

Processing of metallic materials by Selective Laser Melting at elevated temperatures

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Faculty of Mechanical Engineering
Brno University of Technology

Brno, 7th March 2023



**INSTITUTE OF MACHINE
AND INDUSTRIAL DESIGN**

Laser Powder Bed Fusion

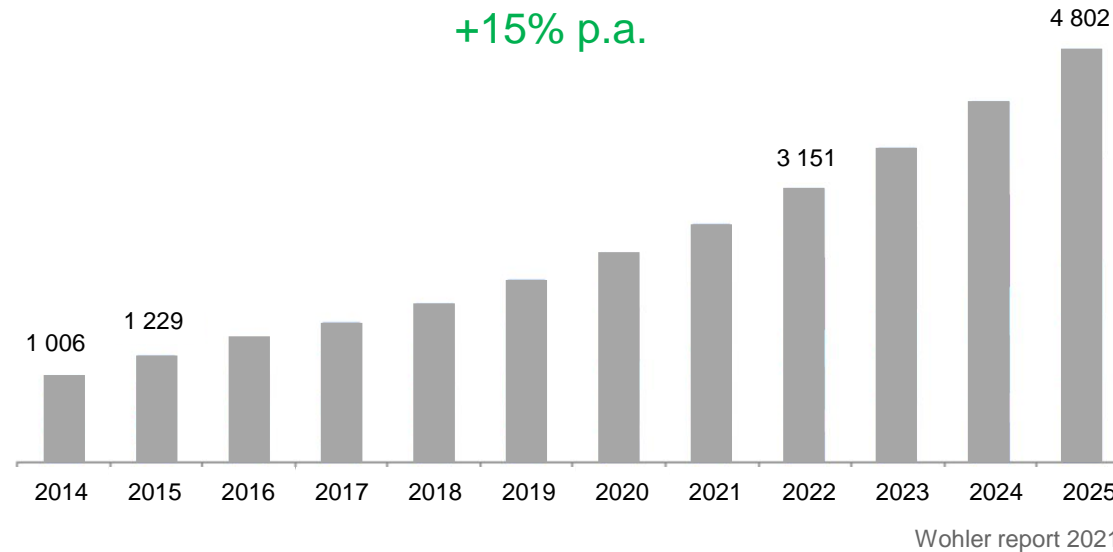
What is the limit for LPBF?

Complex parts

Material efficiency

Refractory materials

Time to market



U.S. 3D printing market (USD million)

Failures

Accuracy

Surface quality

Manufacture time

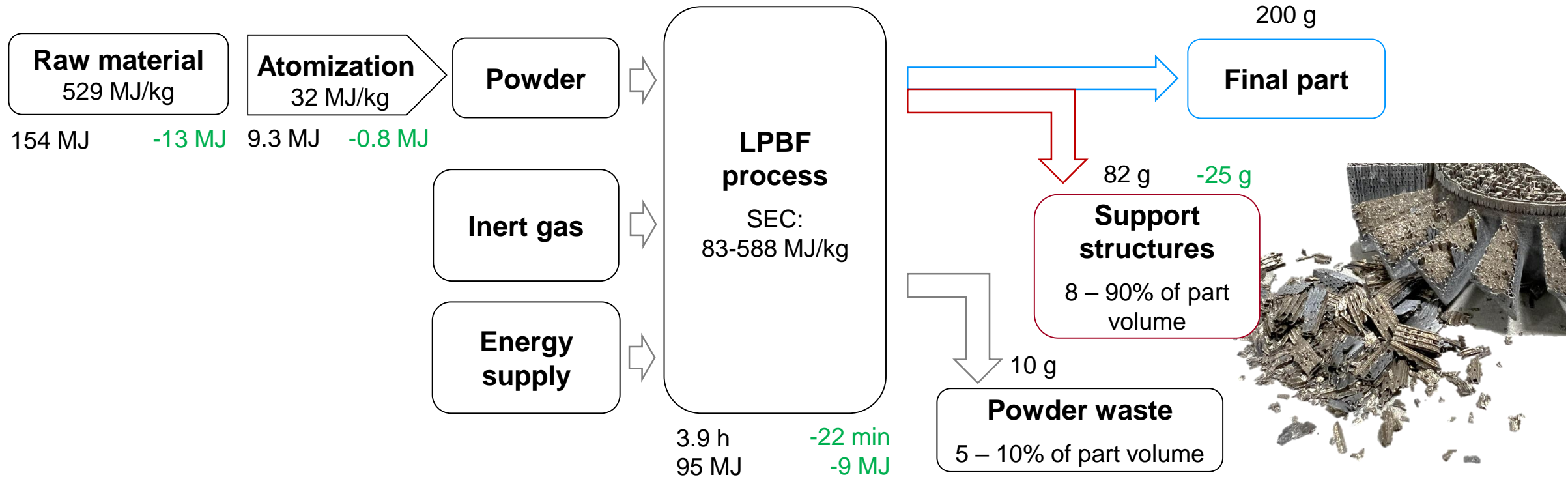
Material portfolio

Energy intensive process

Can we decrease energy intensity?

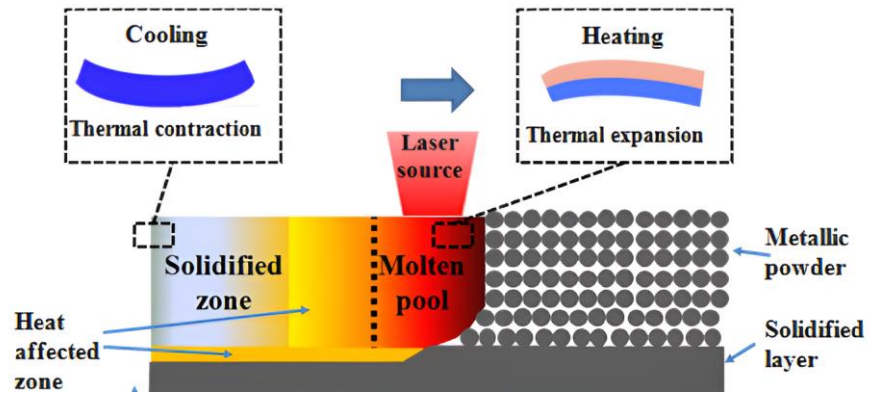
Ti6Al4V case study – specific energy consumption

-30% reduction off support structures



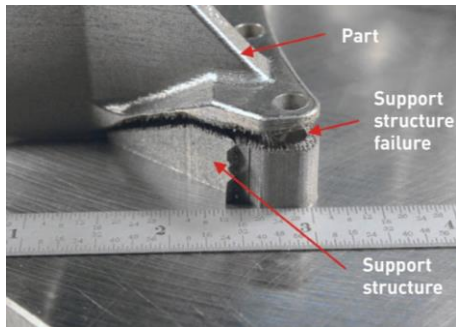
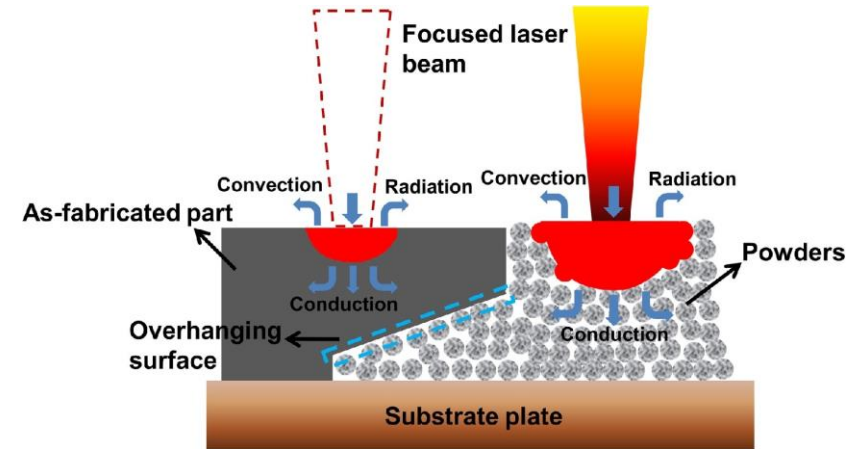
Why do we need support structures?

Residual stresses

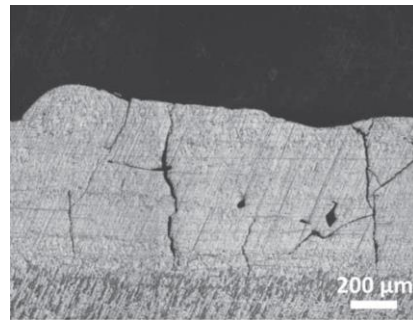


Park 2017

Heat accumulation



metal-am.com



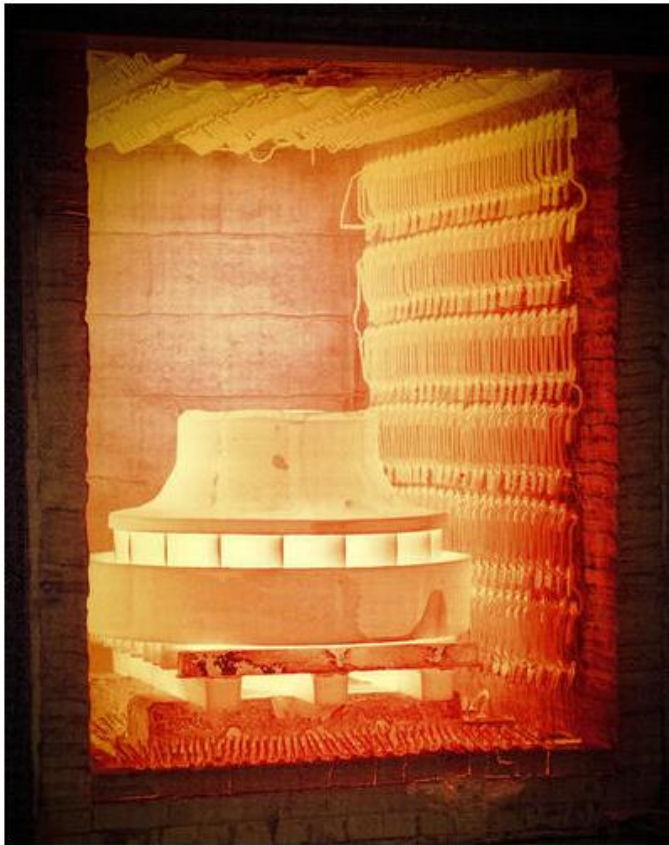
Caprio 2020



Leary 2014

How to mitigate residual stresses?

