NEUTRONS FOR SOCIETY
WAM 2021
ESRF

Characterization methods for additive manufacturing:
Influence of processing strategies on residual stresses, microstructure and defects in AM materials and components

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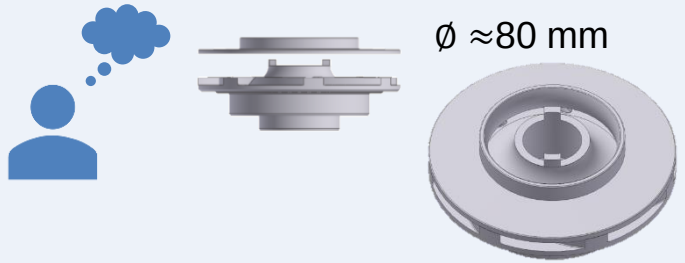
June 2nd, 2021

DLR

Motivation – „easy printing“?!

Rocket Turbo-Pump Impeller*

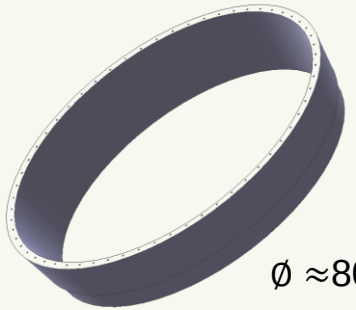


Idea: printed as a single part

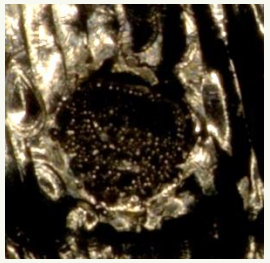
First result:
support cracks, deformation

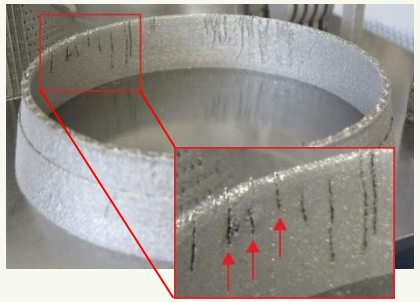
Volume Parameters
Optimization
- Residual Stresses
- Porosity
- Microstructure

Injector element**



Idea: small channels (ø ≈300-400µm)





First result:
blocked channels or cracks

Contour Parameters
Optimization
- Residual Stresses
- Surface Roughness

*Design: W. Kitsche, DLR-RA Lampoldshausen, **Design: M.Ortelt, DLR-BT Stuttgart

Outline

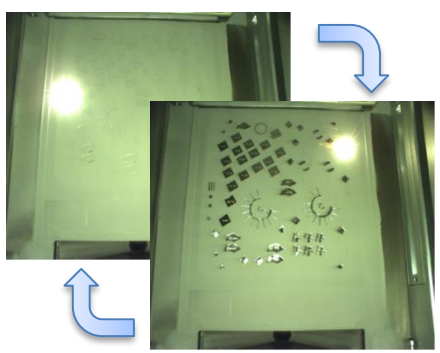
Part I – Cuboids (Ti-6Al-4V)

- Influence Factors for Parameter Optimization
- Residual Stress Measurement – Method
- Optimization of Volume Process Parameters
- Optimization of Contour Process Parameters

Part II – Outlook: Components (Ti-6Al-4V)

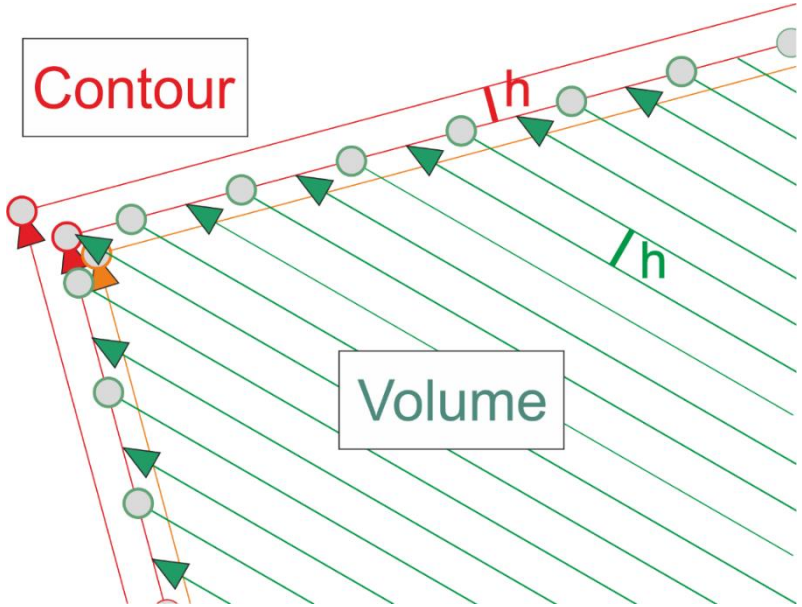
- Transferability: from Coupon to Component

