Willkommen
Welcome
Bienvenue

Empa
Materials Science and Technology

Laser 3-D printing: How important is the heat flow ?

Experiments and Simulations for powder bed and powder feed additive manufacturing

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Laboratory for Advanced Materials Processing
Empa, Swiss Federal Laboratories for Materials Science and Technology

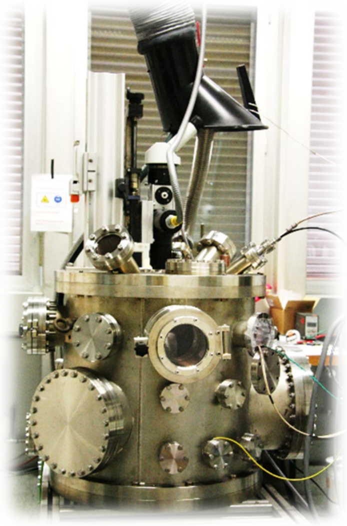
Outline

- Introduction – where are we now?
  - State-of-the-art in metal AM and mission of the laboratory
- Activities – what are we doing?
  - Design of novel alloys and composites for AM
  - Functionality integration by AM
  - Optimization of AM processes
  - Real-time observation, monitoring, closed - loop control
- Outlook – what comes next?

AM equipment at Empa

Beam Mobile1.0

800 µm



Home-built DMD

10 µm

Sisma MySint 100

55 µm

Concept Laser M2

95 µm

AddUp FormUp350

70 µm

AM equipment at Empa

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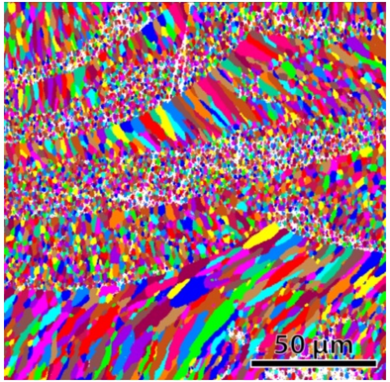
Al_{2xxx} cross section EBSD

Upper part, second laser scan

Cooling rate
~10^6 K/s



Cooling rate
~10^4 K/s

Sisma MySint 100

55 µm

AM equipment at Empa

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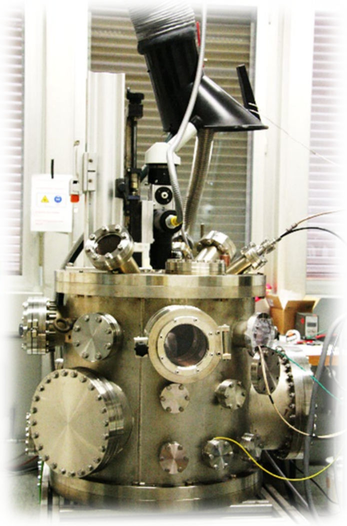
Beam Mobile1.0

800 µm



Home-built DMD

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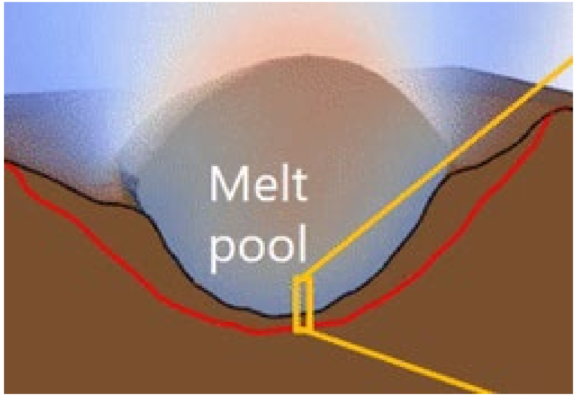
Melt pool sizes and cooling rates