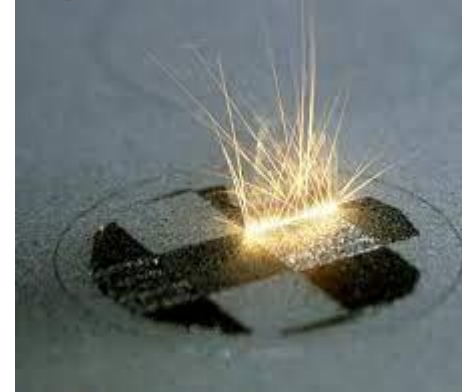
Ex-situ



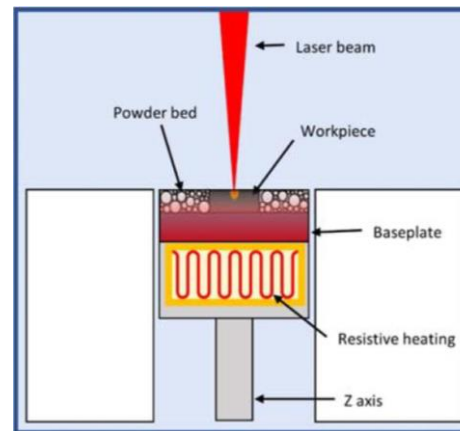
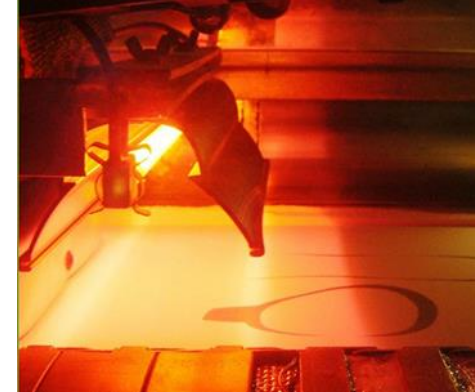
mythriindia.com

In-situ

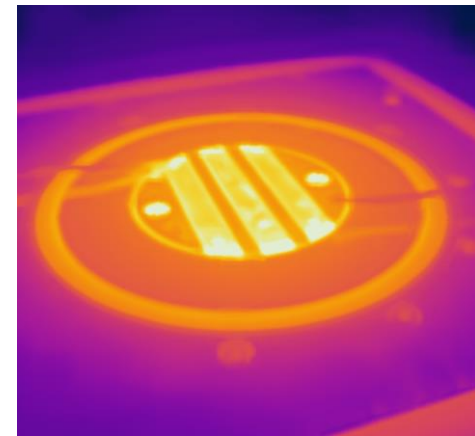
nist.gov



lboro.ac.uk



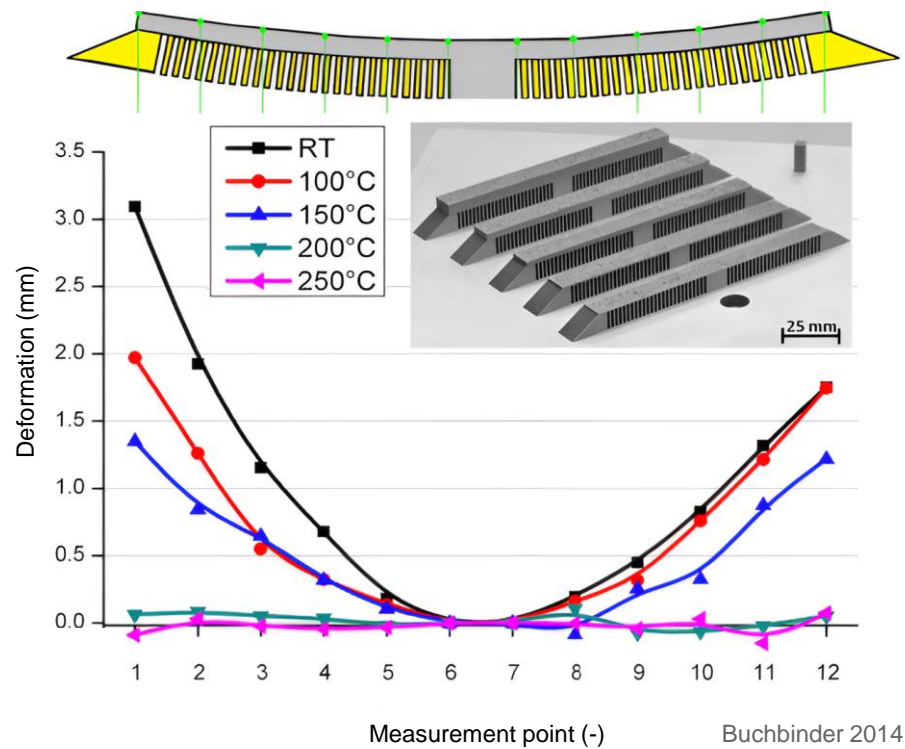
Caprio 2020



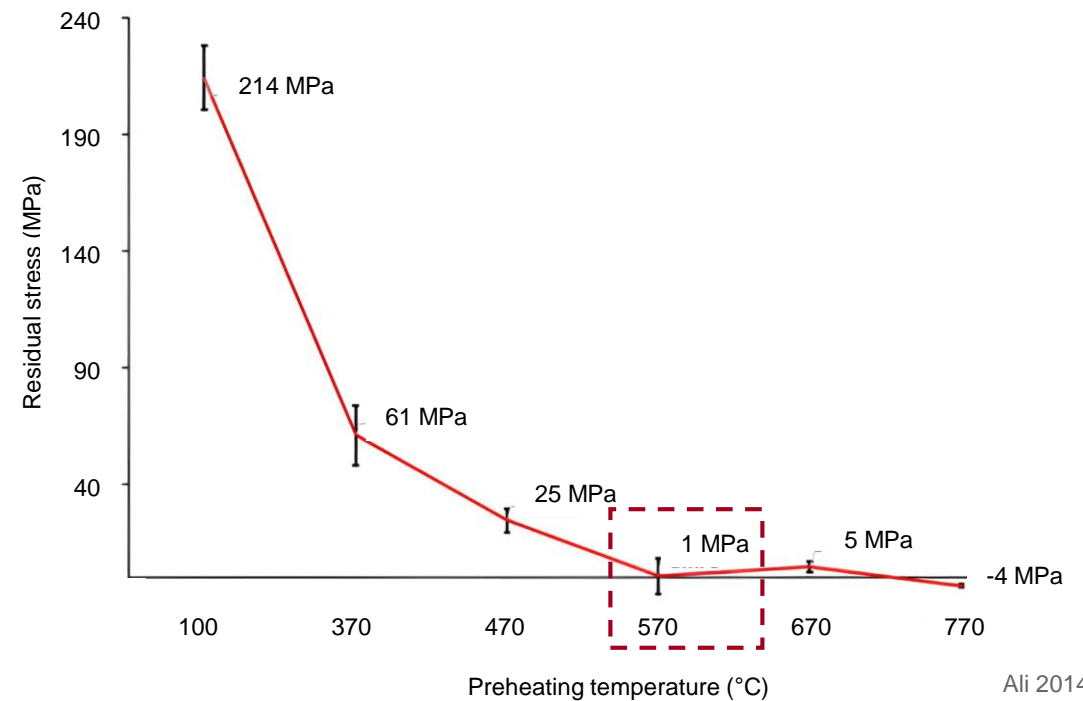
How to mitigate residual stresses?

In-situ powder bed preheating

AlSi10Mg



Ti6Al4V



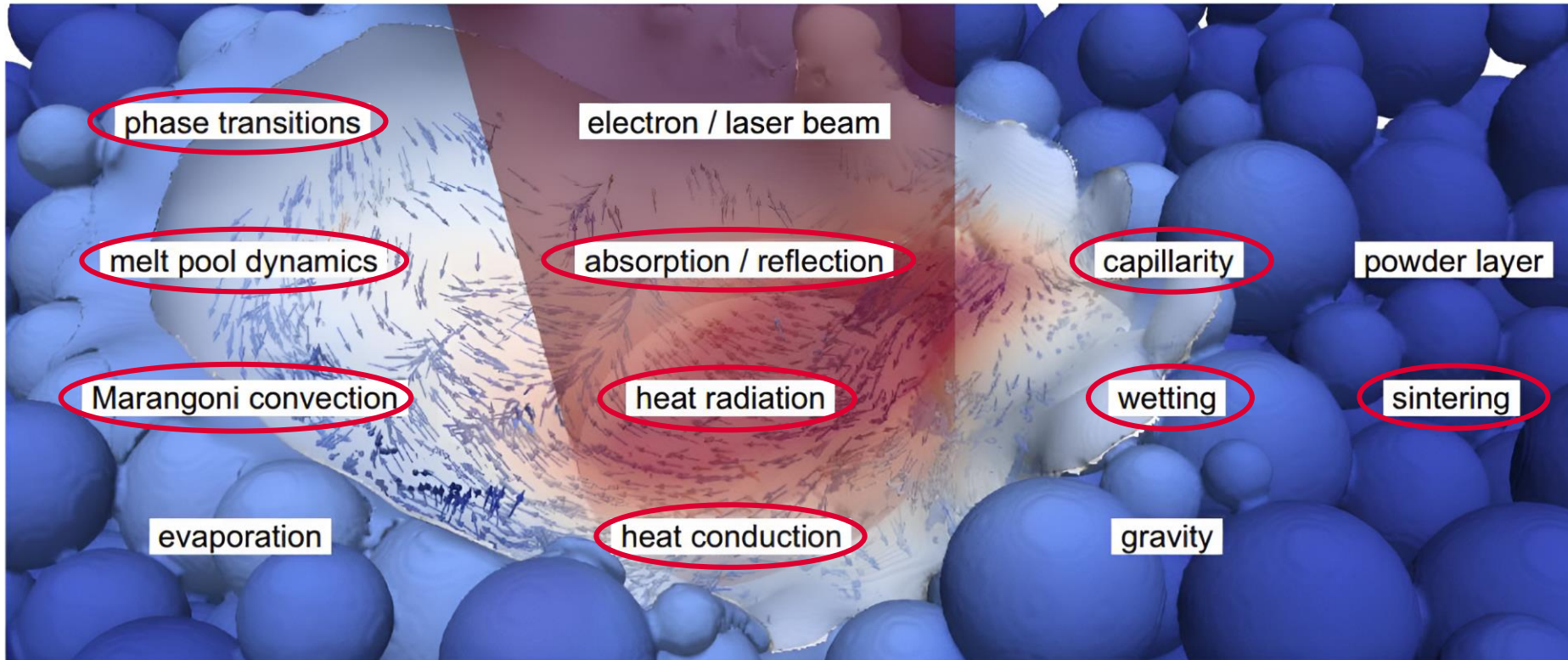
Defence of the PhD thesis

7th March 2023, FME BUT, Brno, Czech Republic

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Powder bed preheating in LPBF

