach and further try to evaluate residual strains by simple modelling. To implement the 2D Gaussian heat source and the melting / solidification transformation phenomenon in the FE model, a user subroutine was used. The model has a basic dimension of 2mm × 2mm × 5mm, and a single scan path was simulated. Preheat temperature range was 400-1000°C. The material property was the temperature dependent values of Ni-based superalloy. In 3D finite element simulation result, the tendency of residual strain reduction with increasing preheat temperature are noted (Fig. 1). This tendency is reasonable agreement with the literature [1]. To simplify the evaluation, simple modelling was developed in this study.

The following equation (1) was formulated based on the concept of dynamic model using thermal strain and plastic strain.

$\varepsilon_{re} = - (\Delta\varepsilon_{th} + \Delta\varepsilon_{p}) \times f(h)$ (1)

Where ε_{re} is residual strain, $\Delta\varepsilon_{th}$ ($\Delta\varepsilon_{p}$) is average thermal (plastic) strain difference between substrate and newly added layer, f(h) is function about component height. It can be noted that FE simulation results and simple modelling are fairly close, order of 0.02% difference.

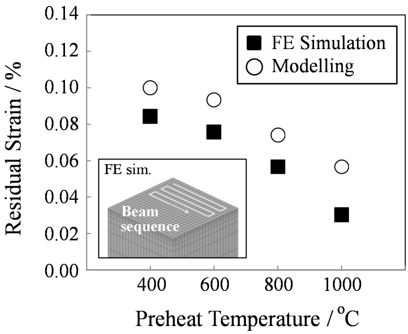


Fig. 1: Residual strains estimated by FE simulation and simple modelling (at center point of added layer).

[1] L.M. Sochalski-Kolbus et al. *Metall. Mater. Trans.* **46A**, 3, 1419-1432 (2015)

Surface Roughness Effects on Mechanical Properties of Ti-6Al-4V Manufactured by Electron Beam Melting

C. A. Terrazas-Nájera[1,]* and A. Diaz[2]

(1) Addaero Manufacturing LLC, New Britain, Connecticut, USA

(2) REM Surface Engineering, Brenham, Texas, USA

Email: cesar.terrazas@addaero-mfg.com

Traditionally, research in the area of additive manufacturing of metals has reported the mechanical properties of specimens that have been machined to the required dimensions for testing. The current EBM technology is capable of producing parts that are in the near-net shape condition but that might require finishing operations for the intended end application. A look at recent EBM literature reveals few studies reporting on the mechanical properties of EBM parts in the as-fabricated condition [1, 2]. As EBM gains more acceptance, some applications might require knowledge of the mechanical properties in the as-fabricated condition or after the surface of the component has been treated rather than machined. The tensile specimens fabricated were oriented according to ASTM F2792-12a [3].

The first objective of this research was to identify the mechanical properties of hot-isostatic pressed (HIPed) Ti6Al4V fabricated by EBM in three conditions: as-fabricated, surface treated using the Extreme ISF® Process (a proprietary surface finishing process developed by REM Surface Engineering for AM-built titanium parts), and machined. As a second objective, this research employed a design of experiment to evaluate the effect on mechanical properties due to the relative position of specimens X/Y specimens during fabrication. In this design of experiment, the studied variables were each specimen's distance relative to the fabrication substrate (bottom, center, top), and the location of the specimen within the fabrication envelope (edge or core).

Obtained average values for UTS and YS (respectively) for horizontal specimens were: 146±2 KSI and 137±3 KSI for as-fabricated specimens; 145±1 KSI and 136±1 KSI for machined specimens; and 150±1 KSI and 142±1 KSI for Extreme ISF® Process treated specimens. For vertical specimens the average UTS and YS values (respectively) were: 137±2 KSI and 122±10 KSI for as-fabricated specimens; 143±1 KSI and 132±1 KSI for machined specimens; 145±2 KSI and 137±2 KSI for Extreme ISF® Process treated specimens. A statistical analysis shows the as-fabricated parts treated with the Extreme ISF® Process show the best performance, while the machined part and the as-fabricated parts do not a significant performance difference in most of the cases. With regards to the analysis using the design of experiment, the results obtained indicate no significant variation on the mechanical properties with respect to location of specimen (edge or core) or distance from the plate (bottom, center, top) for every group of specimens: as-fabricated, Extreme ISF® Process treated and machined. Further, X and Y specimens showed similar values which tended to be higher overall than the Z counterparts, again, in each specific group tested. Overall, the results obtained indicate a consistency of mechanical properties for parts fabricated using the EBM process.

