DESIGN FOR ADDITIVE MANUFACTURING

GUIDELINES AND CASE STUDIES FOR METAL APPLICATIONS

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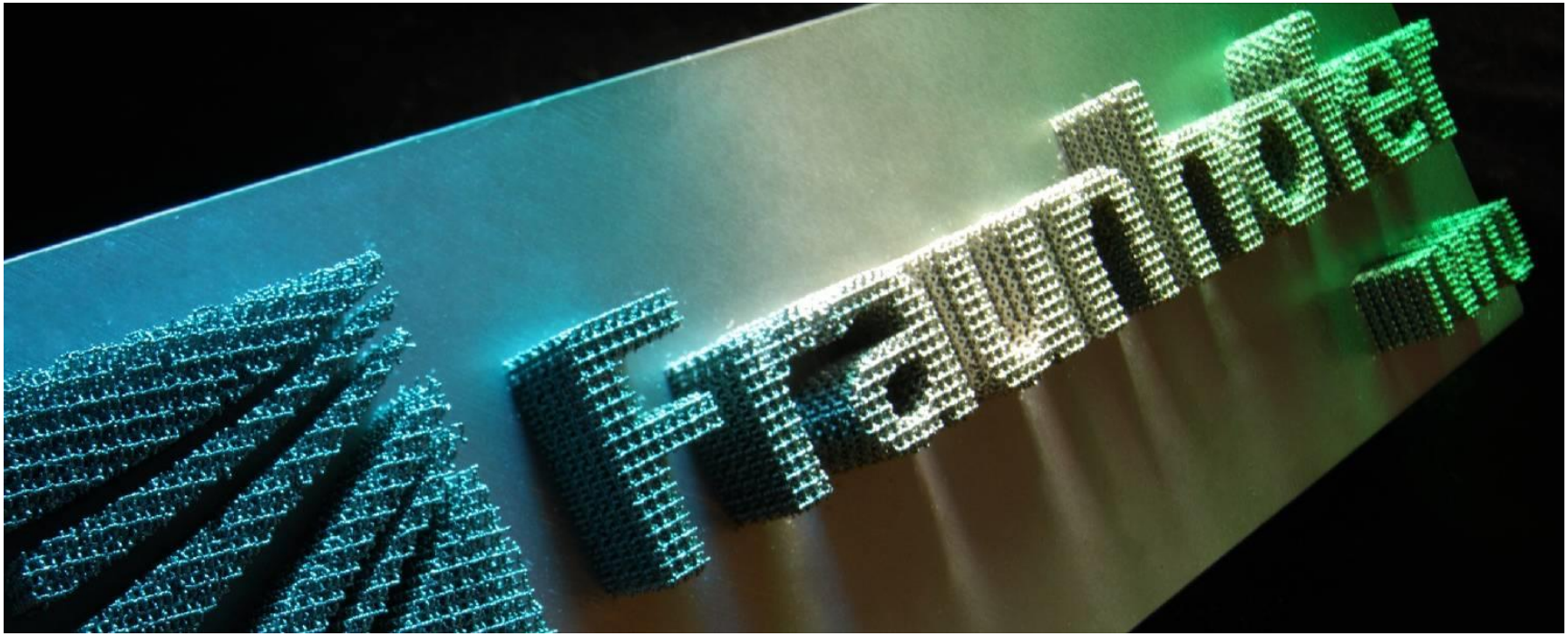


AMC & RAPID Canada 2017 @ CMTS, September 26-27, 2017, Mississauga, ON (Canada)

DESIGN FOR ADDITIVE MANUFACTURING

GUIDELINES AND CASE STUDIES FOR METAL APPLICATIONS

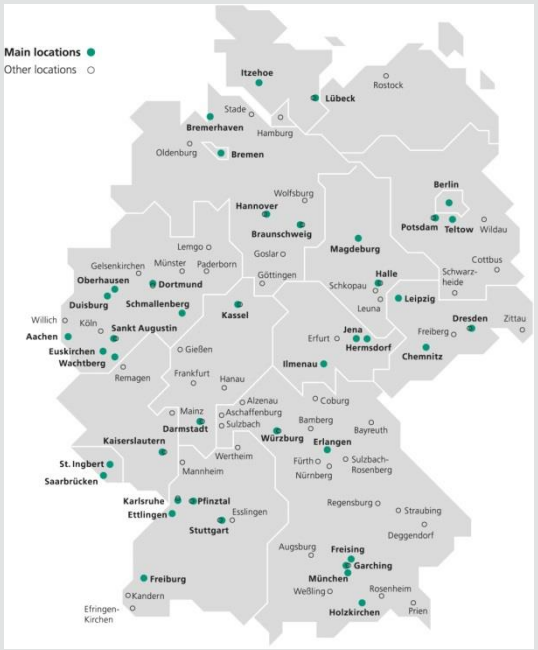
- Introduction to Fraunhofer
- Scope
- AM-specific Design Opportunities
- AM Processes and related Design Principles
- AM-relevant Standards and Guidelines
- Analysis of seven Case Studies
  - Bionic Wheel Carrier of Electric Vehicle
  - Main Gearbox Bracket
  - Calibration Tool for Extrusion Process
  - Heat Exchanger
  - Miniature Heat Exchanger / Cooler
  - Functionally Integrated Implant – MUGETO®
  - Functionally Integrated Tooling Segments
- Summary and Overall Conclusions