Melt pool volume
~1 mm^3 = 1 µl

Home-built DMD

10 µm

Melt pool volume
0.000001 mm^3 =1000 μm^3 = 1 pl

Beam Mobile1.0

800 µm

Cooling rate
~10^3 K/s

Cooling rate
~10^9 K/s

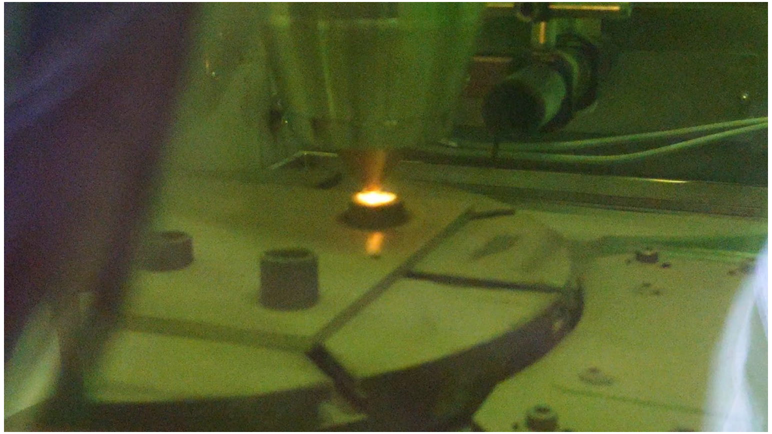
Additive Manufacturing of metals

AM processes for metals

Selective Laser Melting (SLM)

Other terms: Laser cusing, laser sintering, powder bed fusion, laser metal fusion…

Laser (Direct) Metal Deposition



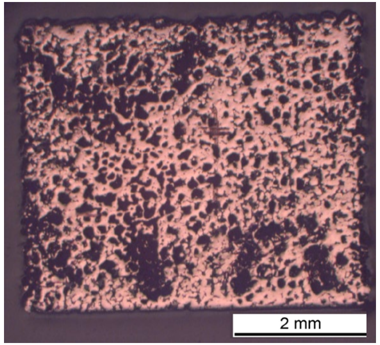
Other terms : laser metal deposition, laser engineered net shaping (LENS)…

Additive Manufacturing of metals

State of the art and problems

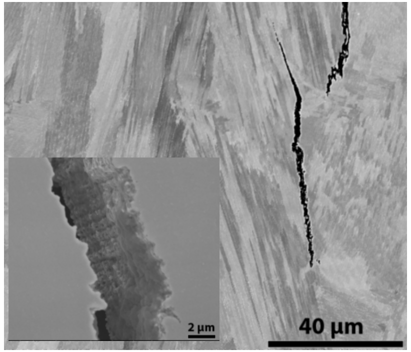
- Up until now, only a few alloys can be reliably used for AM (e.g. SS316L, AlSi10Mg, Ti6Al4V)
- Many technically relevant alloys (Ni superalloys, intermetallics, Cu alloys, precious metal alloys) are notoriously difficult to process
- Useful information on processability is still very limited or not existing!

Porosity



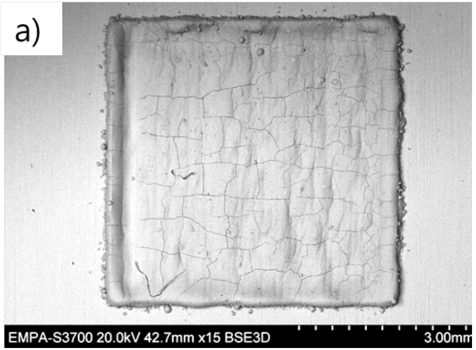
Cu

Solidification cracks



CM247LC

brittle cracks



Ti46Al3Nb

Multi-physics process modeling

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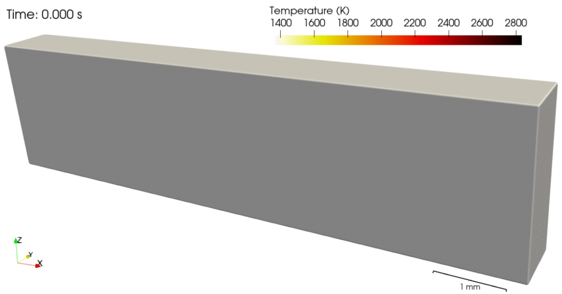
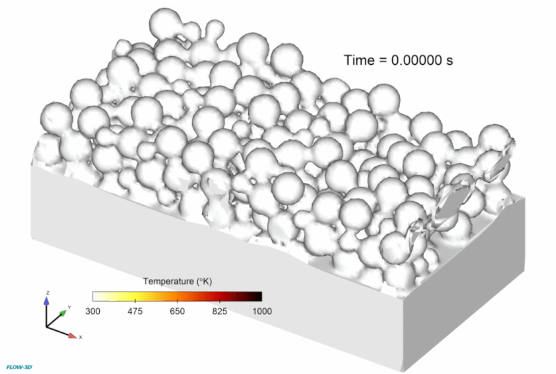
Increasing modelling and computational complexity