[1] L. Ladani. *Metall. Mater. Trans.* A. **46A**, 9, 3835-3841 (2015)

[2] K. Rafi et al. *SFF Symposium 2012,* Austin, U.S. (2012)

[3] ASTM International. ASTM F2792-12a Standard Terminology for Additive Manufacturing.

Selective Laser Vacuum Melting of Refractory Metals at Elevated Temperatures

M. Wahl

Evobeam GmbH, Kurmainzstr. 64, 55126 Mainz, Germany

Email: matthias.wahl@evobeam.com

A high resolution printing metal powder bed process is possible using a laser or an electron beam as an energy source.

Selective laser melting of metals (SLM) is currently processed under an inert gas atmosphere at temperatures up to 500 ° C. The molten pool can not outgas optimally and the resulting residual stresses require extensive anker structures. The additive manufacturing process chain frequently has to be extended by hot isostatic pressing.

The **E**lectron **B**eam **M**elting (EBM) process, takes place in a vacuum at elevated temperatures up to 1100 ° C. This reduces residual stresses and requires less anker structures. On the other hand the electron beam electrostatically charges up the powder particles. To prevent the resulting movement of the powder particles each powder layer has to be presintered with a defocused beam under a partical helium atmosphere prior to selective melting in a hard vacuum. The removal of the pre-sintered powder in narrow hollow structures is challenging.

Therefore, a new machine technology is presented that combines the advantages of SLM and EBM and avoids their dis-advantages. **S**elective **La**ser **Va**cuum **M**elting (SLaVaM) is processed in a high-vacuum furnace to 1100 ° C. The vacuum enables outgassing of the molten pool. Using the laser eliminates the electrostatic charging of the powder particles. This optimizes the material density and it is easier to remove the (unsintered) powder from narrow high structures. The high work pace temperature allows to minimize residual stresses and the required anker structures.

The new machine technology could form the basis for new additive manufacturing processes for high-temperature materials such as refractory metals, titanium aluminides or nickel-based super alloys.

Optimization of the Building Parameters of Electron Beam Melting for Fabrication of Commercially Pure Titanium (CP-Ti)

X. Wang*, K. Yamanaka, K. Shinzawa and A. Chiba

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

Email: w.xiaoyu@imr.tohoku.ac.jp

Electron beam melting (EBM) is a kind of powder-bed-fusion additive manufacturing (AM) technique. Due to the freedom in design and reduced fly-to-buy ratio, EBM has been increasingly used in aerospace and biomedical industries. Titanium and its alloys are suitable for producing components with AM on account of their poor processability. In the present study, process map approach was used to optimize the building parameters, such as electron beam scanning speed and heat input energy density, of CP-Ti.

The CP-Ti specimens (10 mm square 30 mm height) were produced using an Arcam A2X EBM system (Arcam AB, Sweden) with different building parameters. Microstructures and mechanical properties were analyzed through electron backscattered diffraction (EBSD), density measurements, and tensile tests. The process window was determined in terms of surface morphologies of the prepared specimens.

The surface morphologies of the specimens varied with building parameters, as shown in Fig. 1. The line energy of the electron beam for producing dense specimens with high geometric accuracy (i.e. even surface) was found to be 300−600 J/m. The relative densities and tensile properties of the as-built specimens changed with line energy.