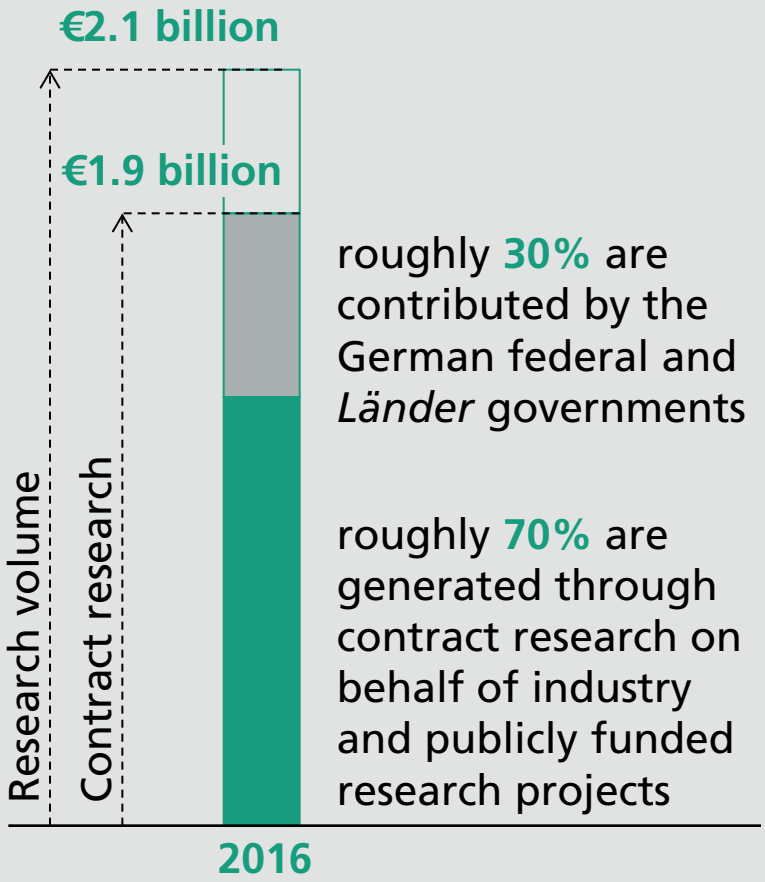
Fraunhofer IWU

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

Fraunhofer IWU

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)

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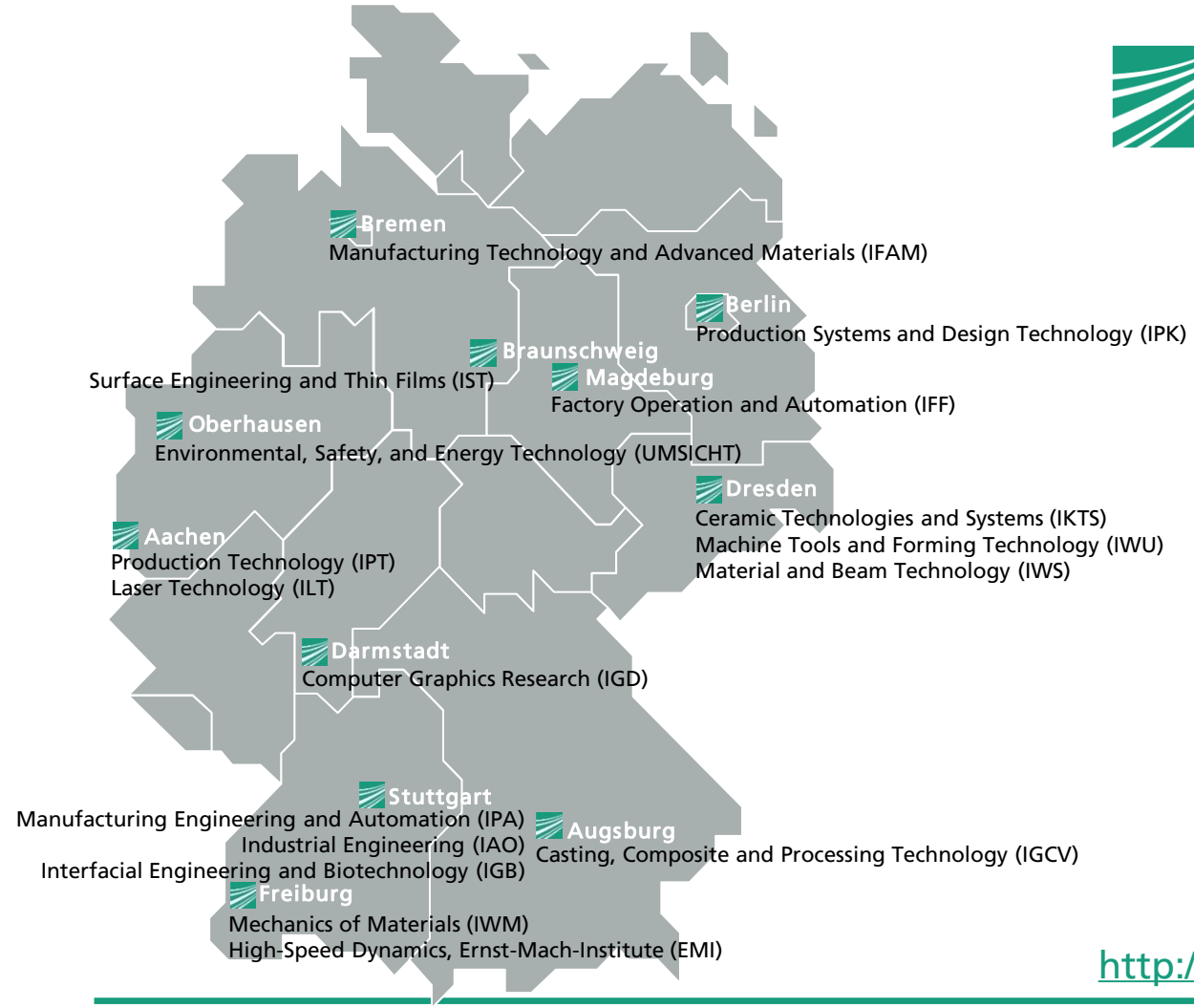
Additive Manufacturing at Fraunhofer

