Design for AM & Metal AM processes

Dr. Bernhard Mueller (Fraunhofer IWU, Dresden, Germany)
Dr. Burghardt Kloeden (Fraunhofer IFAM, Dresden, Germany)

Archivierungsangaben

Additive Manufacturing Workshop, September 29, 2017, McGill University, Montreal (Canada)

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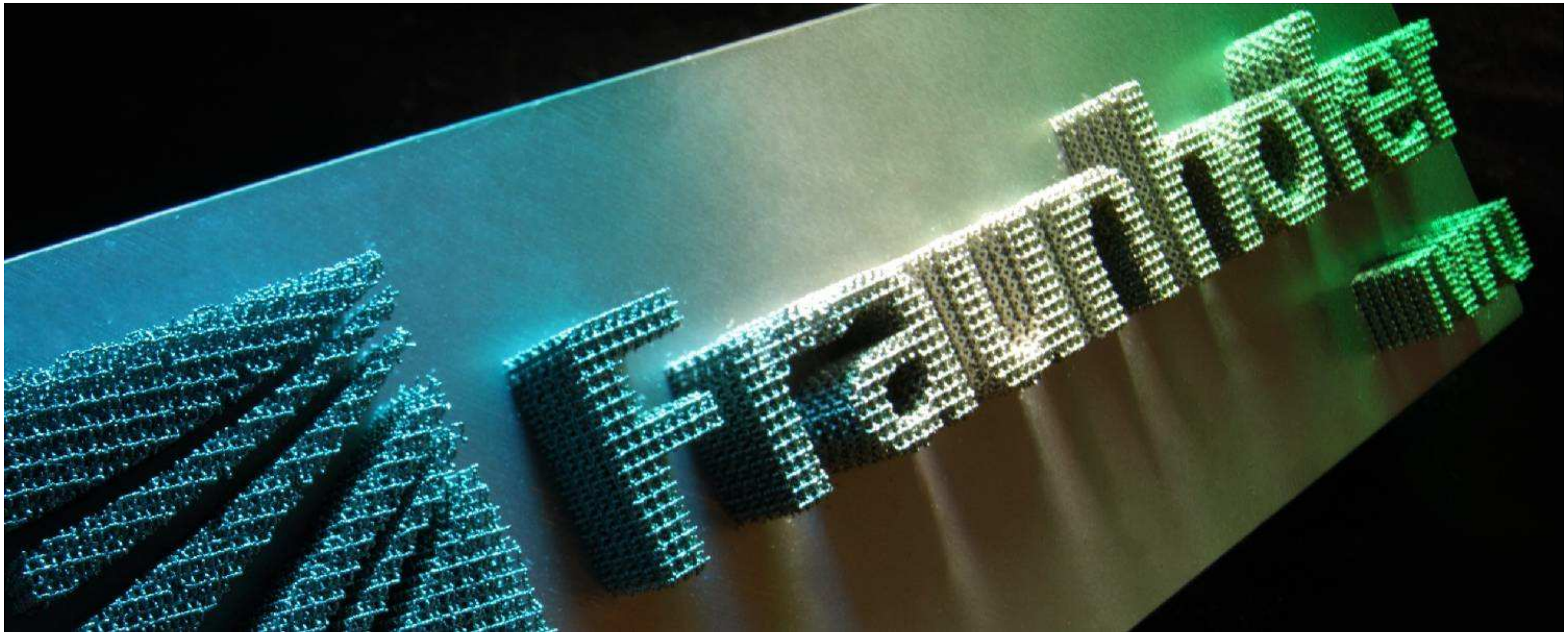
DESIGN FOR ADDITIVE MANUFACTURING

GUIDELINES AND CASE STUDIES FOR METAL APPLICATIONS

Dr. Bernhard Mueller, T. Schnabel, M. Oettel, T. Toeppel, M. Gebauer (Fraunhofer IWU)
Dr. Burghardt Kloeden, C. Aumund Kopp (Fraunhofer IFAM)
K. Hoschke, A. Pfaff (Fraunhofer EMI)



AM workshop @ McGill University, September 29, Montreal (Canada)

Fraunhofer IFAM   Fraunhofer EMI   Fraunhofer IWU

DESIGN FOR ADDITIVE MANUFACTURING

GUIDELINES AND CASE STUDIES FOR METAL APPLICATIONS

- Introduction to Fraunhofer
- Scope
- AM Processes and related Design Principles
- AM-relevant Standards and Guidelines
- Analysis of seven Case Studies
- Summary and Overall Conclusions

→ Complete Study available at:
http://canadamakes.ca/design-additive-manufacturing-guidelines-case-studies-metal/

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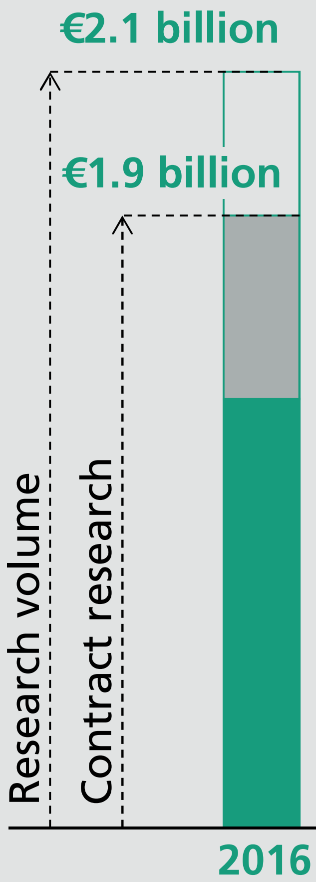
The Fraunhofer-Gesellschaft at a Glance

Applied research for immediate utility of economy and benefit of society

More than
24,500 staff



roughly **30%** are contributed by the German federal and *Länder* governments

roughly **70%** are generated through contract research on behalf of industry and publicly funded research projects

69 Institutes and research units

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Pooling expertise

Fraunhofer Alliances

The Fraunhofer Alliances facilitate customer access to the services and research results of the Fraunhofer-Gesellschaft. Common points of contact for groups of institutes active in related fields provide expert advice on complex issues and coordinate the development of appropriate solutions.

 Adaptronics

 **Additive Manufacturing**

 AdvanCer

 Ambient Assisted Living

 AutoMOBILE Production

 Battery

 Building Innovation

 Cleaning Technology

 Cloud Computing

 Digital Cinema

 E-Government

 Embedded Systems

 Energy

 Food Chain Management

 Lightweight Structures

 Nanotechnology

 Photocatalysis

 Polymer Surfaces

 Simulation

 Traffic and Transportation

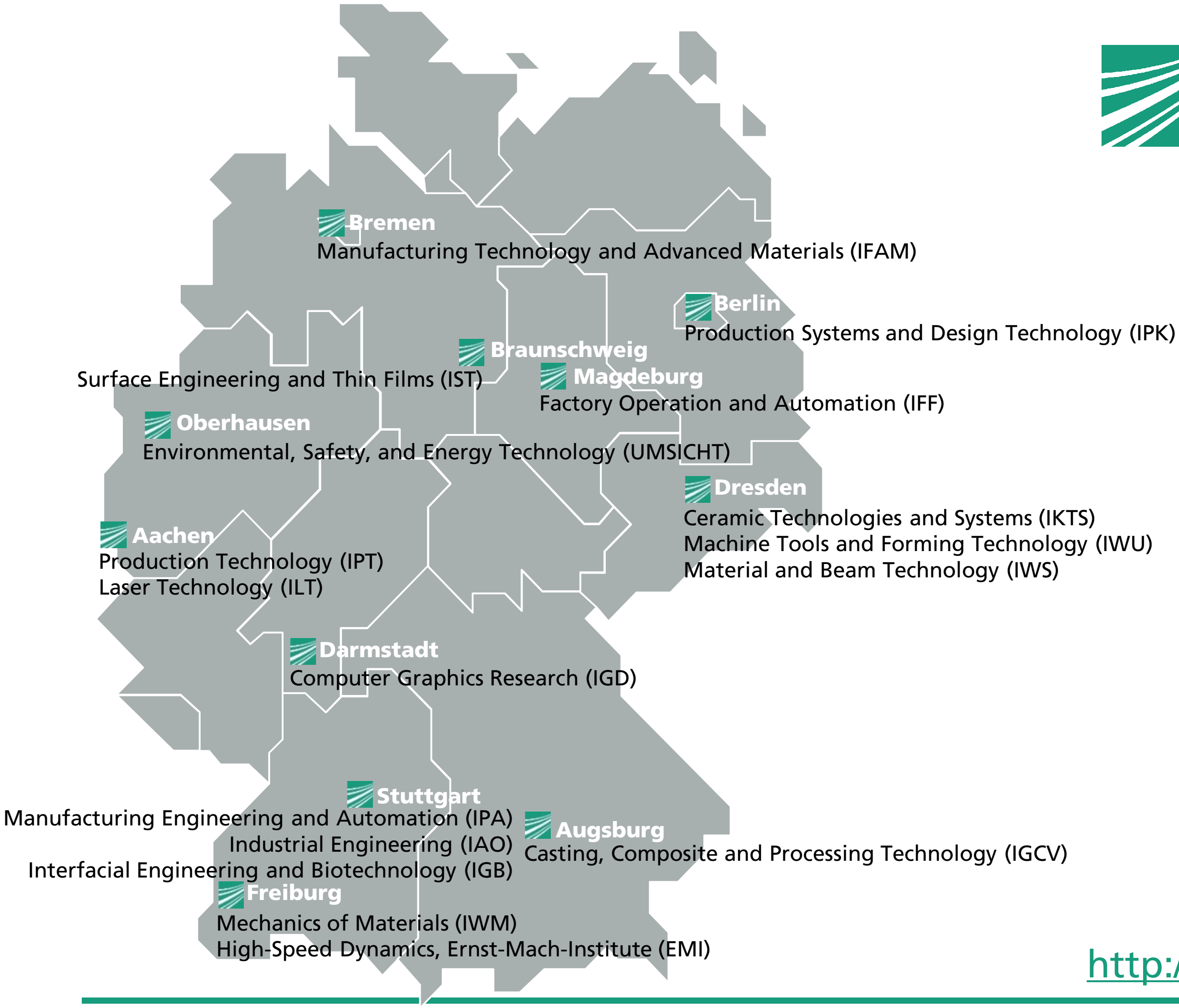
 Vision

 Water Systems (SysWasser)

Fraunhofer IWU

Additive Manufacturing at Fraunhofer

One topic – seventeen institutes – one alliance



Fraunhofer GENERATIV

Fraunhofer Additive Manufacturing Alliance
Spokesman:
Dr.-Ing. Bernhard Mueller

Office:
c/o Fraunhofer IWU
Noethnitzer Straße 44
01187 Dresden (Germany)
http://www.generativ.fraunhofer.de

Fraunhofer Additive Manufacturing Alliance
Research areas

- **Engineering**
  to invent and design new products and develop suitable process chains

- **Materials**
  to adapt new materials

- **Technologies**
  to achieve (cost-)efficient processes

- **Quality**
  to control and ensure manufacturing reproducibility and product quality

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Design for Additive Manufacturing
Scope

- **Main challenges of AM:**
  - AM technologies require a **rethinking in 3D design**
    → still a barrier particularly for SMEs!
  - **Knowledge** about advantages, opportunities and restrictions is essential in order to make AM a competitive manufacturing method
- **The report:**
  - Identification of leading edge **industrial applications and trends** associated with the design for AM
  - Translating AM-specific design rules and principles in a simplified format **accesible to industry**
  - Highlighting **general design principles** for LBM and EBM
  - Evaluation of seven individual components, reviewed and assessed in **detailed case studies**

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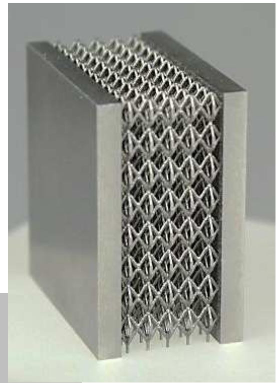
Design for Additive Manufacturing
AM-specific Design Opportunities

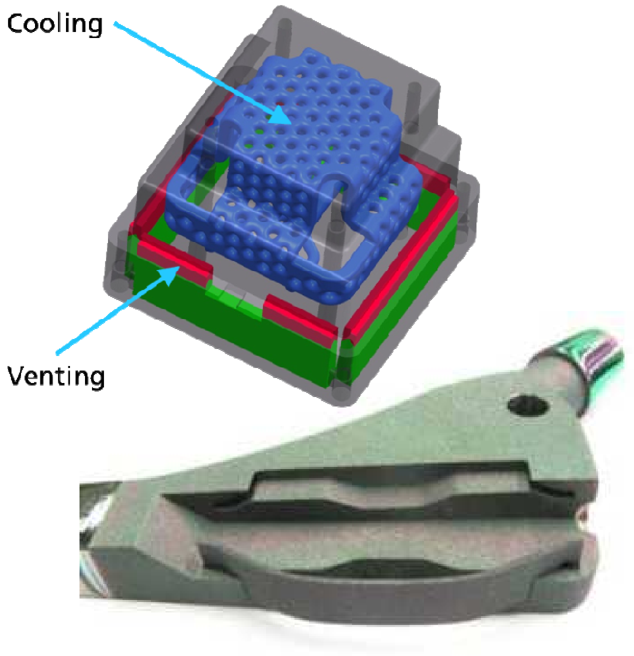
- Design and manufacturing of very **complex** component geometry
- Required information taken directly from CAD data, no need for forming tools etc. → fully **flexible** production

Topology Optimization

Lattice Structures

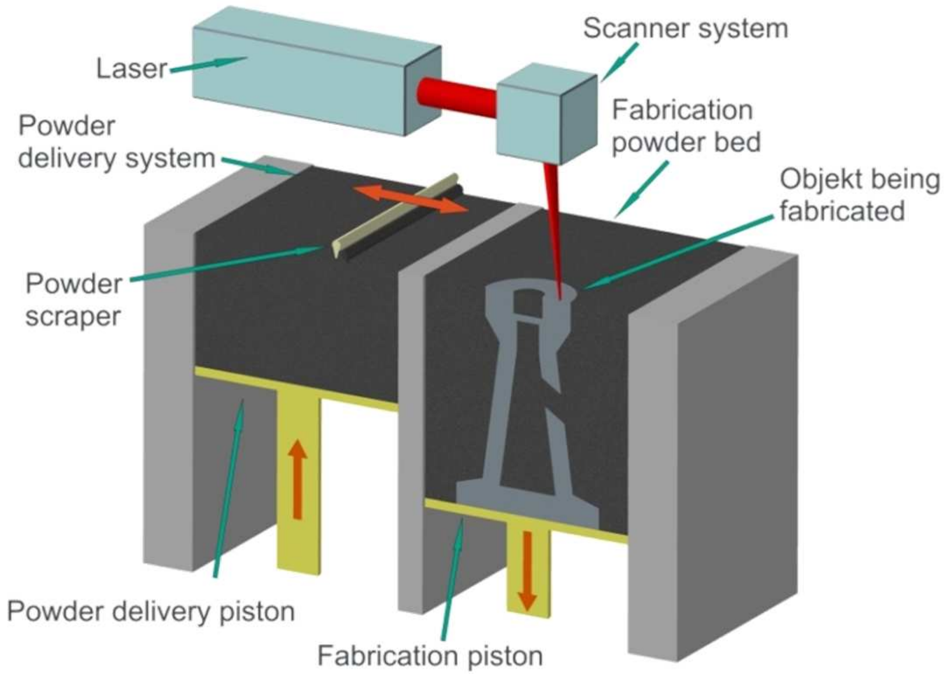


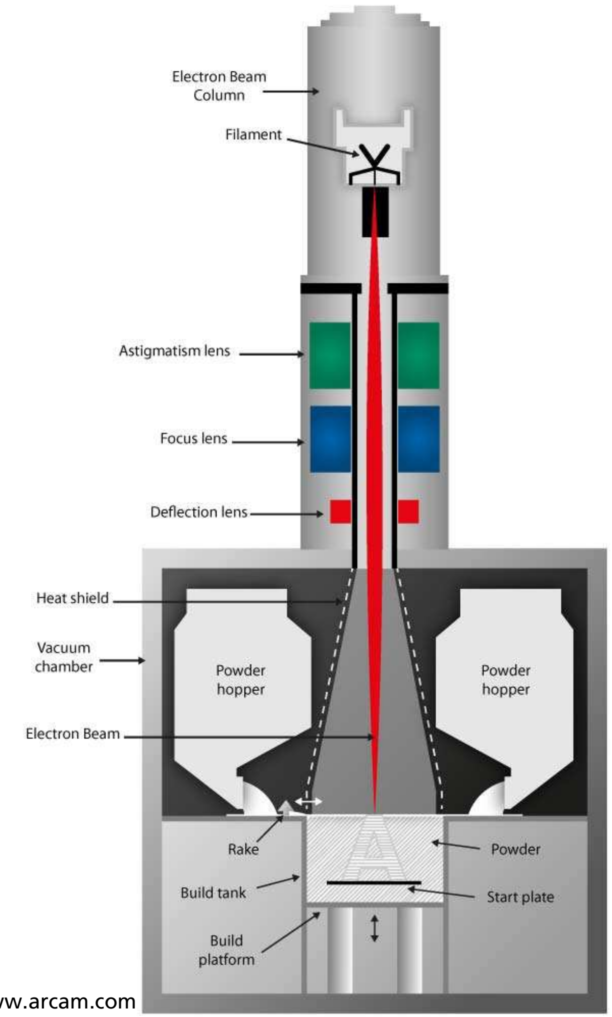
Integrated Functions



AM Processes and related Design Principles

Powder bed based AM processes LBM and EBM



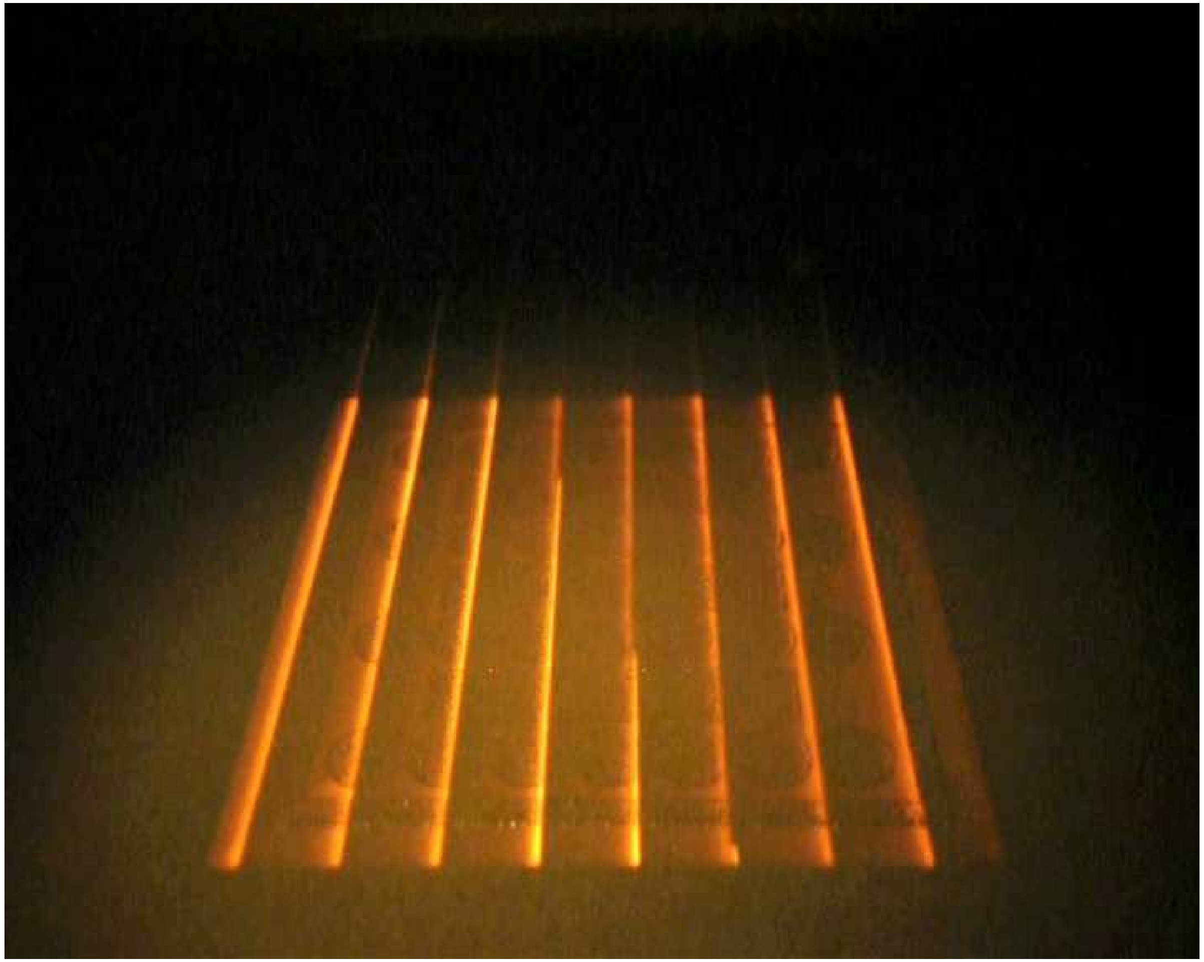


Source: www.arcam.com

AM Processes and related Design Principles
Powder bed based AM process LBM

Source: https://www.youtube.com/watch?v=JU3-O35i5Hw

AM Processes and related Design Principles
Powder bed based AM process EBM



Source: https://www.youtube.com/watch?v=jqjD-FWMexo

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AM Processes and related Design Principles