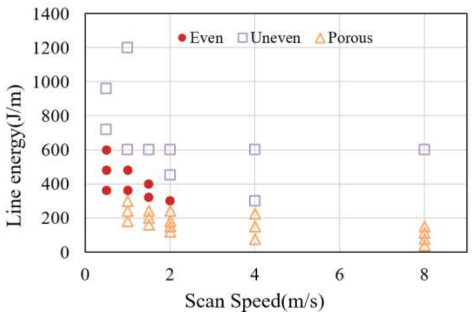


Fig. 1: Process map of CP-Ti for EBM process.

No significant variation in microstructure was observed along the build direction. Because the microstructural morphologies varied with different building parameters from columnar grains to near-equiaxed grains, EBM may provide a method to control microstructure and properties of CP-Ti.

Cellular Structures for Applications in Chemical Engineering

F. Warmuth[1,*], S. Thangaraj[2], G. Do[2],
P. Wasserscheid[2], W. Schwieger[2] and C. Körner[1]

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

(2) Chair of Chemical Reaction Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg, Egerlandstr. 3, 91058 Erlangen, Germany

Email: Franziska.warmuth@fau.de

State-of-the-art chemical engineering uses packed bed reactors consisting of pellets or spheres. Periodic cellular structured via additive manufacturing offer a variety of advantages. Due to the high flexibility in geometry well defined carrier structures can be achieved leading to designed flow properties. Besides possible integrated functionalities also the heat transfer between the reactor wall and its filling can be influenced. Both effects may lead to higher productivity of the reactor.

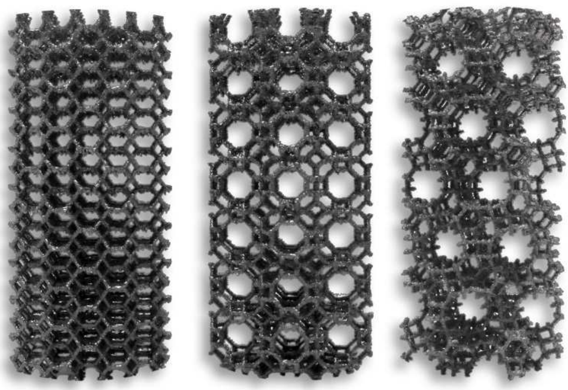


Fig. 1: Example for cellular structure composed of zeolithic unit cells [1].

Two examples of additively manufactured structures will be presented: A carrier structure based on the diamond lattice is compared to a classical packed bed reactor filling regarding heat transfer properties and productivity. Different zeolitic geometries were realized to study the influence of the unit cell on the pressure drop behavior [1].

[1] T. Selvam et al. *Chem. Eng. J.* **288**, 223-227 (2016)

Determining Critical Factors for Fatigue Properties of Ti-6Al-4V Alloy Fabricated by Electron Beam Melting

K. Yamanaka[1,*], X. Shui[1], M. Mori[2] and A. Chiba[1]

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

(2) Department of Materials and Environmental Engineering, National Institute of Technology, Sendai College, 48 Nodayama, Medeshima-Shiote, Natori 981-1239, Japan

Email: k_yamanaka@imr.tohoku.ac.jp

Electron beam melting (EBM) is a powder-bed-fusion addictive manufacturing (AM) technique and has attracted considerable attention from aerospace and biomedical industries. Although numerous studies have been reported on Ti−6Al−4V alloy prepared with EBM, its fatigue performance has not been well characterized. In this work, critical factors influencing fatigue properties of Ti−6Al−4V alloy components fabricated by EBM were determined. The post-processing, i.e., annealing and hot isostatic pressing (HIP), was conducted to study the effects of building defects and microstructure on fatigue properties.

Ti–6Al–4V alloy samples with 18 mm in diameter and 160 mm in height were prepared using an Arcam EBM A2X system. The HIP and annealing were performed at 920°C for 2hr with and without an applied pressure of 100 MPa, respectively. Microstructures, relative densities, distributions of building defects, and tensile properties of the prepared specimens were examined. Fatigue tests were carried out at room temperature with a stress ratio (*R*) of 0.1.