One topic – seventeen institutes – one alliance



Fraunhofer
GENERATIV

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

Office:
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Noethnitzer Straße 44
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http://www.generativ.fraunhofer.de

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Fraunhofer Additive Manufacturing Alliance

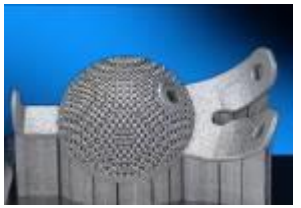
Research areas

- **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

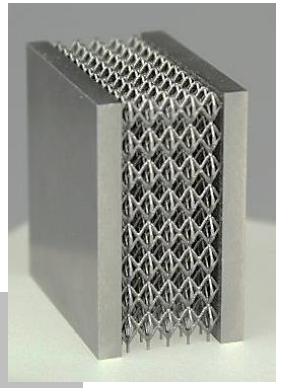
- **Main challenges of AM:**
  - AM technologies require a **rethinking in 3D design**
    → still a barrier particularly for SMEs!
  - **Knowledge** about advantages, opportunities and restrictions is essential in order to make AM a competitive manufacturing method
- **The report:**
  - Identification 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**

Design for Additive Manufacturing
AM-specific Design Opportunities

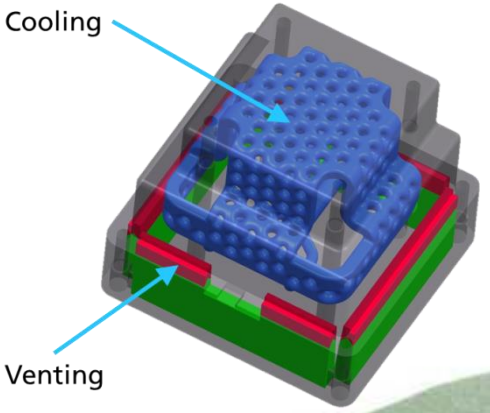
- Design and manufacturing of very **complex** component geometry
- Required information taken directly from CAD data, no need for forming tools etc. → fully **flexible** production