Powder bed based AM processes LBM and EBM

	Laser Beam Melting (LBM)	Electron Beam Melting (EBM)
Energy Source	Laser (up to 1 kW, up to 4 lasers)	Electron Beam (up to 3.5 kW)
Range of Materials	Tool steels, Stainless steels, Aluminium alloys, Titanium and Ti-alloys, Nickel-based alloys, Cobalt-chrome alloys	Titanium and Ti-alloys, Nickel-based alloys, Cobalt-chrome alloys
Controlled Atmosphere	Nitrogen, Argon	Vacuum
Process Temperatures	room temperature, build plate optionally heated up to 250 °C or even higher	Pre-heating of each layer up to 1,000 °C (e.g. for TiAl)
Susceptibility to Residual Stresses	High	Low
Stress-relief heat treatment required	Yes (in most cases)	No (in most cases)
Complexity of parts	High	Medium
Size of Powder Particles (typical range)	10-45 µm	45-105 µm
Part surface roughness (as-built)	R_z = 30-140 µm	Poorer than LBM
Dimensional accuracy	0.1 mm	Poorer than LBM (~ 0.5 mm)
Typical Layer Thickness	30-50 µm	50-100 µm
Process Speed	Poorer than EBM (single laser machines)	High (very high scan rates)

References: [5], [7], [8], [9]

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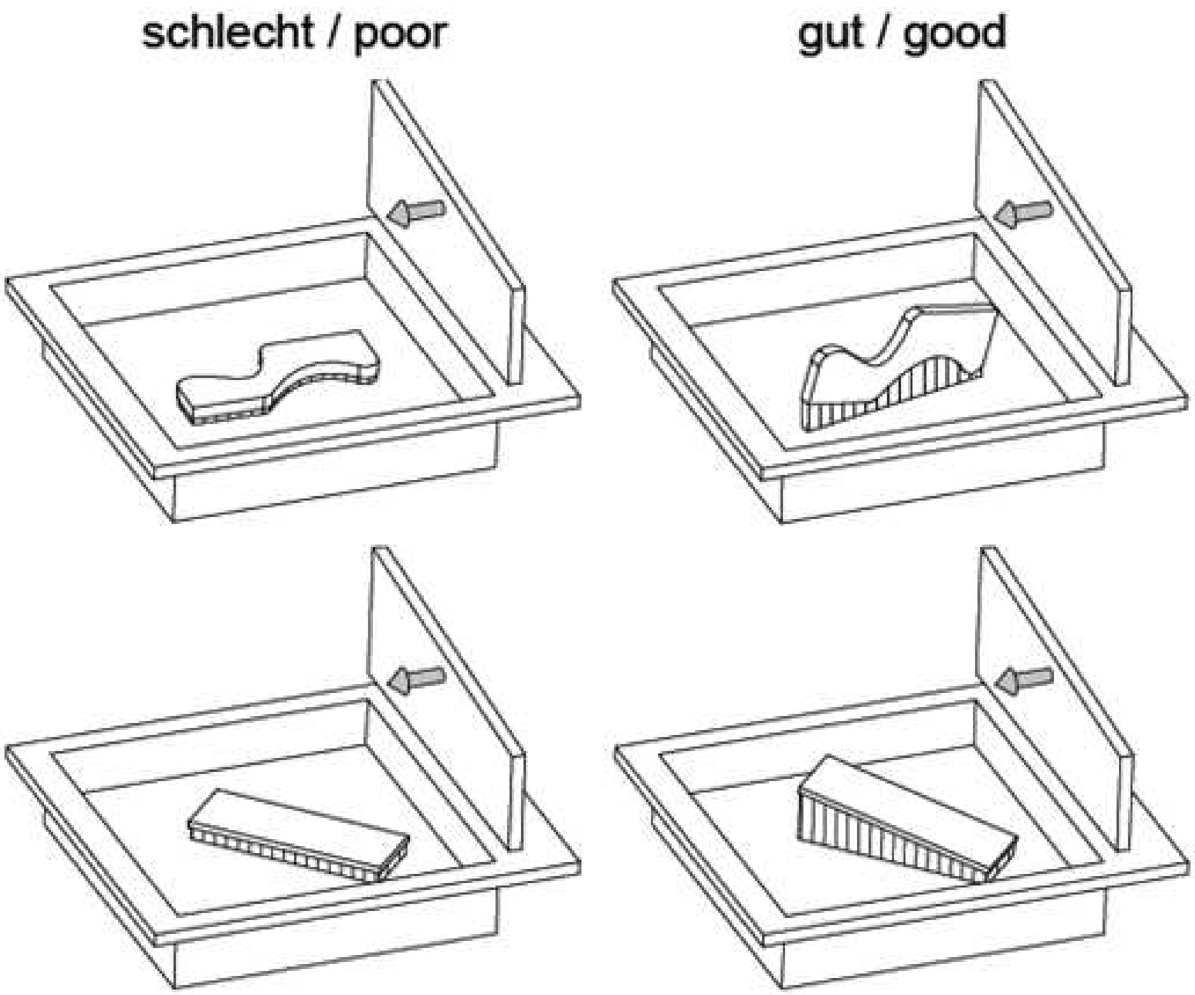
AM Processes and related Design Principles
Part orientation during build

- Orientation, position and arrangement of parts can have a significant influence on the process speed, process stability and various component properties
- Due to insufficient heat dissipation the so-called curl-effect may occur in both processes, LBM and EBM



Reference: [5]

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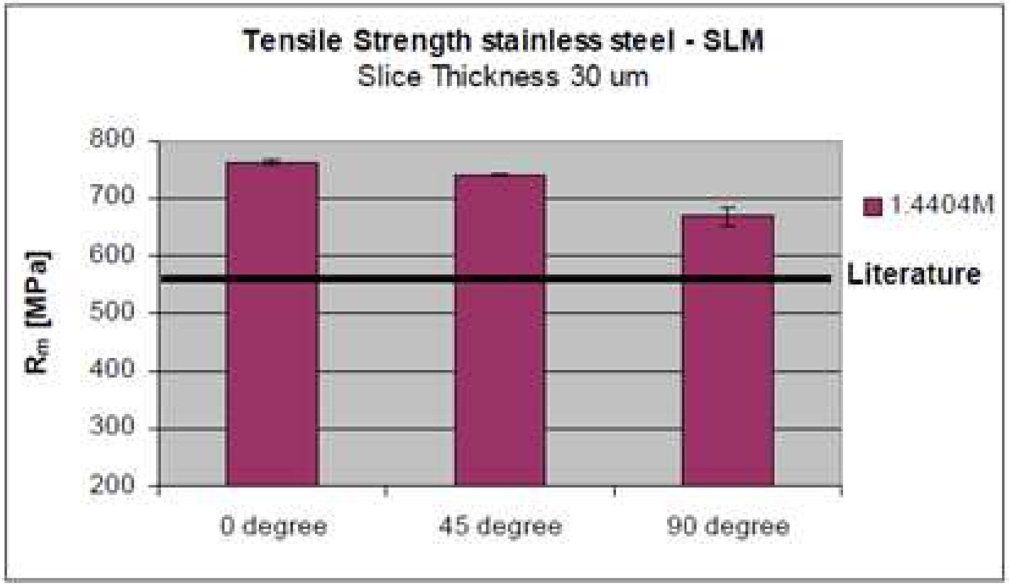
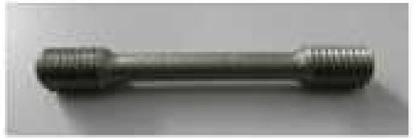
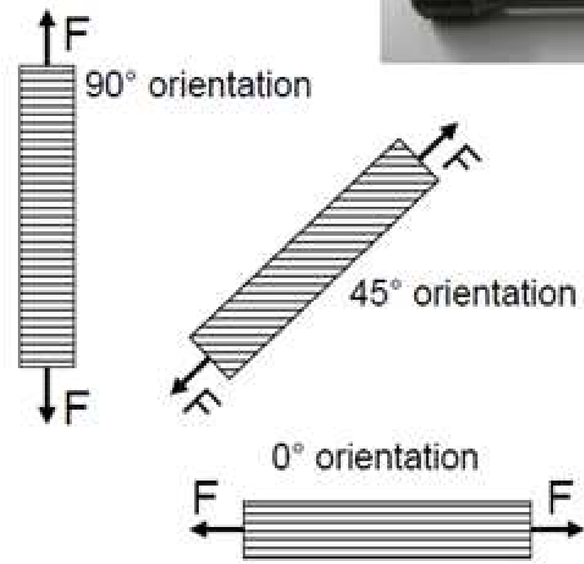
AM Processes and related Design Principles
Anisotropic material properties (as built)

- For LBM in a typical range of about 5 to 15% [10], similar for EBM (e.g. processing 316L)
- Compared to solid objects, this effect is increased for delicate geometries like lattice structures [11]





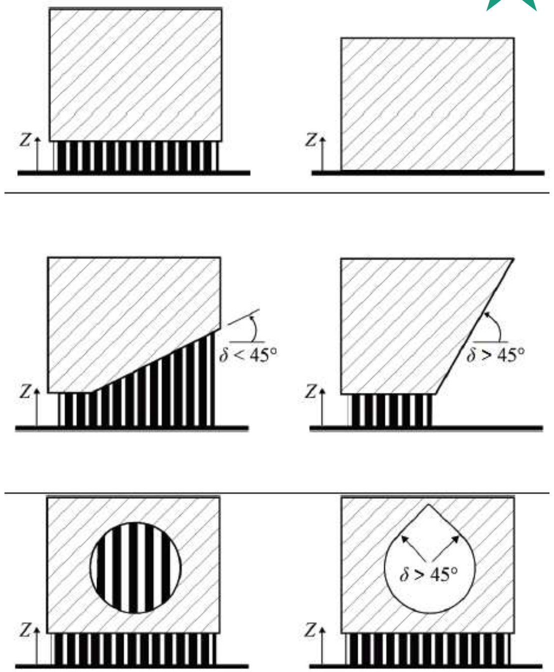


Reference: [10]

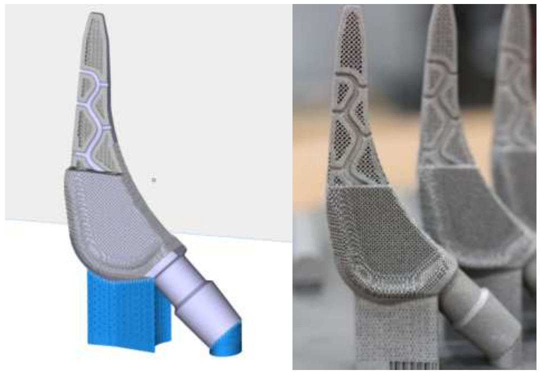
AM Processes and related Design Principles

Support structures

- Purpose of support structures:
  - Fixation of the part on the build platform
  - Support of overhanging structures
  - Heat dissipation, avoidance of residual stresses
  - Compensation of residual stress-induced warping
- Support structures need to be removed after the AM process
- Affected surfaces require adequate mechanical post-processing



Reference: [5]



AM Processes and related Design Principles
Tolerances / Machining allowance

- Accuracy of LBM: ~ +/- 0.1 mm
- Accuracy of EBM: ~ +/- 0,5 mm

KB6

  - Functional surfaces and fits need to be finished by suitable machining processes
  - appropriate machining allowance to be considered during design, at least for those locations on the component which have to fulfil high tolerance requirements

Folie 16

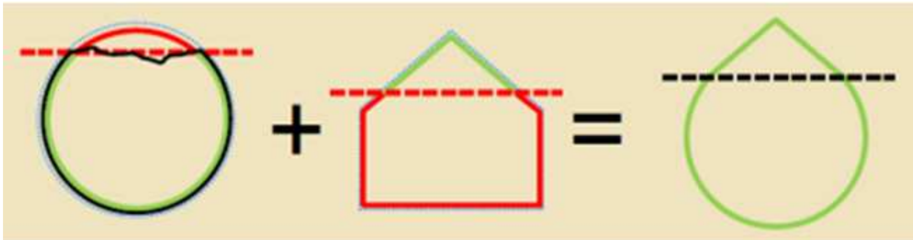
KB6 eher 0,3

Klöden, Burghardt; 19.09.2017

KB8

AM Processes and related Design Principles
Min/Max part/feature size

- **Positive volumes:**
  - **Maximum** size only limited by the AM machine (process chamber)
  - **Minimum** size basically limited by beam focus diameter and feature requirements (e.g. pressure tightness of wall structure)
    → 0.3 mm (LBM) / 0.6 mm (EBM)
- **Negative volumes** (hollow structures, e.g. channels, cavities, bores)
  - Avoid support structures for inaccessible cavities:
    - **Maximum** diameter w/o any need of support: d = 8 mm
    - Align hollow structure (e.g. channel) vertical to build platform
    - Adapt cross-section of structure (round → oval/droplet shape)
    - **Minimum** channel size:
      LBM: 0.4 (straight)
      0.6 (curved)
      EBM: 0.8 (straight)



Reference: [12]

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Folie 17

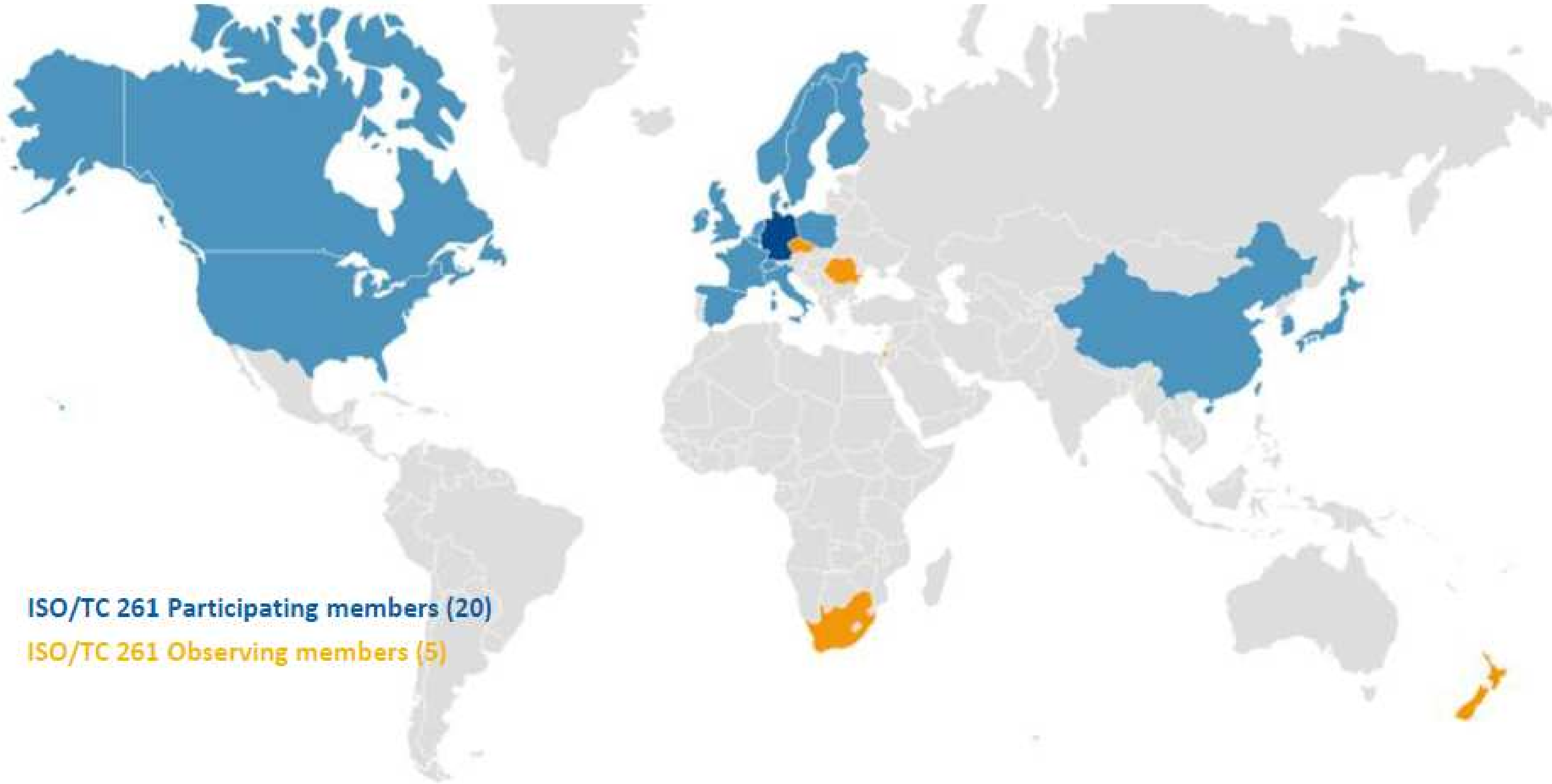
KB8 mit dieser Folie tue ich mich schwer, da im oberen Teil nur bereits Gesagtes wiederholt wird - können wir diesen weglassen und die folgenden Folien evtl. in "Excerpt LBM" und "Excerpt EBM" unterteilen?

