Process monitoring for quality assurance in laser powder bed fusion additive manufacturing

LUT 3D seminar

2.12.2020

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Research Scientist
VTT

My journey

- 1992 born in Outokumpu, FIN
- 2011 started Mechanical Engineering studies at LUT
  - Major in laser processing
  - Learned that you can 3D print metals – cool!
- 2015 Bachelor's thesis at LUT
  - “The effect of focal point parameters in fiber laser welding of structural steel”
- 2016 Master’s thesis at VTT
  - “Utilizing metallic waste streams as raw material for powder-based additive manufacturing”
- 2017 Graduated as M.Sc.(Tech)
- 2017→ working at VTT’s Advanced manufacturing technologies research group

VTT – beyond the obvious

VTT is one of the leading research, development and innovation organizations in Europe. We help our customers and society to grow and renew through applied research. The business sector and the entire society get the best benefit from VTT when we solve challenges that require world-class know-how together and translate them into business opportunities.

Our vision
A brighter future is created through science-based innovations.

Our mission
Customers and society grow and renew through applied research.

Strategy
Impact through scientific and technological excellence.

Established in **1942**

268 M€
Net turnover and other operating income (VTT Group 2018)

2,049
Total of personnel (VTT Group 31.12.2018)

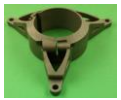
Owned by
Ministry of Economic Affairs and Employment

31%
Doctorates and Licentiates (VTT Group 2018)

44%
From the net turnover abroad (VTT Group 2018)

Experimental facilities

From powder to product – agile pilots

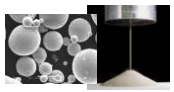


Material & component testing

Post processing

Direct Write Technology

Selective Laser Melting



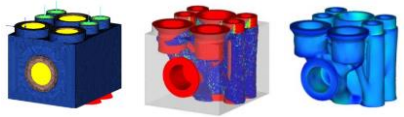
Powder characterization

Plasma spheroidization

Gas atomization

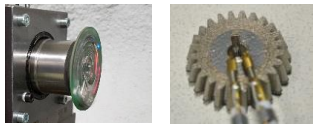
Application Services

Competitive products & new business models



Design for AM

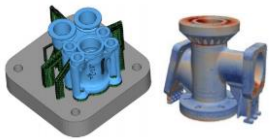
Digital spare parts



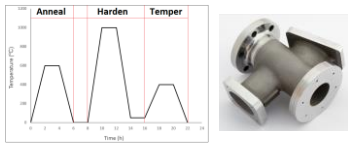
Added intelligence & functionality

Production Services

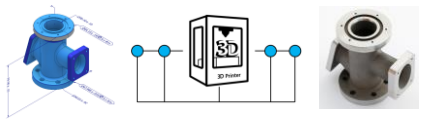
Increased productivity & quality



Thermal distortions mitigation



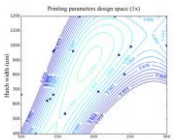
Post-processing



Integration of AM into production

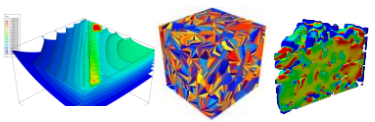
Material Services

Increased quality & material performance

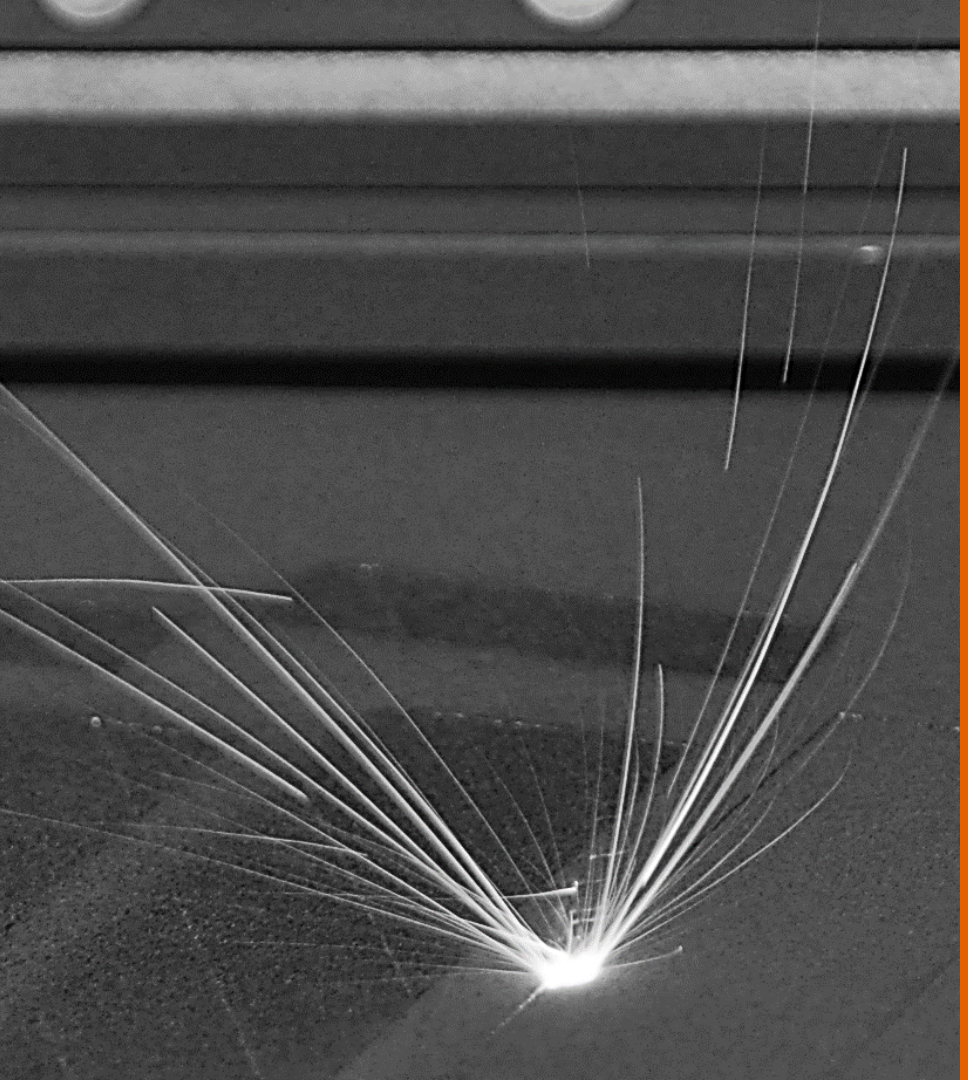


Powder printability

Application driven materials

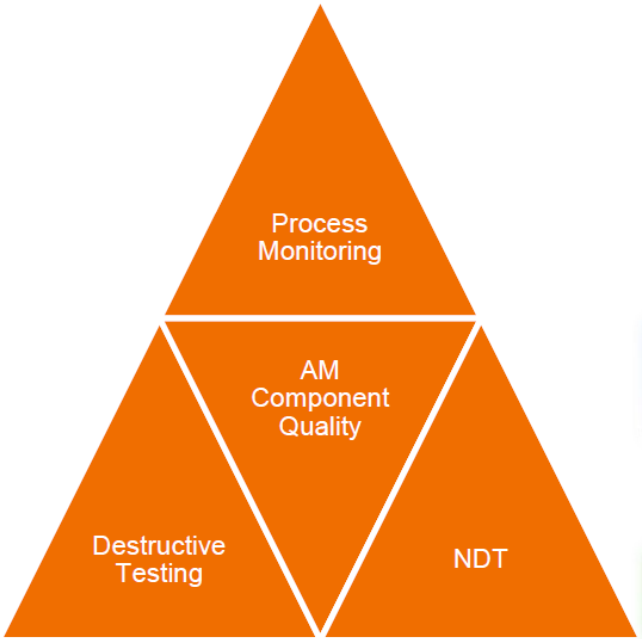


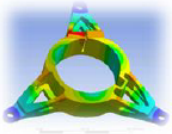
Virtual material factory



Process monitoring methods for L-PBF AM

Quality assurance and control in L-PBF AM





Process Qualification

- to ensure that the general process is controlled and repeatable and can produce components within quality requirements
- This includes: Machine, Powder, Operator

Component Qualification

- to ensure that a particular part can be printed within quality requirements given a certain design, build preparation, orientation, post-processing, etc.