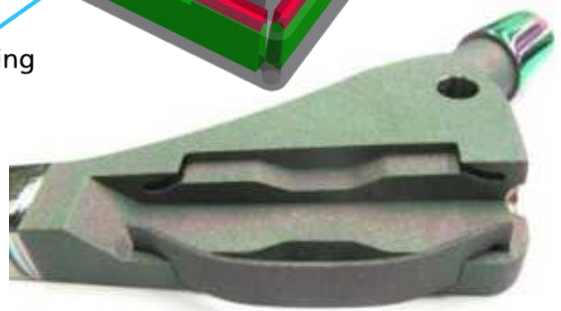
Topology Optimization

Lattice Structures



Integrated Functions





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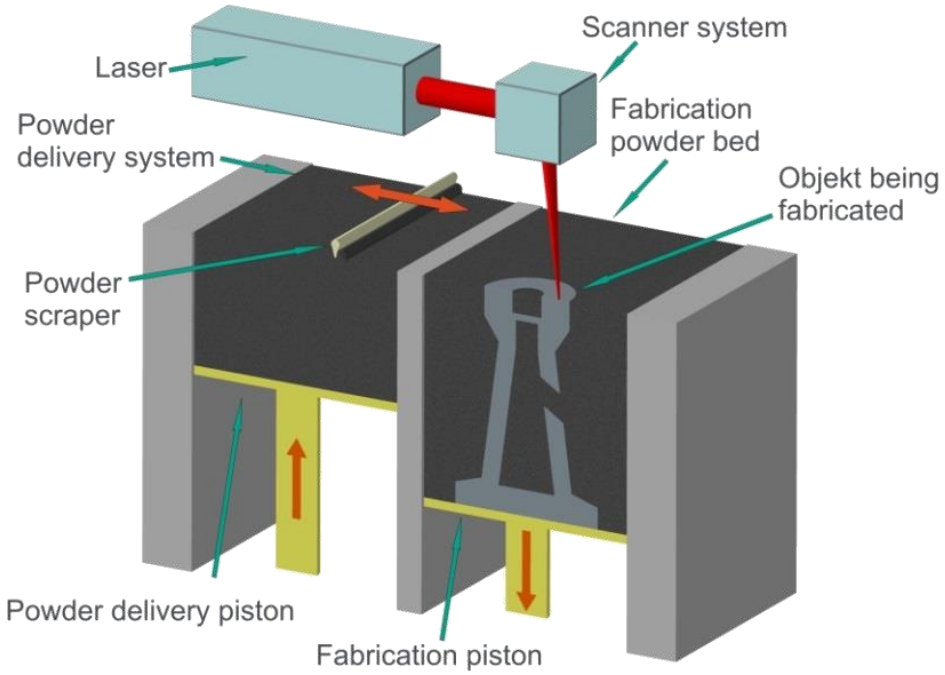
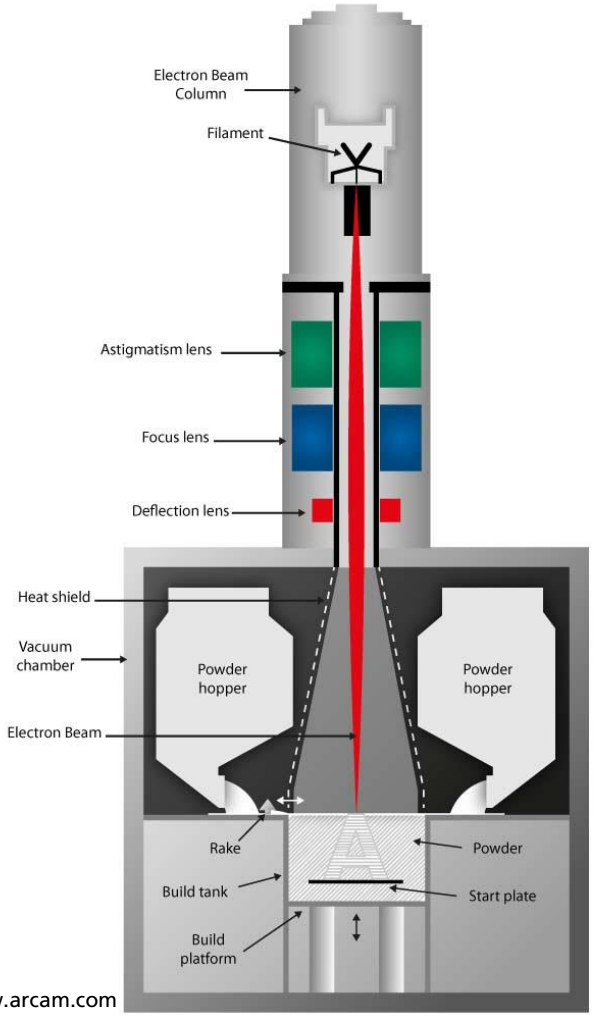
AM Processes and related Design Principles

Powder bed based AM processes LBM and EBM





Source: www.arcam.com

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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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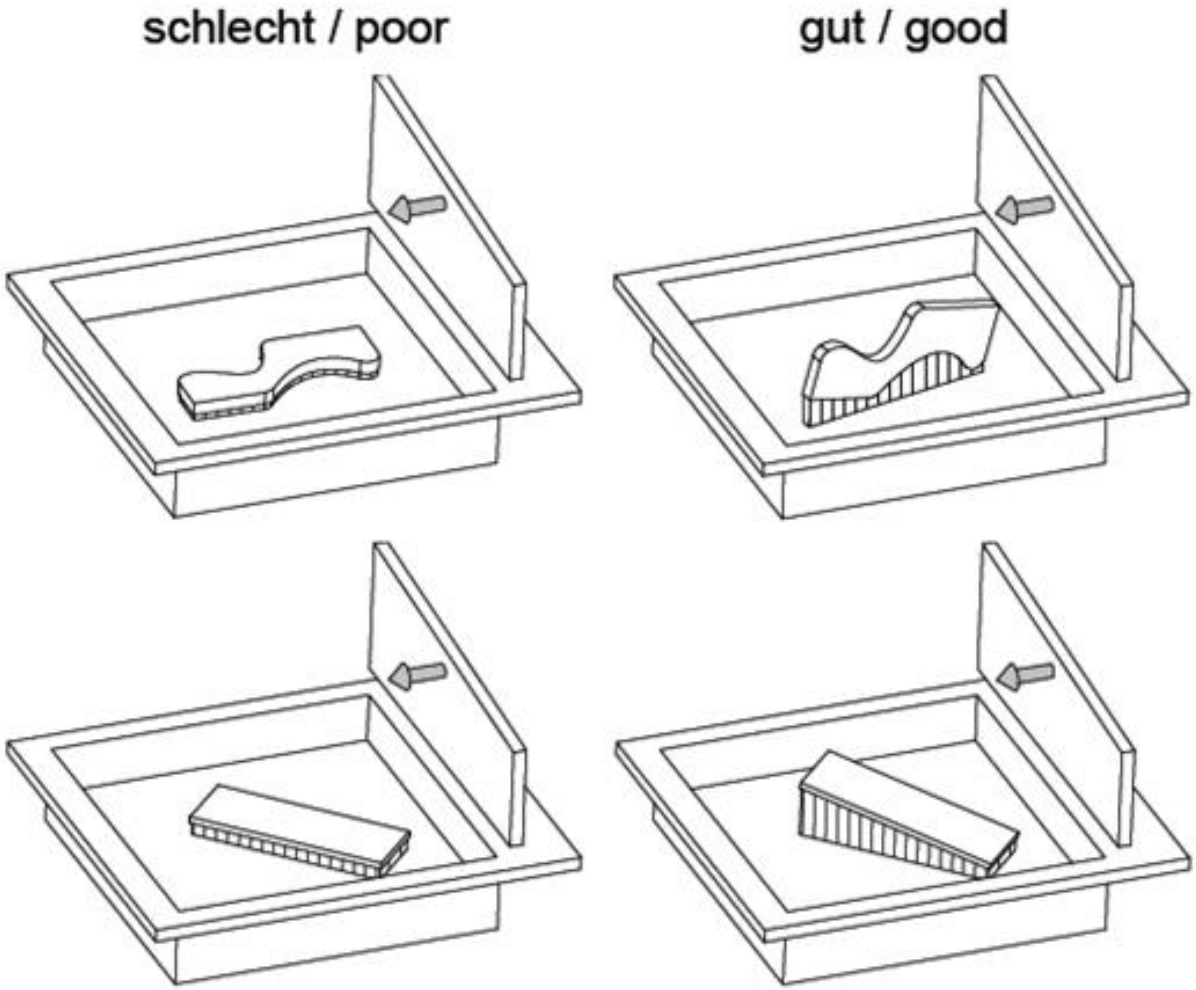
AM Processes and related Design Principles