Klöden, Burghardt; 19.09.2017

Design for Additive Manufacturing
AM-relevant Standards and Guidelines

- **Standards for conventional manufacturing methods**
  - Developed over decades
  - Based on comprehensive theoretical knowledge and broad practical experience
  - Serving either as a guidance or as hard specification in order to define a common language in related industry
- **Standards for Additive Manufacturing**
  - AM technology like LBM and EBM is from particular interest for industry only for a number of years now
    → delevopment of standards for AM is still in an early stage
  - Significant lack with regard to materials and processes

AM-relevant Standards and Guidelines
Countries active in AM standardization



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AM-relevant Standards and Guidelines

Overview of AM-specific standards

	Standard / Guideline	Title
1	ISO 17296-2:2015	Additive manufacturing -- General principles -- Part 2: Overview of process categories and feedstock
2	ISO 17296-3:2014	Additive manufacturing -- General principles -- Part 3: Main characteristics and corresponding test methods
3	ISO 17296-4:2014	Additive manufacturing -- General principles -- Part 4: Overview of data processing
4	ISO / ASTM 52900:2015	Additive manufacturing -- General principles -- Terminology
5	ISO / ASTM 52901-16	Standard Guide for Additive Manufacturing – General Principles – Requirements for Purchased AM Parts
6	ISO / ASTM 52910-17 (supersedes ISO DIS 20195)	Standard Guidelines for Design for Additive Manufacturing
7	ISO / ASTM 52921:2013	Standard terminology for additive manufacturing -- Coordinate systems and test methodologies
8	ISO / ASTM 52915:2016	Standard Specification for Additive Manufacturing File Format (AMF) Version 1.2
9	ASTM F2924-14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
10	ASTM F2971-13	Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
11	ASTM F3001-14	Standard Specification for Additive Manufacturing Titanium-6 Aluminium-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
12	ASTM F3049-14	Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes
13	ASTM F3055-14a	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion
14	ASTM F3056-14e1	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion
15	ASTM F3122-14	Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes
16	ASTM F3184-16	Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion
17	VDI 3405 (supersedes 3404)	Additive manufacturing processes, rapid prototyping - Basics, definitions, processes
18	VDI 3405 Part 2	Additive manufacturing processes, rapid prototyping - Laser beam melting of metallic parts - Qualification, quality assurance and post processing
19	VDI 3405 Part 2.2 (DRAFT)	Additive manufacturing processes, Laser beam melting of metallic parts, Material data sheet nickel alloy material number 2.4668
20	VDI 3405 Part 2.1:2015-07 and related correction dated 2017-01	Additive manufacturing processes, rapid prototyping - Laser beam melting of metallic parts - Material data sheet aluminium alloy AlSi10Mg
21	VDI 3405 Part 3	Additive manufacturing processes, rapid manufacturing – Design rules for part production using laser sintering and laser beam melting
22	VDI 3405 Part 3.5 (DRAFT)	Additive Manufacturing processes, rapid manufacturing – Design rules for part production using electron beam melting

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Design for Additive Manufacturing
Analysis of seven Case Studies

Component		Target Industry
1.	Bionic Wheel Carrier of Electric Vehicle	Automotive / Motorsports
2.	Main Gearbox Bracket	Aerospace
3.	Calibration Tool for Extrusion Process	Energy
4.	Heat Exchanger	Energy
5.	Miniature Heat Exchanger / Cooler	not limited to specific industry
6.	Functionally integrated Implant	Medical
7.	Functionally integrated Tooling Segment	Tooling

Comp. No.	AM technology	Replaced Manuf. Technology	Material	Equipment used
1	LBM	Machining	AlSi10Mg	EOS M 400
2	EBM	Milling	Ti6Al4V	Arcam A2X
3	LBM	Milling and/or investment casting	Stainless Steel 1.4542 = 17-4PH	EOS M 270 Dual Mode
4	LBM	Milling and/or investment casting	Nickel based alloy (~Inconel 718)	EOS M 270 Dual Mode
5	LBM	Stamping, Soldering	AlSi10Mg	Concept Laser M2 Cusing
6	LBM	Casting, Die Forging, Cutting	Ti-6Al-4V	Concept Laser M2 Cusing
7	LBM	Milling, Drilling	1.2709 (AMS6514)	Concept Laser M2 Cusing

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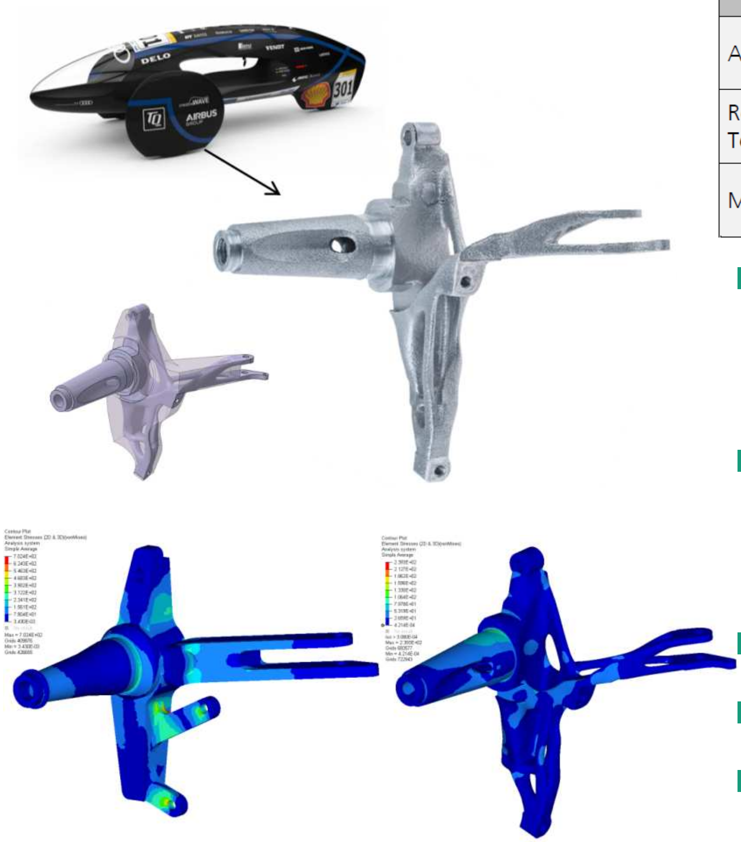
Analysis of seven Case Studies
#1: Bionic Wheel Carrier of Electric Vehicle



Fraunhofer EMI

Case Study Input from:	Fraunhofer EMI	Equipment used:	EOS M 400
AM Technology:	Laser Beam Melting	Equipment Configuration:	OEM Delivery Condition
Replaced Manufacturing Technology:	Machining	Parameter used:	OEM Standard + Customized
Material:	AlSi10Mg	Inert Gas used:	Argon

- Design Objectives:
  - Weight reduction
  - Reduction of parts
- Related Design Features and Benefits
  - Organic shape / topology optimization
  - Achieved weight reduction: ~13%
- Post-processing of functional surfaces: Milling, Drilling
- Requirements for non-functional surfaces: fatigue relevant
- Post-processing of non-functional surfaces: Blasting (peanut shells)
- Post-process heat treatment: N/A

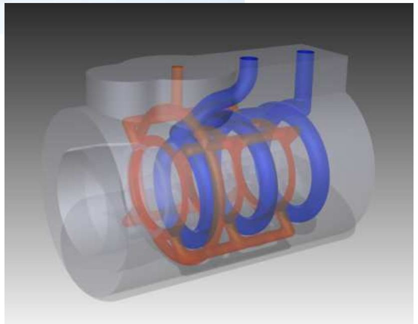
Analysis of seven Case Studies
#2: Main Gearbox Bracket

Case Study Input from:	Fraunhofer IFAM DD	Equipment used:	Arcam A2X
AM Technology:	Electron Beam Melting	Equipment Configuration:	OEM Delivery Condition
Replaced Manufacturing Technology:	Milling	Parameter used:	OEM Standard
Material:	Ti-6Al-4V	Inert Gas used:	- (in vacuo)

- Design Objectives:
  - Weight reduction
  - Reduction of parts
- Related Design Features and Benefits
  - Organic shape / topology optimization
  - Achieved weight reduction: ~60%
- Post-processing of functional surfaces: Milling, Drilling
- Requirements for non-functional surfaces: fatigue relevant
- Post-processing of non-functional surfaces: Electro-chemical polishing
- Post-process heat treatment: HIP

Fraunhofer IFAM

Analysis of seven Case Studies
#3: Calibration Tool for Extrusion Process



Fraunhofer IFAM

Case Study Input from:	Fraunhofer IFAM HB	Equipment used:	EOS M 270 Dual Mode
AM Technology:	Laser Beam Melting	Equipment Configuration:	OEM Delivery Condition
Replaced Manufacturing Technology:	Milling, Investment Casting	Parameter used:	OEM Standard
Material:	Stainless Steel 1.4542 = 17-4PH	Inert Gas used:	Nitrogen

- Design Objectives:
  - Integration of functions
  - Size reduction
  - Reduction of parts
- Related Design Features and Benefits
  - Internal channels / cavities
  - Achieved weight reduction: ~50%
- Post-processing of functional surfaces: Milling, Thread cutting
- Requirements for non-functional surfaces: N/A
- Post-processing of non-functional surfaces: Blasting (glass beads)
- Post-process heat treatment: N/A

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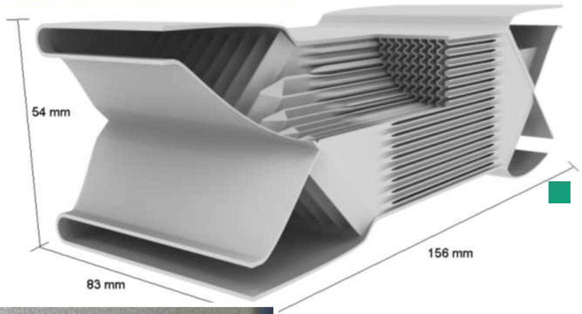
Analysis of seven Case Studies
#4: Heat Exchanger



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IFAM

Case Study Input from:	Fraunhofer IFAM HB	Equipment used:	EOS M 270 Dual Mode
AM Technology:	Laser Beam Melting	Equipment Configuration:	OEM Delivery Condition
Replaced Manufacturing Technology:	Milling, Investment Casting	Parameter used:	Customized
Material:	Nickel based alloy (similar to Inconel 718)	Inert Gas used:	Nitrogen

- Design Objectives:
  - Weight reduction
  - Size reduction
  - Reduction of parts
- Related Design Features and Benefits
  - Internal channels / cavities
  - Achieved weight reduction: ~30%
- Post-processing of functional surfaces: N/A
- Requirements for non-functional surfaces: N/A
- Post-processing of non-functional surfaces: Blasting (glass beads)
- Post-process heat treatment: Stress-relief annealing

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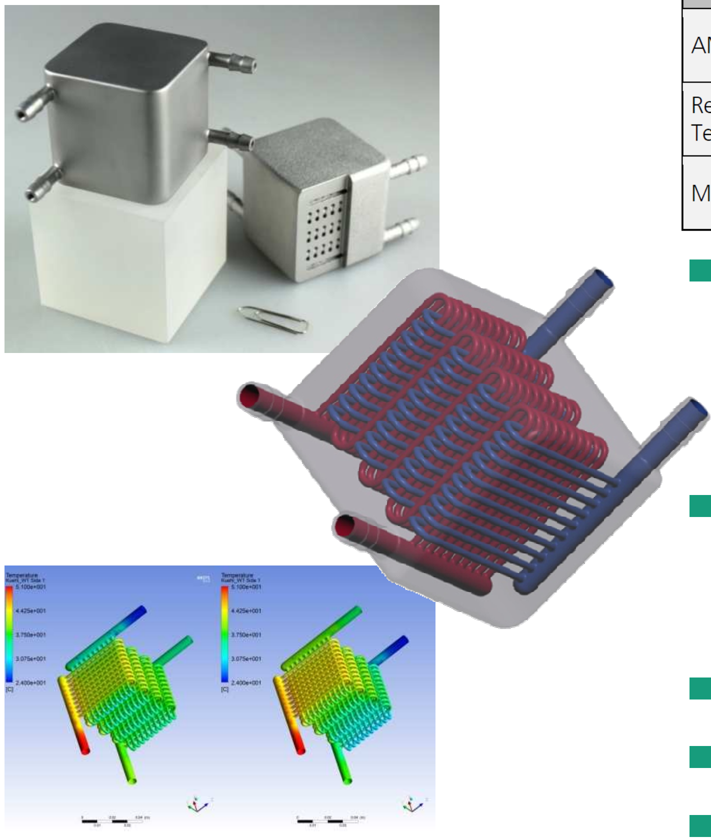
Analysis of seven Case Studies

#5: Miniature Heat Exchanger / Cooler



Case Study Input from:	Fraunhofer IWU	Equipment used:	Concept Laser M2 Cusing
AM Technology:	Laser Beam Melting	Equipment Configuration:	OEM Delivery Condition
Replaced Manufacturing Technology:	Stamping, Soldering	Parameter used:	Customized
Material:	AlSi10Mg	Inert Gas used:	Nitrogen

- Design Objectives:
  - Weight reduction
  - Size reduction
  - Reduction of parts
- Related Design Features and Benefits
  - Internal channels / cavities
  - Achieved weight reduction: >50%
- Post-processing of functional surfaces: Grinding, Polishing
- Requirements for non-functional surfaces: Optical, Aesthetical
- Post-processing of non-functional surfaces: Grinding, Blasting
- Post-process heat treatment: N/A

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Analysis of seven Case Studies

#6: Functionally Integrated Implant – MUGETO®

Case Study Input from:	Fraunhofer IWU	Equipment used:	Concept Laser M2 Cusing
AM Technology:	Laser Beam Melting	Equipment Configuration:	OEM Delivery Cond.
Replaced Manufacturing Technology:	Casting, Die Forging, Cutting	Parameter used:	OEM Standard
Material:	Ti-6Al-4V	Inert Gas used:	Argon

- Design Objectives:
  - Integration of functions
- Related Design Features and Benefits
  - Lattice Structures
  - Internal channels / cavities
- Post-processing of functional surfaces: Turning, Milling, Grinding, Polishing
- Requirements for non-functional surfaces: N/A
- Post-processing of non-functional surfaces: Blasting (corundum)
- Post-process heat treatment: Stress-relief annealing

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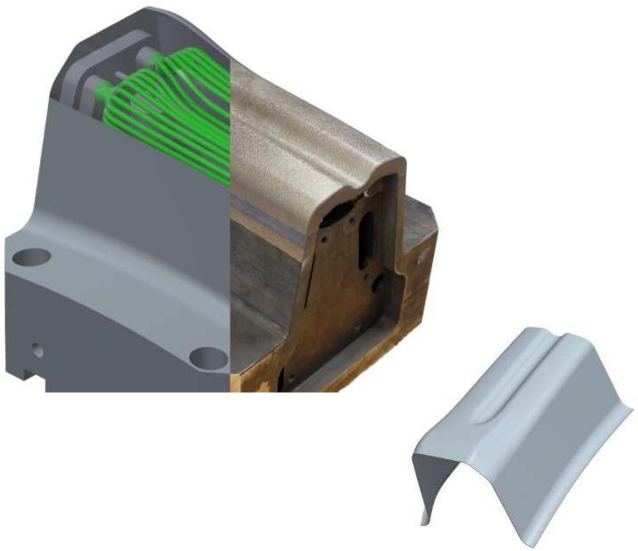
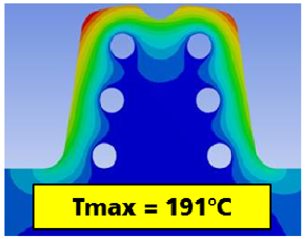
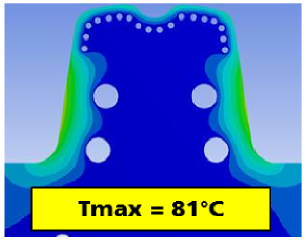
Analysis of seven Case Studies

#7: Functionally Integrated Tooling Segments







Case Study Input from:	Fraunhofer IWU	Equipment used:	Concept Laser M2 Cusing
AM Technology:	Laser Beam Melting	Equipment Configuration:	OEM Delivery Cond.
Replaced Manufacturing Technology:	Milling, Drilling	Parameter used:	OEM Standard
Material:	1.2709 (X3NiCoMoTi18-9-5)	Inert Gas used:	Nitrogen

- Design Objectives:
  - Integration of functions
- Related Design Features and Benefits
  - Internal channels / cavities
- Post-processing of functional surfaces: Machining
- Requirements for non-functional surfaces: N/A
- Post-processing of non-functional surfaces: Blasting (corundum)
- Post-process heat treatment: Stress-relief annealing + hardening

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Analysis of seven Case Studies

Summary

	Bionic Wheel Carrier	Main Gearbox Bracket	Calibration Tool	Heat Exchanger	Miniature Heat Exchanger	Functionally Integrated Implant	Functionally Integrated Tooling Segment
Design Objectives							
Integration of functions	-	-	x	-	-	x	x
Weight reduction	x	x	-	x	x	-	-
Size reduction	-	-	x	x	x	-	-
Reduction of parts	x	x	x	x	x	-	-
Related Design Features and Benefits							
Organic shape / topology optimization	x	x	-	-	-	-	-
Lattice structures	-	-	-	-	-	x	-
Internal channels / cavities	-	-	x	x	x	x	x
Achieved weight reduction	~13%	~60%	~50%	~30%	>50%	-	-
Component- and AM-specific Requirements							
Minimum allowable size of geometrical features / driven by …	2 mm / process and mat.	3 mm / strength requirem.	3 mm / powder removal	0.5 mm / process and mat.	1.5 mm / performance	0.3 mm / process and mat.	2 mm / process and mat.
Maximum allowable size of geometrical features / driven by …	-	-	8 mm / no need for support	3 mm / applic.	8 mm / no need for support	-	8 mm / no need for support
Post-processing of functional surfaces	Milling, Drilling	Milling, Drilling	Milling, Thread cutting	-	Grinding, Polishing	Turning, Milling, Grinding, Polishing	Machining
Requirements (finish) for non-functional surfaces	fatigue relevant	fatigue relevant	-	-	optical / aesthetic	-	-
Post-Processing of non-functional surf.	Blasting (peanut shells)	Electro-chemical polishing	Blasting (glass beads)	Blasting (glass beads)	Grinding, Blasting (corundum)	Blasting (corundum)	Blasting (corundum)
Need for drawings	-	Post-Process	AM and Post-Process	AM and Post-Process	-	Post-Process	-
Post-process heat treatment	-	HIP	-	stress-relief annealing	-	stress-relief annealing	stress-relief annealing + hardening

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Fraunhofer Direct Digital Manufacturing Conference DDMC 2018

Berlin, March 14 - 15, 2018

DDMC2018
Fraunhofer Direct Digital Manufacturing Conference

Range of topics:

- Product Development
- Technologies
- Materials
- Quality

Save the date!