Individual Part QC

- to ensure that every single part is printed within quality requirements. And if it is not, that defects are properly detected and the non-conformity properly recorded.

Background

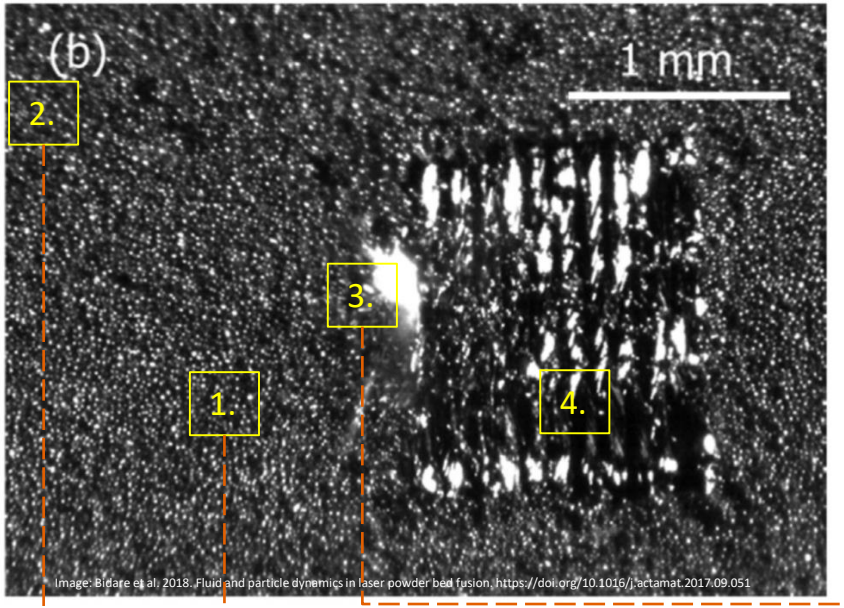


Image: Bidare et al. 2018. Fluid and particle dynamics in laser powder bed fusion. https://doi.org/10.1016/j.actamat.2017.09.051

- Layer-by-layer manufacturing enables us to see the “inside” of the part as it is being built

1. Powder bed
2. Environment
3. Laser melting

→ 4. Built part (quality)

→ Process monitoring → Quality assurance

Goal: Constant (within set limits) signals = constant quality?

Commercially available solutions

1. Powder bed monitoring
   - Images of the powder bed before and/or after re-coating & exposure (usually with CMOS/CCD i.e. “normal” cameras)

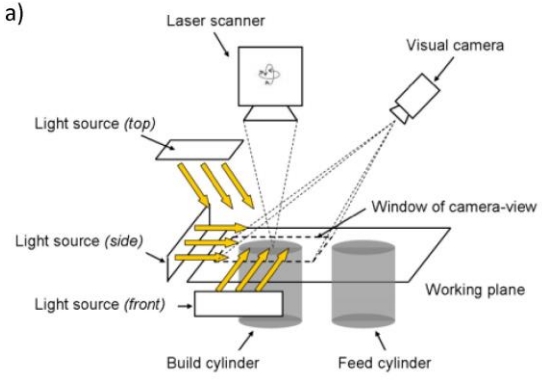
2. Environment
   - Laser power monitoring
   - Oxygen, pressure, gas flow, temperature etc. environmental parameters

3. Thermal signatures monitoring (melt pool monitoring, MPM)
   - On-axis, high spatial and temporal resolution (usually with photodiodes)
   - Off-axis, platform scale field-of-view (usually with IR/near-IR-cameras)

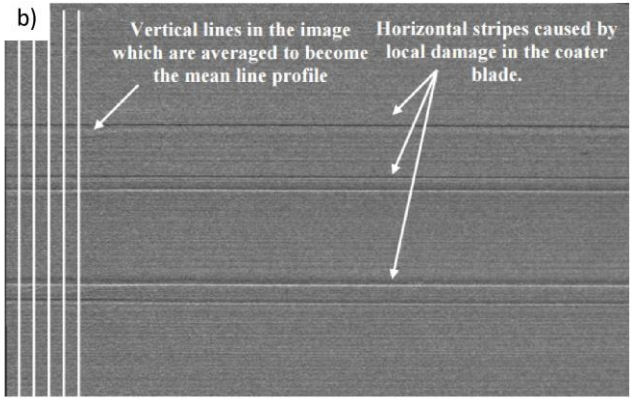
   - Mainly developed by the L-PBF machine manufactures and many of them are OEM-specific systems

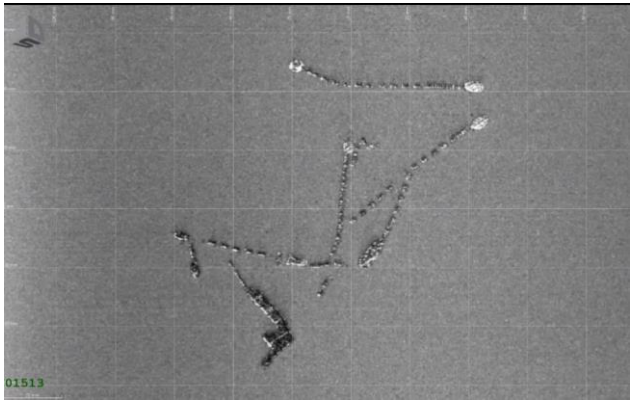
Powder bed monitoring

a)



b)



