AM Technologies: Development and Directions

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Additive Manufacturing is Driving Innovation and Help Overcome Current Barriers by…

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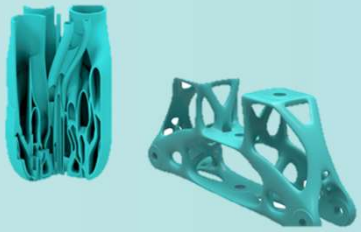
Product transformation
Shift from conventional design to innovative DFAM

Reimagine products

- Reduce weight, material
- Scan-to-product
- Expand performance
- Accelerate innovation cycles



Rethink business

- Individualization, personalization
- Zero inventory – on demand printing
- Design anywhere. Print anywhere.
- Increase competitiveness

STATUS QUO

Reinvent manufacturing

- Eliminate molding/castings/tooling
- Eliminate/simplify assembly process
- Reduce supply chains
- Affordable low volume production

Manufacturing transformation
Shift from prototyping / experimentation to mainstream industrial production

Additive Manufacturing: One Word for Multitude of Process Technologies for a Large Variety of Materials

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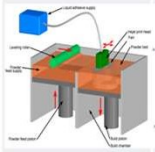
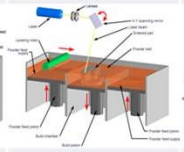
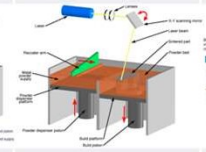
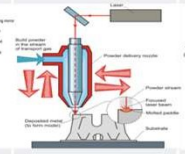
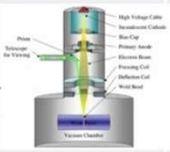
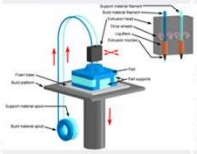
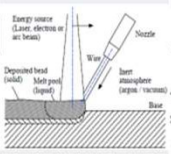
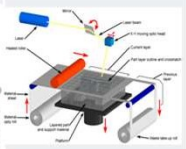
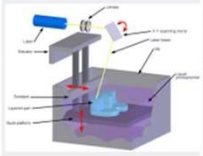
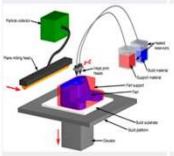
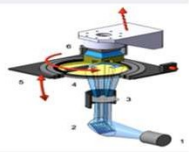
Solid									Liquid		
Powder						Wire		Sheet			
Polymer Metal Ceramic	Polymer Ceramic	Metal Ceramic	Metal	Metal	Metal	Polymer	Metal	Metal Paper	Polymer Ceramic	Polymer	Polymer
Ink-jet based & curing	*Fusing by laser beam*	*Melting by laser beam*		*Melting by electron beam*	*Spraying with nozzle*	*Melt and extrude*	*Melting by laser beam*	*Bonding of layers*	*UV-laser-based curing*	*Ink-jet based & curing*	*Mask Projection*
3D Printing (3DP)	**Selective Laser Sintering (SLS)**	**Selective Laser Melting (SLM)**	**Laser Cladding (LENS, LMD)**	**Electron Beam Melting (EBM)**	**Cold Spray (CS)**	**Fused Deposition Modeling (FDM)**	**Laser Cladding (LC)**	**Laminated Object Modeling (LOM)**	**Stereo-lithography (SLA)**	**Multi-Jet Modeling (MLM)**	**Digital Light Processing (DLP)**
											

Emerging Technologies for Multimaterials, Hybrid Processing and Integrated Solutions

Fast Technology Validation

AM enables paradigm shift in design, testing & validation

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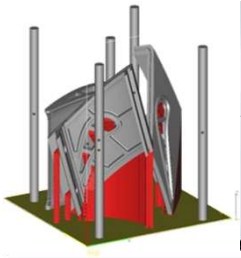
Integrated development: Accelerated iteration cycles in few months

3D (Re-)Design → SLM processing → Post processing → Instrumentation → Testing






Conventional process

"Testing is final validation at the end of development process"

- Sequential development processes
- Conservative development approach
- Moderate development goals
- Long development cycles

Novel paradigm

"Testing is integrated part of development process"

- Parallel and integrated development processes
- Radical development approaches
- Ambitious development goals
- Accelerated development goals, short iteration cycles