Next conference: **MARCH 14-15, 2018**

Program available soon, early bird discount!

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IWU

Dr.-Ing. Bernhard Mueller

Head of Department »Additive Manufacturing«

Fraunhofer Institute for Machine Tools and Forming Technology IWU

Noethnitzer Strasse 44 I 01187 Dresden (Germany)
Telefon: + 49 (0) 3 51 / 47 72-21 36
Fax: + 49 (0) 3 51 / 47 72-23 03
E-Mail: bernhard.mueller@iwu.fraunhofer.de

Fraunhofer
IFAM

Dr. rer. nat. Burghardt Kloeden

Group Manager „Additive Manufacturing – EBM“

Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM

Winterbergstr. 28 I 01277 Dresden (Germany)
Telefon: + 49 (0) 3 51 / 25 37 384
Fax: + 49 (0) 3 51 / 25 37 399
E-Mail: burghardt.kloeden@ifam-dd.fraunhofer.de

Laser-Beam AM Process:
Powder, Process, Application in Industry – Advantages and Challenges

Dr.-Ing. Bernhard Mueller
Fraunhofer Institute for Machine Tools and Forming Technology IWU
Head of Department Additive Manufacturing

Additive Manufacturing Workshop, September 29, 2017, McGill University, Montreal (Canada)

CONTENT

- Introduction/Background: Fraunhofer IWU
- Introduction to Metal Additive Manufacturing
  - Classification and Overview
- Laser Beam Melting
  - Advantages
  - Materials & mechanical properties
  - Comparison to Electron Beam Melting
  - Industrial application potentials
- Status quo of industrial application of Laser Beam Melting in Aerospace
- Further challenges and perspectives in research and industry

Fraunhofer IWU

Profile of the Fraunhofer IWU
Research under the heading “Resource-Efficient Production“

- Founded July 1st, 1991
- Currently approx. 620 employees
- Approx. € 40 million annual budget
- Locations: Chemnitz (headquarters)
  Dresden, Zittau, Wolfsburg, Leipzig
- 3 scientific fields:

Mechatronics and Lightweight Structures	Forming Technology and Joining	Machine Tools, Production Systems and Machining

Archivierungsangaben

Fraunhofer IWU

Profile of the Fraunhofer IWU
Research locations

- 69 institutes in Germany
- IWU Locations

Archivierungsangaben

Fraunhofer IWU

OVERVIEW OF METAL ADDITIVE MANUFACTURING TECHNOLOGIES

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Introduction to Metal Additive Manufacturing
Overview

Additive Manufacturing - Metal

- Powder bed technologies:
  - Laser Beam Melting
    - Selective Laser Melting (SLM)
    - LaserCusing
    - Direct Metal Laser Sintering (DMLS)
    - Laser Metal Forming
    - …
  - Electron Beam Melting (EBM)
- Powder deposition technologies:
  - Laser Engineered Net Shaping (LENS)
  - Direct Metal Depositioning DMD
  - Laser Cladding
- Wire-fed deposition technologies

Fraunhofer IWU

AM Processes and related Design Principles
Powder bed based AM processes LBM and EBM

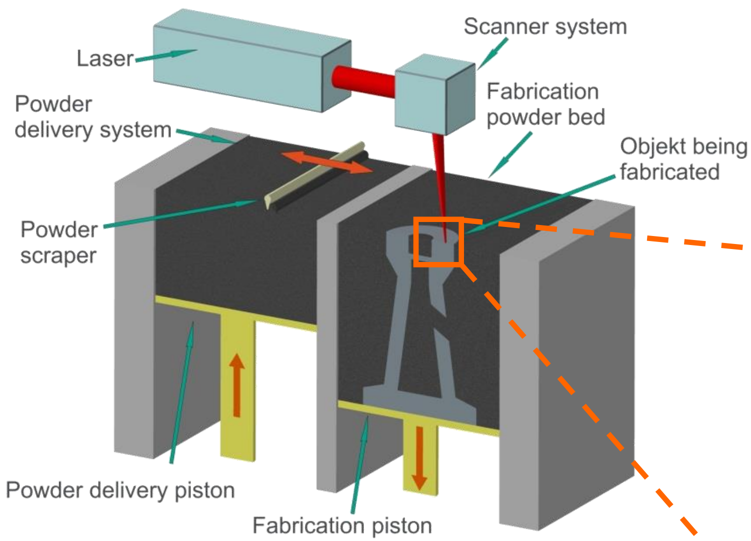
	Laser Beam Melting (LBM)	Electron Beam Melting (EBM)
Energy Source	Laser (up to 1 kW, up to 4 lasers)	Electron Beam (up to 3.5 kW)
Range of Materials	Tool steels, Stainless steels, Aluminium alloys, Titanium and Ti-alloys, Nickel-based alloys, Cobalt-chrome alloys	Titanium and Ti-alloys, Nickel-based alloys, Cobalt-chrome alloys
Controlled Atmosphere	Nitrogen, Argon	Vacuum
Process Temperatures	room temperature, build plate optionally heated up to 250 °C or even higher	Pre-heating of each layer up to 1,000 °C (e.g. for TiAl)
Susceptibility to Residual Stresses	High	Low
Stress-relief heat treatment required	Yes (in most cases)	No (in most cases)
Complexity of parts	High	Medium
Size of Powder Particles (typical range)	10-45 µm	45-105 µm
Part surface roughness (as-built)	R_z = 30-140 µm	Poorer than LBM
Dimensional accuracy	0.1 mm	Poorer than LBM (~ 0.5 mm)
Typical Layer Thickness	30-50 µm	50-100 µm
Process Speed	Poorer than EBM (single laser machines)	High (very high scan rates)

References: [5], [7], [8], [9], cp. http://canadamakes.ca/design-additive-manufacturing-guidelines-case-studies-metal/

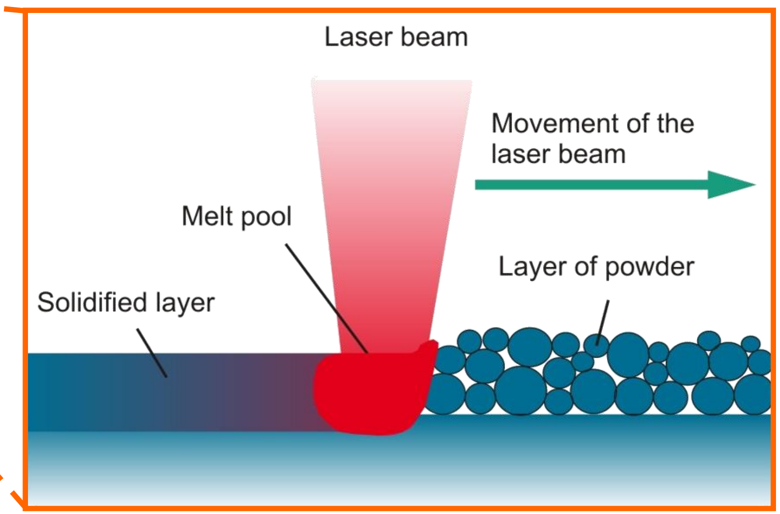
Introduction to Metal Additive Manufacturing

Laser Beam Melting (LBM)

- **direct, single step process,** creating parts out of **series-like metallic material**
- **complete local melting** of the metal powder to a 99.5 - **100 % dense microstructure**

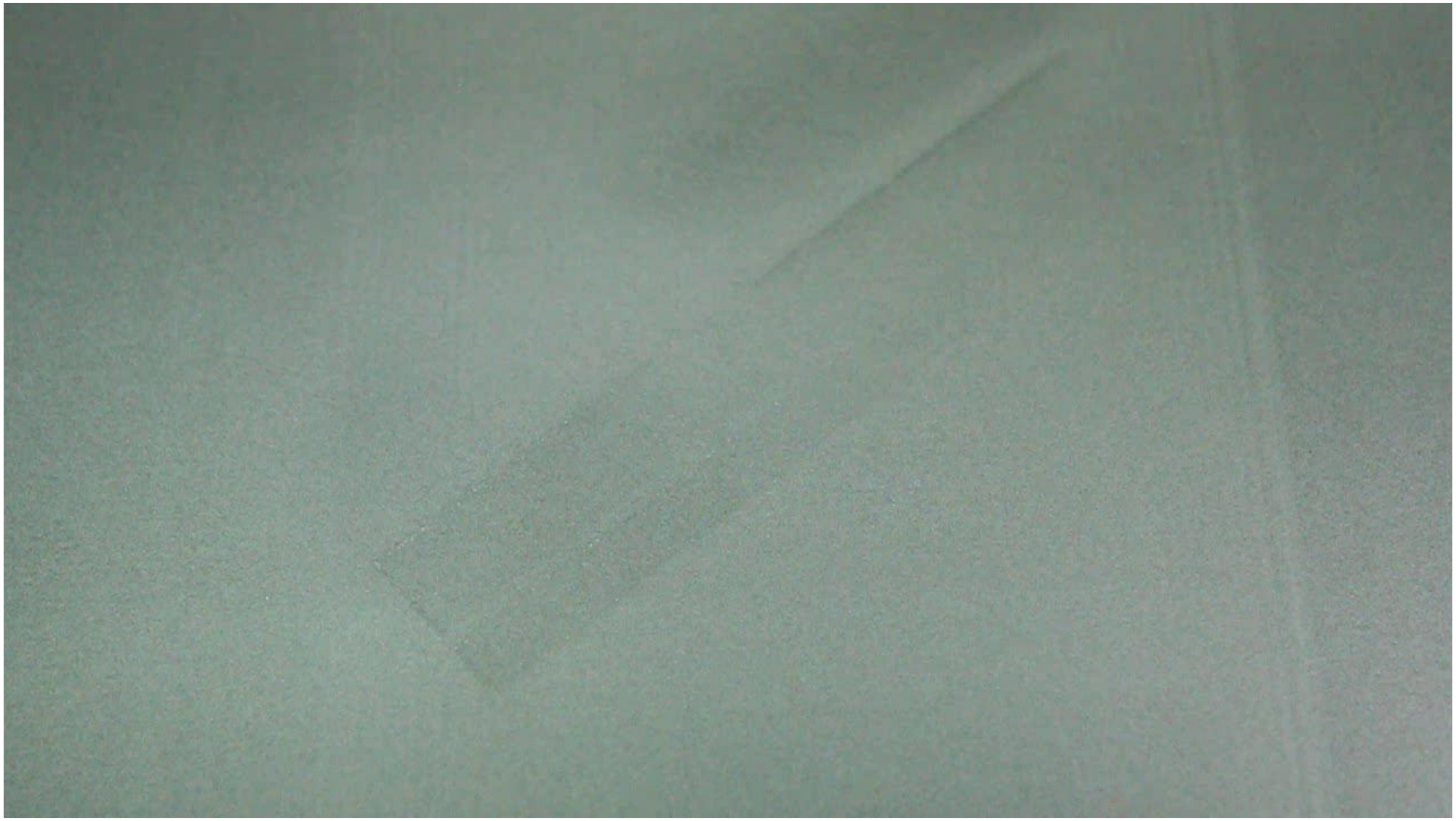


Principle sketch of a laser melting machine



Schematic diagram of laser beam melting

Introduction to Metal Additive Manufacturing
Laser Beam Melting (LBM)



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Laser Beam Melting
Advantages

time to product

- no tools needed
- no job preparation / technology planning
- no NC programming
- single step process

freedom of shape

- arbitrarily complex geometries
- undercuts
- internal geometric shapes
- delicate structures
- geometries not fabricable by cutting, forming or casting

material diversity

- aluminium
- titanium
- cobalt-chrome
- hot and cold work steel
- nickel-base alloy (Inconel)

lightweight construction / bionics

- hollow and lattice-like structures
- 100 % topology optimized parts
- bionic structures
- structures with graded porosity

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Laser Beam Melting

Materials & Mechanical Properties

Material	Condition	Tensile strength R_m [MPa]	Yield strength $R_{p0,2}$ [MPa]	Elongation A [%]	Hardness	Modulus of elasticity [GPa]
Tool steel [1] 1.2709 X3NiCoMoTi 18 9 5	heat treated (490 °C)	2,040 - 2,180	1,870 - 1,940	3 - 5	54 - 56 [HRC]	
Tool steel (stainless) Corrax®	heat treated (525 °C)	1,700	1,600	> 2	48 - 50 [HRC]	
stainless steel 1.4404 X2CrNiMo 17-12-2	as build	640	500	> 15	20 [HRC]	
Titanium [4] 3.7165 TiAl6V4	heat treated	950 - 1,250	800 - 1,100	10 - 20	32 - 36 [HRC]	
Aluminium [2] 3.2381 AlSi10Mg	as build annealed T6 heat treated	353 - 482 221 - 260 281 - 320	210 - 295 126 - 160 222 - 262	2 - 7 10 - 18 5 - 10	95 - 119 [HB] 63 - 74 [HB] 85 - 101 [HB]	67 - 78 57 - 73 69 - 80
Inconel 718 [3] 2.4668 NiCr19NbMo	as build annealed T6 heat treated	929 - 1,308 896 - 1,080 1,334 - 1,545	583 - 945 549 - 922 924 - 1,278	20.2 - 32.7 31.9 - 42.2 6.6 - 19.4	280 - 395 [HV 10] 273 - 320 [HV 10] 453 - 485 [HV 10]	128 - 232 142 - 257 149 - 242

more available Materials : CoCr, 17-4 PH, AlSi12, Hastelloy X

Characteristic values acc. to:
[1] VDI 3405 Blatt 2
[2] VDI 3405 Blatt 2.1
[3] VDI 3405 Blatt 2.2 WIP
[4] VDI 3405 Blatt 2.x in prep.

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Equipment for Laser Beam Melting

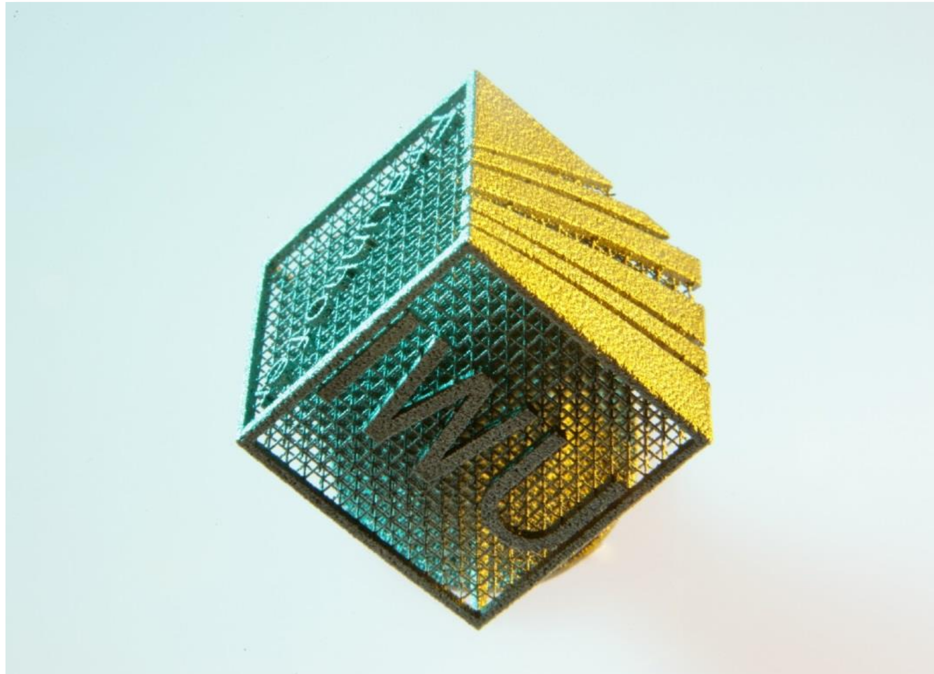
Overview of equipment manufacturers

Laser beam melting (LBM):

- 3D Systems (USA/France/Belgium, former Phenix Systems/LayerWise)
- Additive Industries (Netherlands)
- CONCEPT Laser (Germany)
- EOS (Germany)
- ReaLizer (Germany)
- Renishaw (UK, former MCP-HEK / MTT Technologies)
- SISMA (Italy)
- SLM Solutions (Germany)
- TRUMPF (Germany)

Electron beam melting (EBM):

- ARCAM (Sweden) only!