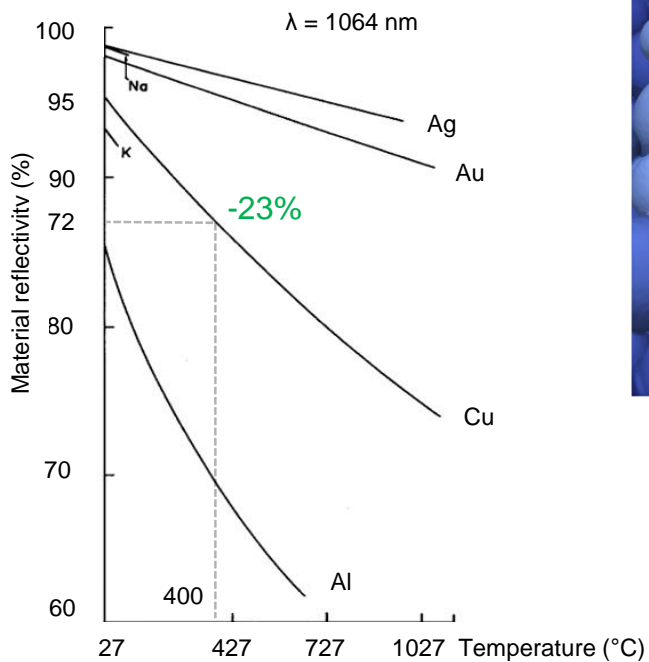
Physical phenomena in metal 3D printing



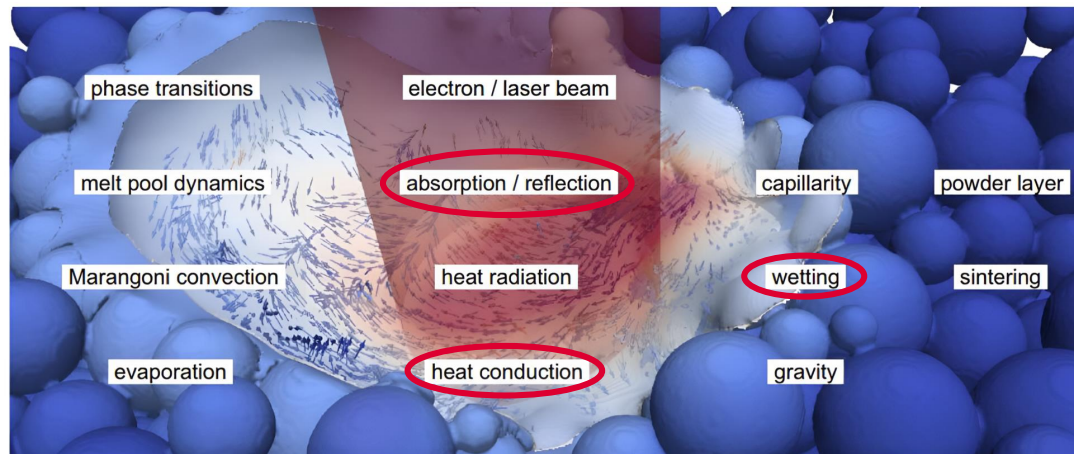
Markl 2016

Powder bed preheating in LPBF

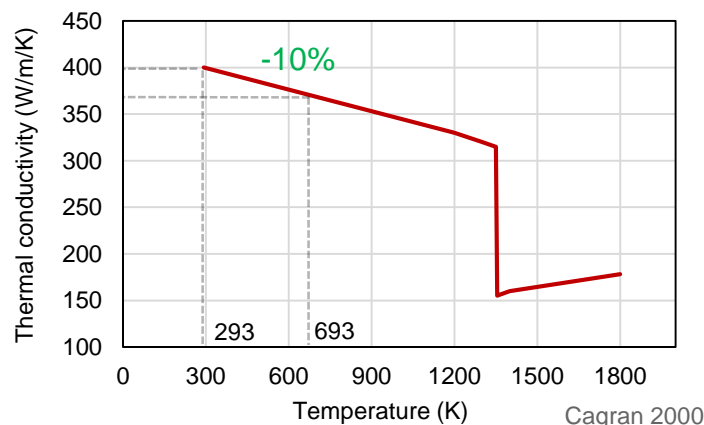
Effect of preheating on physical phenomena



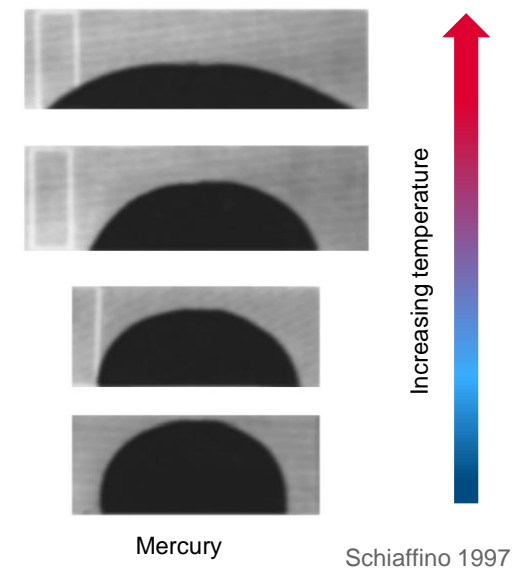
Ujihara 1971



Markl 2016



Cagran 2000



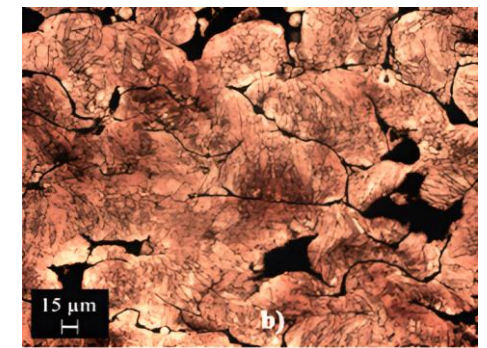
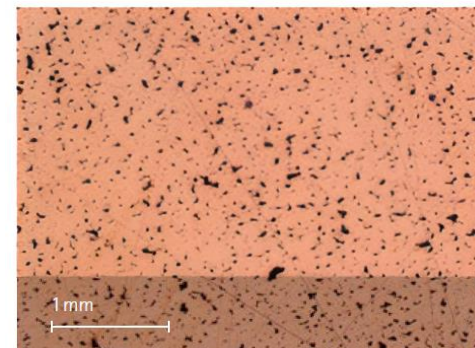
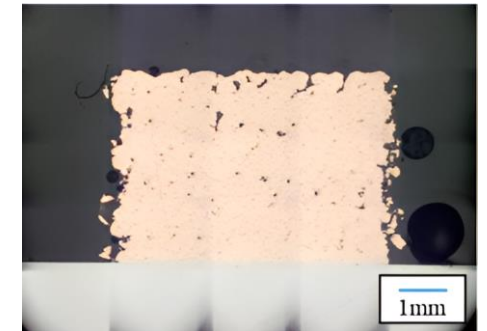
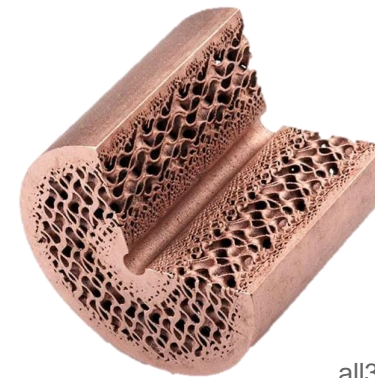
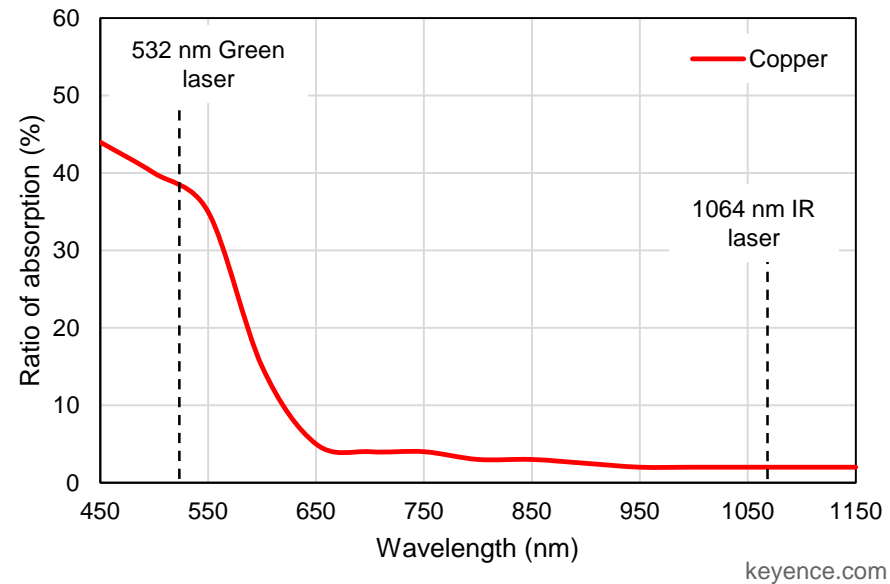
Defence of the PhD thesis

7th March 2023, FME BUT, Brno, Czech Republic

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Processing of copper using LPBF