The fine microstructure was observed in the as-built specimens thanks to the β → α' martensitic transformation during EBM process. No significant difference was noticed in relative density (~100%) and tensile properties, while the microstructures became coarser after the post-processing. However, the fatigue properties of the as-built specimens were lower than those of the HIPed counterparts. The build defects, in particular, pores and unmelted particles significantly influenced the fatigue properties by initiating cracks during cyclic loading.

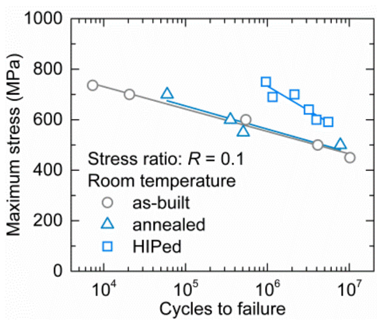


Fig. 1: Fatigue properties of EBM-built Ti–6Al–4V alloy samples.

LIST OF AUTHORS AND PARTICIPANTS

Name	Organisation	Country	p
Abdelghany, Khalid	Central Metallurgical Research and Development Institute	Egypt	
Ackelid, Ulf	Arcam AB	Sweden	34
Adler, Lucas	Friedrich-Alexander-Universität Erlangen-Nürnberg, ZMP	Germany	
Ålgårdh, Joakim	Swerea KIMAB AB	Sweden	
Alhussein, Akram	3A - Applications Additives Avancées S.A.S.	France	36
Aoyagi, Kenta	Tohoku University, IMR	Japan	
Avdovic, Pajazit	Siemens Industrial Turbomachinery AB	Sweden	
Aziziderouei, Mana	Auckland University of Technology	New Zealand	
Baudana, Giorgio	Politecnico di Torino	Italy	47
Bayer, Herbert	Steigerwald Strahltechnik GmbH	Germany	
Bayerlein, Fabian	Technical University Munich	Germany	
Beraud, Nicolas	Université Grenoble Alpes, G-SCOP	France	56
Bläsius, Jana	Robert Bosch GmbH	Germany	
Bögelein, Thomas	Friedrich-Alexander-Universität Erlangen-Nürnberg, ZMP	Germany	
Borrelli, Rosario	Italian Aerospace Research Centre	Italy	22
Botstein, Olga	Technion Israel Institute of Metals	Israel	
Brunhuber, Christian	Siemens AG, PG	Germany	
Buxton, Anita L.	TWI Ltd	United Kingdom	37
Ceriani, Nicola M.	Siemens AG, DF	Germany	

Chauvet, Edouard	Université Grenoble Alpes, SIMAP	France	29
Chiba, Akihiko	Tohoku University, IMR	Japan	41
Dehoff, Ryan	University of Tennessee	United States	
Dendievel, Rémy	Université Grenoble Alpes, SIMAP	France	53
Deng, Dunyong	Linkoping University	Sweden	
Diaz, Agustin	REM Surface Engineering	United States	38
Ding, Xiao	Tohoku University, IMR	Japan	30
Döhler, Tim	Concept Laser GmbH	Germany	
Drescher, Philipp	University of Rostock	Germany	55
Eichler, Simon	Neue Materialien Fürth GmbH	Germany	32
Eriksson, Niklas	Saab AB	Sweden	
Forster, Vera E.	Friedrich-Alexander-Universität Erlangen-Nürnberg, WTM	Germany	57
Franke, Martin	Neue Materialien Fürth GmbH	Germany	
Fujieda, Tadashi	Hitachi, Ltd.	Japan	40
Galati, Manuela	Politecnico di Torino	Italy	48
Garrard, Rebecca	University of Liverpool	United Kingdom	
Ge, Wenjun	Korea Advanced Institute of Science and Technology	South Korea	17
Gennaro, Paolo	GE Avio	Italy	45
Golkar, Farhad	Arcam AB	Sweden	
Gotterbarm, Martin	Friedrich-Alexander-Universität Erlangen-Nürnberg, ZMP	Germany	
Graffel, Benjamin	Fraunhofer FEP	Germany	
Günther, Johannes	Technische Universität Freiberg	Germany	
Guschlbauer, Ralf	Friedrich-Alexander-Universität Erlangen-Nürnberg, ZMP	Germany	
Hallberg, Patrik	Arcam AB	Sweden	
Hamann, Jörg	EOS GmbH	Germany	