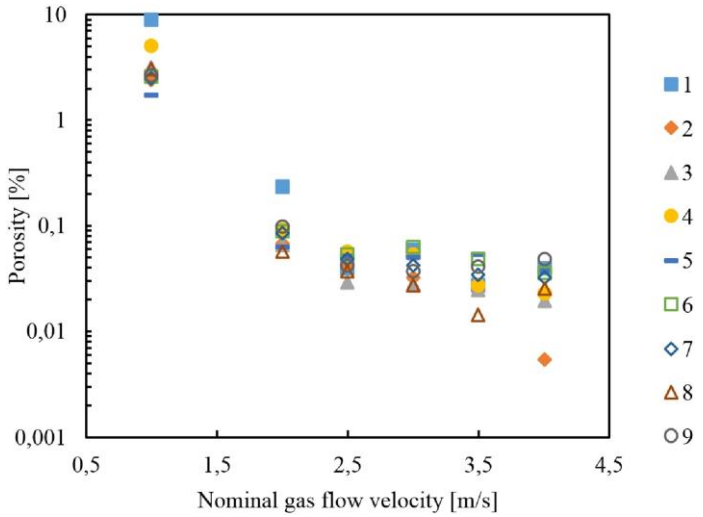


http://sffsymposium.engr.utexas.edu/Manuscripts/2011/2011-17-Craeghs.pdf

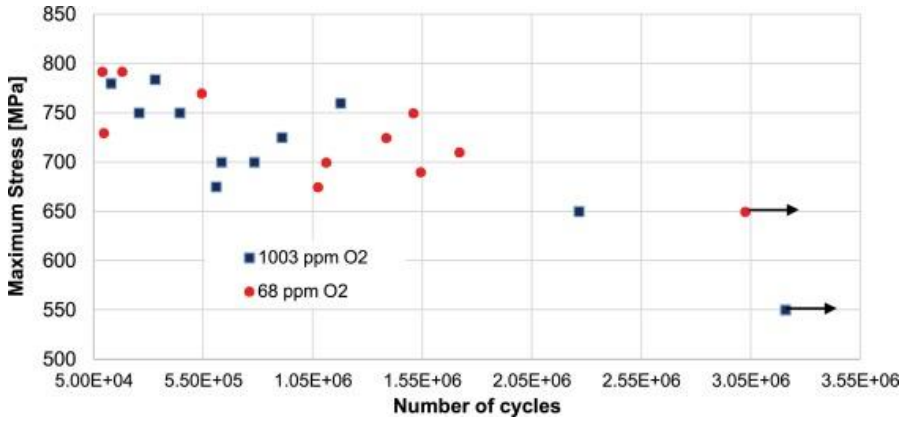
https://www.3dsystems.com/dmp-monitoring-solution

Environment monitoring (gas flow, oxygen)

Gas flow on porosity (316L)

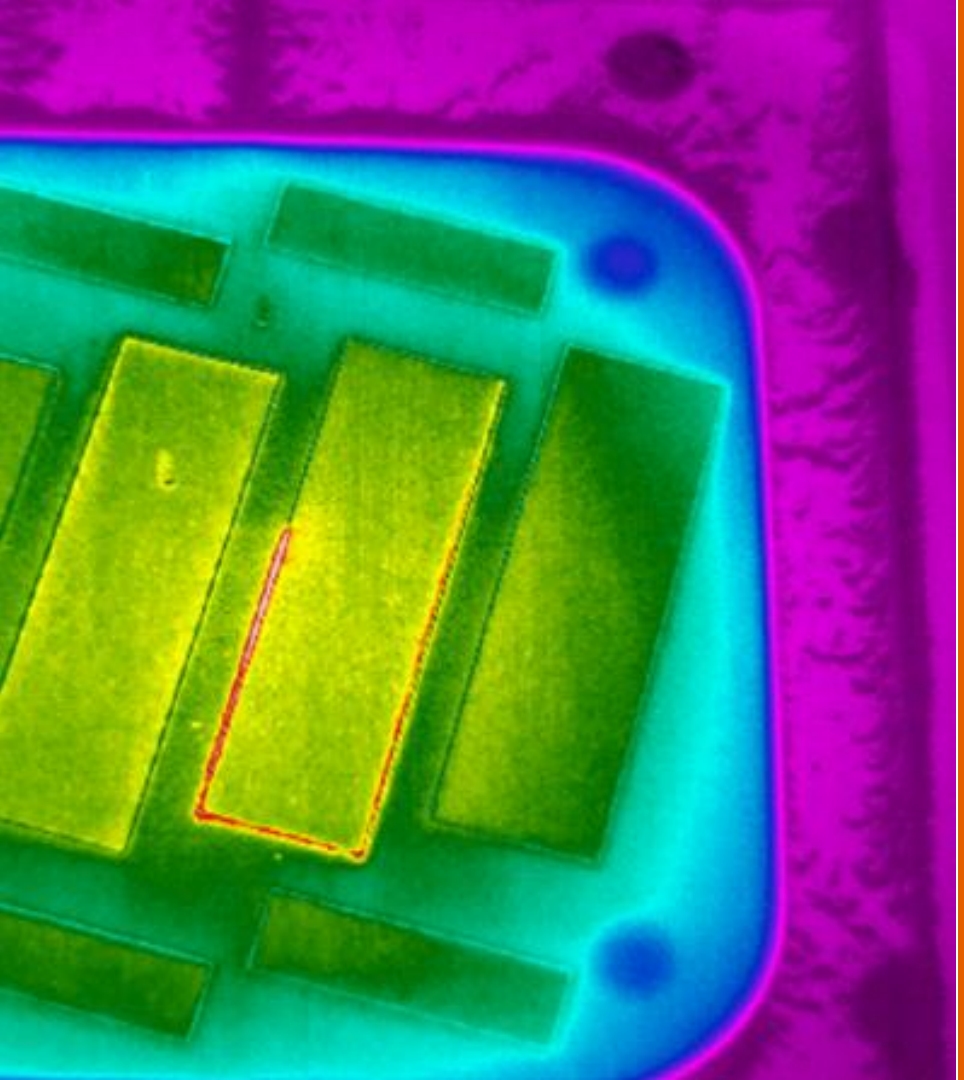


Oxygen concentration on fatigue (Ti64)



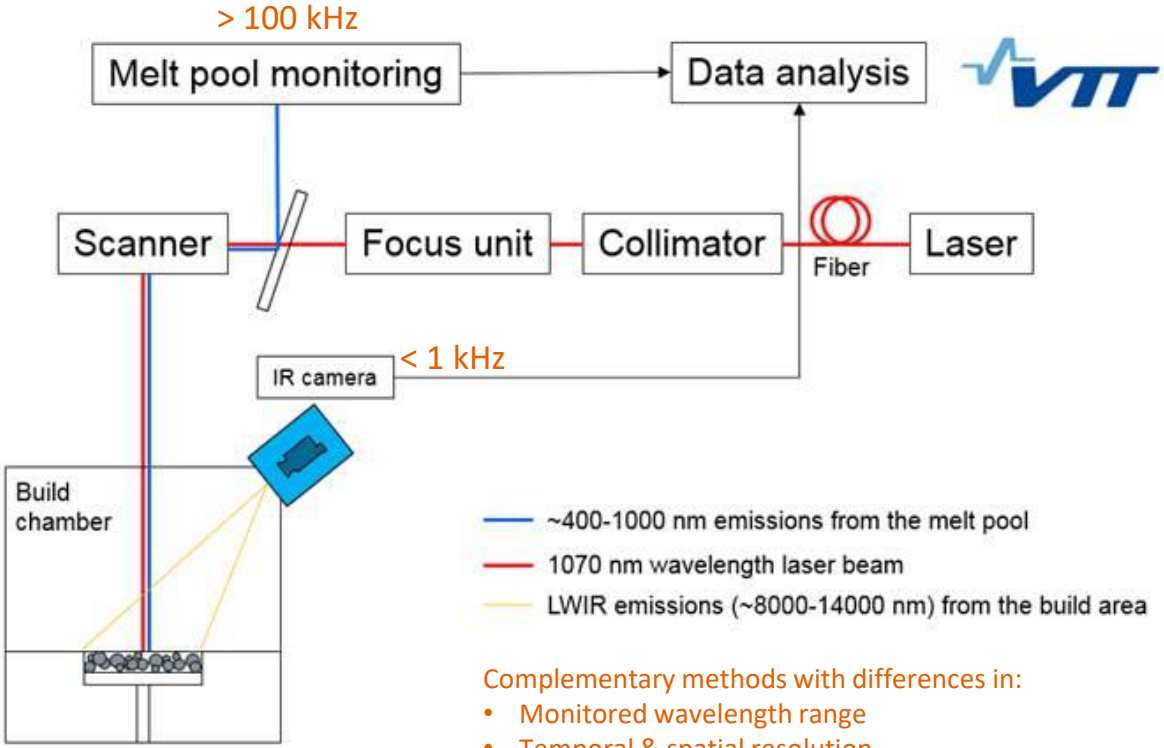
Reijonen et al. 2020. On the effect of shielding gas flow on porosity and melt pool geometry in laser powder bed fusion additive manufacturing. https://doi.org/10.1016/j.addma.2019.101030