Influence factors for parameter optimization (L-PBF)



Machine used for this study:

SLM Solutions 280^{HL} single
(280 x 280 x 300 mm^3; up to 1200 °C; melt pool monitoring; improved: processing atmosphere and mass spectrometry)



Investigated process parameters:

- Hatch distance h
- Laser power P
- Scanning velocity v

Volume Energy Density

$$E_v = \frac{P}{hv}$$

- Number of Contour Lines
- Scan order (Volume/Contour)

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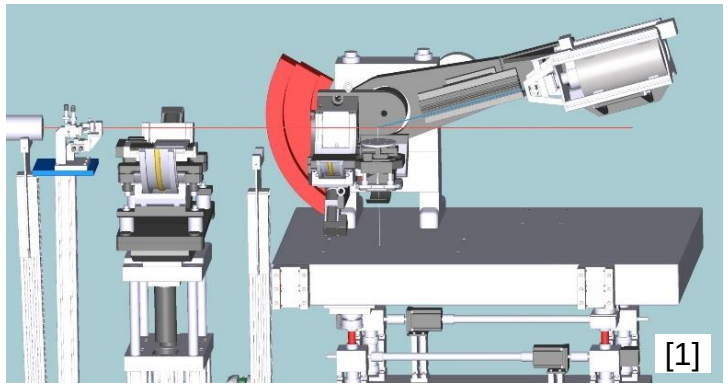
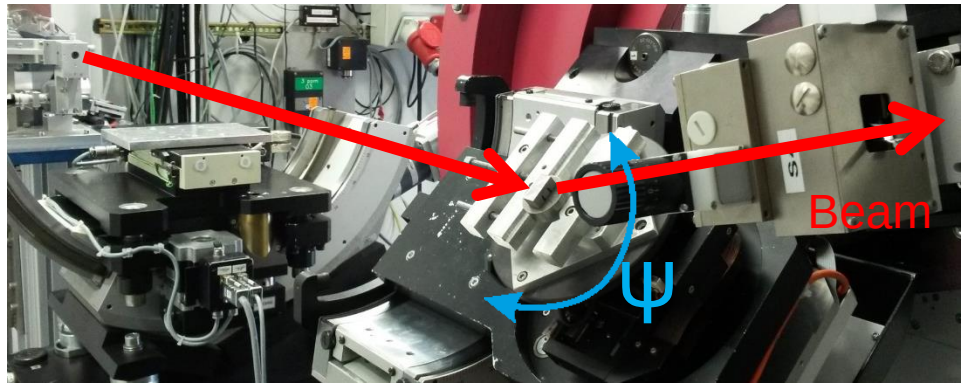
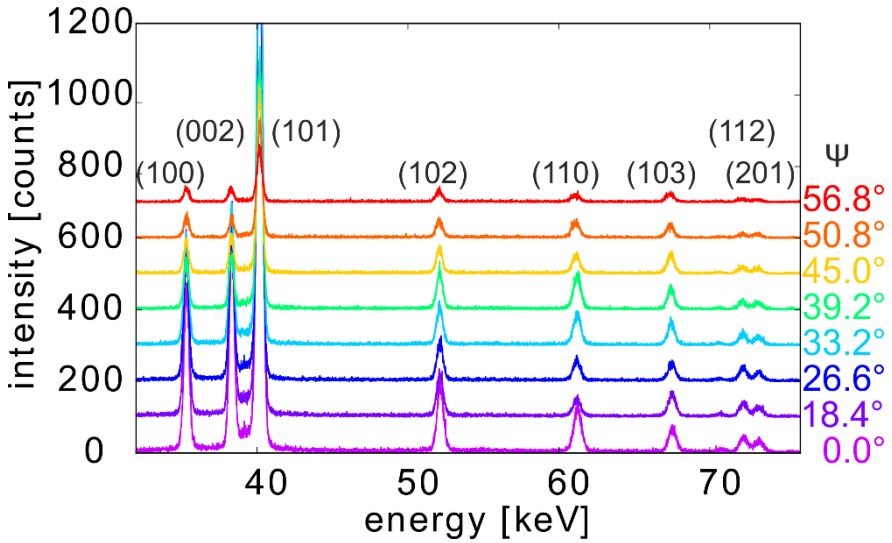
Residual Stress Measurements
Method