High-performance material



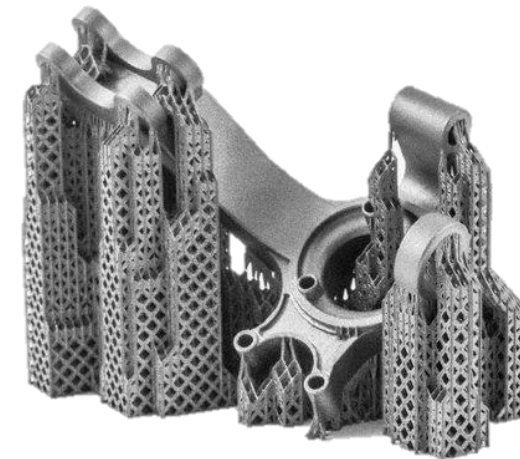
Aim of the thesis

Reduction of residual stress using preheating

Ti6Al4V, Inconel 939

- Reduction of support structures
 - Decrease manufacture time

⇒ Lower energy intensity



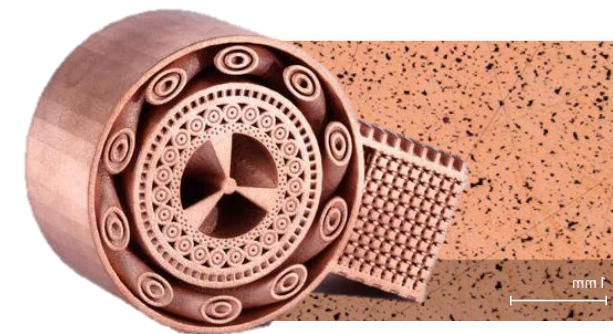
matmatch.com

Increase of relative density of reflective material using preheating

Copper

- Functional improvement
 - High-performance material

⇒ Life cycle energy savings



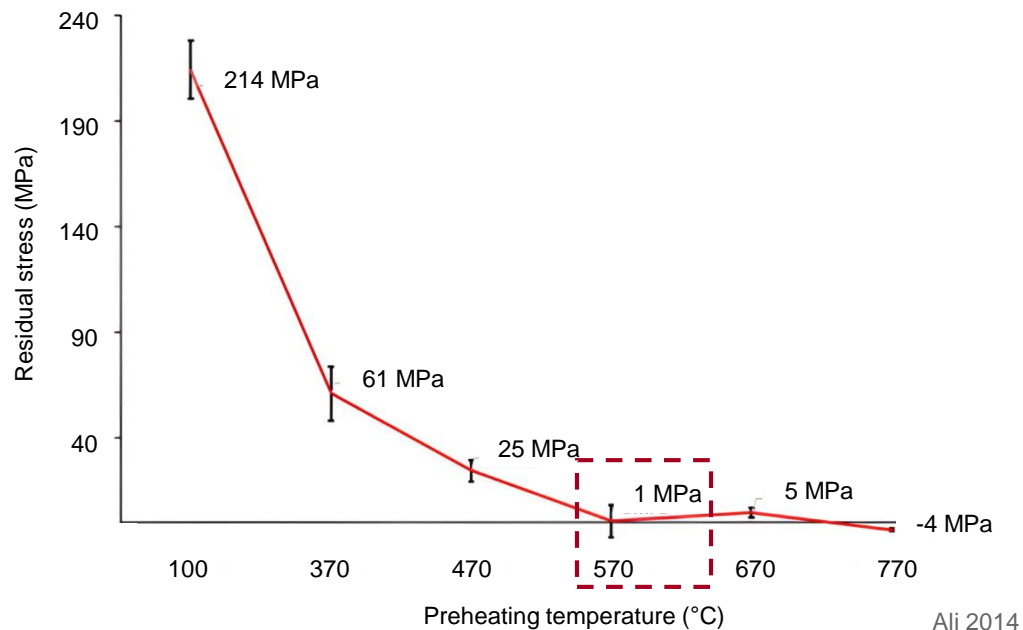
eos.com

Scientific question Q_{1,2}

Reduction of residual stress using preheating

Ti6Al4V

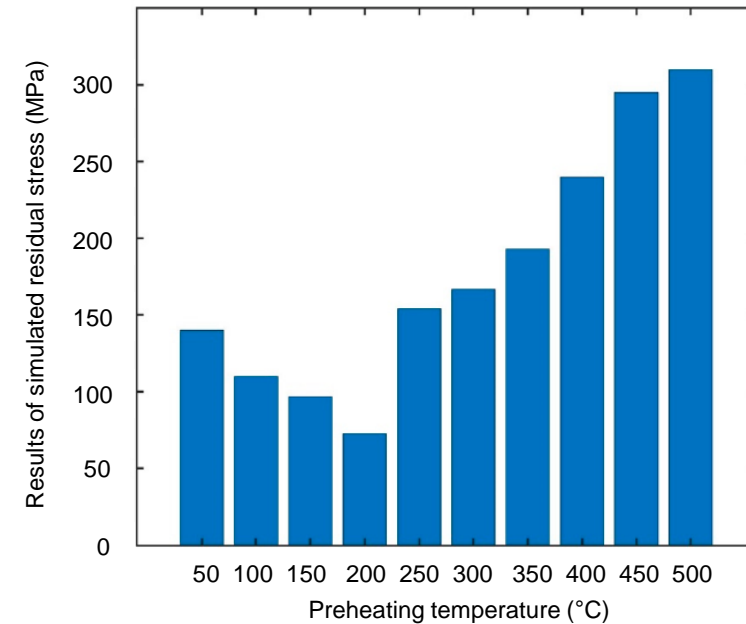
Q₁: Can the right combination of process parameters and preheating to 550 °C lead to the elimination of residual stresses in Ti6Al4V?



Ali 2014

Inconel 939

Q₂: How does preheating affect the residual stresses of Inconel 939?



Mirkoohi 2021

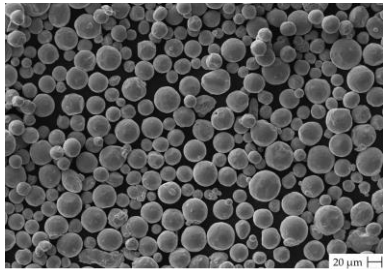
Materials and methods Q_{1,2}

Experiment setup

Specimens preparation

Evaluation method

Ti6Al4V

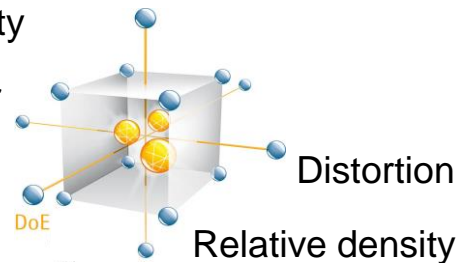


Laser velocity

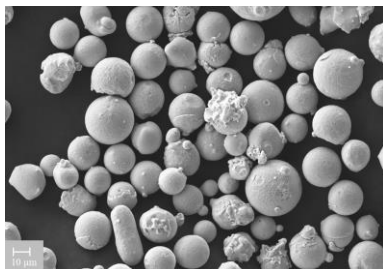
Laser power

Time delay

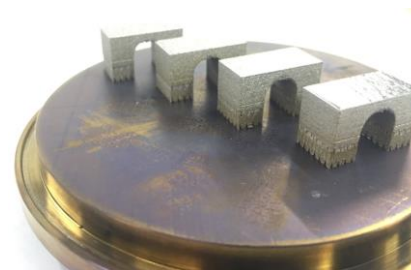
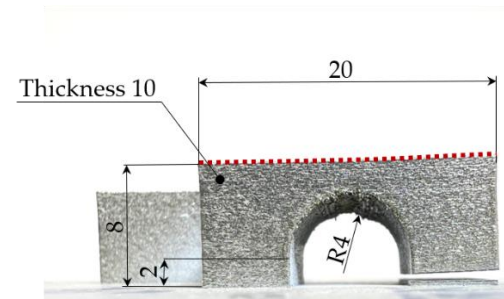
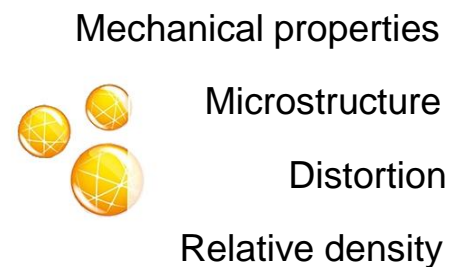
Preheating
200 – 550 °C



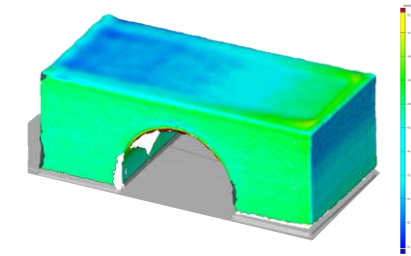
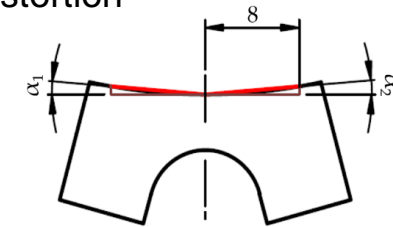
Inconel 939