3 Key Elements in Additive Manufacturing

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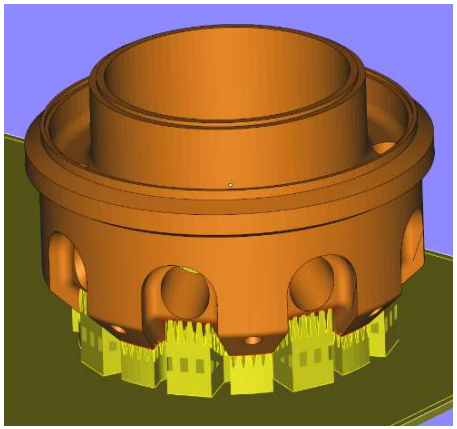

Figure: EOS GmbH

Figure: KASTO Win AMC

DATA PREPARATION
- Part Design / Export / Import / Modification
- STL Creation
- Support Structure Creation
- Build Simulation

MACHINE PREPARATION
- Build plate leveling
- Powder loading
- Recoater Setup
- Build Loading
- Build Plate Loading/Unloading

POST PROCESSING
- Powder Removal
- Powder Recycling
- Part Removal
- Build Plate Clean
- Supports Removal
- Surface Finishing
- Final Machining
- Heat Treatment

Reimagining Design, Production and Service to Accelerate Technology Download Through Additive

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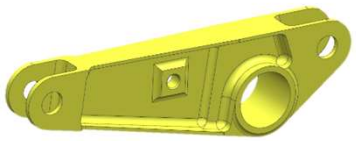
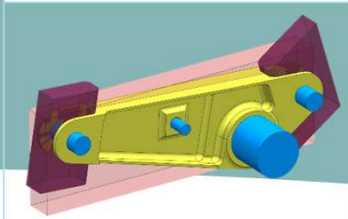
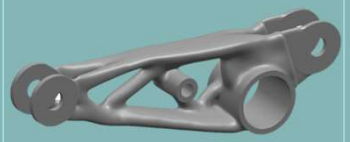
Requirements / original design



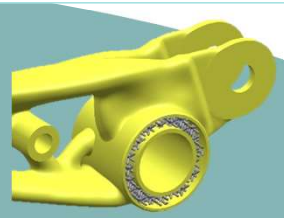
Generative design



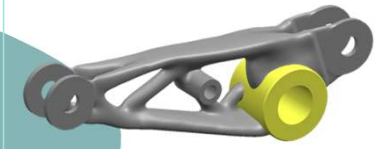
Topology optimization



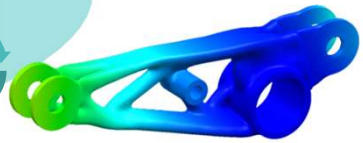
Light weighting*



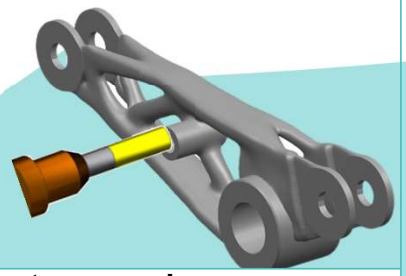
Adapt design
Convergent Modeling™



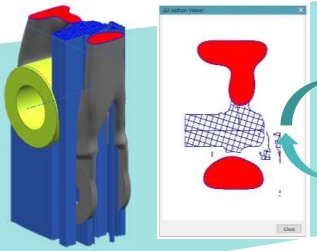
Validate
Product and process simulation



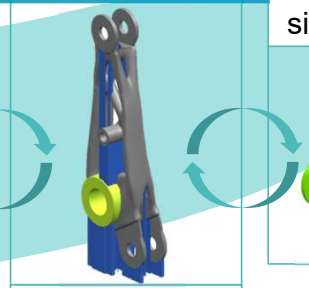
Final part



Post processing (heat treatment, machining and inspection)



Slicing, hatching printing, monitoring*



Prepare for printing*

* Powered by Materialise

Process and Material (Data) Development
Overview

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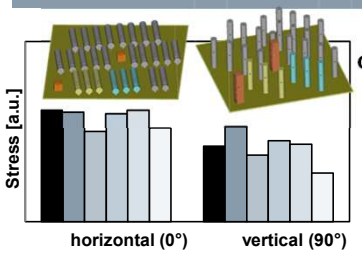
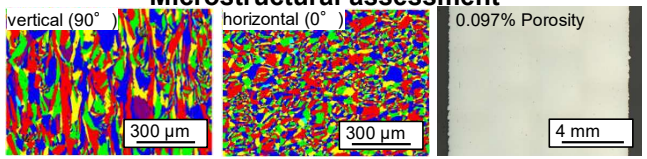
Process Development