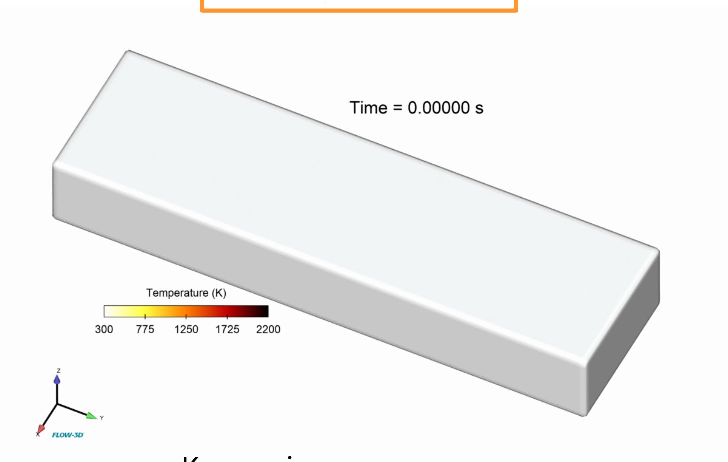
Laser welding

Powder Bed Fusion

Direct Energy Deposition





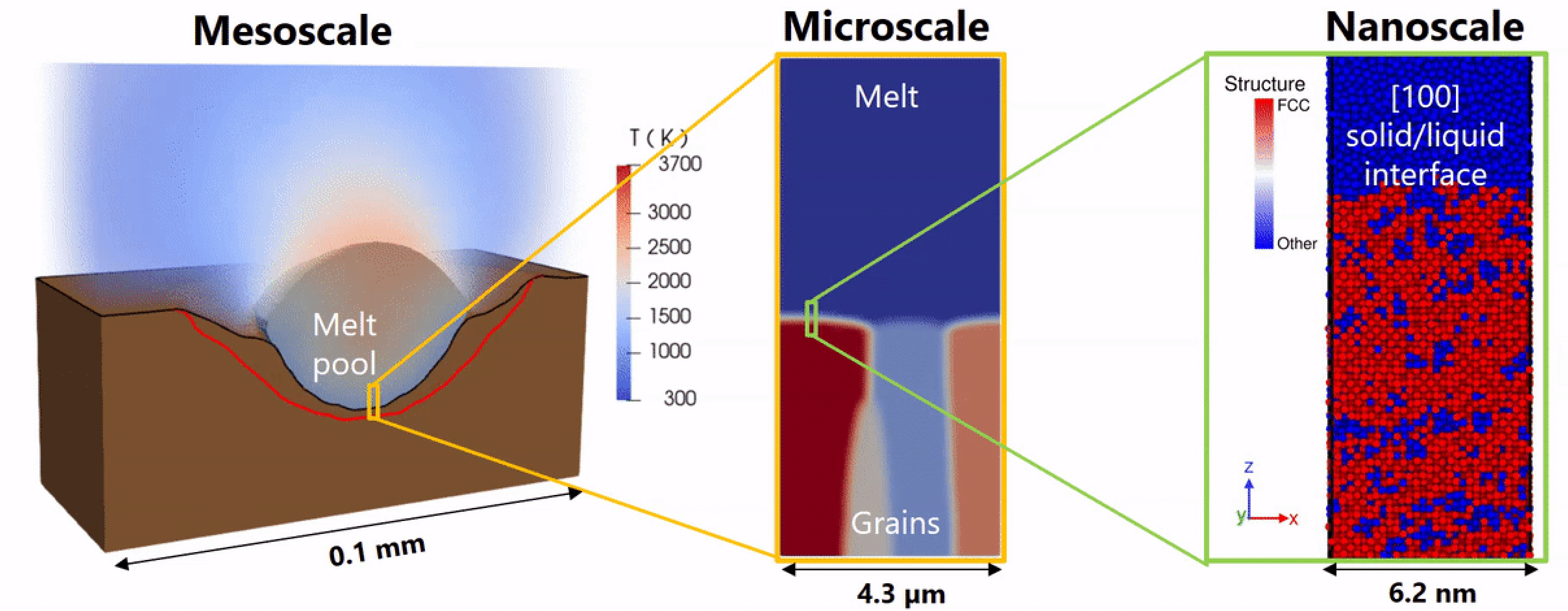


Known issues:
- Surface humps
- Keyhole-induced pores

Known issues:
- Particle sliding, denudation
- Balling
- Spattering

Known issues:
- Debris accumulation
- Powder clustering and agglomeration

Multiscale microstructure modeling



Multiscale modeling of solidification microstructure in copper after laser melting

Activities – what are we doing?