INDUSTRIAL APPLICATION POTENTIALS

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Industrial Application Potentials

- **Lightweight Design**
  - → omit all volume/mass without function (biomimicry, topology optimisation)
  - → miniaturisation/downsizing
  - → lattice structures
- **Freedom of design**
  - → design to function
  - → manufacturing the impossible
  - → individualisation/flexibilisation
- **Functionalisation**
  - → geometrical
  - → in terms of material
  - → integrative

Added value in product or equipment

- → enhanced efficiency
- → conserved ressources
- → increased performance
- → completely new product features

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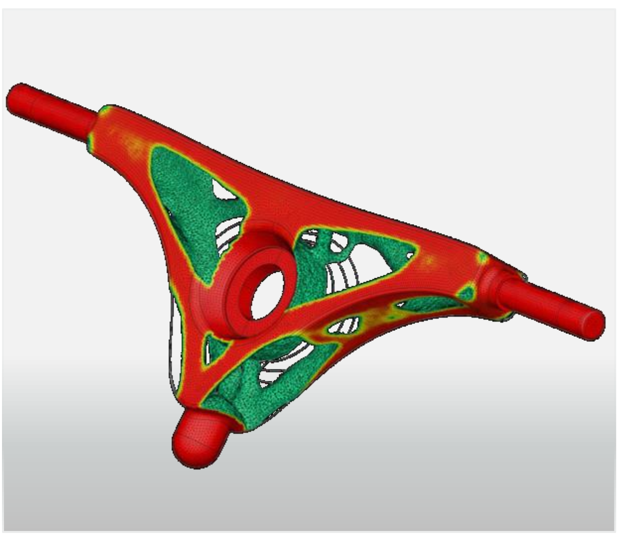
Industrial Application Potentials
Lightweight Design through Topology Optimisation

- ✓ improved functionality
- ✓ optimised stress distribution
- ✓ weight reduction (up to 50 %)
- ✓ ressource efficiency

3D Pioneers Challenge

Best student project and **3DPC 2017 winner** in the category **Design**



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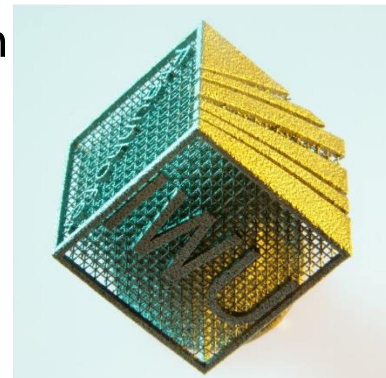
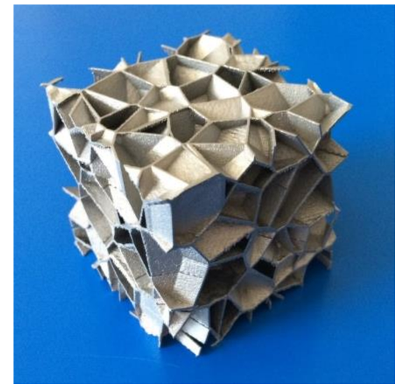
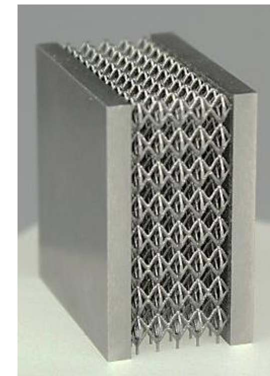
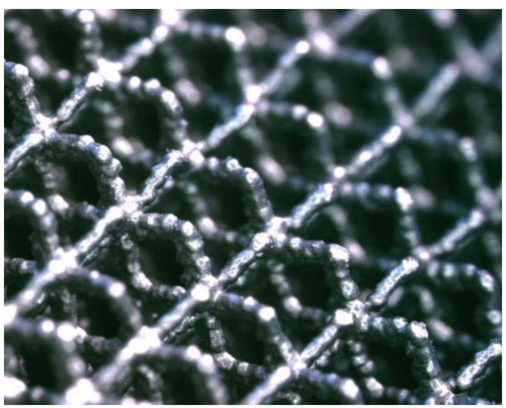
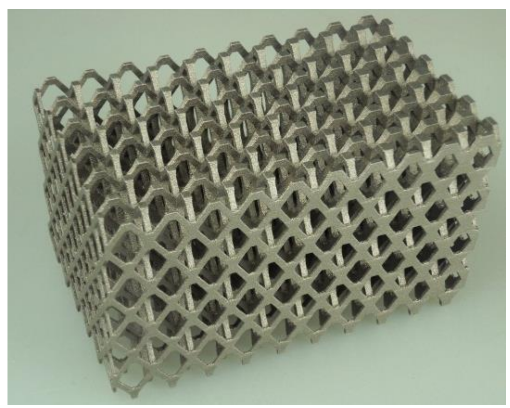
Industrial Application Potentials
Lightweight Design through Lattice Structures

Lattice structure integration in parts for specific properties

- ✓ extreme weight reduction
- ✓ graded structures
- ✓ locally varying properties
- ✓ "fit to function"



Need for research:

- ✓ material behaviour
- ✓ mechanical properties
- ✓ stiffness and absorptivity

Industrial Application Potentials
Functionalisation

- **geometrical**
  - ➔ functional channels and cavities
    - ➔ temperature management (e.g. conformal cooling)
    - ➔ heat exchangers & coolers
    - ➔ media supply & disposal, e.g. (compressed) air, fluids, drugs, …
- **in terms of material**
  - ➔ high performance materials (e.g. Scalmalloy®, high strength steels, …)
  - ➔ functional materials (smart materials, magnetic materials)
  - ➔ multi-material parts (metal-metal, metal-ceramics, …)
  - ➔ adaptronic parts and products
  - ➔ complex assemblies & products „from one print job“
- **integrative**
  - ➔ integration of functional elements & parts
  - ➔ sensors and actuators
  - ➔ electrical/electronic function

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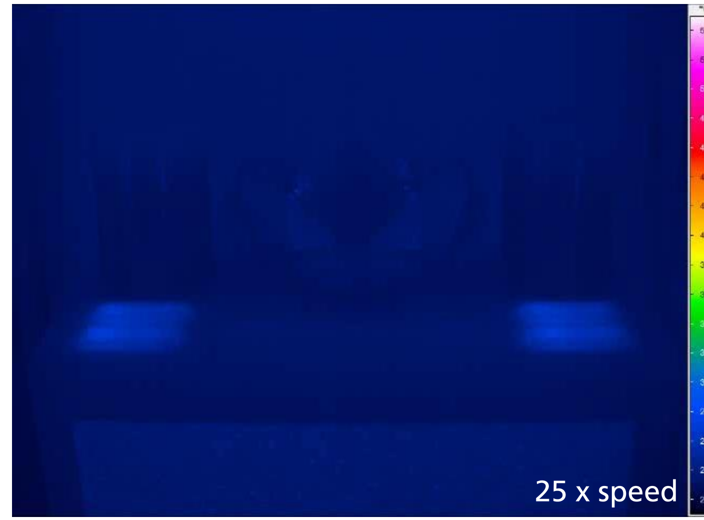
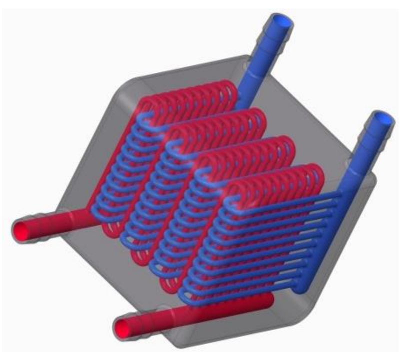
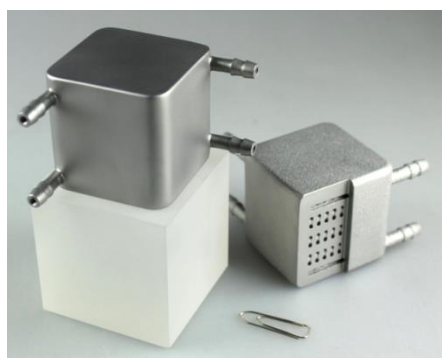
Industrial Application Potentials
Geometrical Functionalisation: Heat exchangers

- Development of components and assemblies for thermal management, e.g. power electronics (e-mobility)
- Development of complex components for process engineering

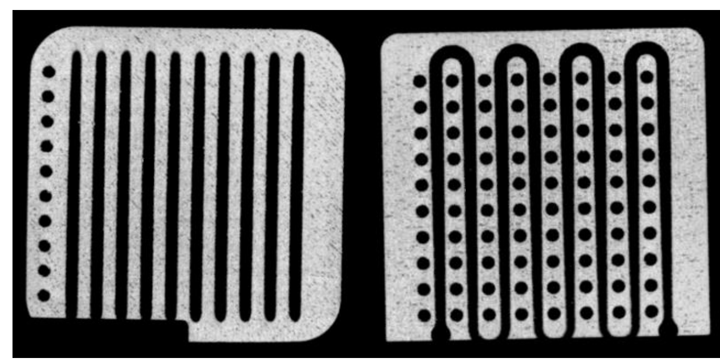




3D CAD model of innovative AM heat exchanger



Additively manufactured innovative heat exchanger



Evaluation / inspection by µCT scan

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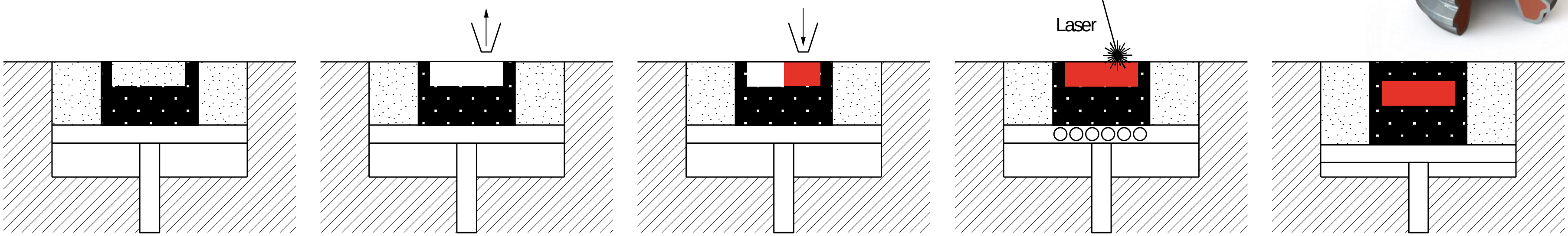
Industrial Application Potentials

Functionalisation in terms of material: Multi-material

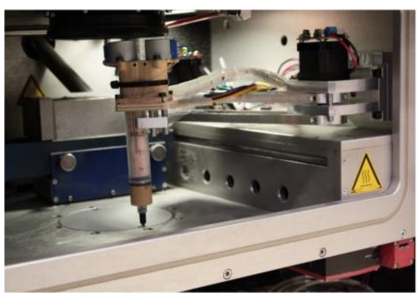
Combination of Laser Beam Melting with Dispensing of Paste



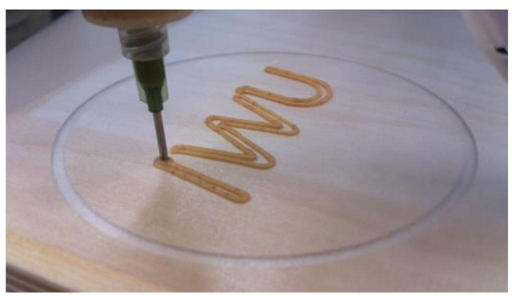
producing a cavity in LBM process | removing powder in the cavity | Inserting pasty secondary component with dispenser | thermal curing of the paste | proceeding the LBM process

- utilisation of industrial screen printing pastes
- equipment set-up at IWU (integration in Realizer SLM 100)

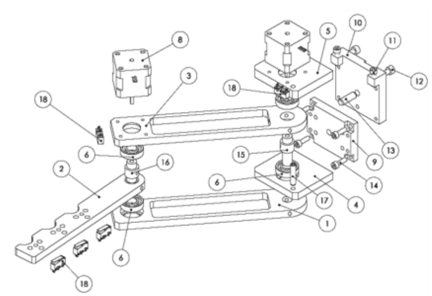
layer thickness of copper paste
Top: 0.25 mm, Bottom: 0.75 mm



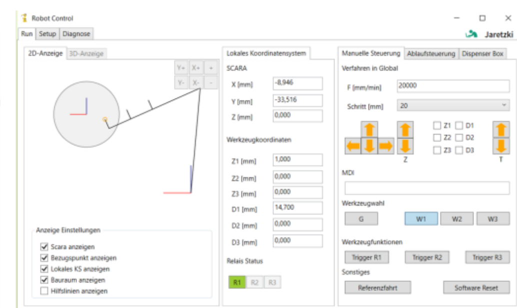
Realizer SLM 100 – process chamber with first dispenser system prototype



successful printing test, considering the visco-elastic behavior of paste



robot arm – exploded view drawing



custom control software

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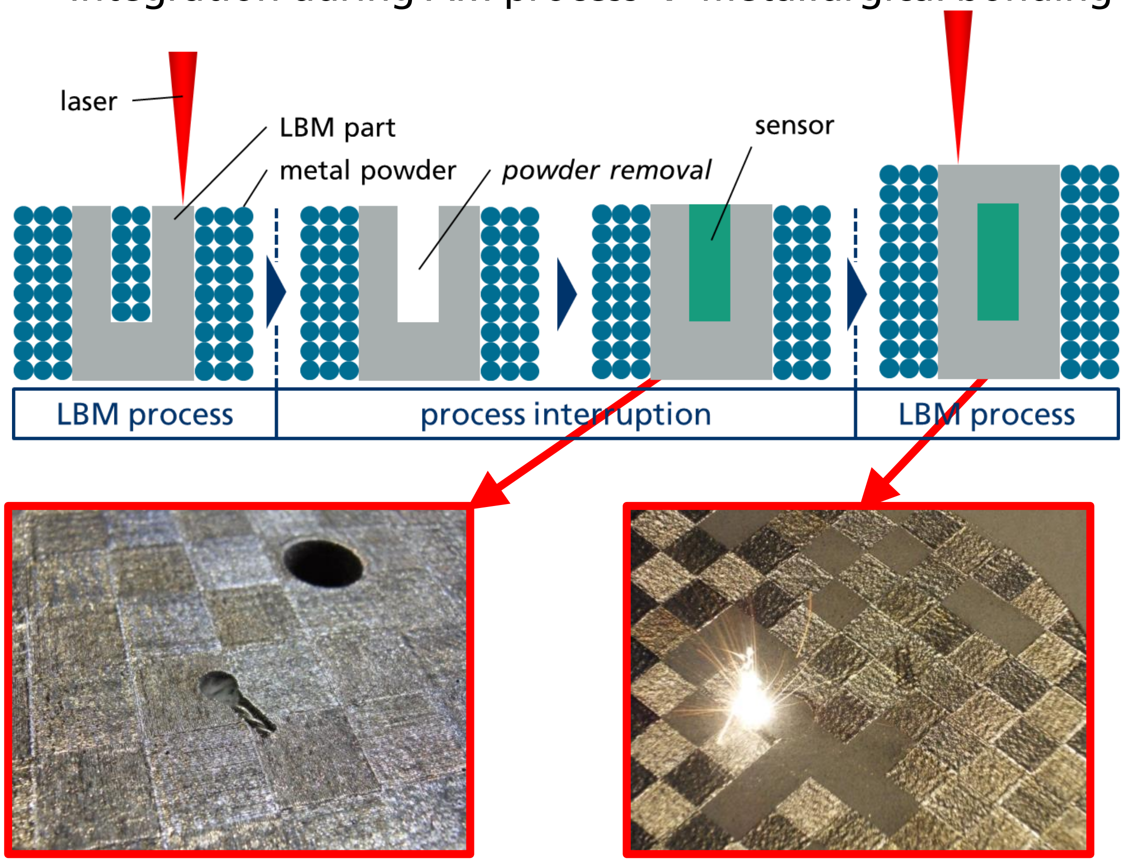
Industrial Application Potentials

Integrative Functionalisation: Sensor/actuator integration

<u>Approach:</u>

- Integration during AM process → metallurgical bonding for precise real-time measurement



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BRAUN CarTec
ringele
inspire irpd institute for rapid product development
Schweizerische Eidgenossenschaft
Confédération suisse
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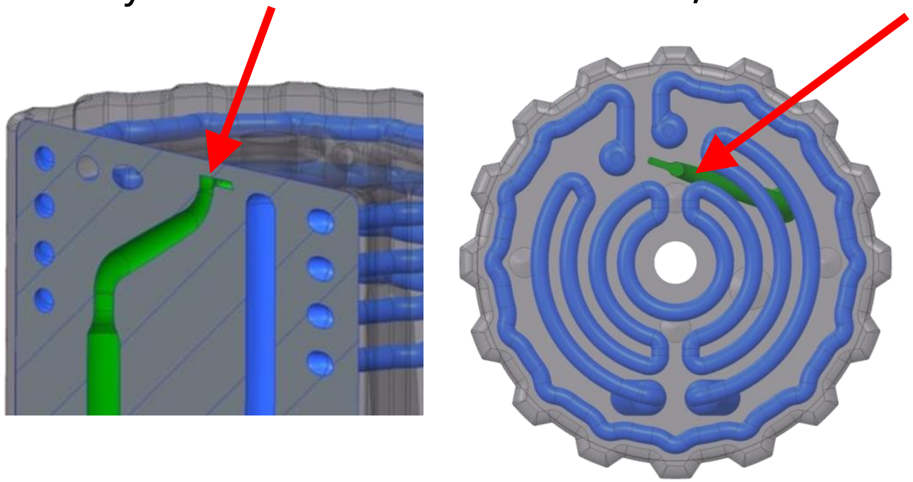
Confederaziun svizra
Kommission für Technologie und Innovation KTI
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung
Fraunhofer IWU

Industrial Application Potentials

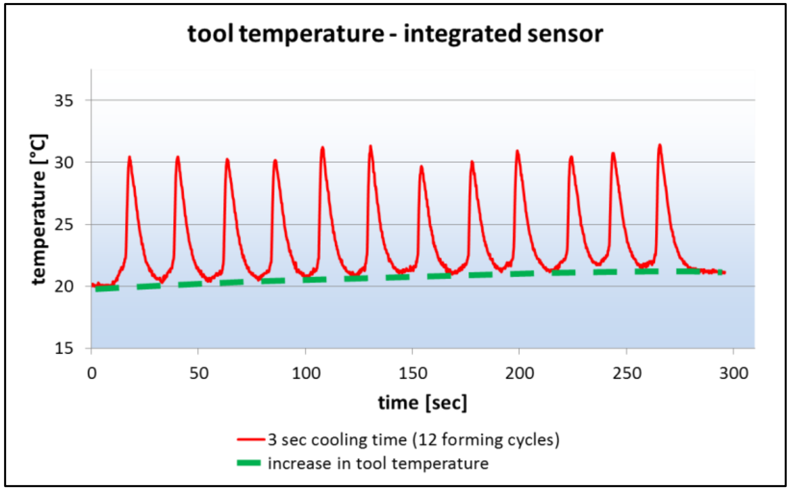
Integrative Functionalisation: Sensor/actuator integration

Approach:

- Integration of a thermocouple into the punch
- Only 3 mm distance to the surface, close to inlet and oulet



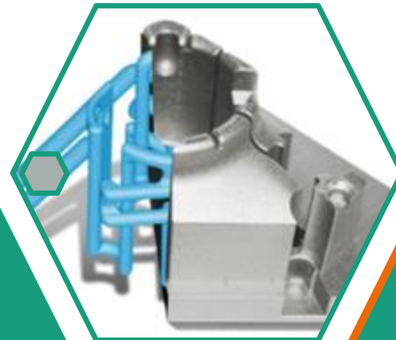
Position of the thermocouple within the punch (CAD model)



Temperature profile over 12 forming cycles
at 3 seconds holding/cooling time

Results:

- Successful integration of thermocouple in the die → proof of concept
- Significant reduction of cooling/holding time from 10 s to 3 s



Tooling (mold and die making)

Aerospace

Medical and dental technology

Automotive Motorsports

STATUS QUO OF INDUSTRIAL APPLICATION

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Status quo of industrial application
Market volume per industrial sector

- Consumer products largest customer of additive manufacturing at the moment

CONSUMER PROD./ELECTRONICS


Source: Kuhn-Stoff

AM revenue [EUR m]: 370

> Production of tools and manufacturing equipment such as grippers
> Production of embedded electronics, e.g. RFID devices

AUTOMOTIVE


Source: Rennteam Uni Stuttgart

AM revenue [EUR m]: 320

> Primarily used for rapid prototyping esp. for visual aids and presentation models
> Production of special components for motorsports sector, e.g. cooling ducts

MEDICAL/DENTAL


Source: SLM Solutions

AM revenue [EUR m]: 280

> Production of dental bridges, copings, crowns, caps and invisible braces
> Customized prosthetics such as head implants

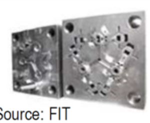
AEROSPACE


Source: Morris Techn. Inc.

