

# In-situ Monitoring der Additiven Fertigung von Metallen im LPA Prozess mittels Optischer Emissionsspektrometrie (OES) und Thermografie (TT)

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## Kurzfassung

Einer der aussichtsreichsten Ansätze, die Qualität und Sicherheit der gefertigten Teile in der metallbasierten additiven Fertigung (AM) zu erhöhen und die Notwendigkeit aufwändiger und zeitintensiver, zerstörender oder zerstörungsfreier Prüfungen (ZfP) nach der Fertigung zu verringern, liegt in dem Einsatz von in-situ Prozessüberwachungstechniken. Viele wichtige Prozessgrößen bei der additiven Fertigung sind thermischer Natur, wie z.B. die Temperatur des Schmelzbades. Aufgrund der Zugänglichkeit zum Werkstück während des Bauprozesses bieten sich optische Verfahren zur Temperaturbestimmung an. Für die Thermografie und Optische Emissionsspektrometrie im IR-Bereich, welche für die in-situ Anwendung prinzipiell als geeignet angesehen werden können, gibt es allerdings noch wenig konkrete praktische Umsetzungen, da die Möglichkeiten und individuellen Grenzen dieser Methoden, angewendet auf AM, noch nicht ausreichend erforscht sind. Aus diesem Grund verfolgt die BAM mit dem Projekt „Process Monitoring of AM“ (ProMoAM) im Themenfeld Material das Ziel, Verfahren des Prozessmonitorings zur in-situ Bewertung der Qualität additiv gefertigter Metallbauteile weiterzuentwickeln.

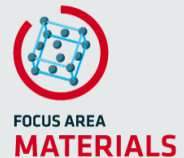
Im Beitrag wird der Fokus auf eine Versuchsserie gelegt, bei der Aufbau von Probekörpern aus dem austenitischen Edelstahl 316L mittels Laser-Pulver-Auftragschweißen (LPA) durch od. mit Hilfe von IR-Spektrometrie und Thermografie in-situ überwacht wurde. Hierbei stellen u.a. die hohe Bandbreite der zu messenden Temperaturen, die Bestimmung der Emittivität und ihre Änderung bei Phasenübergängen des Metalls große experimentelle Herausforderungen dar, wobei jede Methode individuelle Vor- und Nachteile aufweist, welche verglichen werden.

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## **IN-SITU MONITORING DER ADDITIVEN FERTIGUNG VON METALLEN IM LPA PROZESS MITTELS OPTISCHER EMISSIONSSPEKTROMETRIE (OES) UND THERMOGRAFIE (TT)**

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I.B. Gornushkin and A. Gumenyuk



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## **Outline**

- 
- Introduction
    - Thermal radiation
    - The spectrum of molten pools
  - Experimental setup and techniques
    - AM-Machine
    - Thermography cameras
    - Optical emission spectroscopy
  - Results
    - SWIR vs MWIR thermography
    - Temperature determination using regression analysis (OES)
    - Comparison OES vs Thermography
  - Summary and Outlook

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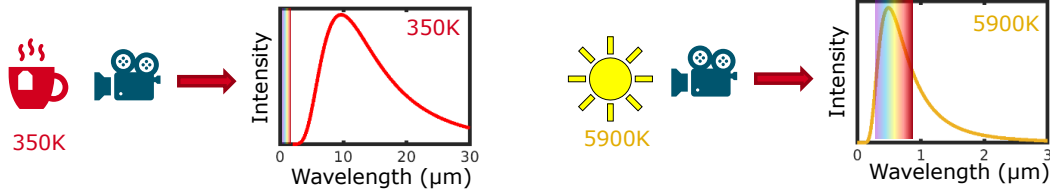
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## Thermal radiation

Every object with  $T > 0$  emits EM radiation:



With increasing temperature the maximum of the radiation shifts to smaller wavelengths and increases in intensity

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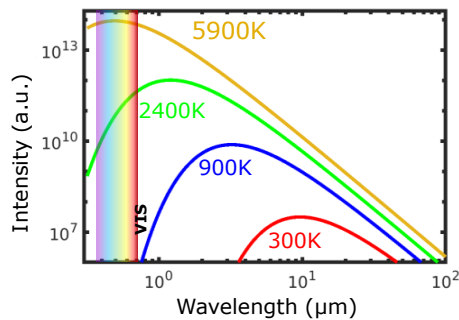
Comparison of in-situ OES and thermography in the LMD process

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## Thermal radiation

Planck's law – Black-body radiation

Planck's law describes the intensity for black-bodies (100% optical absorption)



Problem :

Real objects are not perfect black  
(optical absorption  $< 100\%$ ) !