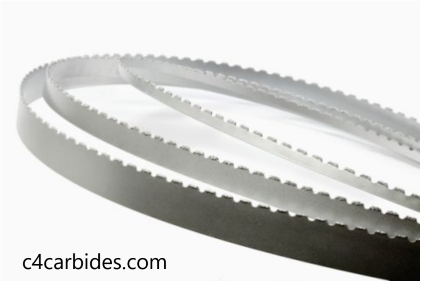
Materials and Applications

Ni and Al superalloys
steels, Ti alloys,

Arcam.com

- Power generation
- Turbo machinery
- Engine parts

(nano-)particle
reinforced MMCs



- Abrasive tools
- Heat exchangers
- Medical technology

Au and Pt alloys
Silicon

- Watches
- Jewelry

large parts >1 m

small parts <1 mm

Alloy design for AM

Development of high-performance alloys and composites

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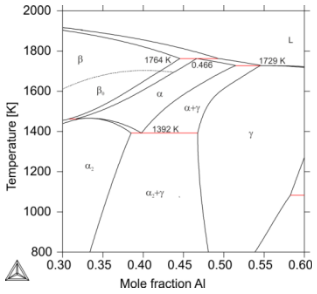
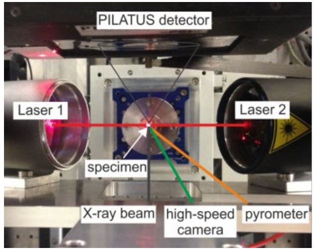
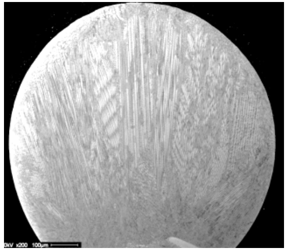
Computational Materials Design



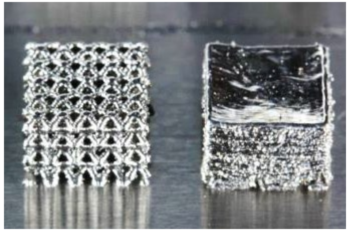
- Thermodynamics/kinetics
- Finite Elements
- Computational Fluid Dynamics
- Phase field simulation

Ex situ and *in situ* experiments





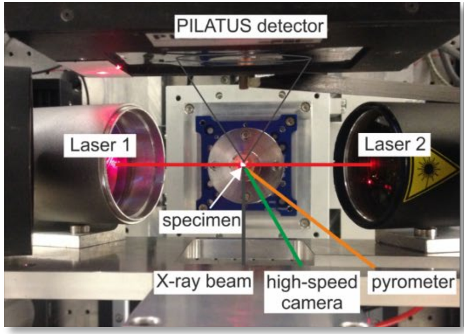
- Rapid solidification
- In situ synchrotron
- High speed imaging