The influence of oxygen on the chemical composition and mechanical properties of Ti-6Al-4V during laser powder bed fusion (L-PBF). https://doi.org/10.1016/j.addma.2019.100980



Monitoring thermal signatures in L-PBF

Monitoring thermal signatures

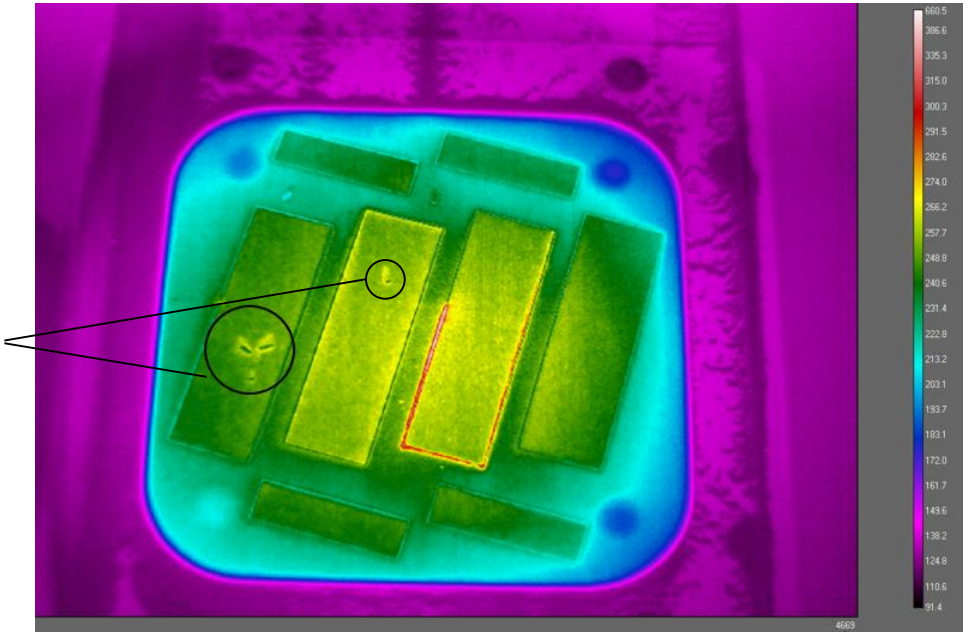


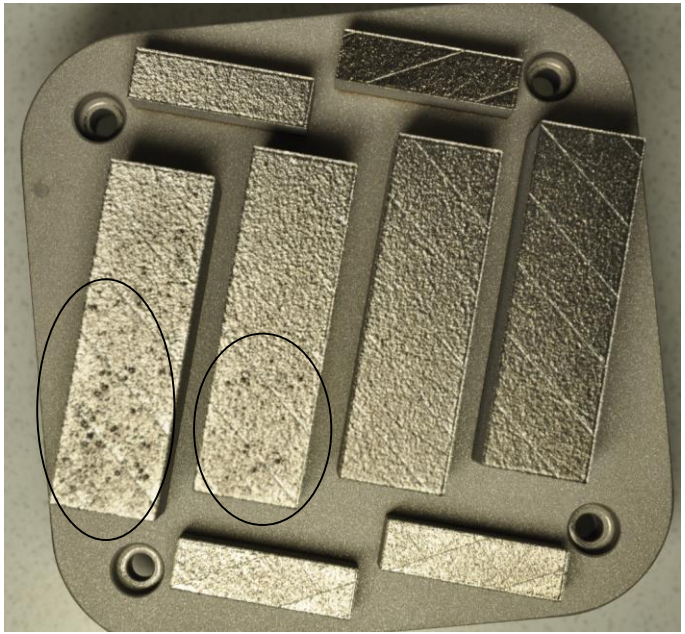
Complementary methods with differences in:

- Monitored wavelength range
- Temporal & spatial resolution
- On/off axis

Off-axis thermal monitoring at VTT

Spatter landing at the left hand side parts

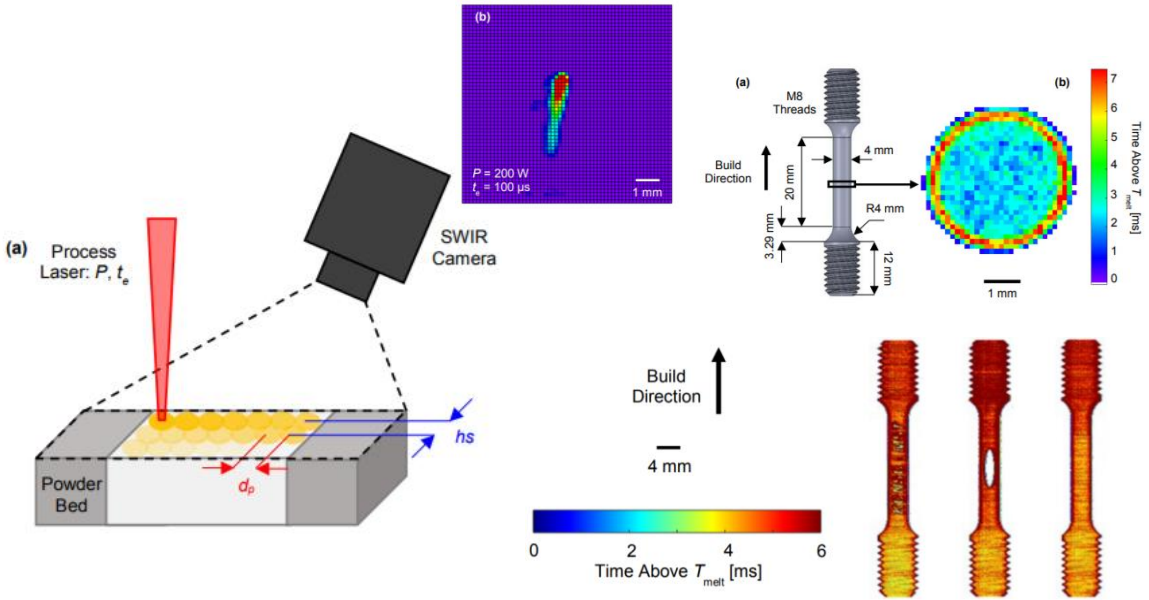


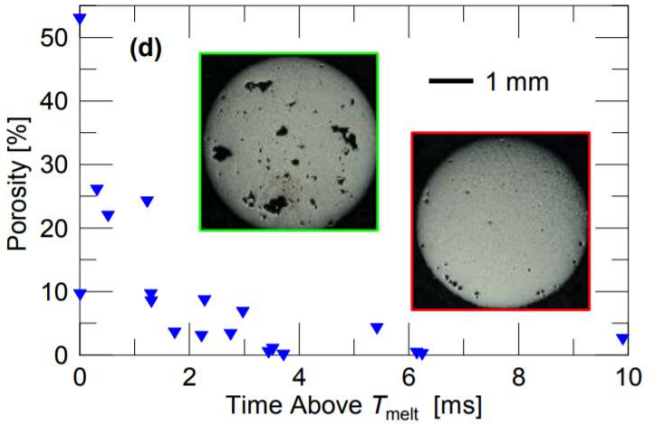


Images: VTT

- Thermal camera FLIR A655sc at VTT
- Experimental material, non-optimal powder size & parameters caused excessive spattering