Effect :

Lower optical absorption results in lower thermal radiation

Solution :

Introducing a multiplicative correction term (Emissivity)  
in the range of 0 to 1

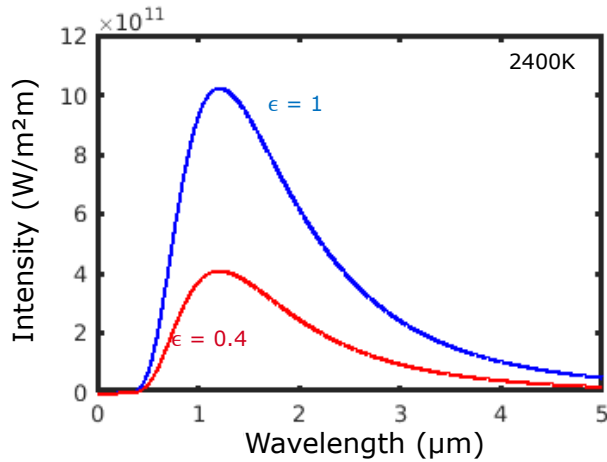
Allows to determine the temperature by intensity or shape!

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# Thermal radiation

## Emissivity



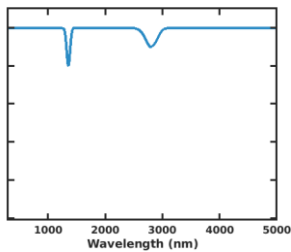
Emissivity of the molten pool can depend on:

- Material / Oxidation
- State of matter
- Temperature
- Angle
- Surface roughness
- Wavelength

The emissivity is needed to determine the temperature from the intensity

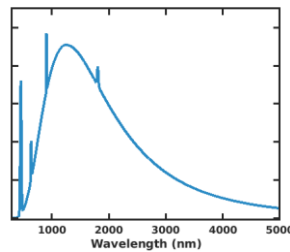
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# The optical spectrum of molten pools



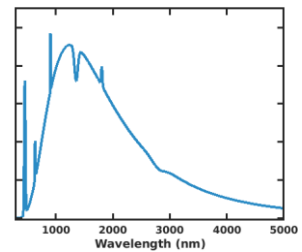
Transmission of the atmosphere

×



Thermal Radiation + Atomic Emission

=



Theoretical Molten Pool Spectrum

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## Experimental Setup

### AM-Machine

Laser metal deposition (LMD):

TruLaser Cell 3000 (Trumpf)  
+ TruDisk 16002 (Trumpf, wavelength: 1030 nm)

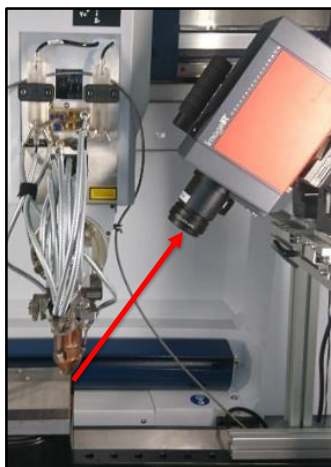
Powder feeder: Flowmotion Twin (Medicoat) with oscillating conveyor

- Build chamber:  $800 \times 600 \times 400 \text{ mm}^3$
- Five-axis-machine
- Coaxial three-jet-nozzle
- Max. laser power (LMD): 5 kW
- Max. focal diameter: 3,8 mm
- Typ. Welding speed: 20 mm/s