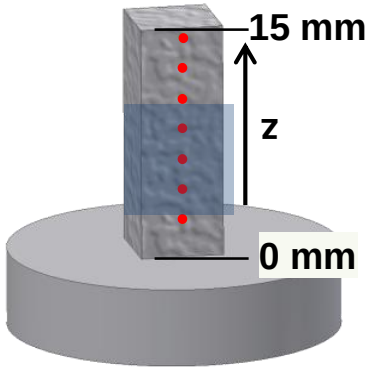
- Synchrotron source BESSY II (HZB, Berlin, Germany)
- Beamline 7T-MPW-EDDI (energy-dispersive mode of diffraction)
- Measurement in reflexion (subsurface)
- No texture near surface
  - isotropic diffraction elastic constants
- $Sin^2\psi$-method
- Material: Ti-6Al-4V
- Peak (103) used for stress calculation



[1] HZB https://www.helmholtz-berlin.de

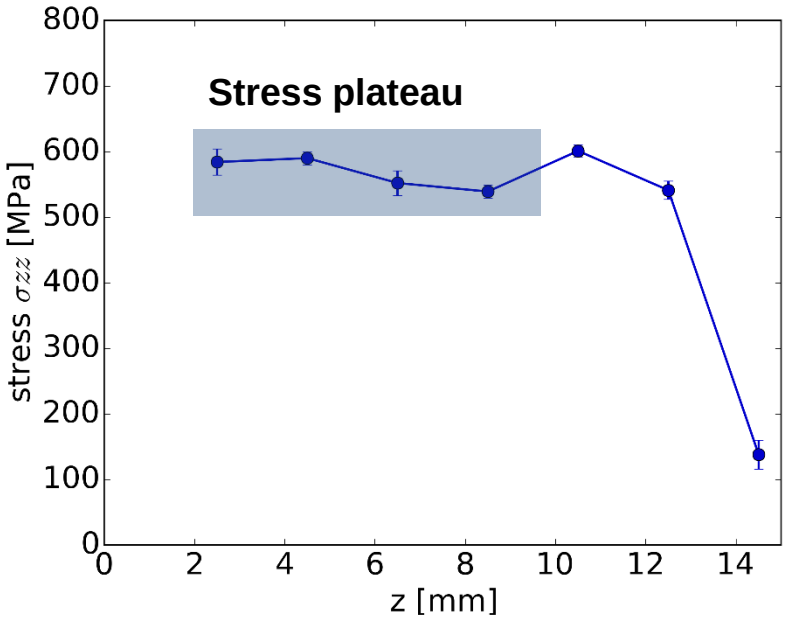
Residual Stress Measurements
Specimens

Measurement Positions



5x5x15 mm³

Stresses in Build Direction



- **High tensile stresses** in build direction
- **Stress plateau** in the middle
  → stress values in this region will be averaged for further comparisons

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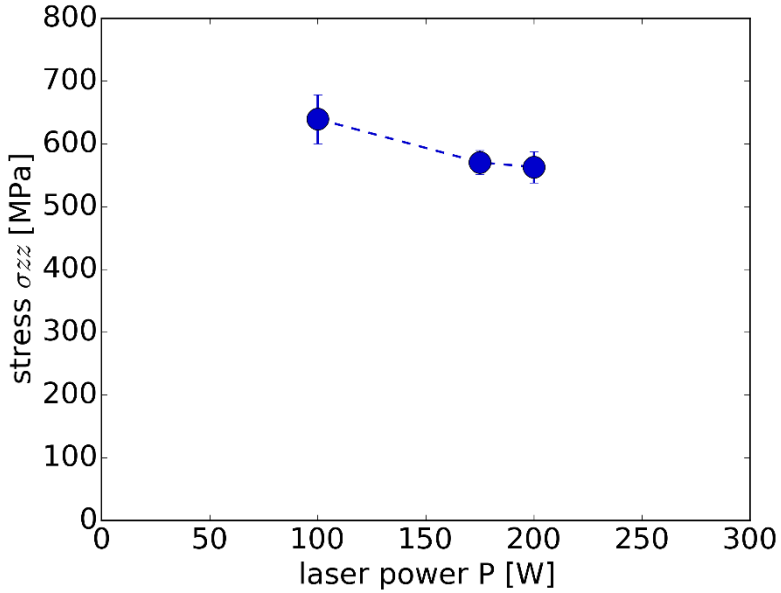
- Transferability: from Coupon to Component