AM revenue [EUR m]: 180

> Production of lightweight parts with complex geometry, e.g. fuel nozzles
> Stationary turbine components
> Reworking of burners (stat. turbine)

TOOLS/MOLDS


Source: FIT

AM revenue [EUR m]: 230

> High usage for manufacturing inserts and tools/molds with cooling channels
> Direct tooling (tools made via AM) and indirect tooling (patterns made via AM)

OTHER


Source: CPM

AM revenue [EUR m]: 330

> Several other industrial areas such as military, architectural, oil & gas, space
> Consumer markets, e.g. customized design objects, collectibles, jewelry

Source: Roland Berger Strategy Consultants (2014)

Status quo of industrial application
Aerospace: Series production

Pioneer applications for series production

Fuel injection nozzle
(source: GE Aviation)

- Part of the new GE LEAP jet engine
- 19 nozzles per engine
- By 2020 more than 100,000 parts
- Technical benefits!
  - 25 percent lighter
  - Once 18 parts → with AM one
  - 5 times more durable due to an improved cooling system

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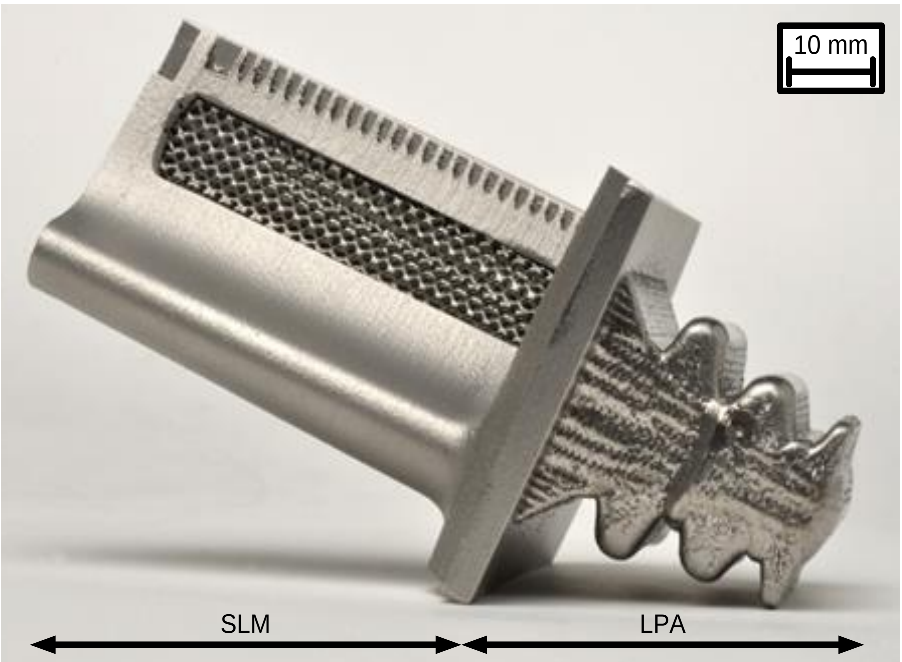
Status quo of industrial application

Aerospace: Combination of powder bed & powder deposition



© IPK

Turbine blade: Build-up with additive process chain
60 % time savings compared to SLM manufacturing

Additive process chain:

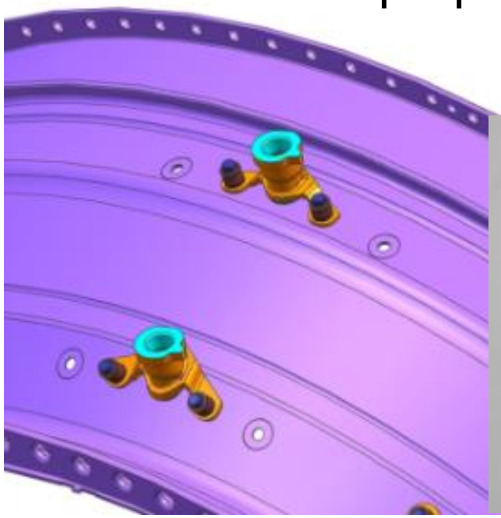
- Selective Laser Melting for additive manufacturing of complex structures
- Laser metal deposition for additive manufacturing with high deposition rate

Source: Fraunhofer IPK

Status quo of industrial application

Aerospace: Series production

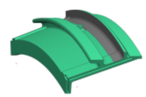
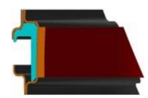
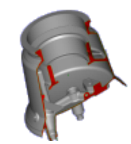
- <u>**Boroscope bosses for A320NEO**</u>
- Two part numbers per engine
- All development engines provided with AM parts
- Start of production in 2013
- Production ramp-up in 2016



Source: MTU Aero Engines

Status quo of industrial application

Aerospace: Roadmap Categorization

	CATEGORY 0	CATEGORY 1	CATEGORY 2	CATEGORY 3	CATEGORY 4	CATEGORY 5	CATEGORY n
MTU part portfolio	▪ Bolts ▪ Small Sheets ▪ Levers ▪ Bosses ▪ Inserts 	▪ Seal Carrier 	▪ Outer Air Seals ▪ Shrouds 	▪ Inner Air Seals ▪ Interstage Seals 	▪ Var. Guide Vanes ▪ Blades ▪ Honeycombs 	▪ Panels ▪ Fairings ▪ Bearing Cases 	▪ New Design ▪ Gamma' strength-ening materials 
Supply Bus.			▪ Race engine parts 	▪ Commercial engine Parts 	▪ Guide vanes 	▪ Injection nozzles 	▪ Injection nozzles 

Archivierungsangaben

Quality Requirements

Source: MTU Aero Engines

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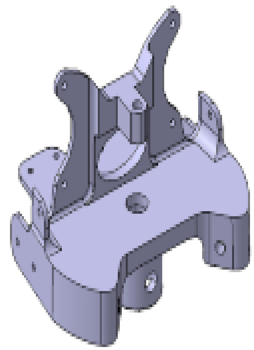
Status quo of industrial application

Aerospace: Design solutions

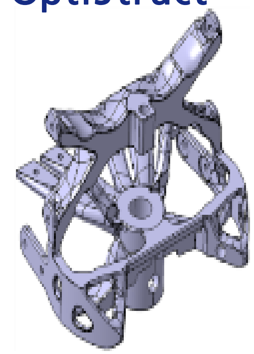
To take maximum advantage of the ALM process, The components must be redesigned / optimised

After redesign and drawing your own bamboo structure (refer to lesson 1)

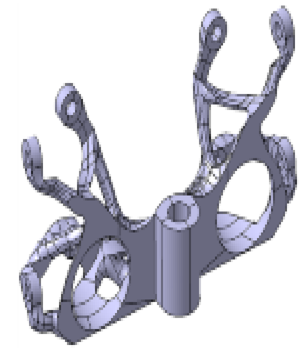
Catia – MSC Patran/Nastran



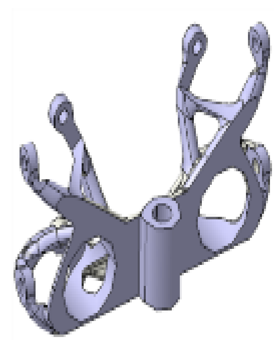
Catia – HyperMesh & OptiStruct



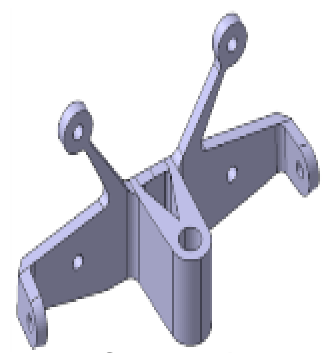
Catia – HyperMesh & OptiStruct



PTC Creo – Solid Thinking & OptiStruct



Catia – HyperMesh & OptiStruct



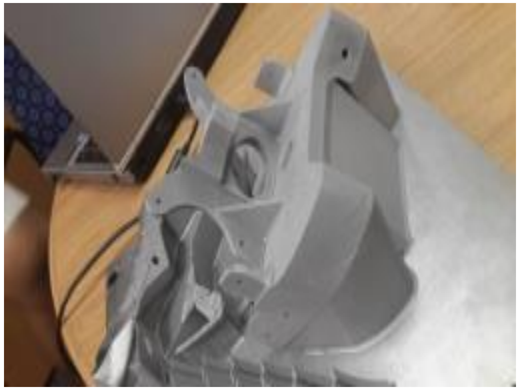
Source: Aerosud Aviation

Fraunhofer IWU

Status quo of industrial application
Aerospace: Design solutions





Source: Aerosud Aviation

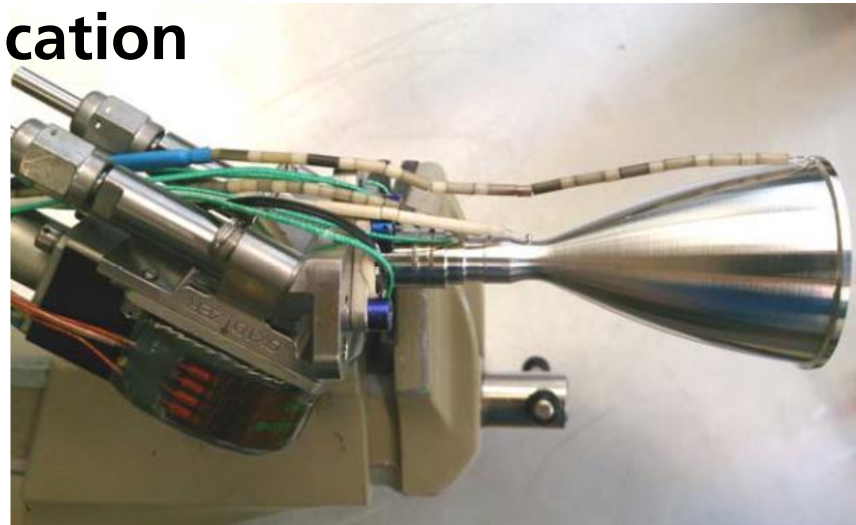
Status quo of industrial application

Aerospace: Space application

World´s first 3D printed platinum combustion chamber for space applications !!!

Successfully Hot Firing Campaign 5th of May, 2015:

- **1,1 hrs firing time**
- **618 ignitions**
- **26 thermal cycles**
- **with a 32 min longest single burn**
- highest throat temperature of **1253°C** was reached



Source: European Space Agency

Archivierungsangaben

Status quo of industrial application
Aerospace: Space application

Weight:
- 60%
1114 g → 456 g
+

Max displacement (by analysis):
- 37%
0.076 mm → 0.048 mm
+

1st Eigen frequency (by analysis):
+ 20%
180 Hz → 216 Hz
+

Production time:
+ 6%
37h + small brackets (12h) → ~ 52 h (incl. T6 HT)
–

Buy-to-fly ratio:
- 97%
56 kg → 0.84 kg
+

Lead Time
From weeks to days
+

Costs:
- 53%
8000€ → 3800 €
+

Source: European Space Agency

Fraunhofer IWU

Status quo of industrial application

Aerospace: Space application

Adaptateur charge utile (ACU) for VEGA

- Made of AlSi10Mg
- Result in **3 brackets** / launcher
- Up to > 63 % mass savings
- Verification approach: NDI at coupons and part level
- Completed FLPP project (TRL4)

Adaptateur Charge Utile (ACU) of Space Launcher

Connector Support (original)
0.453kg
Assembled from 4 parts

Integrated solution	Topology Optimized	Topology Opt. II
0.385kg	0.197kg	0.168kg
- 15% weight	- 56% weight	- 63% weight
1 part	1 part	1 part (bionic design)

Source: European Space Agency

AIRBUS DEFENCE & SPACE

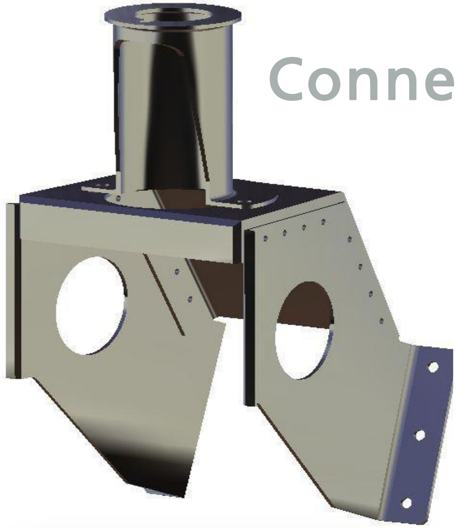
CATEC CENTRO AVANZADO de TECNOLOGÍAS AEROESPACIALES

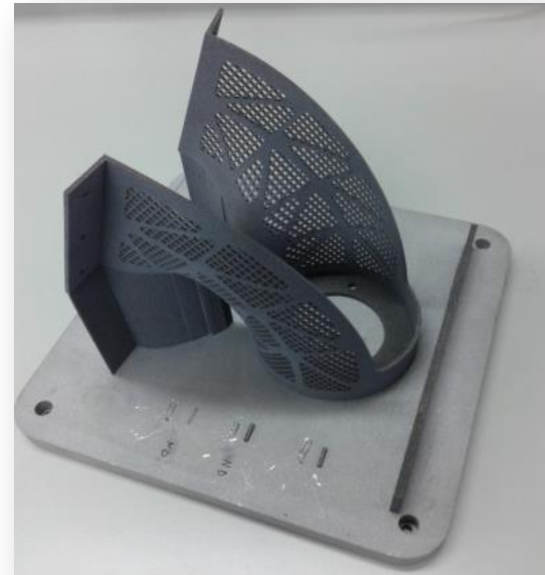
Status quo of industrial application

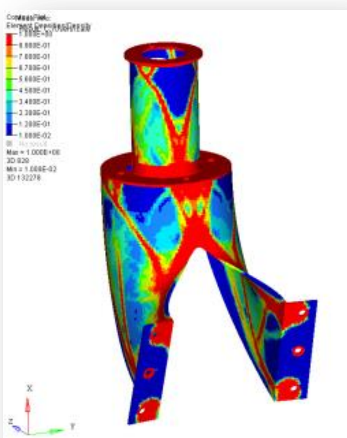
Aerospace: Space application

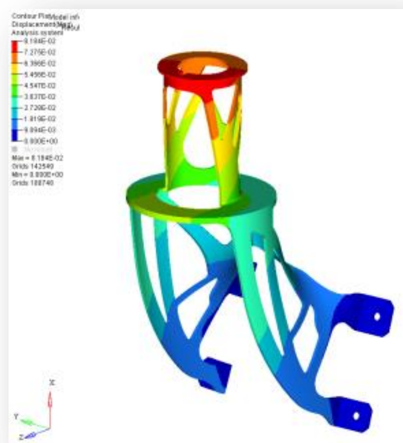
Connector Support (AlSi12)

-62.9% @ -0.285 kg







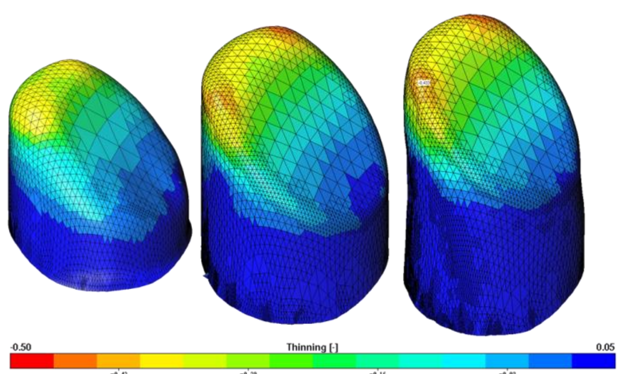


Source: European Space Agency

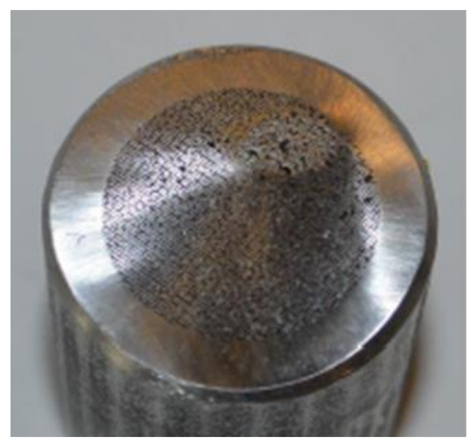
Status quo in industrial application

Tooling: Cold sheet metal forming

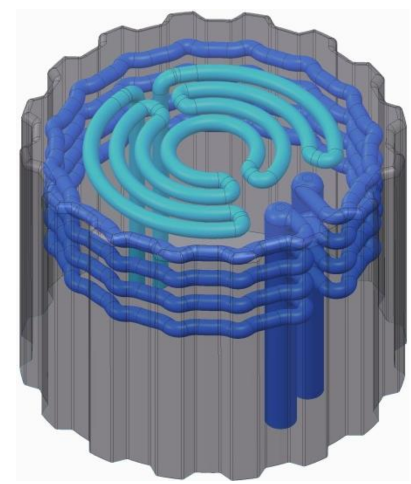
- European Manunet project called HiperFormTool
- combining die tempering and lubrication within the same AM tool



FEA of material thinning for each drawing phase
→ determination of optimal position for lubrication



combining dense and porous structures



cooling system within die (punch)

FURTHER CHALLENGES AND PERSPECTIVES IN RESEARCH AND INDUSTRY

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Future prospects of Metal Additive Manufacturing

Today	Tomorrow	In Future

■ Prototypes
■ Pre-series parts
■ Small batch production for very few selected parts
■ First tooling applications (particularly for plastics injection moulding)
	■ Series production of
	  ■ Small batches
	  ■ Spare parts
	  ■ Assembling aids
	  ■ Fixtures and tools
		■ Wide use for the production
		  ■ Individual parts
		  ■ Assembly groups
		  ■ Tooling

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Further reasearch challenges

- Productivity ↑ ➡ Costs ↓
- Approval of medical and aerospace products
- Surface roughness ↓
- Dimensional accuracy ↑
- Process reliability ↑
- Residual stress and warpage ↓

Further reaserch challenges

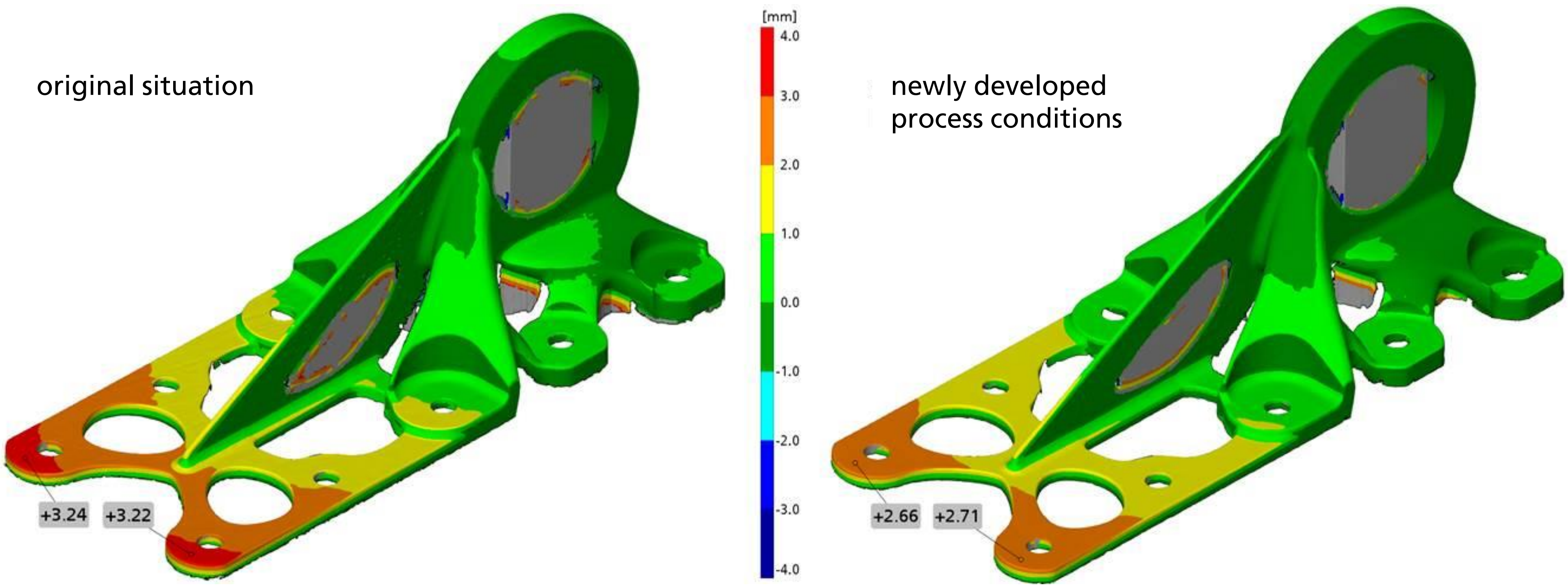
Residual stress/ warpage

Project on determination and minimization of residual stresses and warpage

<u>results:</u>

- Reduction of warpage by up to 63 % possible

Bracket „Mammoth“ (provided by Airbus, material AlSi10Mg)