Off-axis melt-pool monitoring





- Short-wave infrared (SWIR) camera (~1000-3000 nm)

http://sffsymposium.engr.utexas.edu/sites/default/files/2018/182%20UseofSWIRImagingtoMonitorLayerToLayerPart.pdf

Melt pool monitoring at VTT

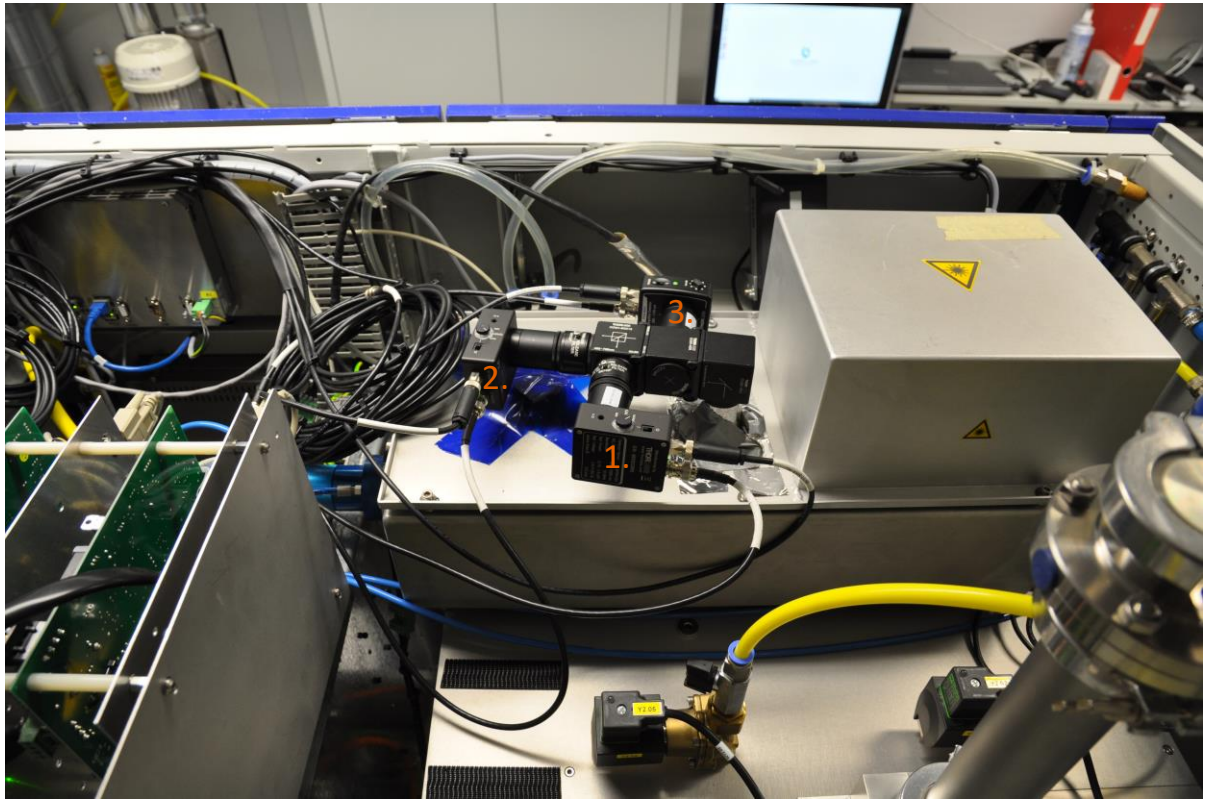


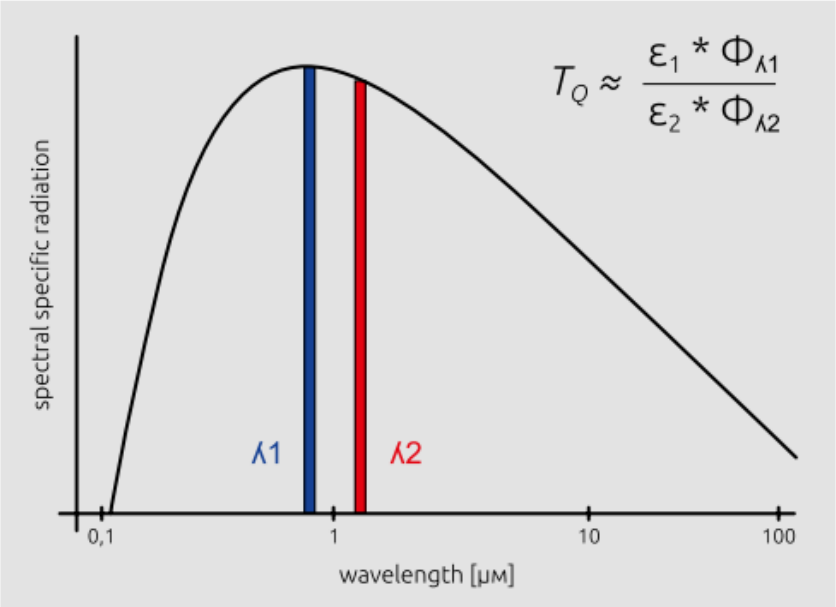
Image: VTT

- PrintRite3D MPM by Sigma Labs Inc. installed into SLM Solutions 125 HL L-PBF system
- Data acquisitions at 100 x 100 µm grid at 200 kHz
- 3 photodiodes
  1. 636 ± 5 nm
  2. 650 ± 5 nm

  } TEP metric

  3. 350-1100 nm = TED metric

Operating principle (TEP metric)



Book, A. Principle, advantages, limitations and applications of two-colour pyrometers in thermal processes. Technical Reports, KELLER HCW GmbH. TR_006_201507_en

Spectral radiance of a surface per unit frequency or wavelength from Planck's law:

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/(\lambda k_B T)} - 1}$$

Limitations

	ε1 = 0.95 and ε2 = 0.93 Δε = 0.02 / (ε1)/(ε2) = 1.022		ε1 = 0.4 and ε2 = 0.38 Δε = 0.02 / (ε1)/(ε2) = 1.053	
Measuring channel	**Displayed temperature**	**Deviation ΔT**	**Displayed temperature**	**Deviation ΔT**
One-colour channel λ1	796 °C	-4 °C	731 °C	-69 °C
One-colour channel λ2	794 °C	-6 °C	723 °C	-77 °C
Two-colour	823 °C	+23 °C	856 °C	+56 °C