Hansen, Björn	pro-beam AG & CO: KGaA	Germany	
Harrysson, Ola	North Carolina State University	United States	24
Heinrichsdorff, Frank	Siemens AG, CT	Germany	
Heinze, Christoph	Siemens AG, CT	Germany	
Henkes, Tom	Techspace Aéro (Safran)	Belgium	
Humm, Stephan	Heraeus Germany GmbH	Germany	
Janson, Stephan	iwb Anwenderzentrum Augsburg der TU München	Germany	18
Johansson, Sven	Arcam AB	Sweden	
Jüchter, Vera	Friedrich-Alexander-Universität Erlangen-Nürnberg, ZMP	Germany	46
Kahlin, Magnus	Linköping University	Sweden	
Karnatak, Nikhil	Safran	France	
Kergaßner, Andreas	Friedrich-Alexander-Universität Erlangen-Nürnberg, LTM	Germany	
Khademzadeh, Saeed	Amirkabir University of Technology	Iran	49
Kirchner, Alexander	Fraunhofer IFAM	Germany	35
Klassen, Alexander	Neue Materialien Fürth GmbH	Germany	
Kobiela, Karol Adrian	Wroclaw University of Technology	Poland	
Koizumi, Yuichiro	Tohoku University, IMR	Japan	58
Köpf, Johannes	Friedrich-Alexander-Universität Erlangen-Nürnberg, ZMP	Germany	
Körner, Carolin	Friedrich-Alexander-Universität Erlangen-Nürnberg, WTM	Germany	
Krasnorutskyi, Sergii	Technische Universität Braunschweig	Germany	
Kremer, Mathias	Arcam AB	Sweden	
Kuo, Che-Nan	Metal Industries Research & Development Centre	Taiwan	59
Legrell, PerErik	Umeå University and Västerbottens Läns Landsting	Sweden	51

Li, Shujun	Institute of Metal Research, Chinese Academy of Sciences	China	54
Lin, Feng	Tsinghua University, DME	China	
Liu, Jianrong	Institute of Metal Research, Chinese Academy of Sciences	China	23
Ljungblad, Ulric	Arcam AB	Sweden	12 60
Lodes, Matthias A.	Friedrich-Alexander-Universität Erlangen-Nürnberg, ZMP	Germany	44
Loftus, Zachary	Lockheed Martin	United States	
Looschen, Aline	Friedrich-Alexander-Universität Erlangen-Nürnberg, EAM	Germany	
Löwer, Thorsten	pro-beam AG & CO: KGaA	Germany	
Maaßen, Michael	Steigerwald-Strahltechnik GmbH	Germany	
Macquaire, Bruno	Safran	France	
Madeja, Marcin	Wroclaw University of Technology	Poland	61
Markl, Matthias	Friedrich-Alexander-Universität Erlangen-Nürnberg, WTM	Germany	28
Matlák, Jiří	Brno University of Technology	Czech Republic	
Medina, Francisco	Buffalo Manufacturing Works	United States	14
Niendorf, Thomas	University of Kassel	Germany	20
Noack, Kai	Institut für Füge- und Schweißtechnik	Germany	
Ohldin, Patrik	Arcam AB	Sweden	
Osmanlic, Fuad	Friedrich-Alexander-Universität Erlangen-Nürnberg, WTM	Germany	
Paquit, Vincent	Oak Ridge National Laboratory	United States	
Peng, Hui	Beihang University	China	43
Petelet, Matthieu	Arcam CAD to Metal Ltd	United Kingdom	
Pettersson, Maria	Arcam AB	Sweden	