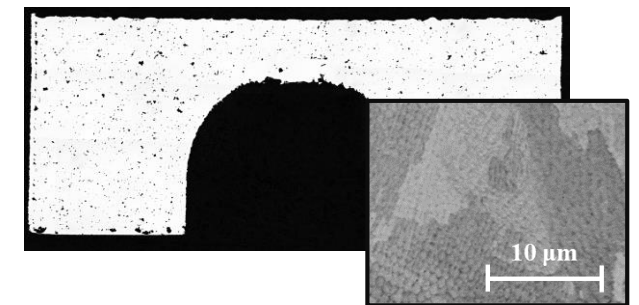
Preheating
RT, 200, 400 °C



Distortion



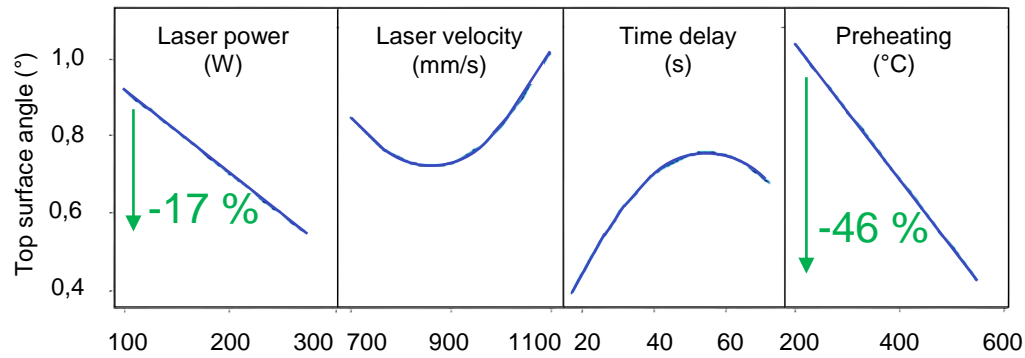
Relative density and microstructure



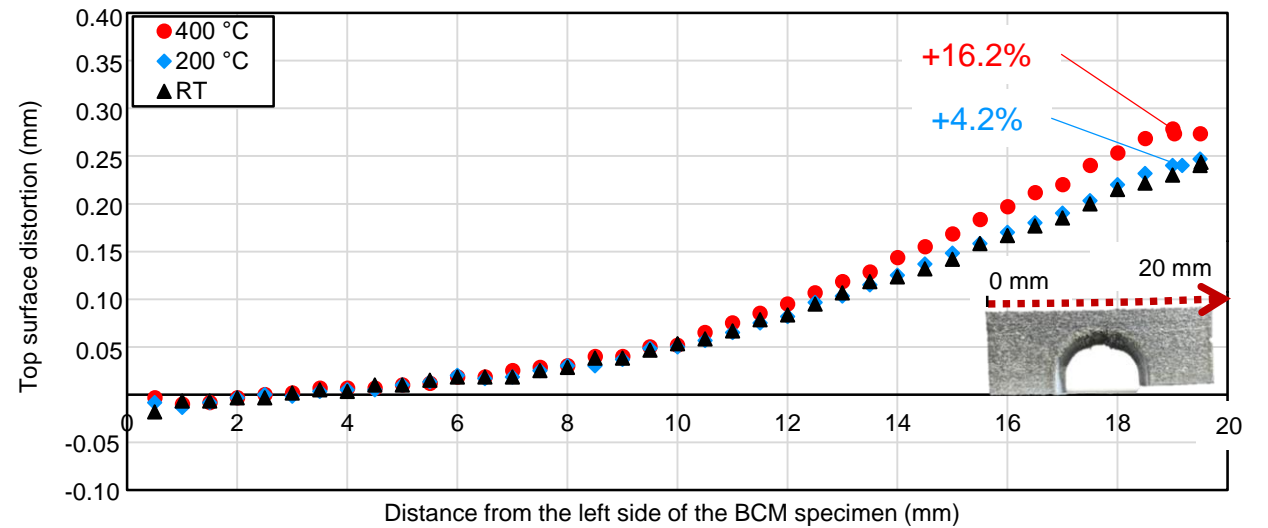
Results $Q_{1,2}$

Distortion and residual stresses

Ti6Al4V



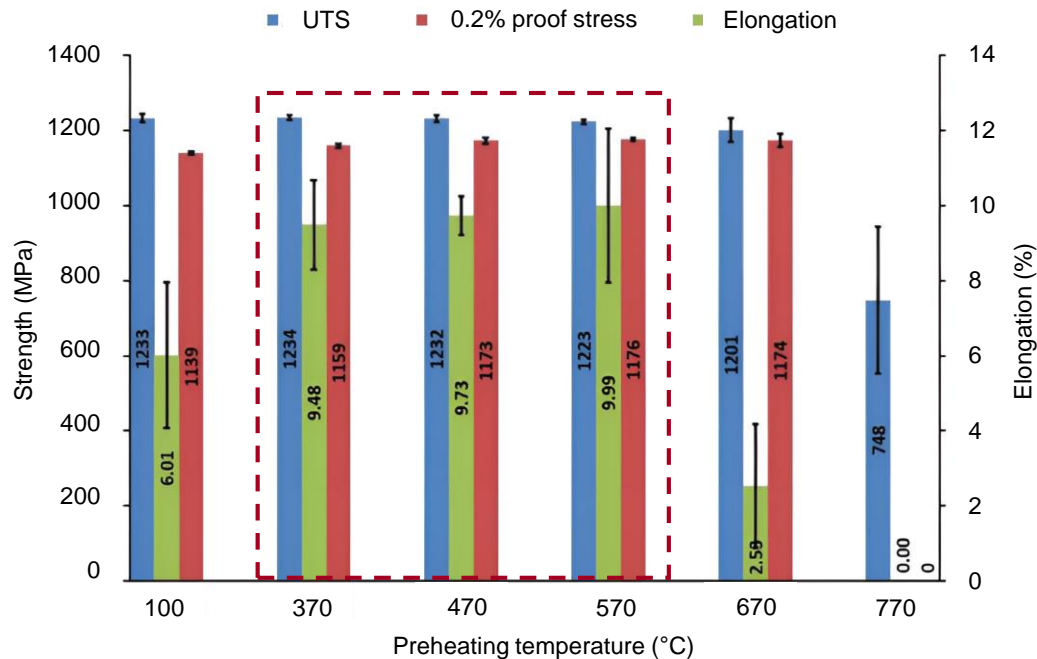
Inconel 939



Results Q_{1,2}

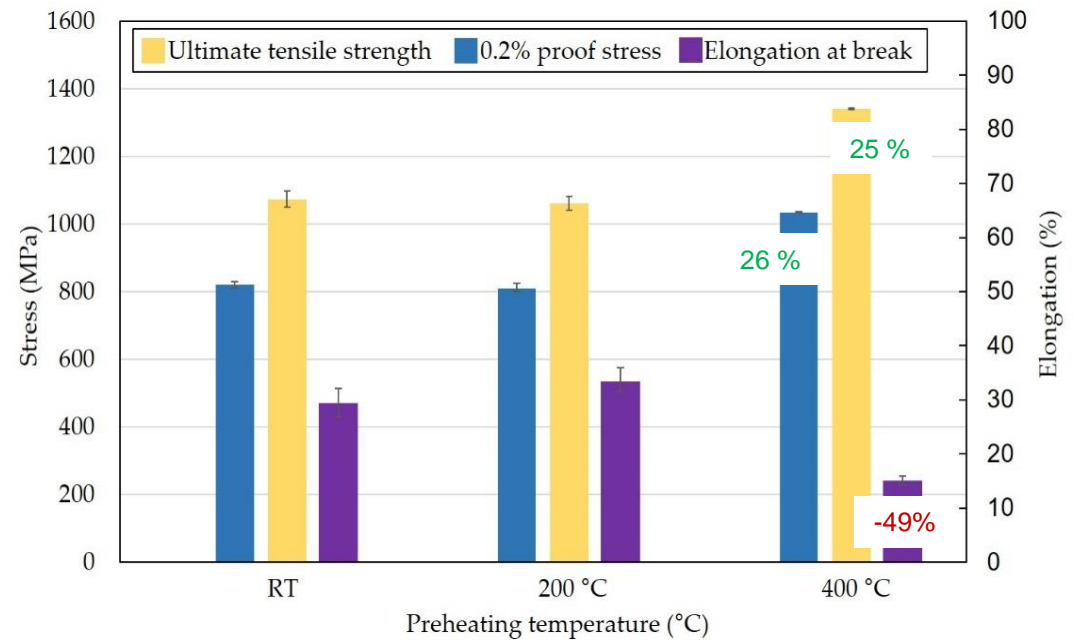
Mechanical properties

Ti6Al4V



Ali 2014

Inconel 939



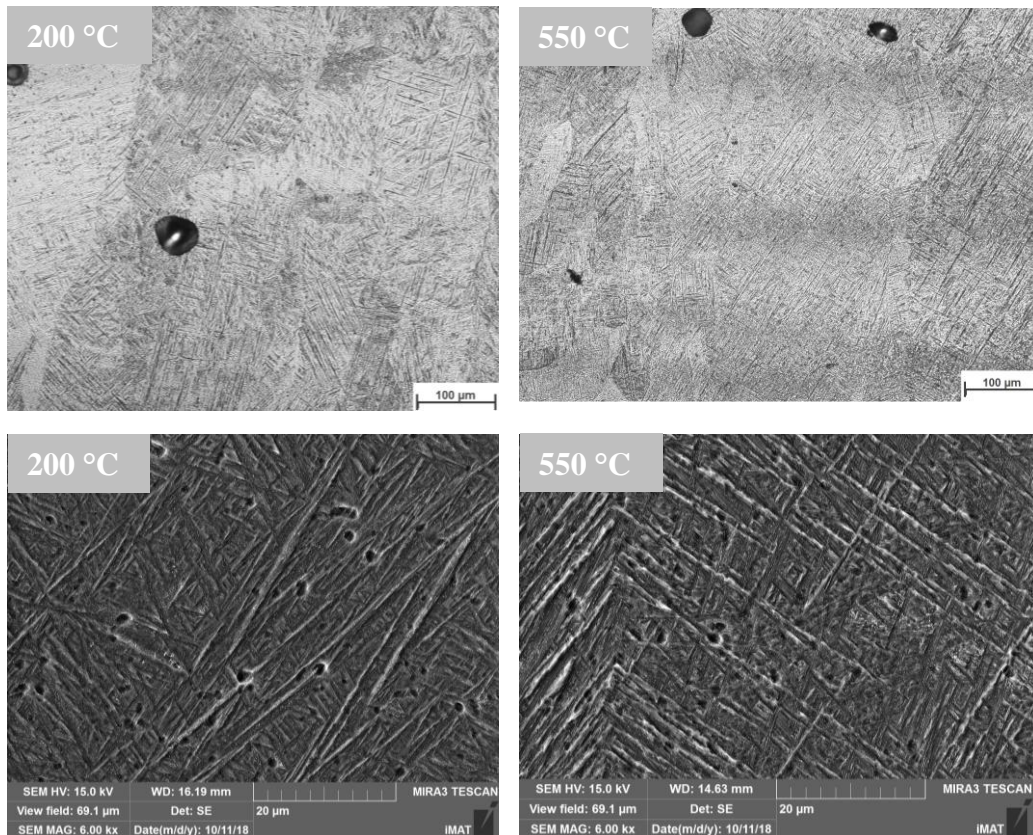
Hardness +12 %

Results $Q_{1,2}$

Microstructure

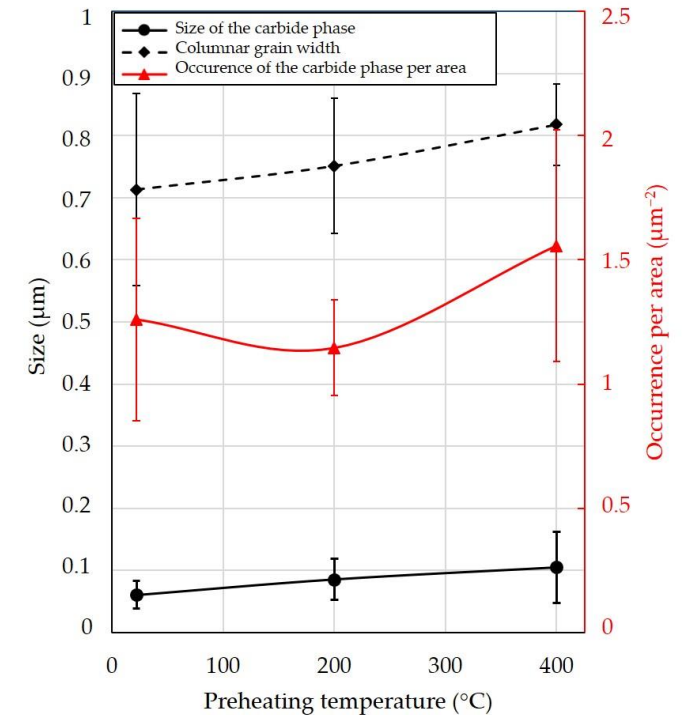
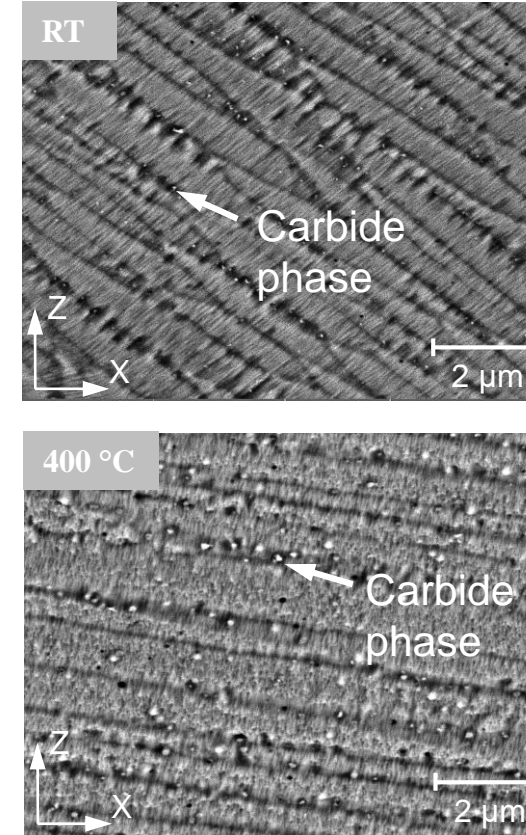
Ti6Al4V

RD +3%



Inconel 939

RD ±0%



Size **+72 %**

Occurrence per area **+24 %**

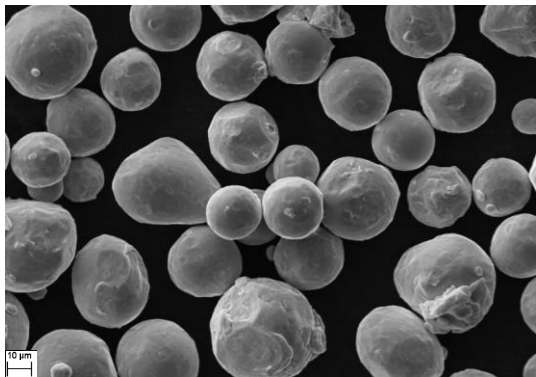
Defence of the PhD thesis

7th March 2023, FME BUT, Brno, Czech Republic

Results $Q_{1,2}$

Unfused powder

Ti6Al4V



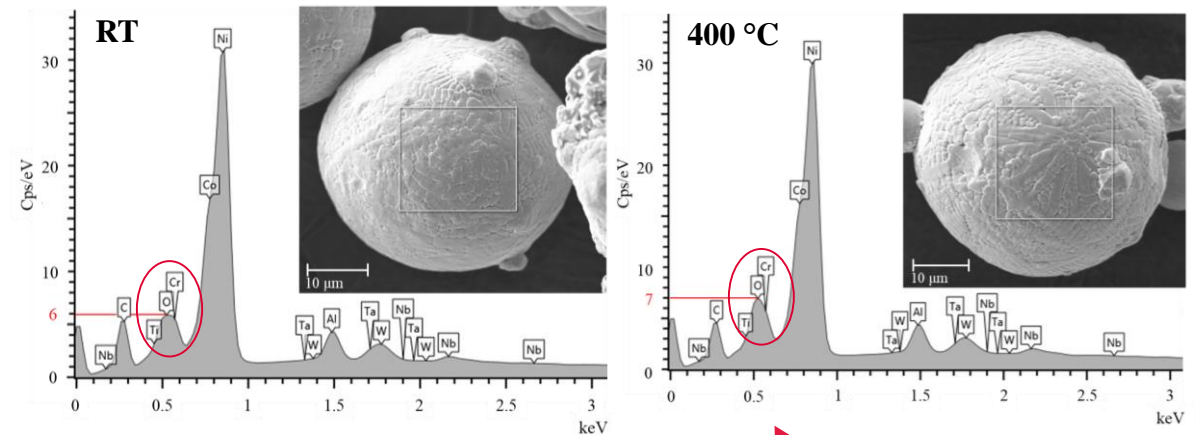
Powder exposed to 550 °C



Inconel 939



Powder State / Checked Elements	O (wt %)	H (wt %)
ASTM B348 Grade 5	Max. 0.20	Max. 0.0125
Virgin Ti6Al4V	0.087	0.0020
Ti6Al4V 200 °C	0.120	0.0020
Ti6Al4V 550 °C	0.330	0.0168