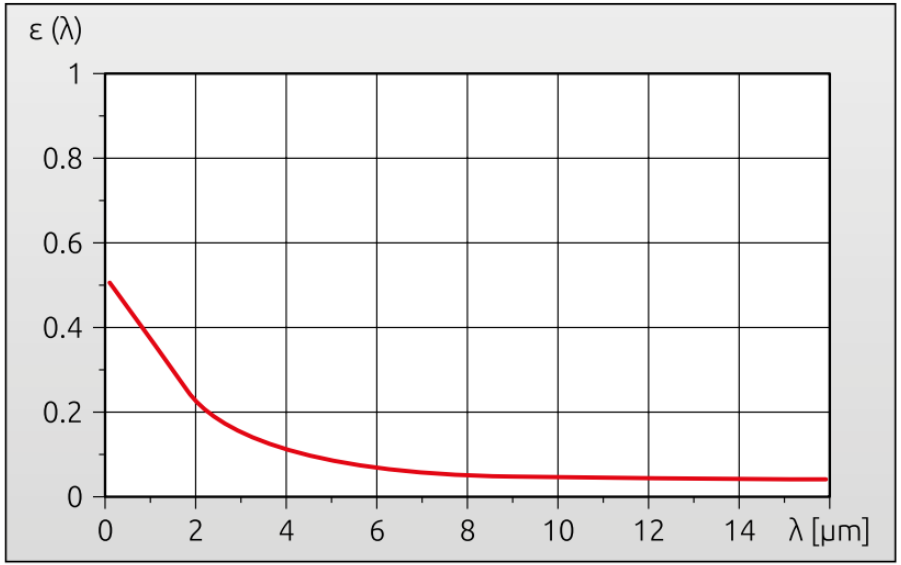


Fig. 3 *The emissivity of metals decreases with an increasing measuring wavelength.*

Book, A. Principle, advantages, limitations and applications of two-colour pyrometers in thermal processes. Technical Reports, KELLER HCW GmbH. TR_006_201507_en

What is it monitoring?

P-sensor 400-600 nm = visible light (vapor plume)
R-sensor 1064 nm = laser reflections
T-sensor 1100-1800 nm = substrate / surrounding material

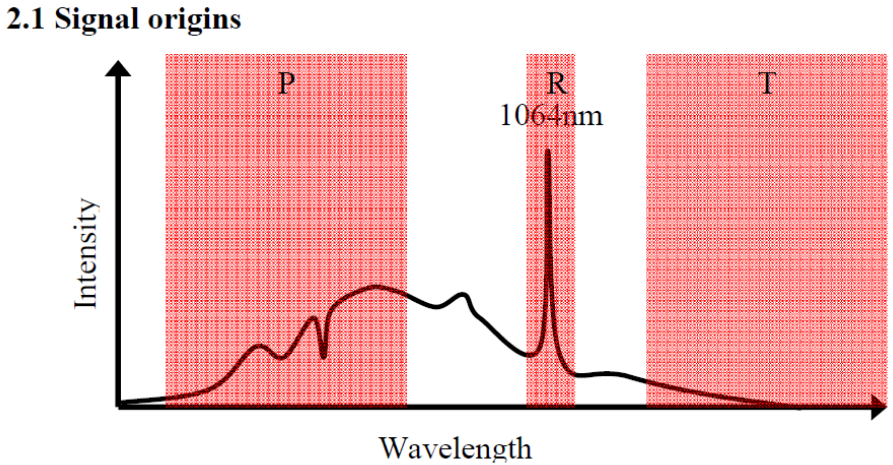


Fig.2 Typical intensity distribution of the electromagnetic signal from Nd:YAG welding, and the wavelength range of the three sensors.

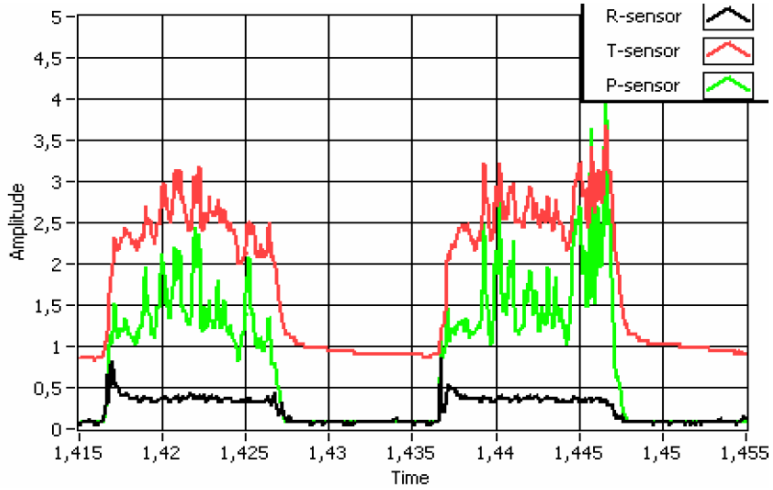
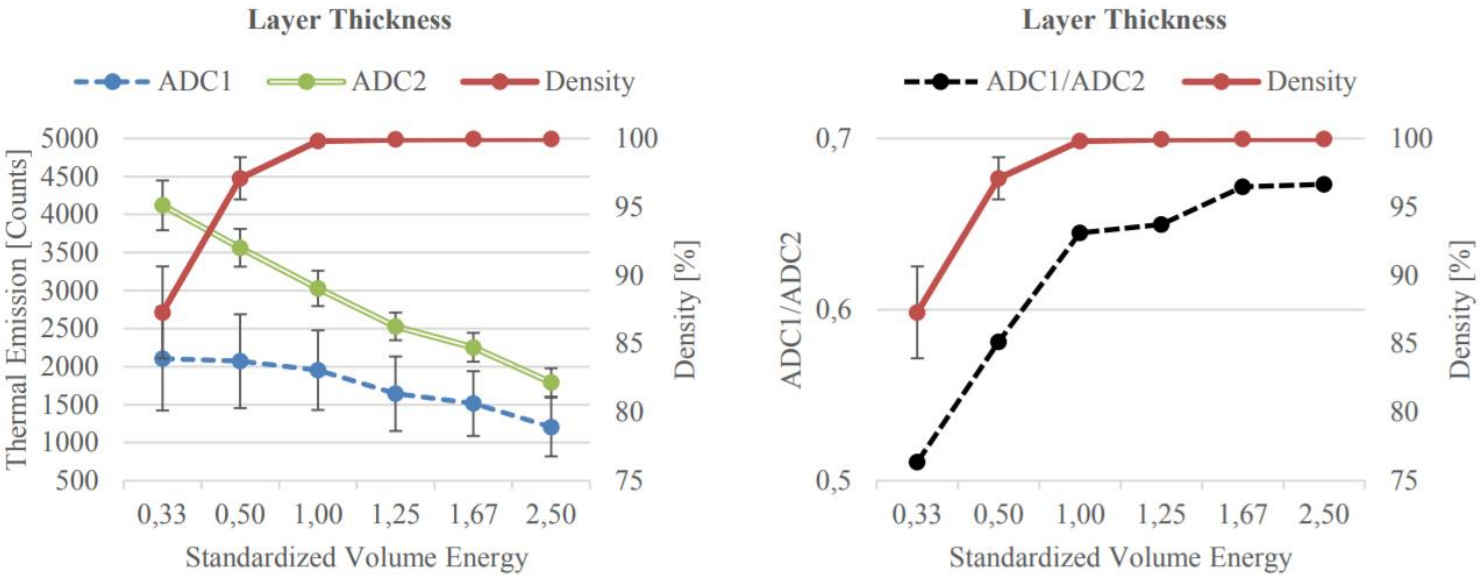


Fig.8b Signal value in the centre of the weld

Eriksson et al. BASIC STUDY OF PHOTODIODE SIGNALS FROM LASER WELDING EMISSIONS. In: 12th NOLAMP proceeding 2009: Nordic Laser Materials Processing Conference ; 24th - 26th August 2009 in Copenhagen

Does it correlate with anything?