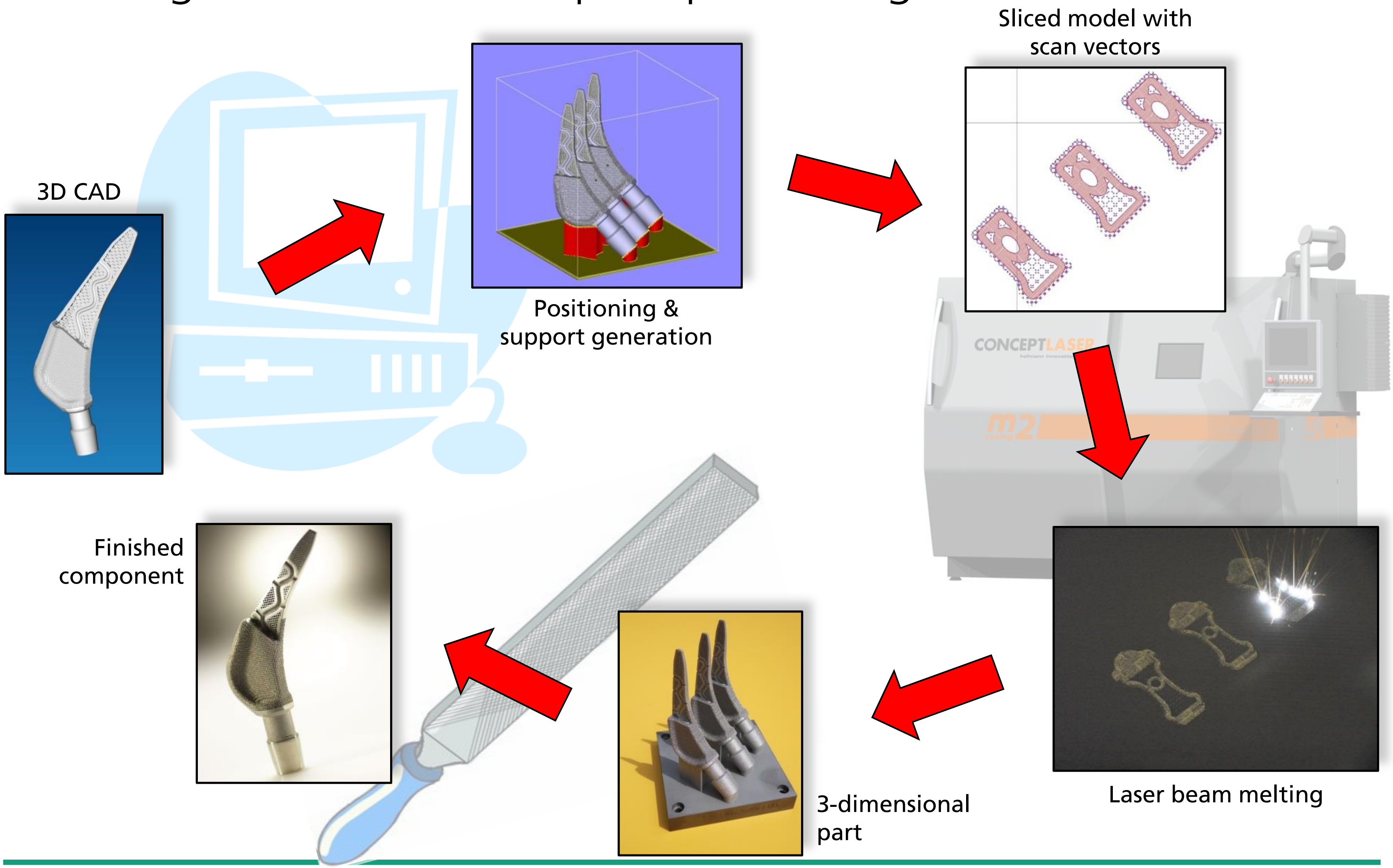


Archivierungsangaben

ALLIANZ INDUSTRIE FORSCHUNG
DVS FORSCHUNG
UNIVERSITÄT DUISBURG ESSEN
Fraunhofer IWU

Additive mass production

Challenges: Process chain/post-processing



Archivierungsangaben

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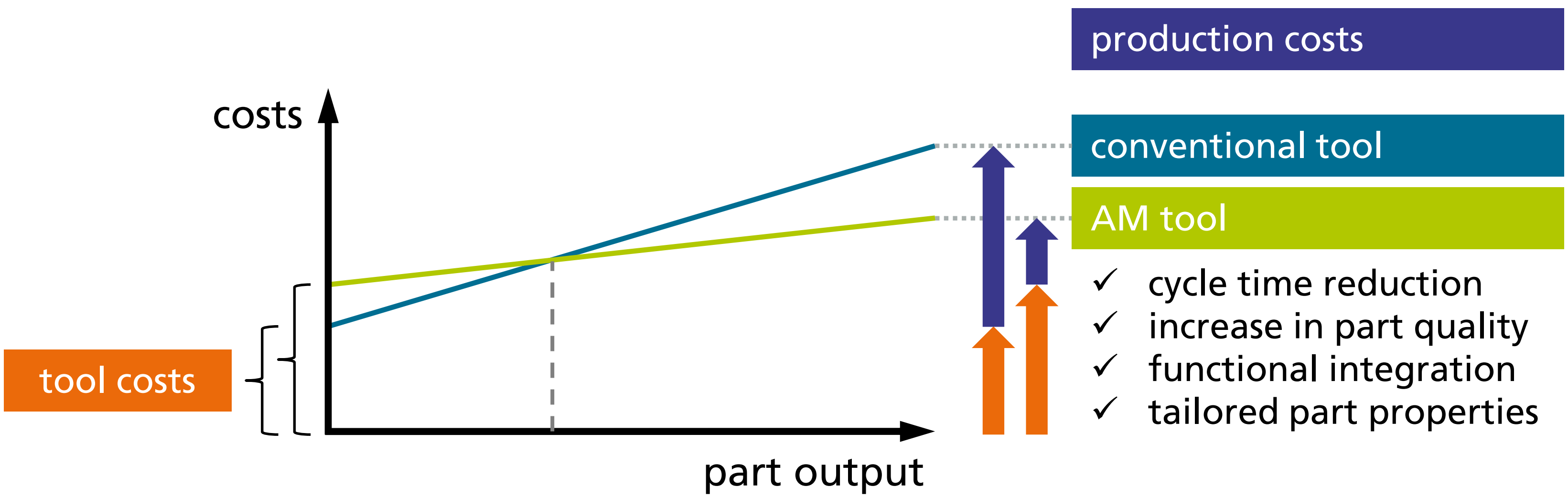
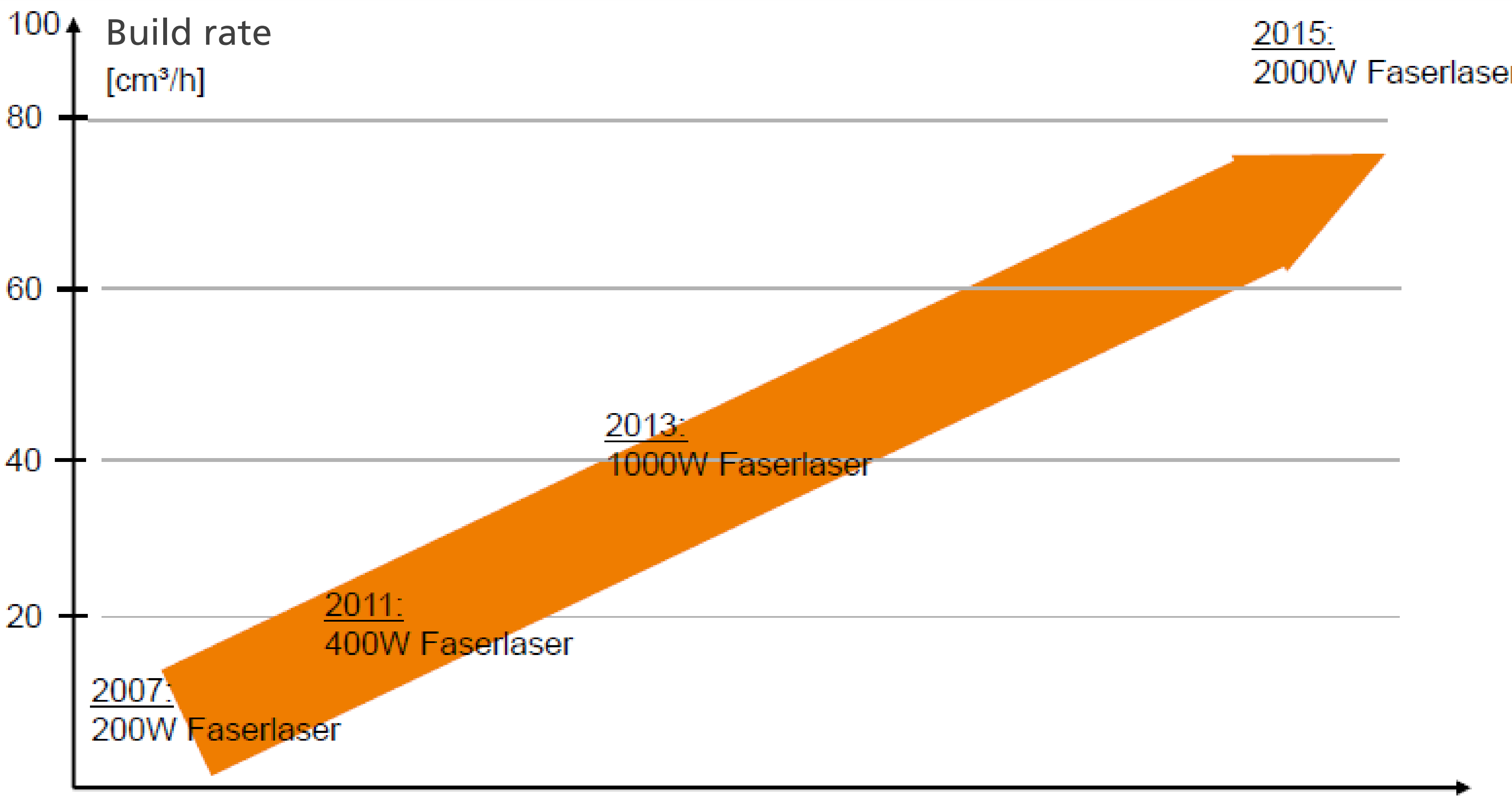
Additive mass production

Challenges: Cost/Economic viability



Additive mass production
Challenges: Productivity



(source: Concept Laser GmbH)

Archivierungsangaben

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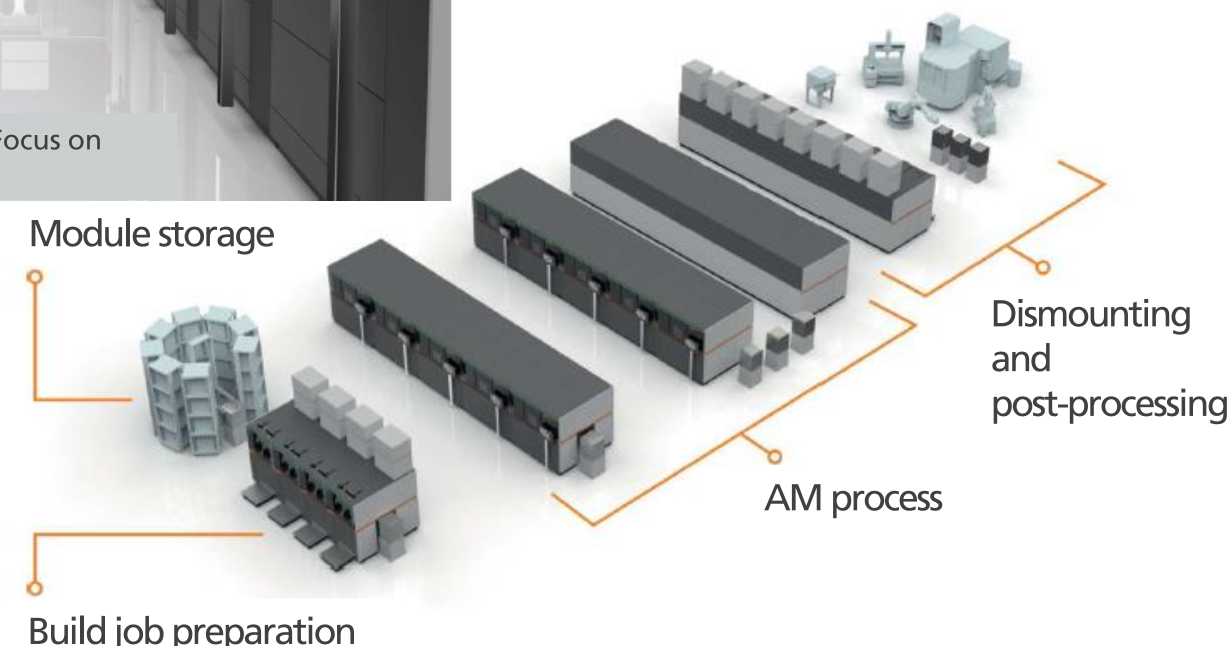
Additive mass production

Challenges: Equipment capable for mass production



(source: Concept Laser GmbH)

Archivierungsangaben

Thank you for your kind attention!

Dr.-Ing. Bernhard Mueller
Department Manager »Additive Manufacturing«
Spokesman Fraunhofer Additive Manufacturing Alliance

Fraunhofer Institute for Machine Tools and Forming Technology IWU

Postal address:
Reichenhainer Str. 88
09126 Chemnitz
Germany

Visitor address:
Noethnitzer Str. 44
01187 Dresden
Germany

Phone: + 49 (351) 4772-2136
Fax: + 49 (351) 4772-2303

E-Mail: bernhard.mueller@iwu.fraunhofer.de

Archivierungsangaben

Fraunhofer IWU

Electron Beam Melting @ Fh IFAM Dresden

Metal Additive Manufacturing @ Fraunhofer IFAM

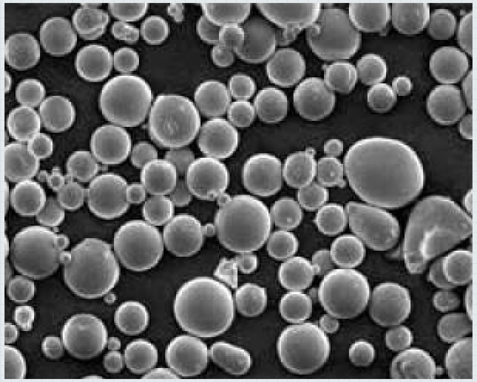
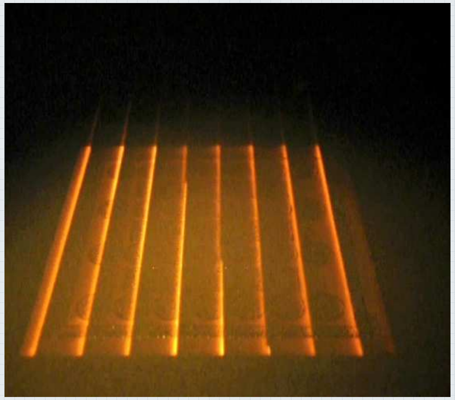
- **Laser Beam Melting (LBM) [HB]**
- **Electron Beam Melting (EBM) [DD]**
- **3D Metal Printing - Screen Printing approach (3DMP) [DD]**

- **3D Metal Printing - Binder Jetting approach (3DP) [HB]**

- **Fused Filament Fabrication (FFF) [DD]**

ELECTRON BEAM MELTING

IFAM-DD competence

Powder	Design	Electron Beam Melting
▪ Accredited laboratory for powder characteri-sation ▪ New methods for powder assessment 	▪ Design rules ▪ Topology optimization 	▪ Process development ▪ New materials ▪ Prototypes and Components 

ELECTRON BEAM MELTING

Projects (I)

TiAlCharger

- FP 7 (EU-SME), 02/13-06/15
- Partners: TWI, ICSI, Josch, Arcam, …
- Feasibility study for TiAl turbocharger wheels

Work packages IFAM

- Process development for Ti-48Al-2Nb-0.7Cr-0.3Si
- Part production

Powder properties (I)
non-standard material

- problems with EBM processing of non-standard-powder: smoke events occurred repeatedly
- flowability was identified as being not sufficient – powder got stuck on the rake, non-uniform powder layers can lead to smoke
- idea: adding a fraction of larger particles to the powder (wider PSD) → this improved flowability noticeably and processing became possible
- Packing density increased

	Batch 1 (45 – 120 µm)	Batch 2 (45 – 150 µm)
Hall Flow Test	28±2 s	22.5±0.2 s
Apparant Density	2.18 g/cm³	2.23 g/cm³

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powder properties (II)
composition powder and part (TiAl – RNT650)

	Al [wt%]	Cr [wt%]	Nb [wt%]	Fe [wt%]	O [wt%]	N [wt%]	C [wt%]	S [wt%]	Ti [wt%]
POWDER	34.1	2.37	4.78	0.03	0.084	0.004	0.006	<0.001	Bal.
specimen	32.7	2.30	4.86	0.05	0.079	0.006	0.014	<0.001	Bal.