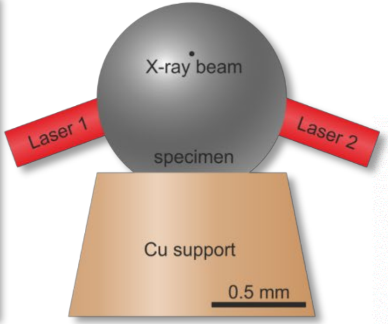


Novel alloys for AM

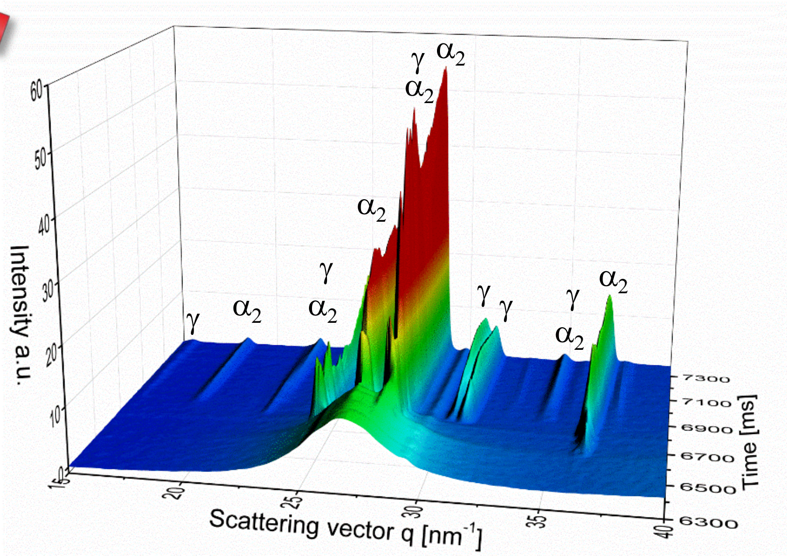
Rapid alloy screening

Real time investigation of ultrafast solidification processes





Ti-48Al



/C. Kenel et al. Scientific Reports 7 (2017) 16358/

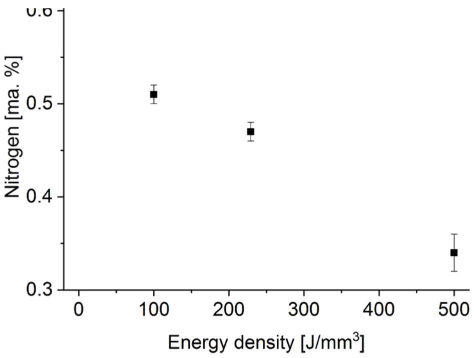
/C. Kenel et al., Scripta Mater 114 (2016) 117/

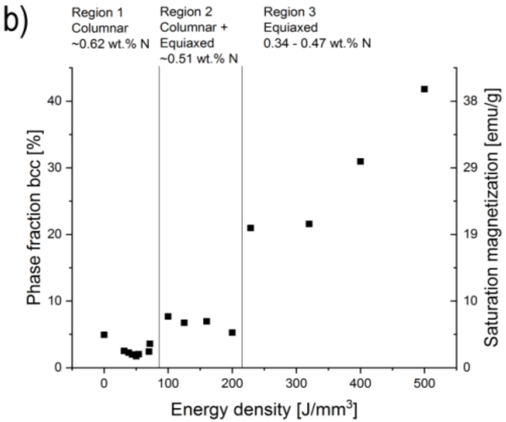
Swiss Light Source (SLS) @ PSI Villigen

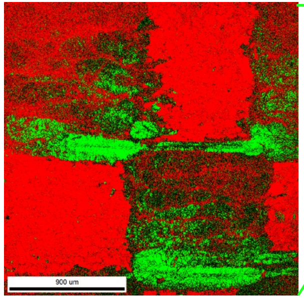
AM of functional materials

3D magnetic patterning via in situ alloy modification

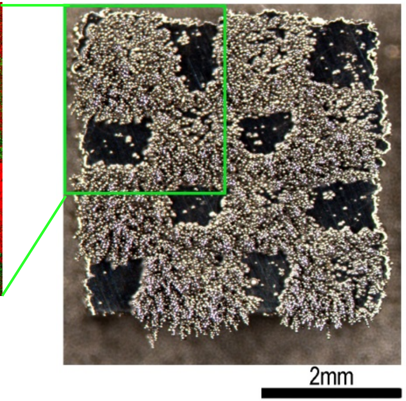
- AM of high nitrogen austenitic stainless steel
- Controlled evaporation of nitrogen during LPBF process (*in-situ* de-alloying) leads phase changes ranging from fcc (paramagnetic) to fcc/bcc (ferromagnetic)
- Site specific control of magnetic properties is possible by varying the laser parameters







Red fcc, Green bcc



/A. Arabi-Hashemi et al., Applied Materials Today 18 (2020) 100512/

Process optimization for AM

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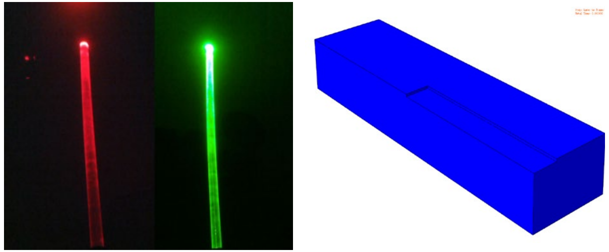
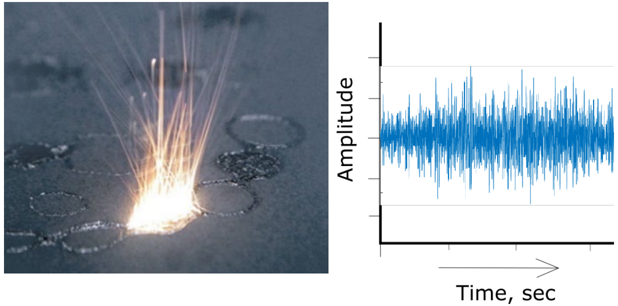
AM process
optimization