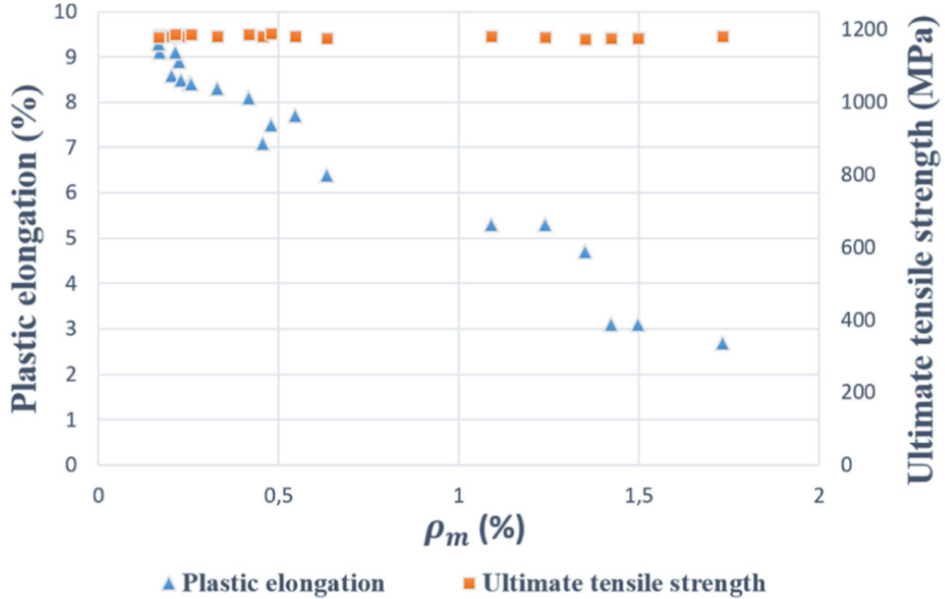


- > 1070 nm
- On-axis
- 2 photodiodes

Figure 8: Correlation between photodiode response due to ADC1 and ADC2 (left) as well as ADC1/ADC2 (right) and volume energy variation via layer thickness change.

https://sffsymposium.engr.utexas.edu/sites/default/files/2017/Manuscripts/InSituMeltPoolMonitoringandtheCorrelationt.pdf

Does it correlate with anything?



- 1150 nm–1800 nm
- Off-axis, platform scale view photodiode

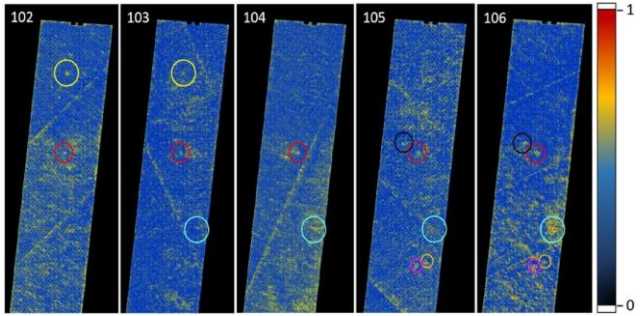
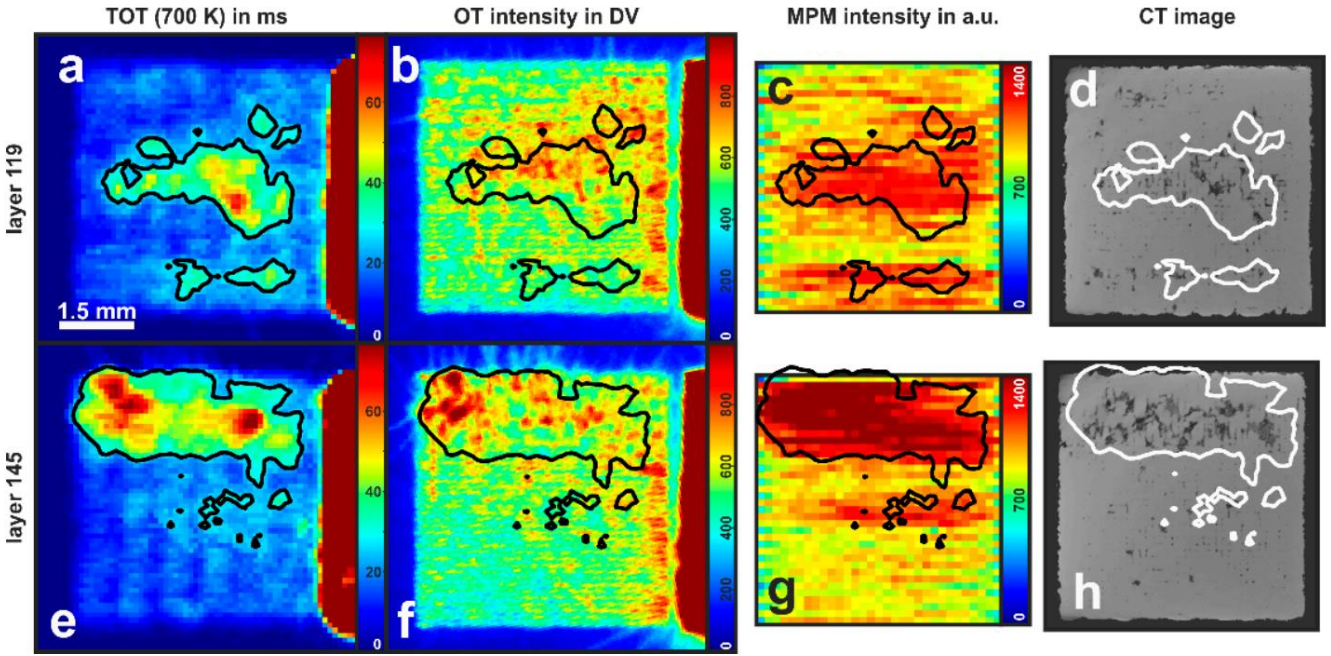


Fig. 6. Plastic elongation and ultimate tensile strength for Ti-6Al-4V ELI cylinders plotted as a function of *DMP-meltpool event volume to part volume ratio* (ρ_m).

Correlation of selective laser melting-melt pool events with the tensile properties of Ti-6Al-4V ELI processed by laser powder bed fusion. https://doi.org/10.1016/j.addma.2018.05.004

Does it correlate with anything?



- MPM
  - 100 kHz
  - > 1070 nm
  - On-axis
  - 2 photodiodes
- OT
  - 1 image/layer
  - Off-axis
  - 855 nm–905 nm
- Thermography
  - 900 Hz
  - Off-axis
  - 2000-5700 nm
- TOT = time over threshold

In-Situ Defect Detection in Laser Powder Bed Fusion by Using Thermography and Optical Tomography—Comparison to Computed Tomography. doi:10.3390/met10010103