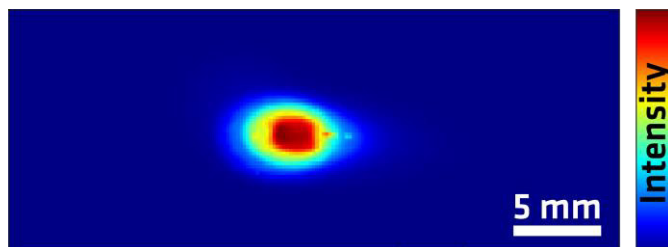
## Experimental techniques

### Thermography



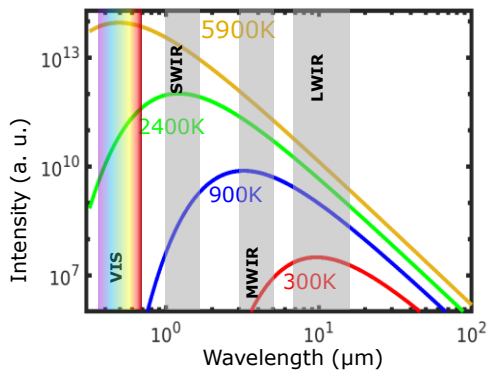
IR sensitive camera / 2D sensor array:

- One intensity value per pixel: No spectral data
- Determination of temperature: Radiometric model
- Spatially resolved



## Experimental techniques

### Thermography



### MWIR Camera

- Infracore ImageIR 8300
- 3 - 5  $\mu\text{m}$
- 250 x 120 x 160 mm
- 3,3 kg
- Fixed position



~100k€

### SWIR Camera

- Allied Vision Goldeye
- 0,9 - 1,7  $\mu\text{m}$
- 78 x 55 x 55 mm
- 0,35 kg
- Fixed position or moving



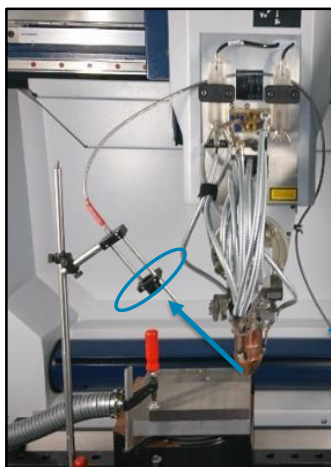
~30k€



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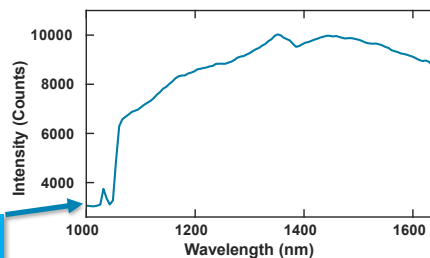
## Experimental techniques

### Optical Emission spectroscopy



Spectro  
meter

- Lens collects radiation analyzed by spectrometer
- Spectroscopic data: Emission Lines + Thermal Radiation
- $\varnothing$  ROI  $\sim$  2mm; No spatial resolution
- Fixed position or moving with the molten pool



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## Results

### SWIR vs MWIR thermography



10 layers single welding line  
"Wall" structure



OES, SWIR and MWIR simultaneously!

Ø laser spot: 2.4 mm  
Laser power: 1.2 kW  
Rate of travel: 21.7 mm/s  
Material: AISI 316L

10-05-2021 Comparison of in-situ OES and thermography in the LMD process



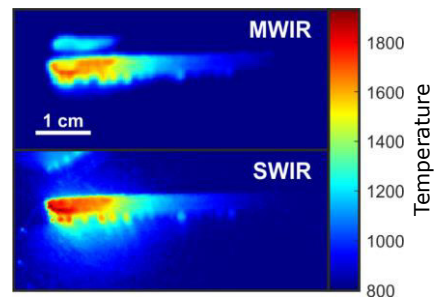
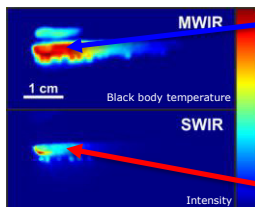
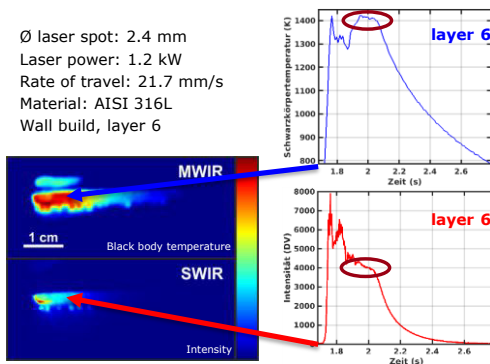
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## Results