- **experimental**
  - Al, Cr, Nb, Fe detected by ICP
  - C, N, O, S detected by LECO
- **results**
  - impurity content remains at the same level between powder and part
  - main difference is Al content → loss of about 1.4 wt% during build job with the chosen process parameters

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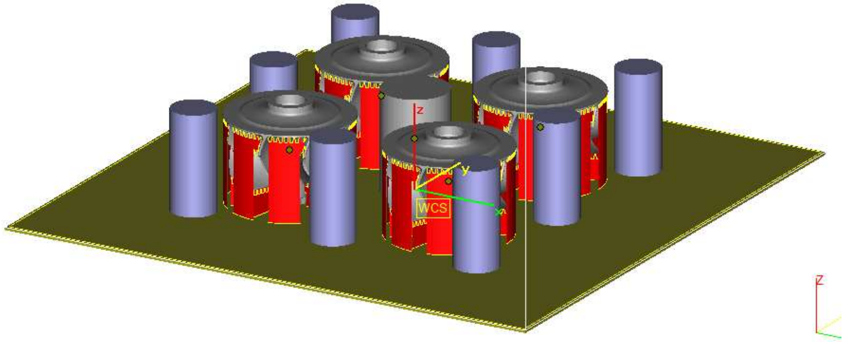
Feasibility demonstrator TC wheel (I)



- **progress and problems**
  - sample placement and supports were changed
  - build job finished successfully

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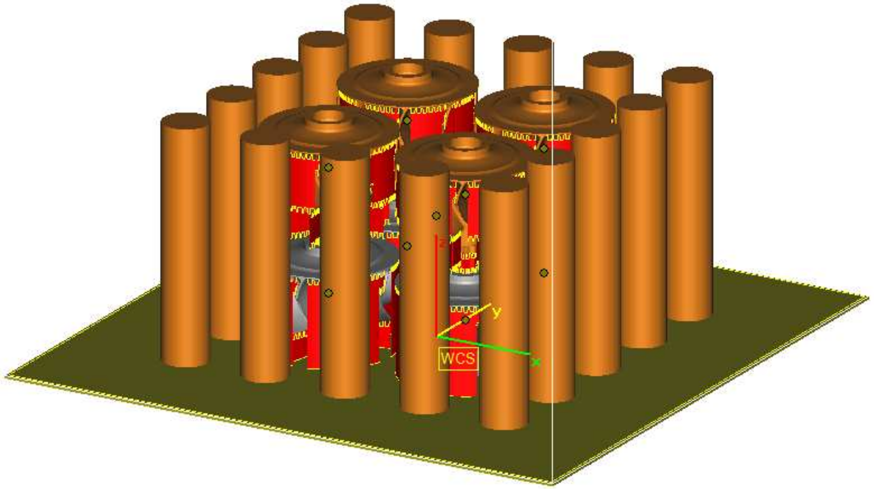
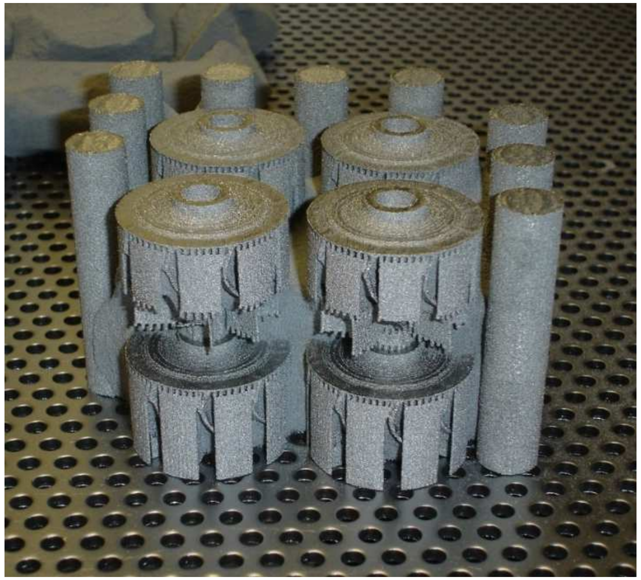
Feasibility demonstrator TC wheel (II)





- **progress and problems**
  - first test of multi-layer placement of TC wheels
  - sample placement and supports were adapted to
  - build job finished successfully

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ELECTRON BEAM MELTING

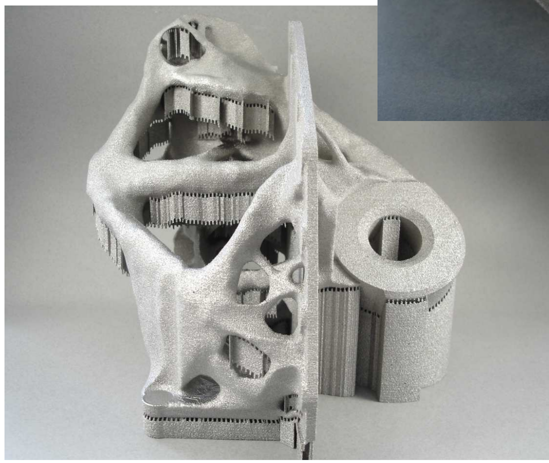
Projects (II)

GenFLY

- BMWi (LuFo), 01/14-03/17
- Partners: Airbus, Liebherr, LZN, …
- Increase of TRL of PBF processes for use in aerospace industry
- Consideration of whole process chain

<u>Work packages IFAM</u>

- design
- powder, manufacturing (EBM)



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Powder properties (II) comparison LBM - EBM

Powder		EOS	Concept Laser	SLM Solutions	Arcam
D_{10}	µm	21.9	20.2	28.2	51.4
D_{50}	µm	31.9	29.8	36.6	73.2
D_{90}	µm	46.3	43.7	49.2	107.8
Flowability	s	39.3	53.2	31.7	21.8
Apparent density	g/cm³	2.46	2.54	2.45	2.59
Tap density	g/cm³	2.83	2.83	2.73	2.81
Al-content	%	6.49	6.38	6.37	5.75
V-content	%	4.09	3.91	3.90	3.97
Fe-content	%	0.24	0.22	0.22	0.21
O-content	%	0.188	0.147	0.143	0.116
N-content	%	0.010	0.009	0.016	0.017

- LBM: differences in particle size (~8 µm)
- LBM: differences in flowability (32 – 53s)
- EBM: low Al content
- Oxygen contents 1200 – 1900 ppm

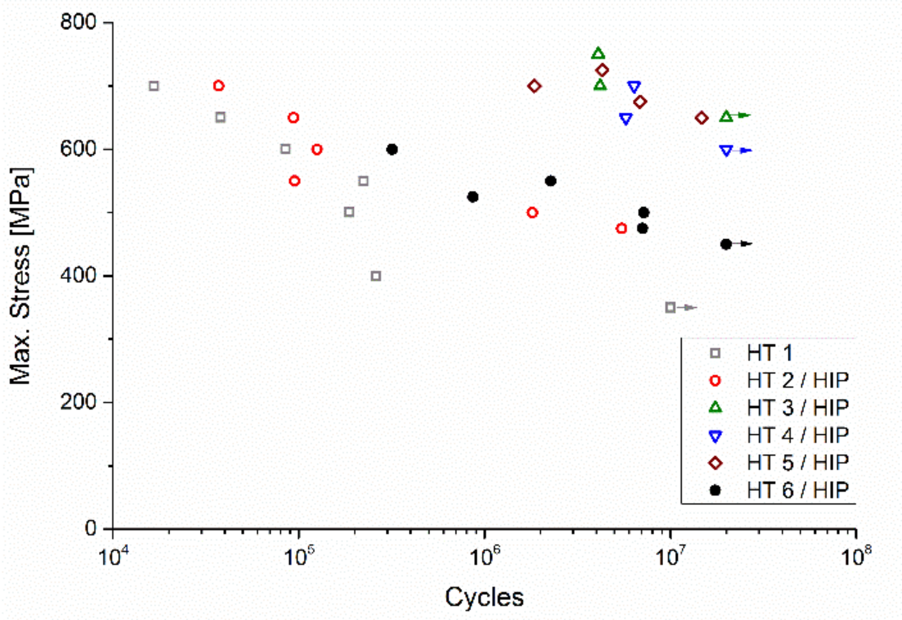
Powder properties (II) comparison LBM - EBM

Powder		LBM	EBM
D_{10}	µm	32.8	52.9
D_{50}	µm	44.1	73.7
D_{90}	µm	62.5	104.6
Flowability	s	31.4	28.3
Apparent density	g/cm³	2.32	2.37
Al-content	%		6.42
O-content	%	0.119	0.118
N-content	%	0.005	0.005

- LBM: powder specified in such a way that it should work on LBM machines of different manufacturers – based ib the results up to now, this seems to be possible
- EBM: processing of powder in machine not as well possible as with powder from manufacturer (worse flow behaviour), but it works and generated very promising properties

Material overview
Ti-6Al-4V

- **HCF (IFAM samples)**
- HT 1: fatigue limit (10^7 cycles) at 350 MPa
- 340 MPa for as-built (EBM) Ti-6Al-4V
- HIP treatment reduces remaining porosity, lifts „knee“ above 10^6 cycles
- HT 3 run-out at 650 MPa
- VAR forging stock (polished): 550 MPa
- HT 6: reduction in HCF stability



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Topology optimization of aerospace part
optimization result (II)

- step 1: scale 1:2, material: Ti-6Al-4V (1st design)
- step 2: full scale part (recalculated design after changes in loads, rivet holes, …)
  - dimensions in build chamber (x/y/z): 171 / 179 / 158 mm
  - build time: 29h
- for testing, part has been completely surface-treated (CNC + electro-polish)


1st design


2nd design, as-built


2nd design, finished

Topology optimization of aerospace part (II)
demonstrator part production (bell crank Liebherr)

- Topology optimization was done at Laserzentrum Nord (LZN)
- Manufacturing by LBM (@LZN) and EBM (@IFAM)

demonstrators manufactured by EBM

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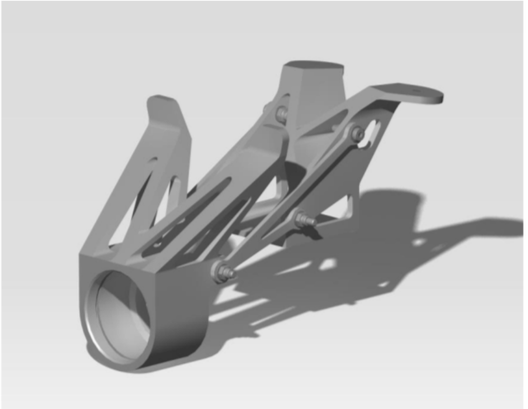
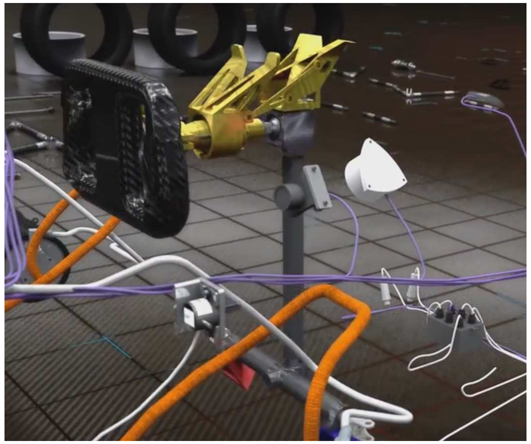
Steering Column Mount

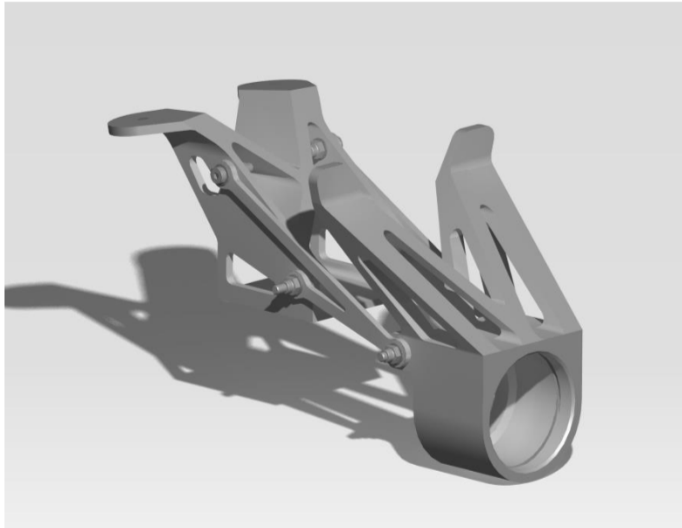
- Assembly of 18 parts
  - Two milled aluminium alloy parts
  - 2 water cut aluminium alloy clamps
  - 14 standard parts
- Overall weight about 514 g
- Max deformation 0,5 mm
- Compromises on conventional part:
  - Max. stiffness limited due to joining of parts
  - Relative movement between bearing and angled gear → internal forces
  - subtractive manufacturing technics

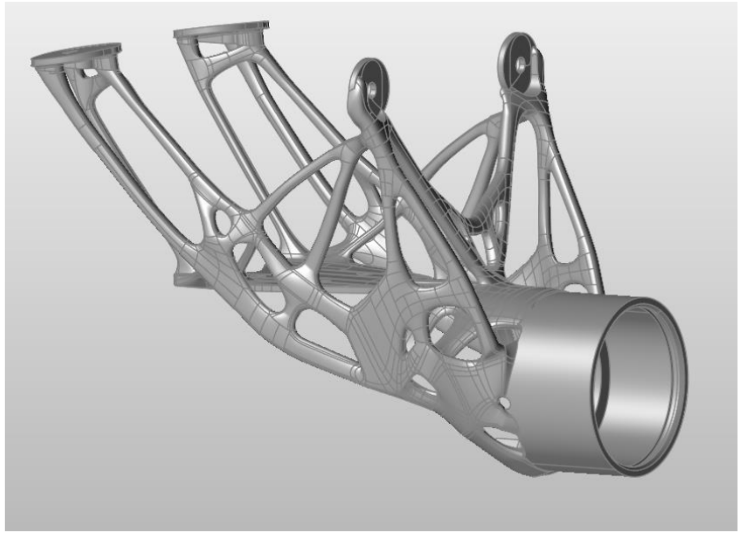




Optimization results

- 2-step optimization using solidThinking Inspire
- stiffness increased by factor 5
- weight reduction: ca. 35%
- manufacturing time: 1 week (vs. 1 month)





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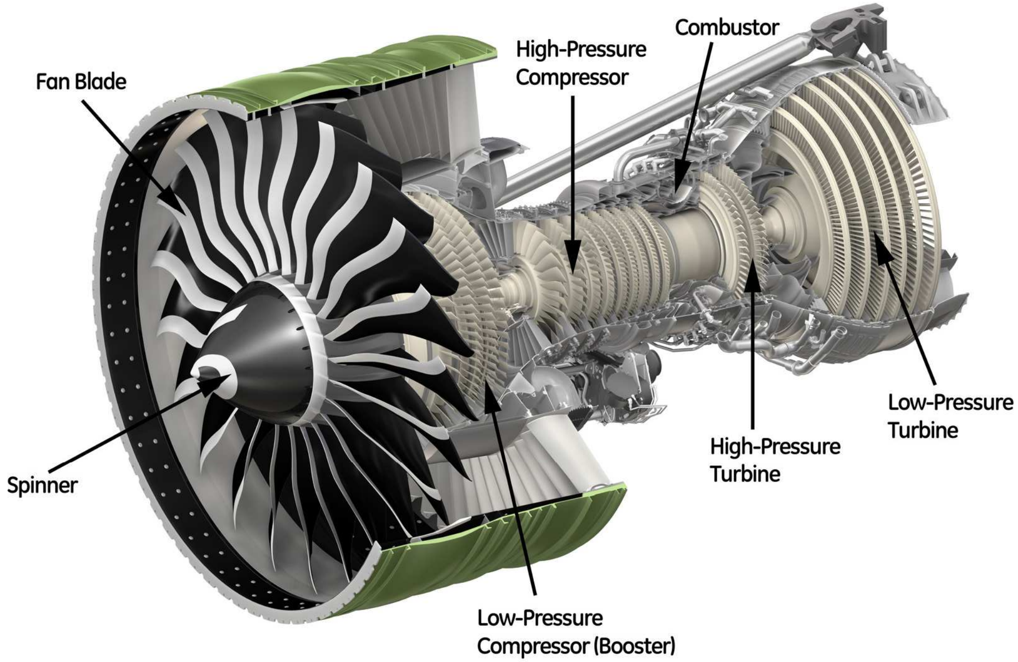
serial and prototype parts – medical

Source: www.arcam.com, personal communication

serial and prototype parts – Avio GE TiAl

- low pressure turbine blade for GE9X
- alloy GE (48-2-2), height 325 mm
- Stage 5 & 6, each with 114 blades → overall 228 blades per aero engine
- Start of production: 2017
- Entry into service: 2019



Source: personal communication

serial and prototype parts – Avio GE TiAl

- EBM-manufactured turbine blades for different aero engines (from left to right): LEAP, GEnx, GE90, GE9X

Source: http://www.gereports.com/post/94658699280/this-electron-gun-builds-jet-engines/ (last access: 02 Dec 2016)

Our Competence & Outlook

- **Competence**
- ***Powder***
  - analysis, specification, qualification
- ***AM Process – EBM***
  - Process development – new materials, optimization of current materials
  - Process optimization – build rate, tailoring of properties
- ***Design***
  - Rules and tools
  - Current focus: topology optimization

- **Outlook**
  - EBM sees and will see new materials being qualified for the process
    - @IFAM: new projects started in 2017 on e.g. steels and superalloys
  - design aspects will become more important
    - @IFAM: 3 new projects started in 2017
  - And … new machines
    - 1st system (A2X): 2013
    - 2nd system (Q20): 2016 … and continuing

ELECTRON BEAM MELTING

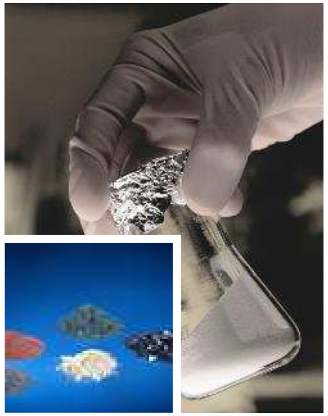
EBM Application Center @ IFAM Dresden

Thank you for your attention!

Dr. Burghardt Klöden

burghardt.kloeden@ifam-dd.fraunhofer.de

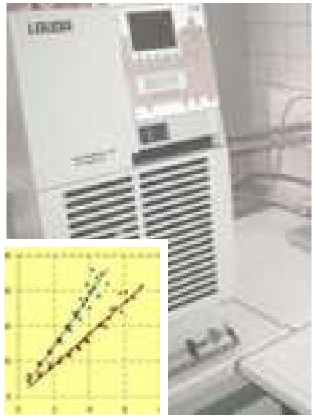
+49 351 2537-384



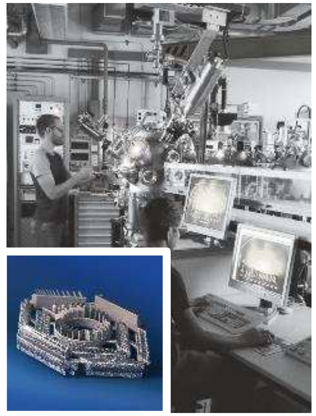
Powder characterization/ Powder modification

Preparation

Additive Manufac-turing by EBM



Characterisation



Prototype / compo-nent manufacturing

IF AM – then IFAM

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