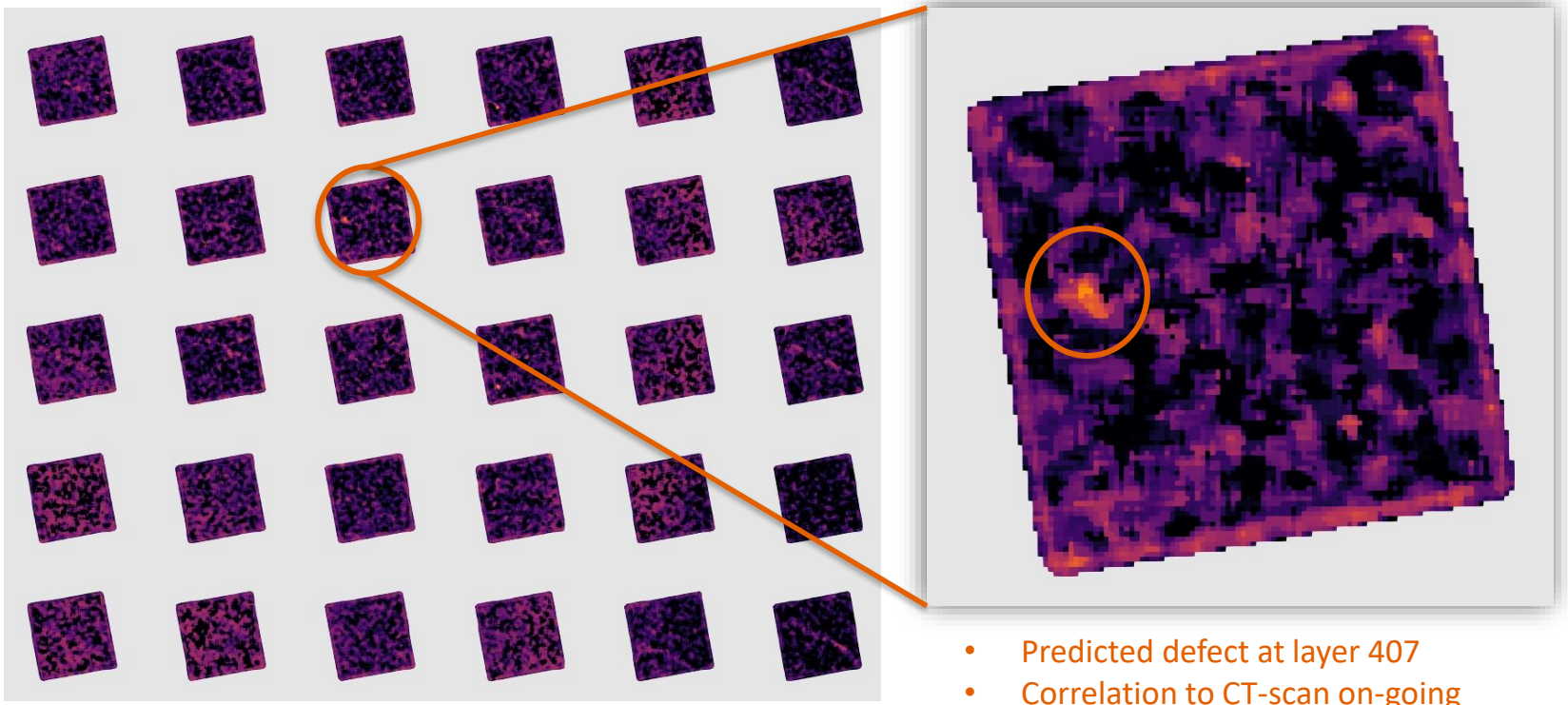
Melt pool monitoring as quality assurance

- Two approaches to quality assurance:

- Identify process signatures that correlate with a defect
  - Can be used for unique geometries (batch size 1)

- Record the signature of a qualified build and maintain the signal within set limits
  - potential for closed-loop process *control*
  - Serial production

Identify signatures (anomalies) and correlate with defects



- Predicted defect at layer 407
- Correlation to CT-scan on-going

Image: VTT

Maintain signal within set threshold limits

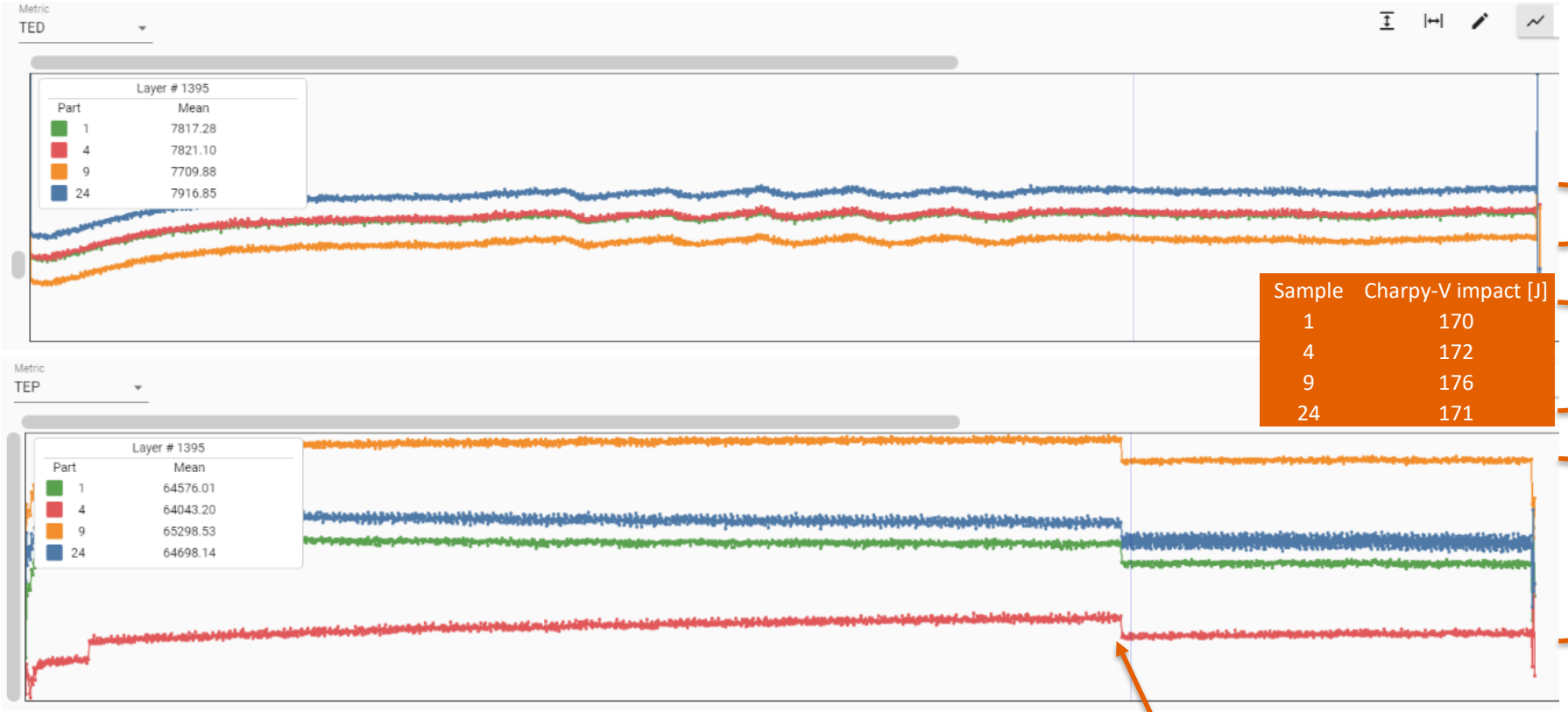


Image: VTT

Summary

- Many process monitoring technologies available for L-PBF
  - Often a combination of different technologies applied
- Main focus on various means of monitoring thermal signatures
  - On-axis / off-axis
  - Photodiodes / thermal cameras
  - Spectral range
  - Temporal & spatial resolution
- Correlation of the signal metrics with L-PBF part quality is an on-going topic of research

beyond
the obvious

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www.vtt.fi
www.vttresearch.com/3d-printing/

01/12/2020