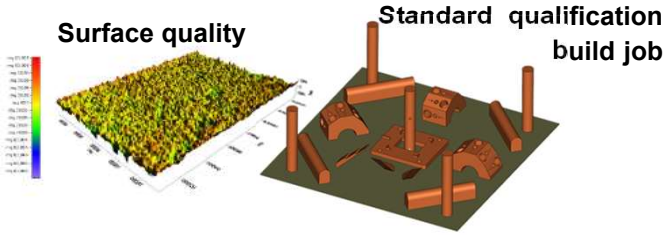
UTS for different sets of process parameters

Microstructural assessment

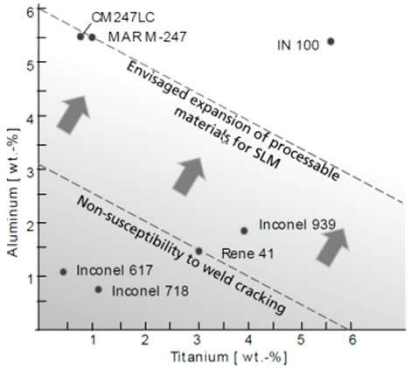


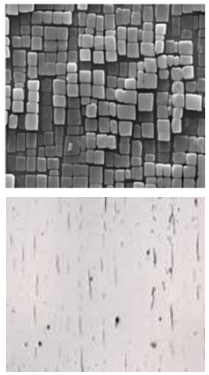
Surface quality

Standard qualification build job



Challenge for Hot Gas Path Applications



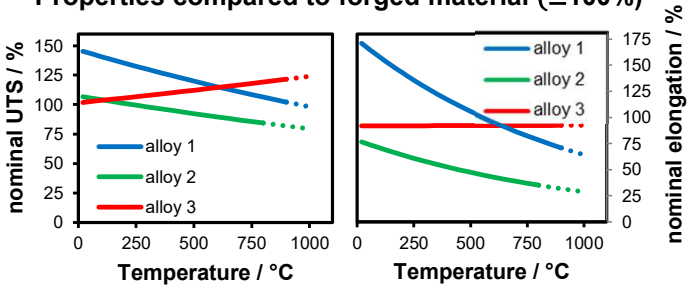


γ'-Precipitation impact on weldability:

Additional solidification stress due to γ'-precipitation exceeds fracture toughness of alloy → micro cracking

Material Data Generation

Properties compared to forged material (≙100%)



Distinctive properties in AM materials:

T, t, dynamic, anisotropy, residual stress, distortion, defects, microstructure…

Huge range of data for several temperatures needed:

tensile, HCF, LCF, creep/stress rupture, TMF, corrosion, physical props….

- Material design tools not available yet
- Limited range of materials for gas turbine applications available
- Time consuming and costly validation (full qualification: >> 500 k€; 1.5 to 2 years)
- Costs of post processing/high volume qualification - variable

Use Cases for Additive Manufacturing

Lead time and performance gains are the major drivers

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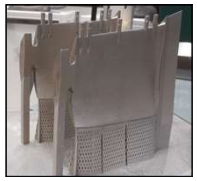
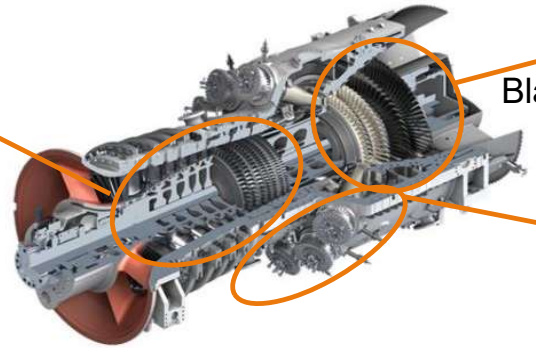
Drivers	Technology Validation	Production	After Market	
	Rapid Development	Rapid Manufacturing	Rapid Repair	Spare Parts on Demand
Lead time & Availability	↑	↗	↑	↑
Costs	↗	↗	↗	↗
Performance & Innovation	↑	↑	→	→

Compressor
Small Parts





Turbine
Blades & Vanes
Small Parts

Combustion System
Burner
Swirler/Nozzle/Filter/Mixer

High Tech components with complex design and high potential to improve customer value (efficiency, durability)