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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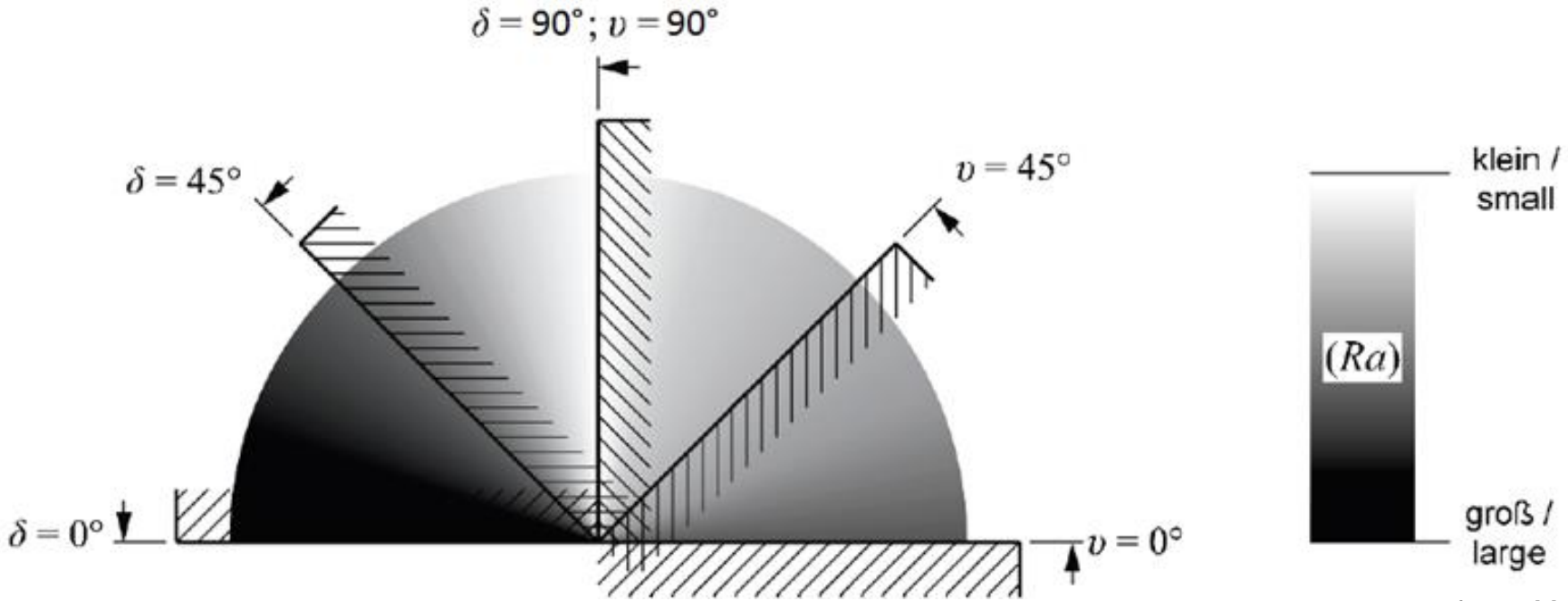
AM Processes and related Design Principles

Surface roughness dependent on build angle

- Depending on the angle between part surface and build platform, surface roughness differs noticeably
- Both, for LBM and EBM, this effect is significant:
  LBM: R_z = 30 - 140 µm [5]
  EBM: R_z = 150 - 300 µm



Reference: [5]