### SWIR vs MWIR thermography



Ø laser spot: 2.4 mm  
Laser power: 1.2 kW  
Rate of travel: 21.7 mm/s  
Material: AISI 316L  
Wall build, layer 6



Solidification temperature: 1650K  
• MWIR → adjustment of emissivity  
• SWIR → radiometric model

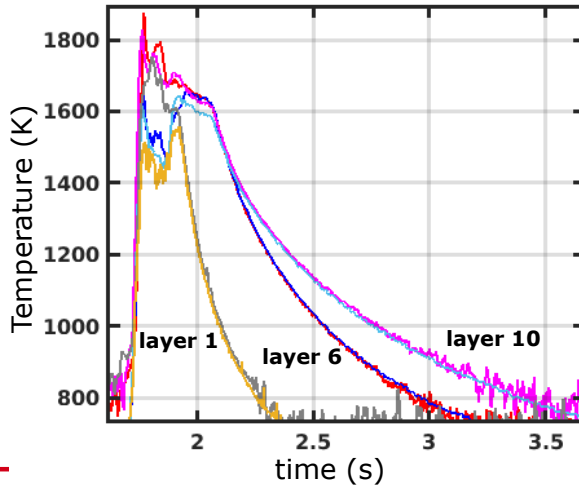
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## Results

### SWIR vs MWIR thermography



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Temperature of the solid phase equal for SWIR and MWIR

→ SWIR useable

Liquid phase shows deviating temperatures

→ Effect of the emissivity change

Cooling process slows down for higher layer numbers

→ Effect on microstructure?



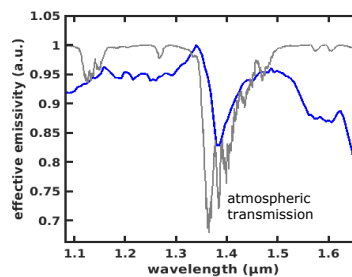
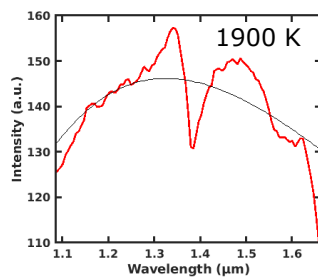
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## Results

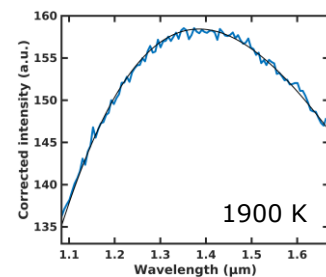
### Temperature determination using regression analysis (OES)



Reference: Graphite furnace



Lord, S. D., 1992, NASA Technical Memorandum 103957



Fit results 20-50 K to high

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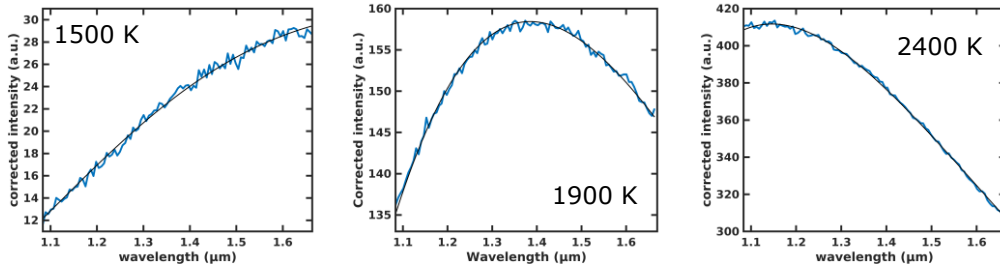
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## Results

Temperature determination using regression analysis (OES)

Correction applied at different temperatures:

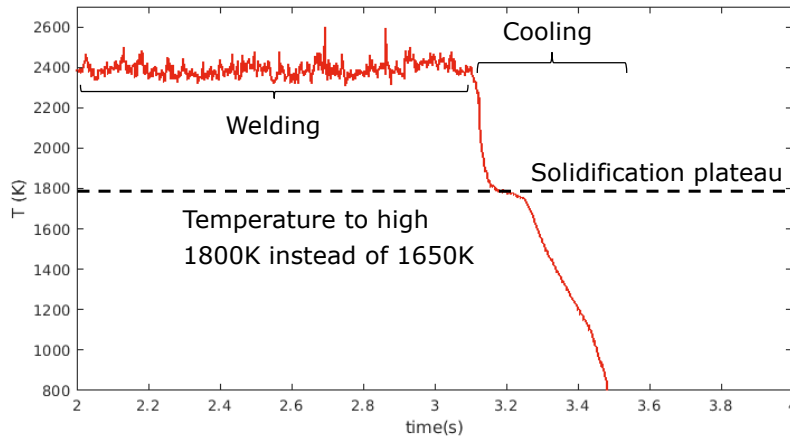


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## Results

Temperature determination using regression analysis (OES)

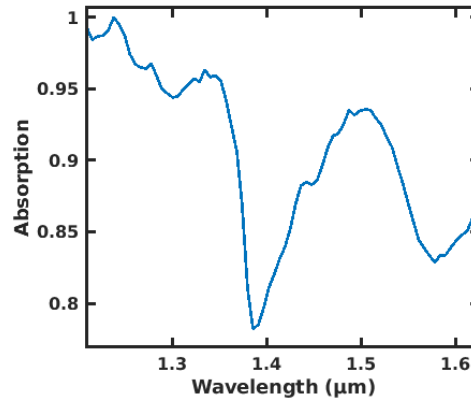
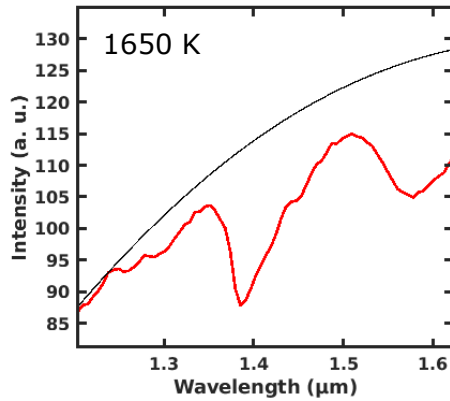
OES fixed relative to molten pool



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## Results

Temperature determination using regression analysis (OES)

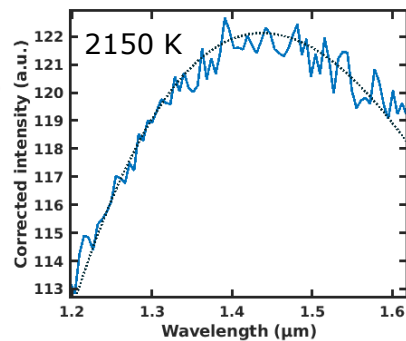
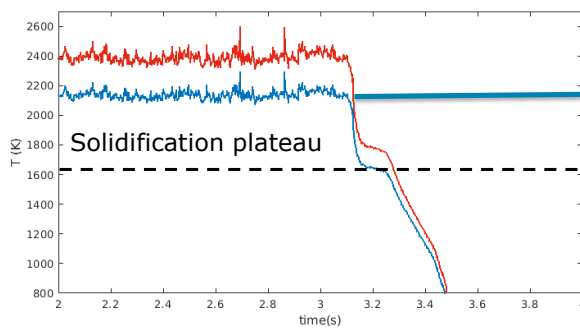


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## Results

Temperature determination using regression analysis (OES)



- Emissivity constant in spectral region.
- Accurate Temperature of the liquid phase!

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### OES:

- Accurate temperature of the liquid phase from fit
  - No atomic emission lines at normal conditions
- Ongoing work: absorption spectroscopy for plume composition

### Thermography:

- Accurate temperature of the solid phase using radiometric model
  - Overheating and Cooling curves → Microstructure?
  - Shape/Size of molten pool → Balling instability?

Thank you for your attention!

10-05-2021