Pobel, Christoph R.	Friedrich-Alexander-Universität Erlangen-Nürnberg, ZMP	Germany	62
Rai, Abha	Friedrich-Alexander-Universität Erlangen-Nürnberg, WTM	Germany	
Ramsperger, Markus	Friedrich-Alexander-Universität Erlangen-Nürnberg, ZMP	Germany	33
Rännar, Lars-Erik	Mid Sweden University	Sweden	50
Riedlbauer, Daniel	Friedrich-Alexander-Universität Erlangen-Nürnberg, LTM	Germany	19
Risse, Jeroen	Fraunhofer ILT	Germany	
Ryall, Chris	Manufacturing Technology Centre	United Kingdom	
Schillen, Volker	Materialise GmbH	Germany	
Schloffer, Martin	MTU Aero Engines AG	Germany	
Schmetterer, Clemens	Fraunhofer UMSICHT	Germany	63
Schuchardt, Torsten	Institut für Füge- und Schweißtechnik	Germany	
Schwankl, Matthias	Friedrich-Alexander-Universität Erlangen-Nürnberg, WTM	Germany	
Shrager, Max	Techion Israel Institute of Metals	Israel	
Shui, Xiaoli	Tohoku University, IMR	Japan	21
Snis, Anders	Arcam AB	Sweden	
Söderberg, Hans	Sandvik AB	Sweden	
Soldner, Dominic	Friedrich-Alexander-Universität Erlangen-Nürnberg, LTM	Germany	
Sonsky, Jiri	Institute of Thermomechanics of the CAS, v. v. i.	Czech Republic	
Strondl, Annika	Swerea KIMAB AB	Sweden	
Su, Yu-Lun	Metal Industries Research & Development Centre	Taiwan	64
Tadano, Satoshi	Toshiba Co. Ltd	Japan	65

Taschauer, Michael	Pankl Racing Systems AG	Austria	
Terrazas-Najera, Cesar Adrian	Addaero Manufacturing LLC	United States	66
Tidehag, Per	Umeå University and Västerbottens Läns Landsting	Sweden	
Todd, Iain	University of Sheffield	United Kingdom	13
Tosi, Riccardo	University of Birmingham	United Kingdom	16
Tsai, Meng-Hsiu	Metal Industries Research & Development Centre	Taiwan	27
Tyrach, Annette	Friedrich-Alexander-Universität Erlangen-Nürnberg, EAM	Germany	
Vassa, Alexandre	Tekna Group	France	26
Viebach, Ina	Friedrich-Alexander-Universität Erlangen-Nürnberg, EAM	Germany	
Wagner, Eberhard	pro-beam systems GmbH	Germany	
Wahl, Matthias	Evobeam GmbH	Germany	68
Wang, Xiaoyu	Tohoku University, IMR	Japan	69
Warmuth, Franziska	Friedrich-Alexander-Universität Erlangen-Nürnberg, ZMP	Germany	70
Wattelar, Alexandre	Techspace Aéro (Safran)	Belgium	
Willert-Porada, Monika	University of Bayreuth	Germany	
Winkelmann, Lane	REM Surface Engineering	United States	
Wong, Hay	University of Liverpool	United Kingdom	
Wright, Andrew	Reliance Precision Ltd.	United Kingdom	
Yamanaka, Kenta	Tohoku University, IMR	Japan	71
Yan, Wentao	Tsinghua University, DME	China	15
Zhou, Bin	Tsinghua University, DME	China	25

CONFERENCE COORDINATOR

Prof. Carolin Körner
Conference Coordination
Chair of Metals Science and Technology (WTM)
Friedrich-Alexander-Universität Erlangen-Nürnberg
Martensstraße 5 · 91058 Erlangen
Phone: +49 9131 85-27528
Email: carolin.koerner@fau.de

CONTACT

Dr. Matthias Markl
Program Coordination
Chair of Metals Science and Technology (WTM)
Friedrich-Alexander-Universität Erlangen-Nürnberg
Martensstraße 5 · 91058 Erlangen
Phone: +49 9131 85-28748
Email: matthias.markl@fau.de

Aline Looschen
Administration Coordination
Cluster of Excellence
Engineering of Advanced Materials (EAM)
Nägelsbachstraße 49b · 91052 Erlangen
Phone: +49 9131 85-20846
Email: aline.looschen@fau.de

ENGINEERING OF ADVANCED MATERIALS