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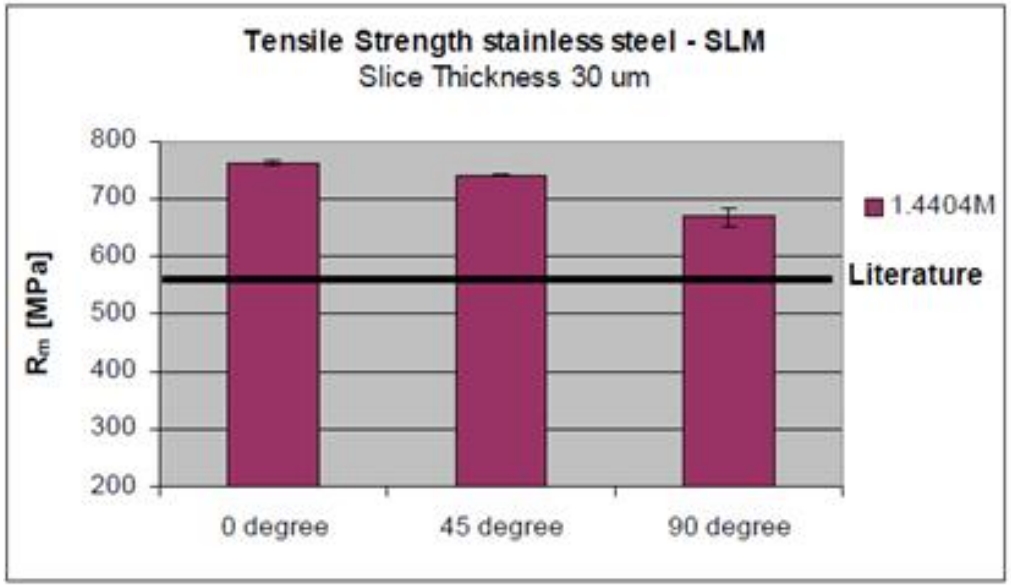
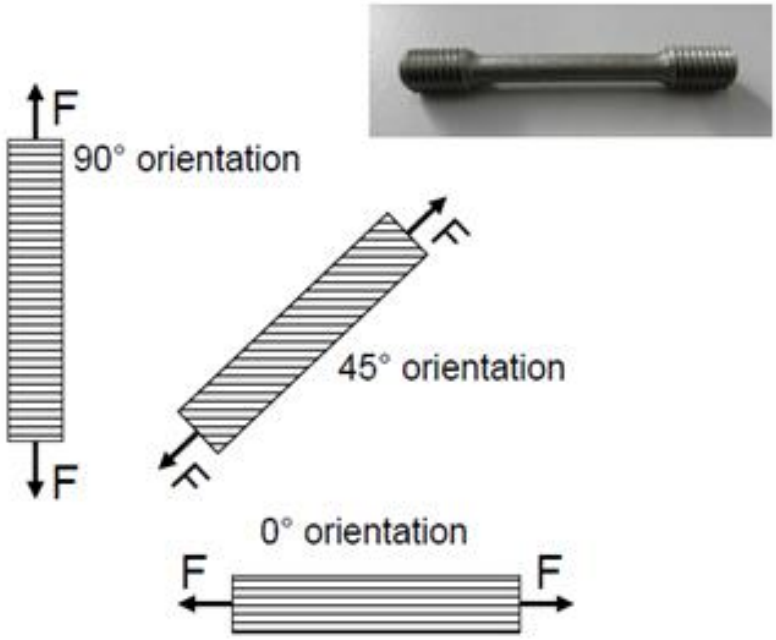
AM Processes and related Design Principles

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]

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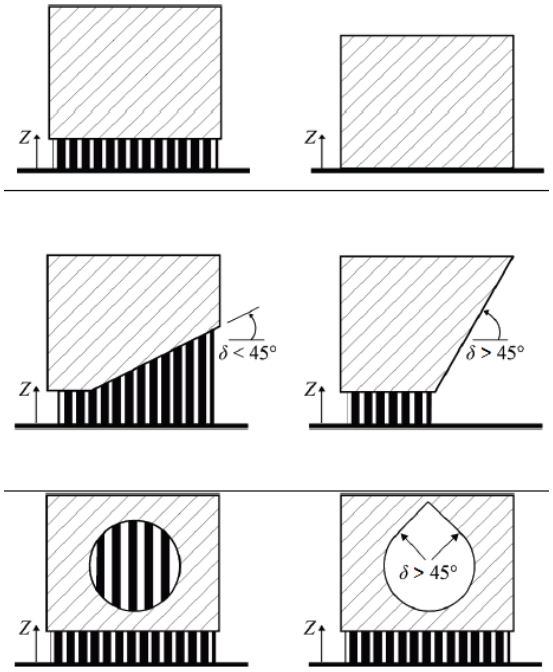
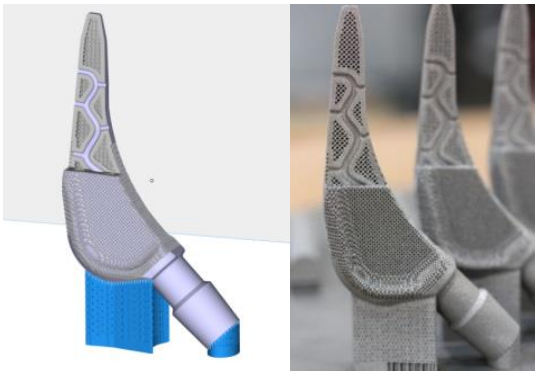
AM Processes and related Design Principles

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]



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AM Processes and related Design Principles

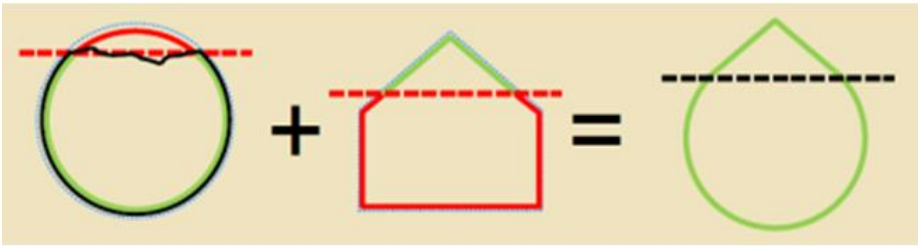
Tolerances / Machining allowance

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

  - 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

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)