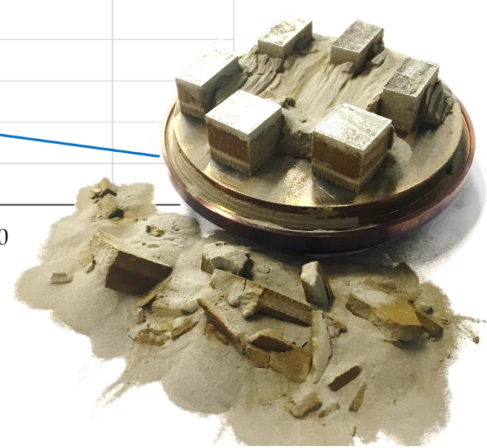
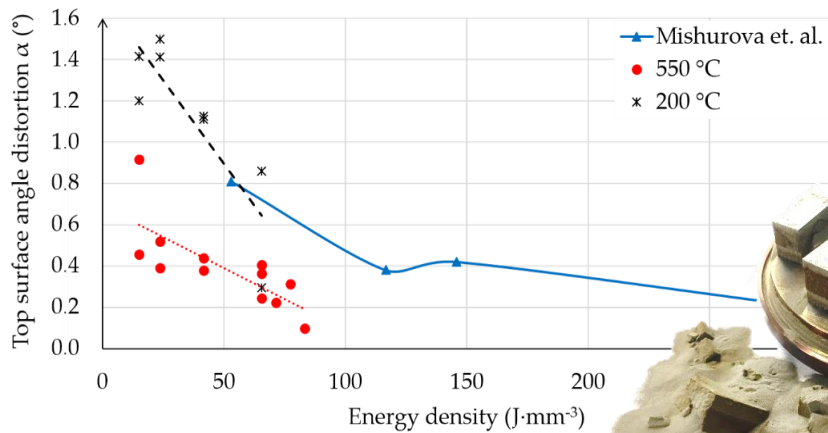


Discussion Q_{1,2}

Can we use preheating for reduction of residual stresses?

Ti6Al4V

Q₁: Can the right combination of process parameters and preheating to 550 °C lead to the elimination of residual stresses in Ti6Al4V?

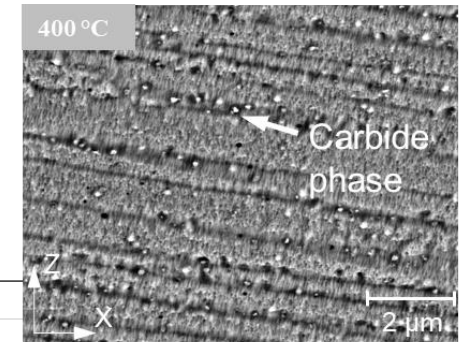
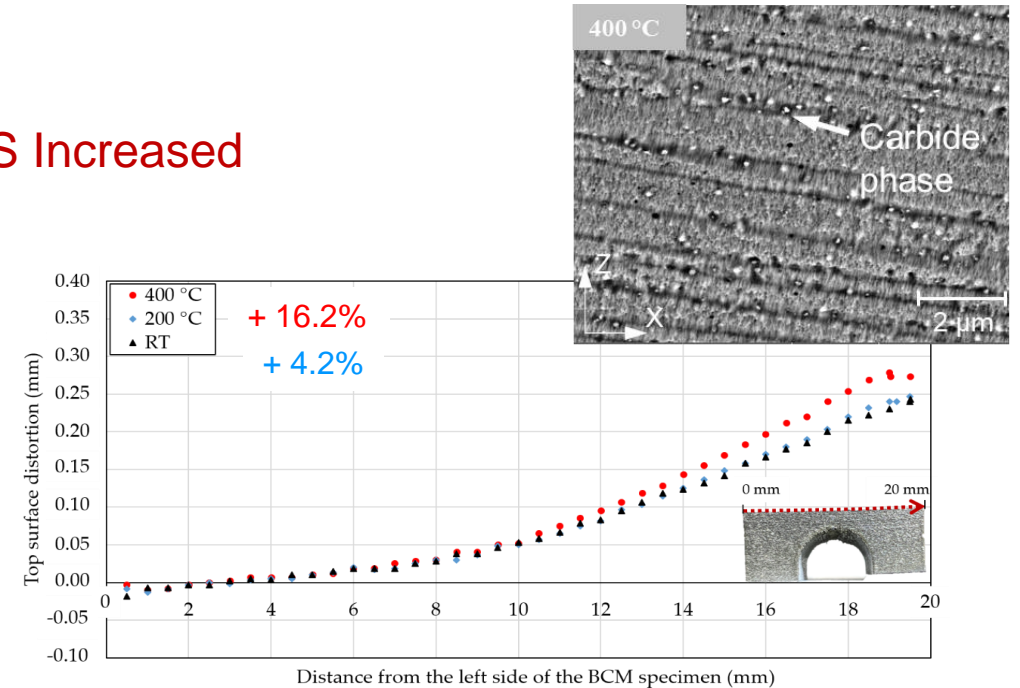


H₁: Not confirmed

Inconel 939

Q₂: How does preheating affect the residual stresses of Inconel 939?

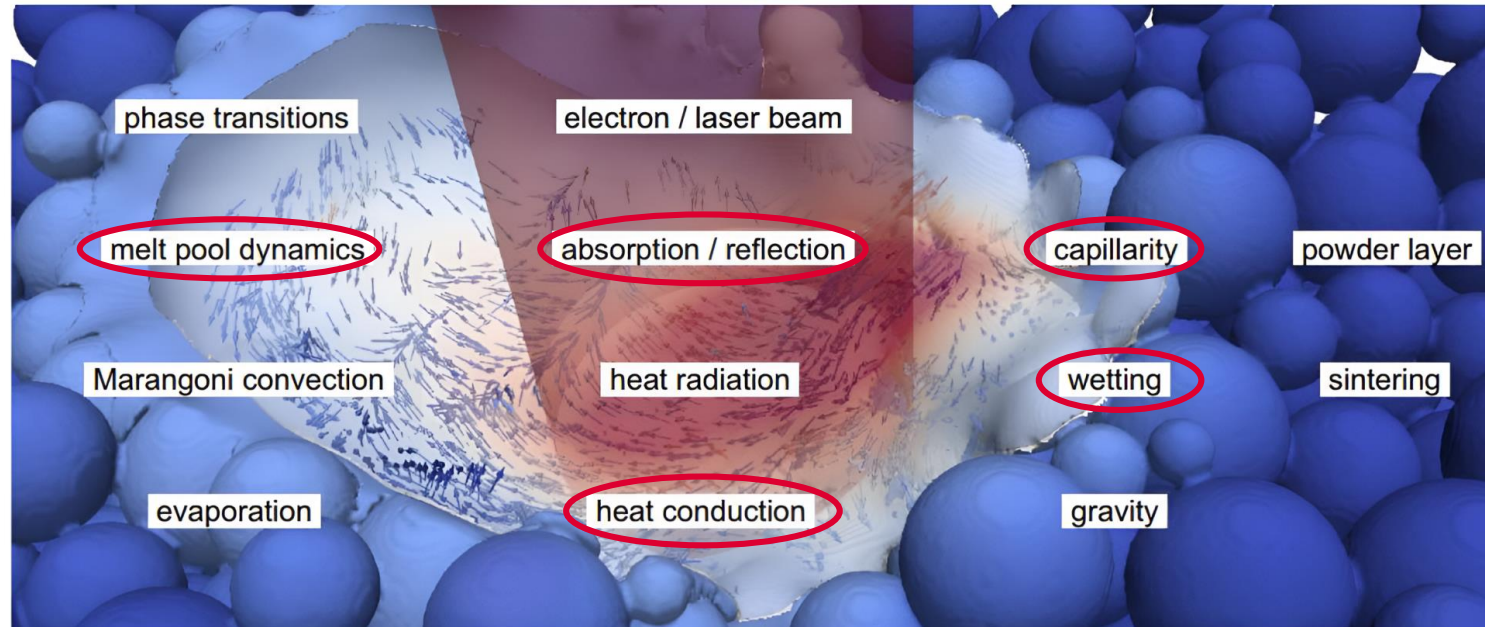
RS Increased



Scientific question Q₃

Can we increase relative density of reflective materials using preheating?

Q₃: What is the effect of preheating on the relative density of copper specimens prepared with an LPBF system using IR fibre laser?