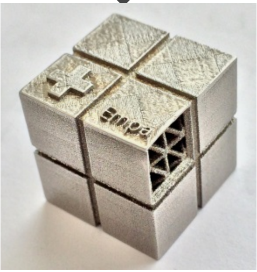
LuckLaser.com

- pulsed laser processing
- two-color laser processing
- optimized heat transfer

in situ
process monitoring



- acoustic emission
- thermography
- high speed imaging
- optical emission spectroscopy



AM parts with improved properties

Optimization of AM processes

Directed energy beam deposition of silicon

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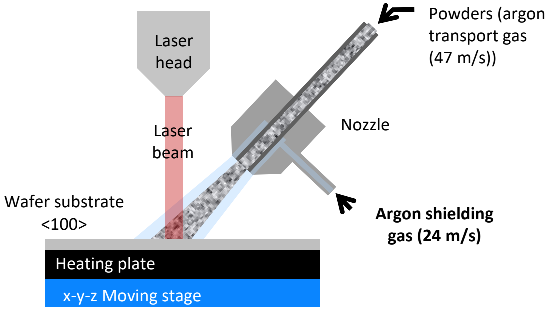
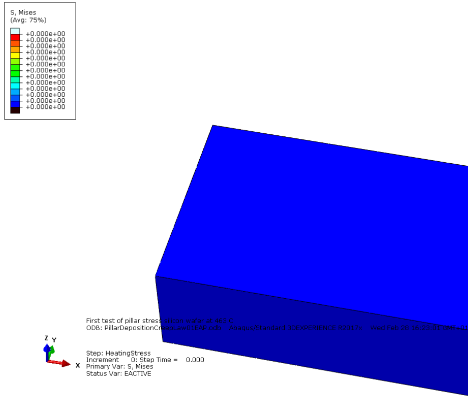
- Fabrication of Si pillars from >10 µm powder using pulsed laser
- Process optimization using finite element simulations and in-situ monitoring to control heat flows
- Epitaxial growth was maintained on more than 1 mm of pillar height

Schematic of DED setup

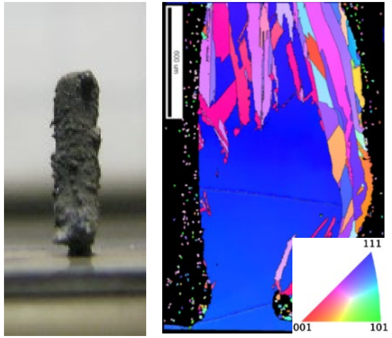


Simulation of temperature and stress fields



High speed imaging of Si deposition

Si pillars on wafer



/M. Le Dantec, et al. Proc. Int. Conf. Add. Manu. in Products and Applications (2018)/

Monitoring of 3-D metal printing: our approach

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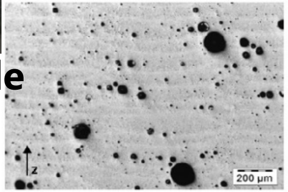
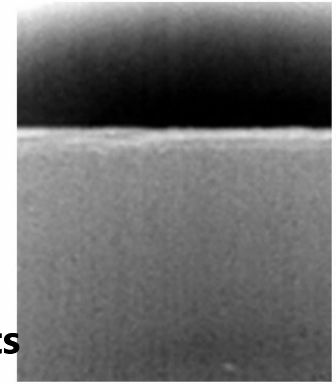
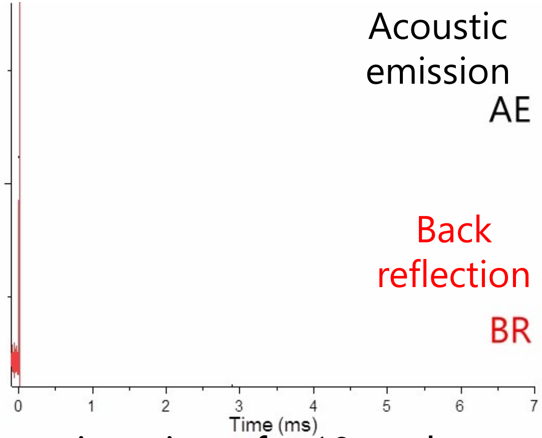
Bad sample