Build Simulation, In-situ Monitoring for Rapid Qualification

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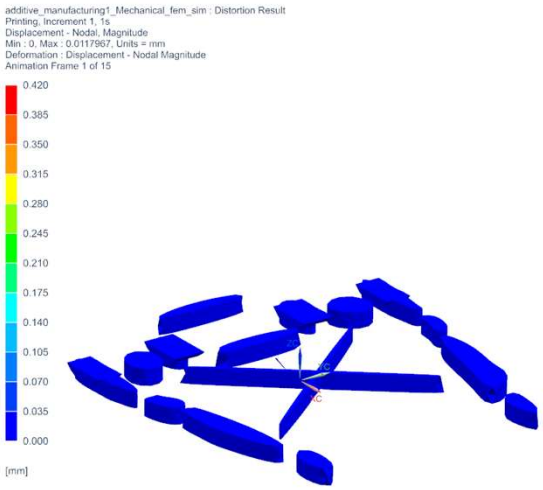
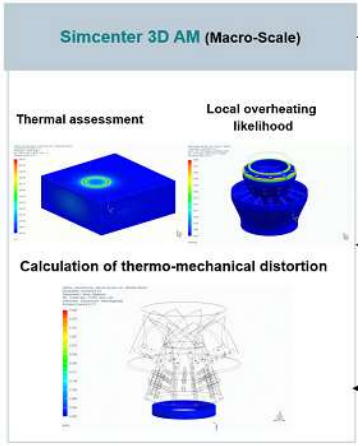
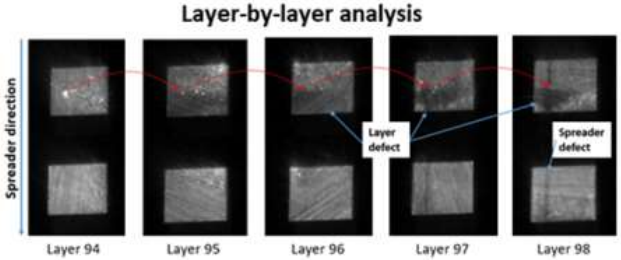
- Digital products to simulate the 3D printing process for AM
- Open architecture and physics based modeling
- Digital twin of production to simulate:
  - Temperature with and without powder
  - Probability of overheating
  - Distortion before support, after heat treatment as build
- Compensation workflow
- Prediction of shrink lines
- Recoater interference
- Stiffness calculation



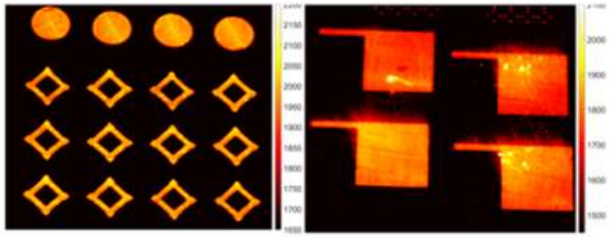


- What can it detect?
  - Most process anomalies
    - Spatter
    - Spreader defects
    - Layer defects or short feeds
    - Warping
    - etc.
  - Heat distribution and uniformity

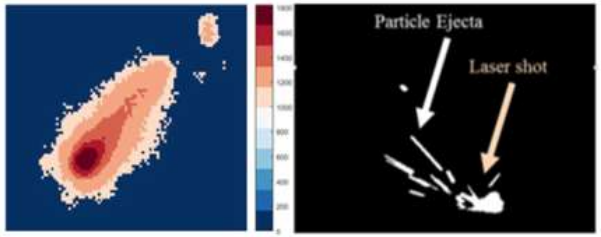
Thermal Tomography



Thermal map shows process and defect evolution



Direct view and particle ejecta show melt pool detail



Combination of techniques for closed loop control

What to expect with AM

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Design	Equipment & Process	Materials	Implementation	Mindset
• Design for AM • Data handling • Lifing tools for AM design	• Capacities, build chamber sizes • Productivity → accelerated processes (multiple lasers) • Drive down AM part costs • Transferability and standardization • Robustness and repeatability → process control	• Enlarged range of materials • Hard-to-weld materials • Simplified material's qualification • Continous powder quality	• Production line integration Standardized interfaces • Digitalization of full process chain • Seamless and streamlined data flow • Industrial EHS standards	• More confidence in engineering community • But DON'T burn AM with wrong perceptions • Exploit the full potential and the new „freedom of design"

- CANNOT print EVERYTHING and DO NOT expect to print EVERYTHING
- Don't expect to save money by using conventional design in AM
- Machines are expensive, and still need further development
- Design freedom is free, but prototyping /design /development costs are uncertain
- Every parameter changed is not completely independent, Parameter development takes time and $$$
- Years and $$$$ to develop custom AM systems for particular system
- Powder loss during processing
- Quality Control ????? Long Road, Tracking large datasets - if possible, save all print data