Markl 2016

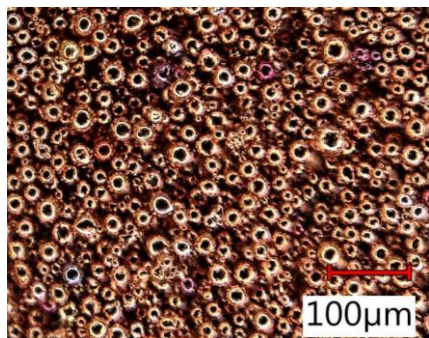
Materials and methods Q₃

Experiment setup

Specimens preparation

Evaluation method

Copper



Laser velocity

Laser power

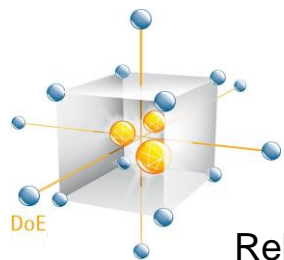
Hatch distance

Layer thickness

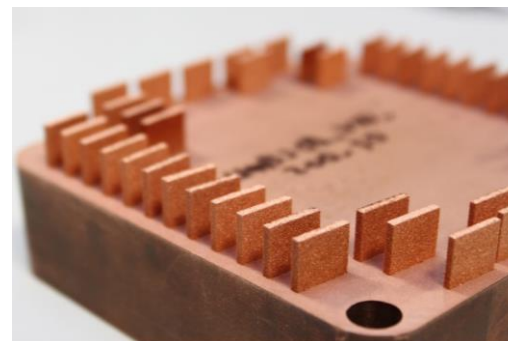
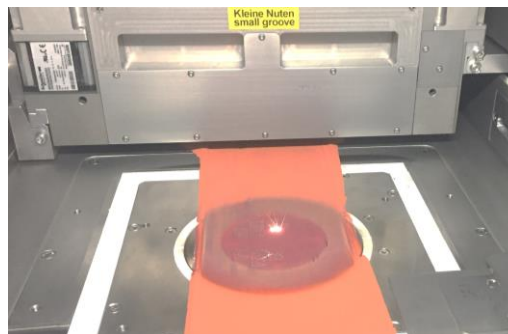
Preheating

200 – 400 °C

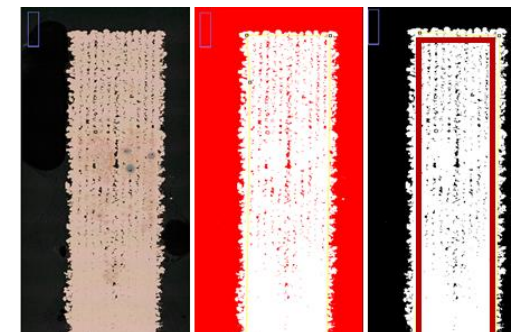
Scanning strategy



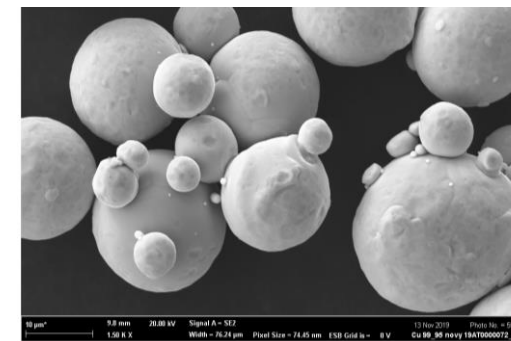
Relative density



LOM



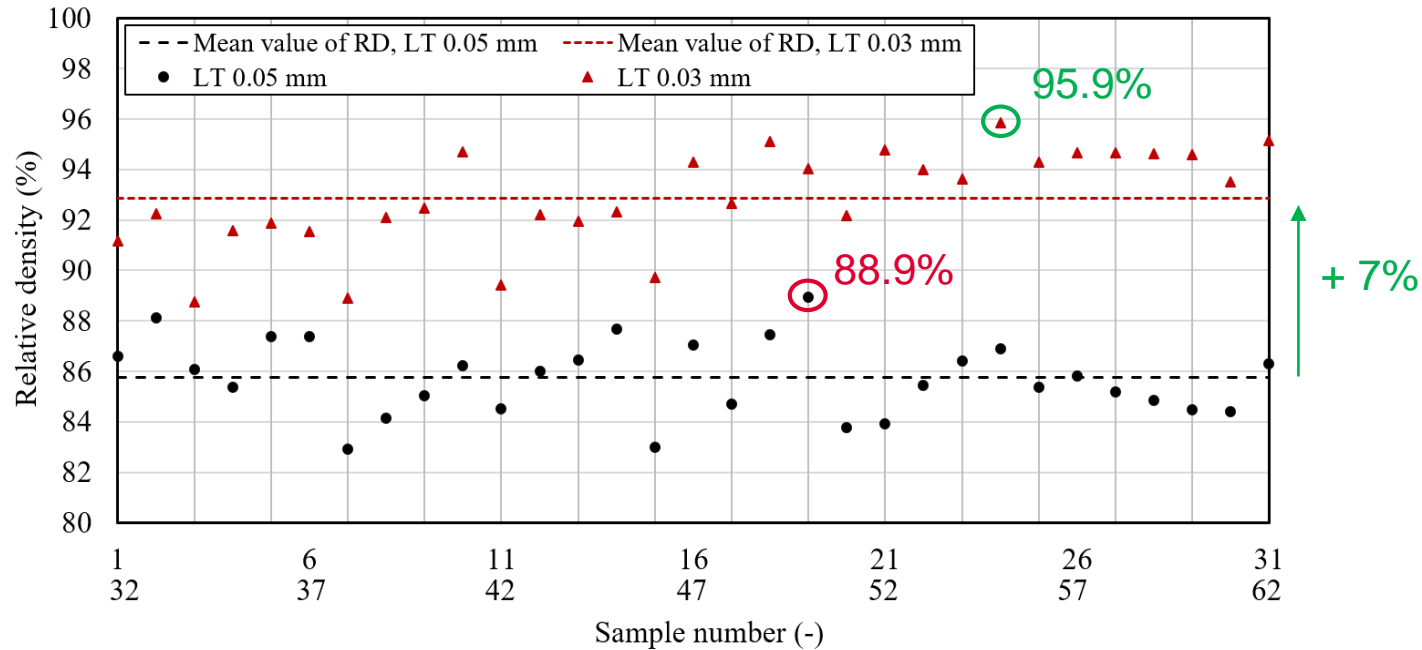
SEM, EDX



Results Q₃

50 μm or 30 μm layer thickness?

Preheating 200 °C



Specimen 2
50 μm
88.1%



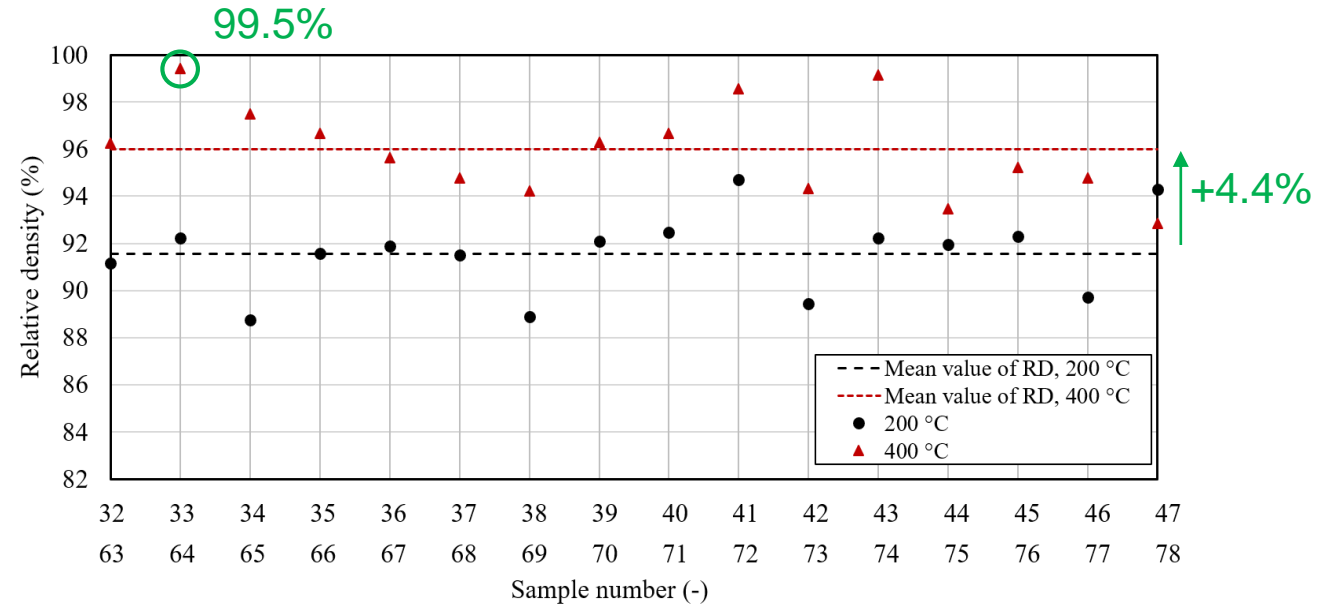
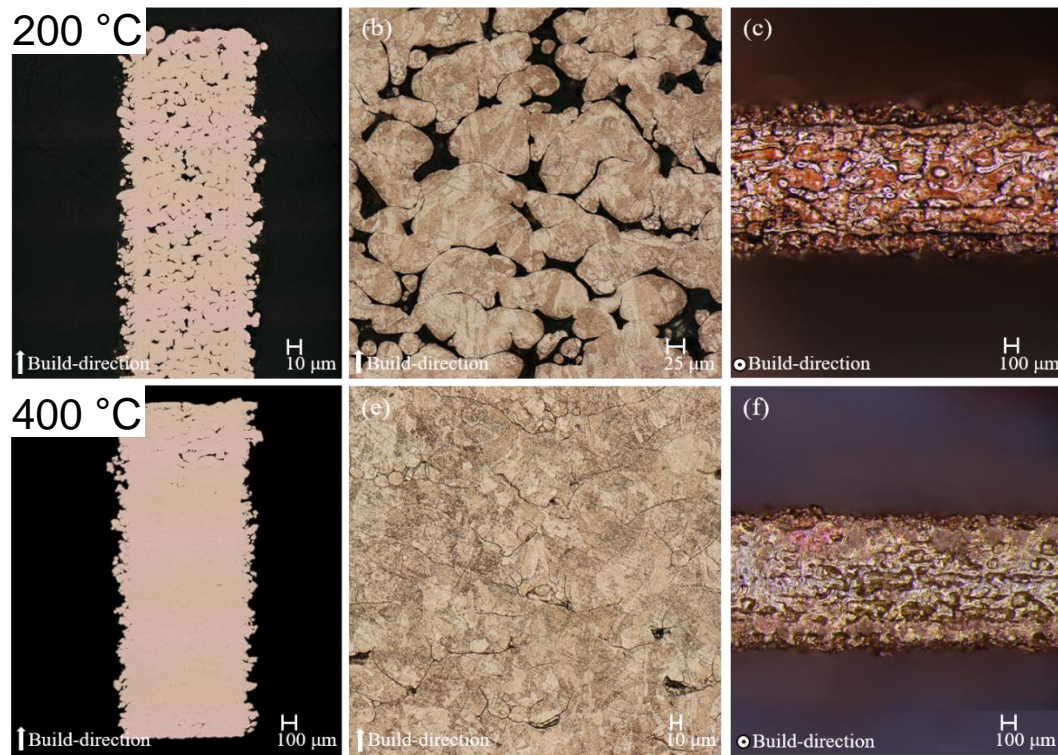
Specimen 33
30 μm
92.2%