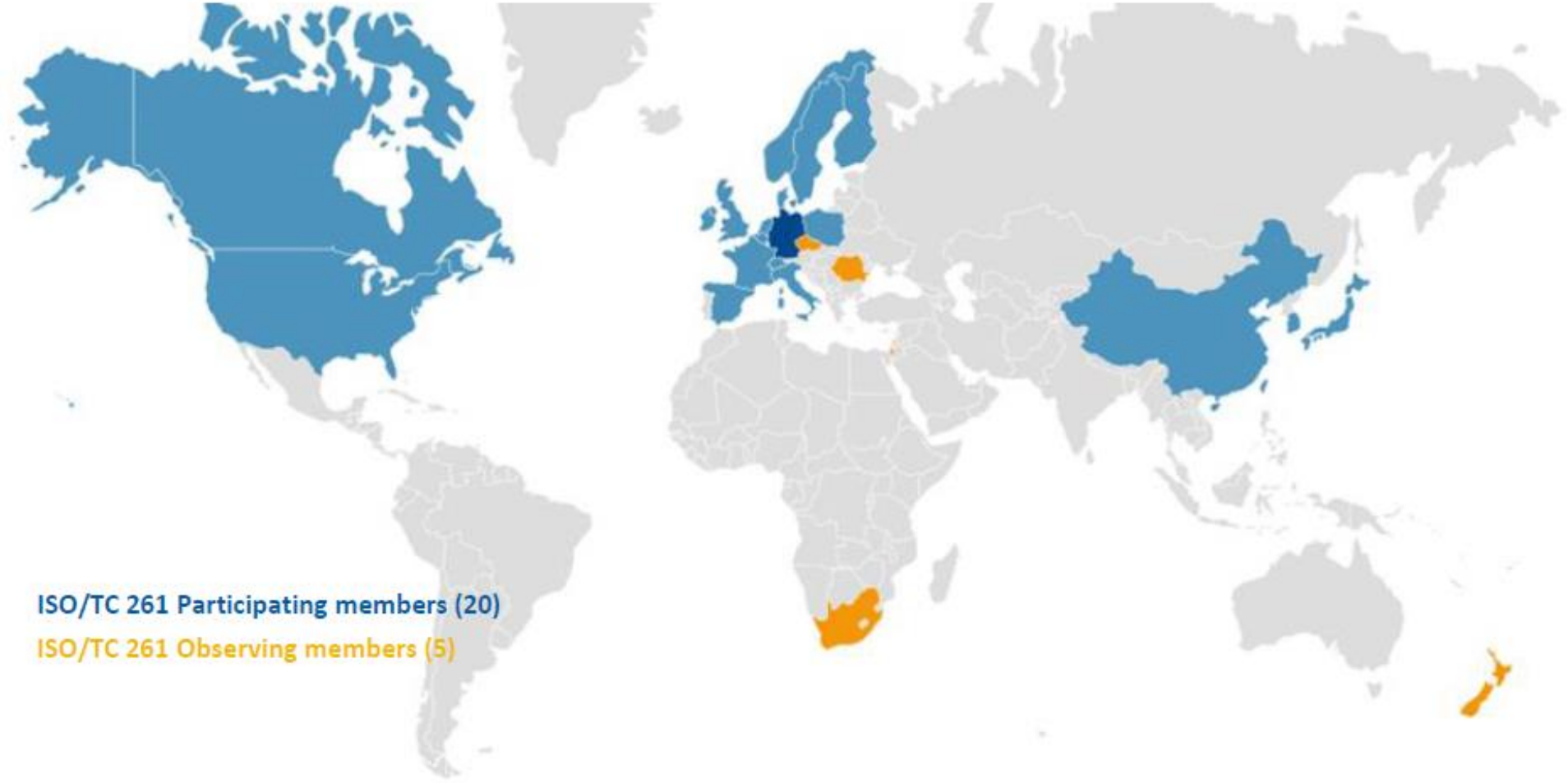
Reference: [12]