Good sample



Invisible defects





High speed X-ray imaging of a 10 ms laser pulse

Sensors

Machine learning / Artificial intelligence

Human intelligence

Monitoring of 3-D metal printing: major results

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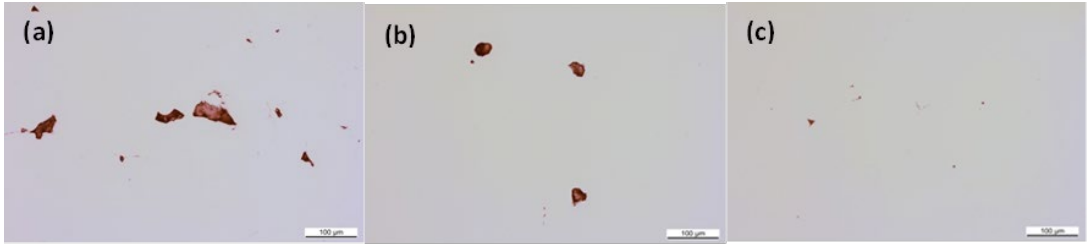
Classification accuracies: process quality > 90%

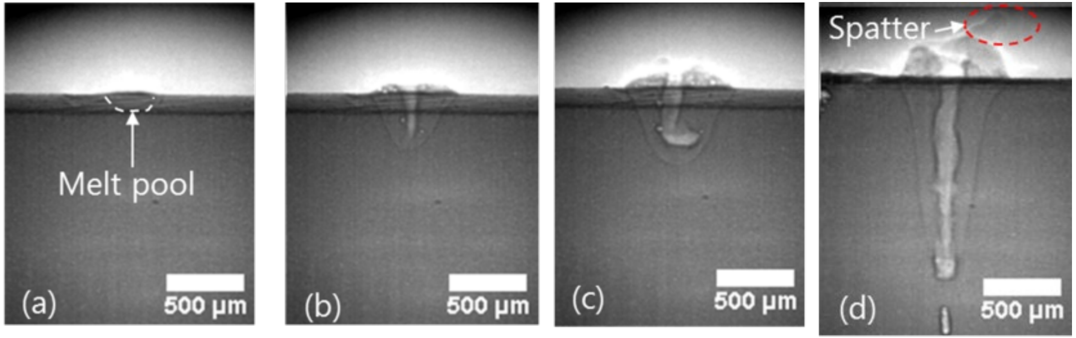
Shevchik S.A., Kenel C., Leinenbach C. and Wasmer K., Additive Manufacturing, Vol. 21, Issue May 2018, pp: 598-604, 2018

Shevchik S.A., Masinelli G., Kenel C., Leinenbach C., and Wasmer K., IEEE Transactions on Industrial Informatics, Vol. 19, Issue 9, pp: 5194-5203, 2019



Porosity 1,4% 0,3% 0,1%

Classification accuracies: process regimes> 91%



Conduction weld **Stable keyhole** **Unstable keyhole** **Spatter**

Classification accuracies
⇒ pore formation > 87%
⇒ pore removal > 73%

Shevchik S.A., Le-Quang T., Meylan B., Vakili-Farahani F., Olbinado M.P., Rack A., Masinelli G., Leinenbach C., and Wasmer K., Scientific Report, Vol. 10, paper ID: 3389, 2020

Real-time monitoring & control: major results

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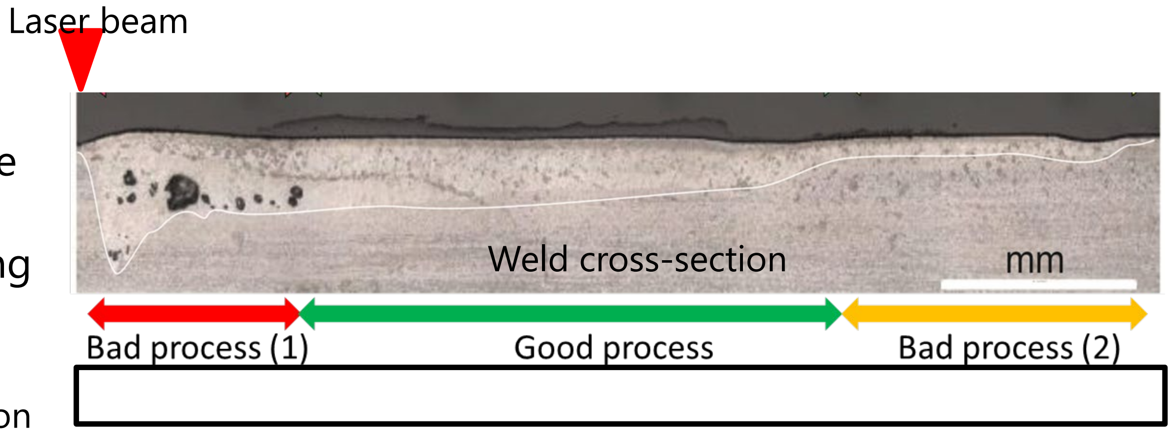
Real-time process monitoring