Results Q₃

Effect of preheating

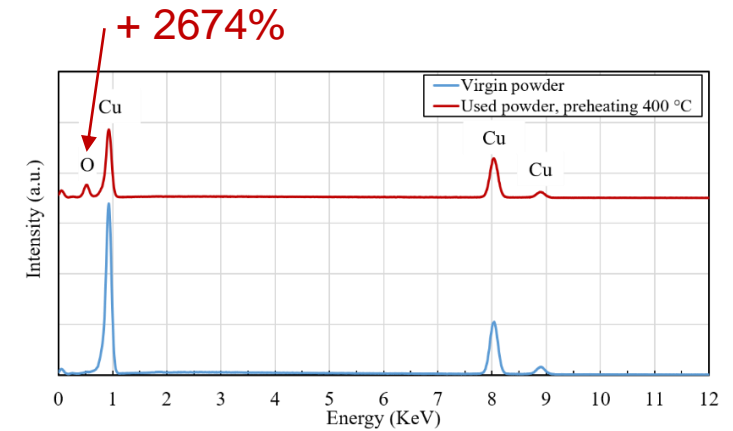
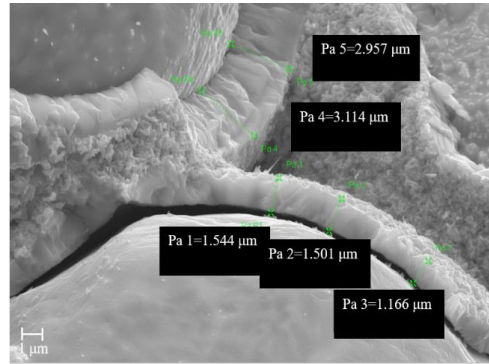
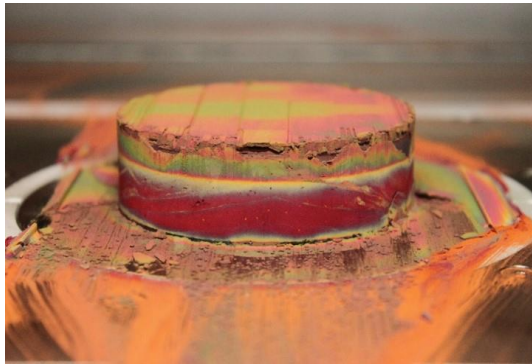
Layer thickness 30 μm



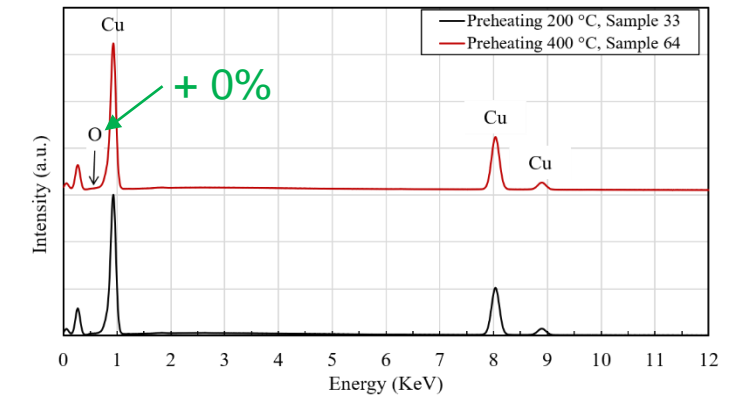
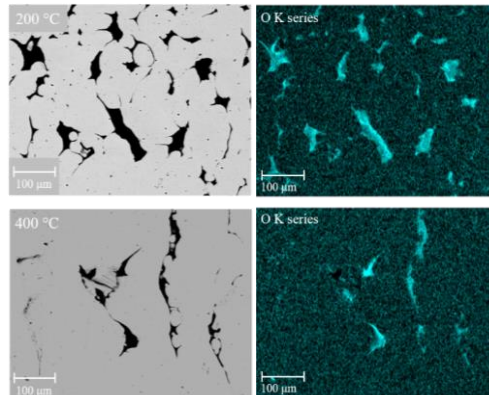
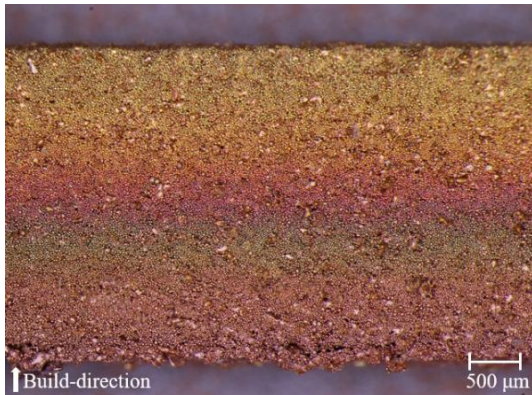
Results Q₃

Effect of preheating on unfused powder?

Powder
400 °C



Specimen
400 °C



Discussion Q₃

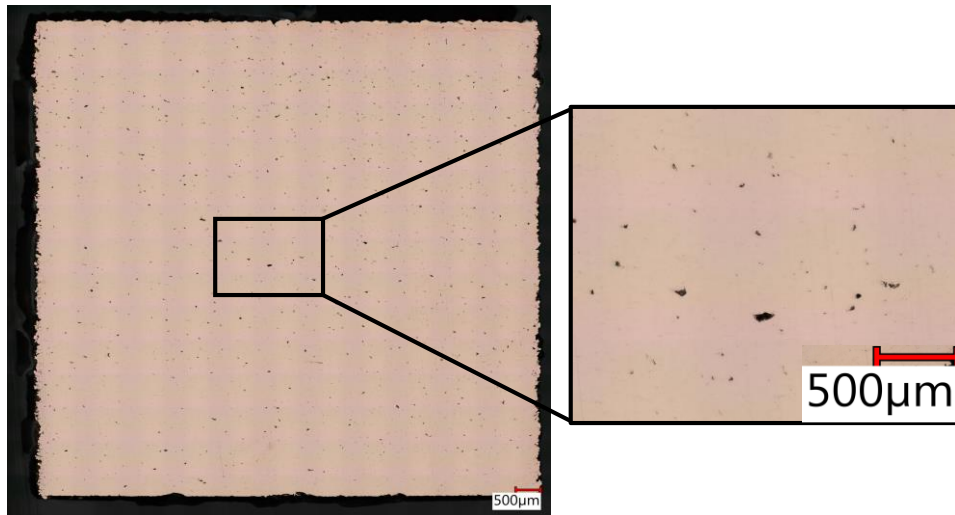
Can we increase relative density of reflective materials using preheating?

Q₃: What is the effect of preheating on the relative density of copper specimens prepared with an LPBF system using IR fibre laser?

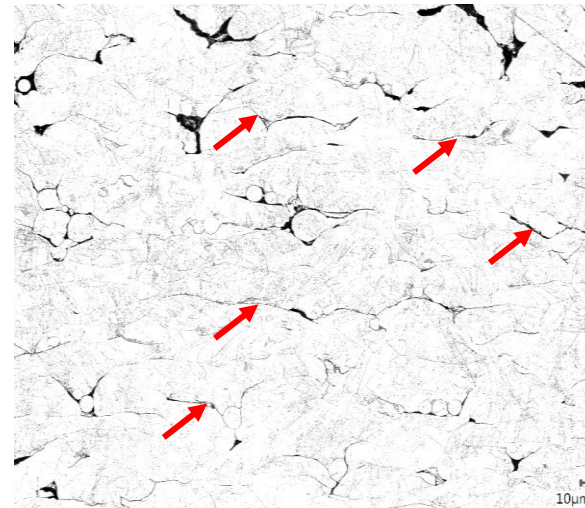
Confirmed

Preheating significantly increases relative density

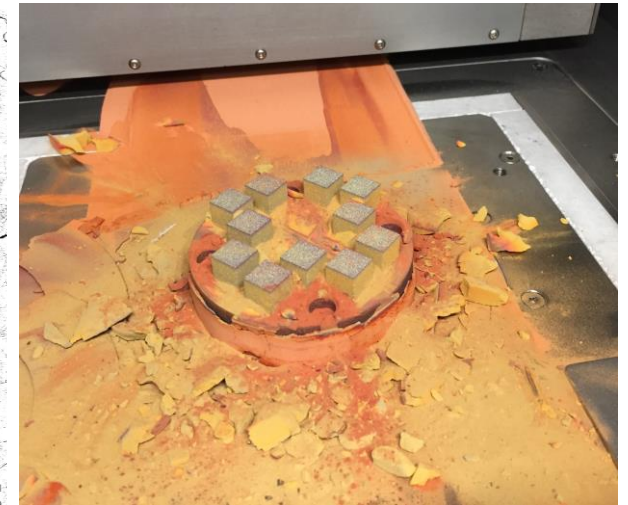
RD over 99 %



Layer bonding



Powder oxidation

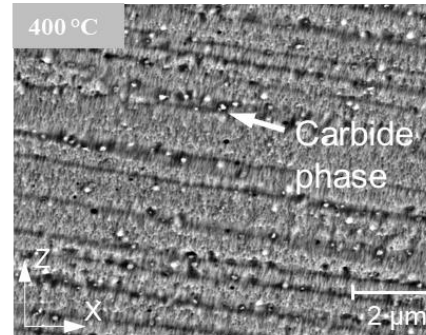


General conclusion

Can we decrease energy intensity of LPBF using preheating?

Ti6Al4V – Lower residual stresses

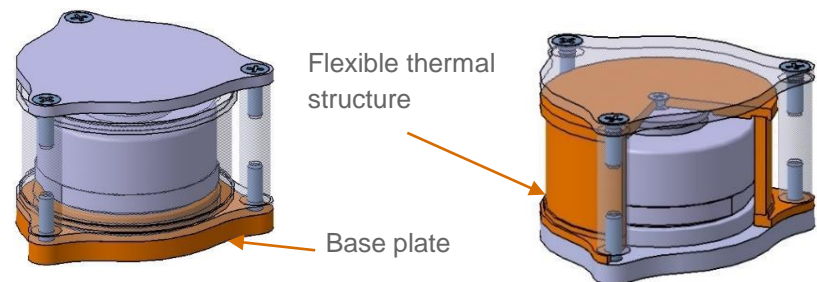
Inconel 939 – Higher residual stresses



Life cycle energy savings

RD of copper over 99 %

Perspective for high conductive materials Cu, Ag, Au



Miniaturized heat-switch component Al 150 W/m/K → Cu 386 W/m/K

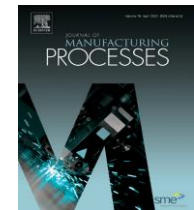


Base plate and flexible thermal structure made of ALSi10Mg, Mašek 2022

List of publications

Related to the dissertation thesis

- **MALÝ, Martin**, Christian HÖLLER, Mateusz SKALON, Benjamin MEIER, Daniel KOUTNÝ, Rudolf PICHLER, Christof SOMMITSCH a David PALOUŠEK. Effect of Process Parameters and High-Temperature Preheating on Residual Stress and Relative Density of Ti6Al4V Processed by Selective Laser Melting. *Materials* [online]. 2019, 12(6), 930. ISSN 1996-1944. Available at: doi:10.3390/ma12060930
- **MALÝ, Martin**, Klára NOPOVÁ, Lenka KLAURKOVÁ, Ondřej ADAM, Libor PANTĚLEJEV a Daniel KOUTNÝ. Effect of Preheating on the Residual Stress and Material Properties of Inconel 939 Processed by Laser Powder Bed Fusion. *Materials* [online]. 2022, 15(18), 6360. ISSN 1996-1944. Available at: doi:10.3390/ma15186360
- **MALÝ, Martin**, Daniel KOUTNÝ, Libor PANTĚLEJEV, Laurent PAMBAGUIAN a David PALOUŠEK. Effect of high-temperature preheating on pure copper thick-walled samples processed by laser powder bed fusion. *Journal of Manufacturing Processes* [online]. 2022, 73, 924–938. ISSN 15266125. Available at: doi:10.1016/j.jmapro.2021.11.035



Other publications

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