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

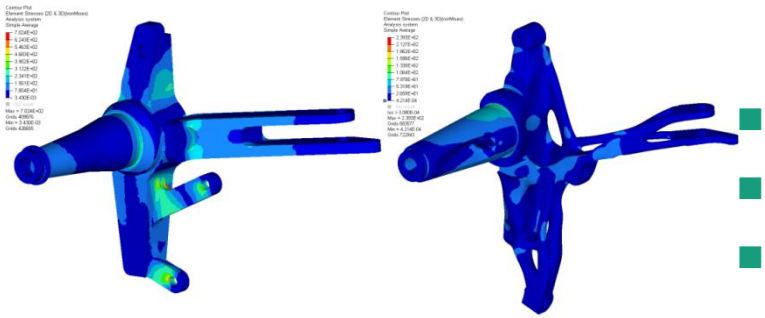
Analysis of seven Case Studies

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

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

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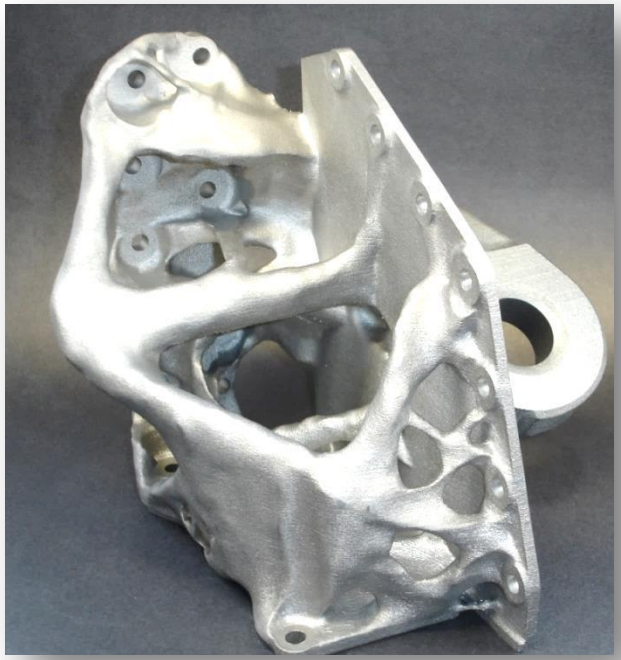
Analysis of seven Case Studies

#2: Main Gearbox Bracket



Fraunhofer IFAM

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

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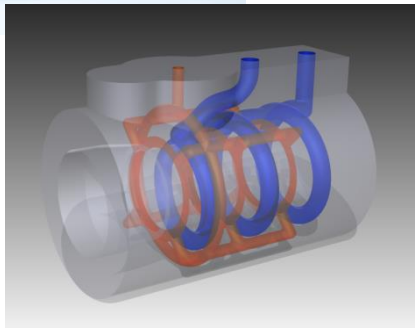
Analysis of seven Case Studies

#3: Calibration Tool for Extrusion Process



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

Fraunhofer IFAM

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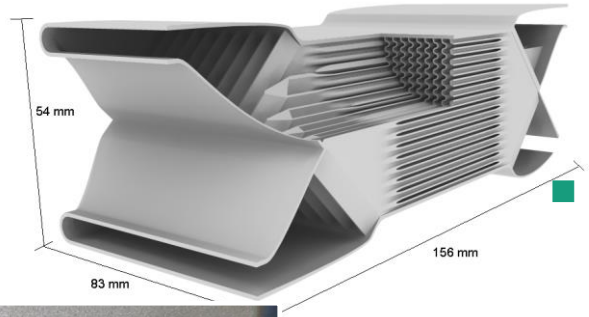
Analysis of seven Case Studies

#4: Heat Exchanger



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:	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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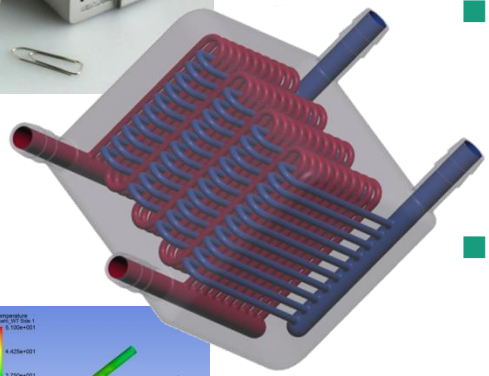
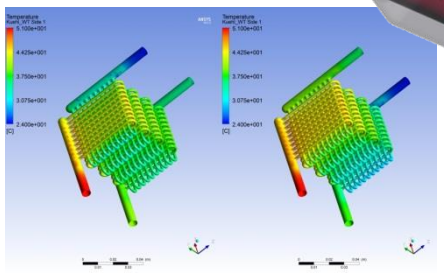
Analysis of seven Case Studies

#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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#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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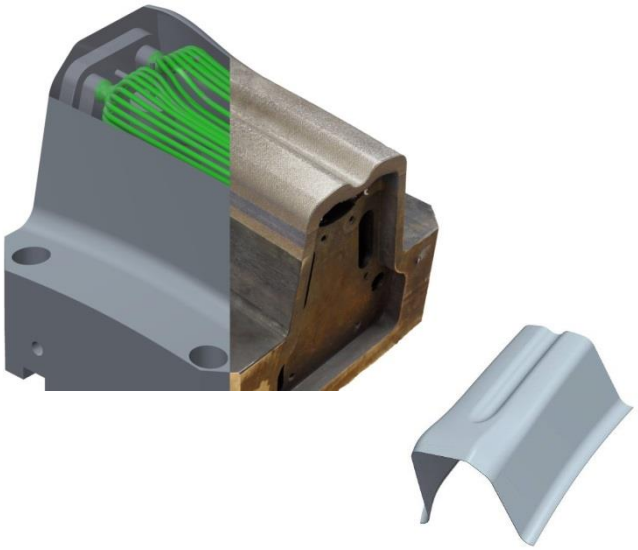
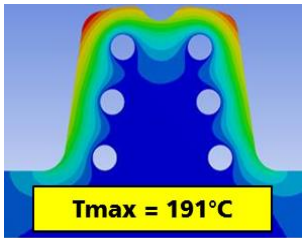
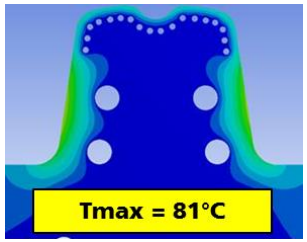
#7: Functionally Integrated Tooling Segments







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

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