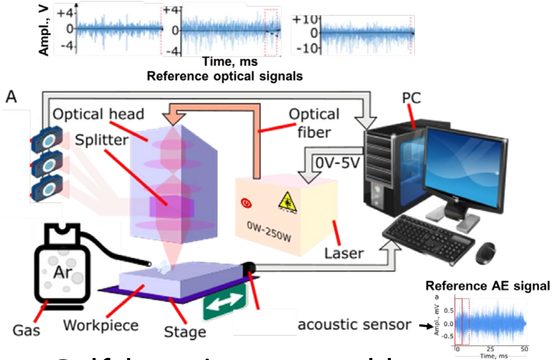
Quality classification



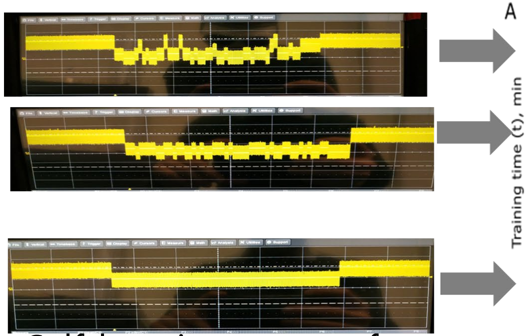
Classifications

- Accuracy > **90%**
- Distance = **25 µm**
- Time:
  - Today **70 ms**
  - Tomorrow **1 µs**
  - Planned **100 ns**

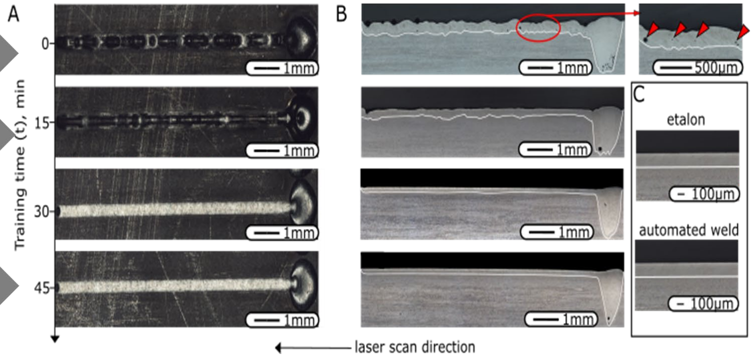
Shevchik S.A., Le-Quang T., Vakili-Farahani F., Neige F., Meylan B., Zanoli S., and Wasmer K., IEEE Access, Vol. 7, Issue 1, pp: 93108 - 93122, 2019



Self-learning control loop



Self-learning process for defect free laser welding



Comparision self-learning control and etalon

Masinelli G., Le-Quang T., Zanoli S., Wasmer K., and Shevchik S.A., IEEE Access, 2020

Outlook – what comes next?

Emerging research fields at Empa

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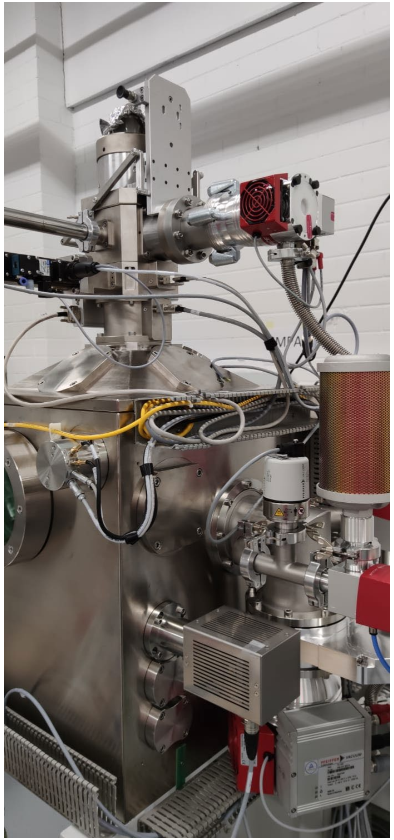
- Multi-physics simulation of AM processes
- AM of functionally graded multi-materials
- AM of shape memory alloys (NiTi and Fe-based)
- Design and fabrication of mechanical meta-materials
  for vibration damping/seismic damping
- Wire feeding electron beam AM
- Monitoring and control of complex processes
  laser welding, AM



Thank you for your attention