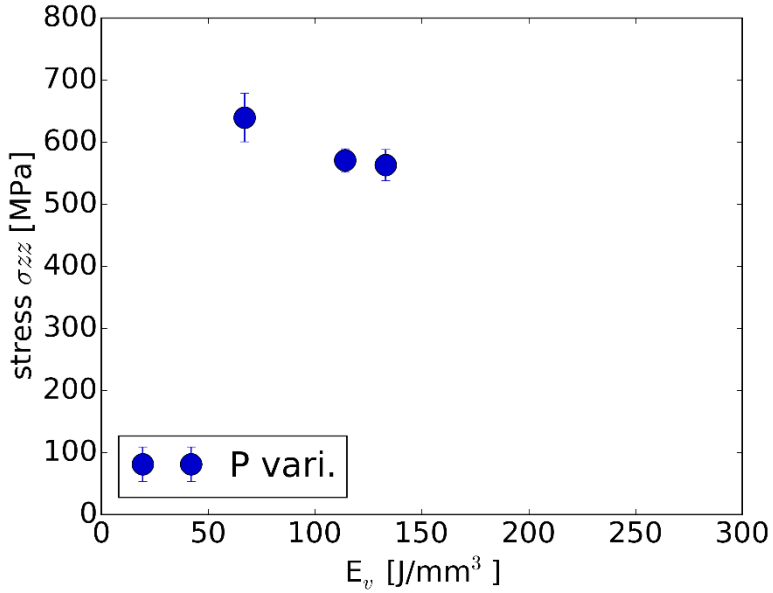
Optimization of Volume Process Parameters
Residual Stresses

Variation of

- Laser Power P



$$E_v = \frac{P}{hv}$$

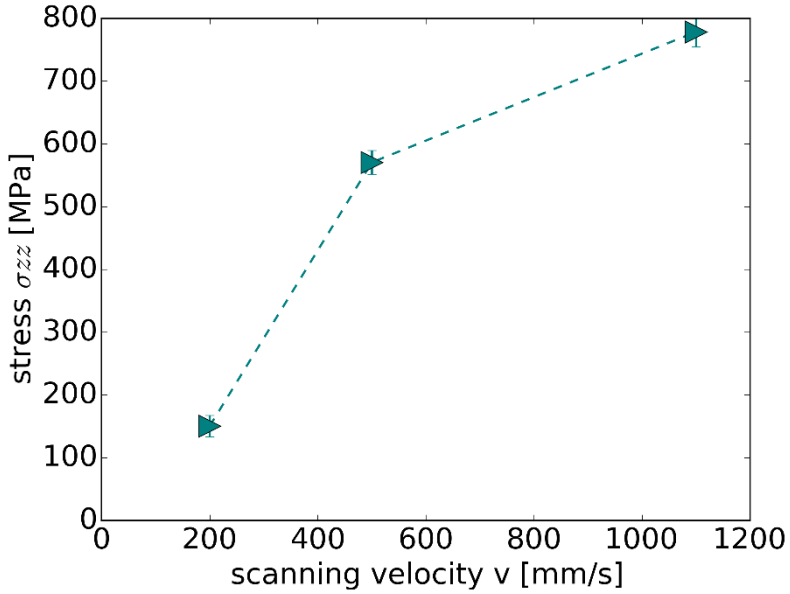


Mishurova, T., Artzt, K., Haubrich, J., Requena, G., & Bruno, G. (2019). Metals, *9*(2), 261

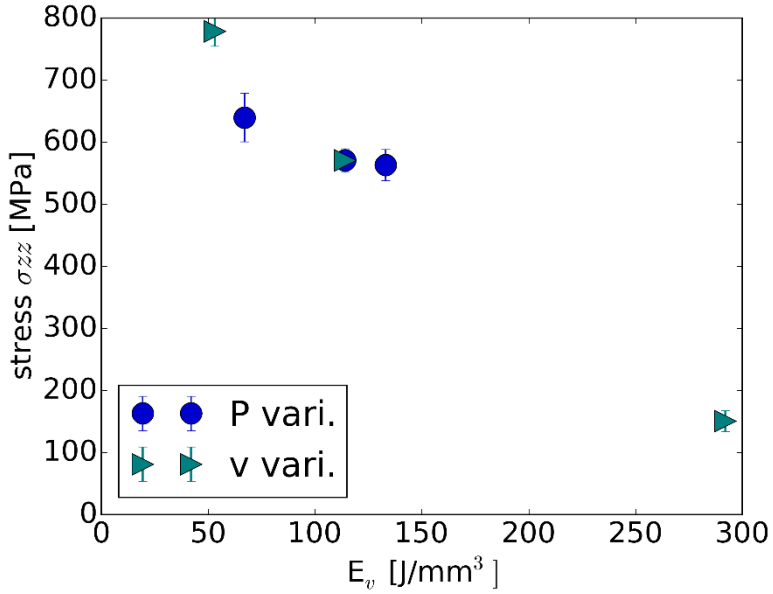
Optimization of Volume Process Parameters
Residual Stresses

Variation of

- Laser Power P
- Scanning Velocity v



$$E_v = \frac{P}{hv}$$

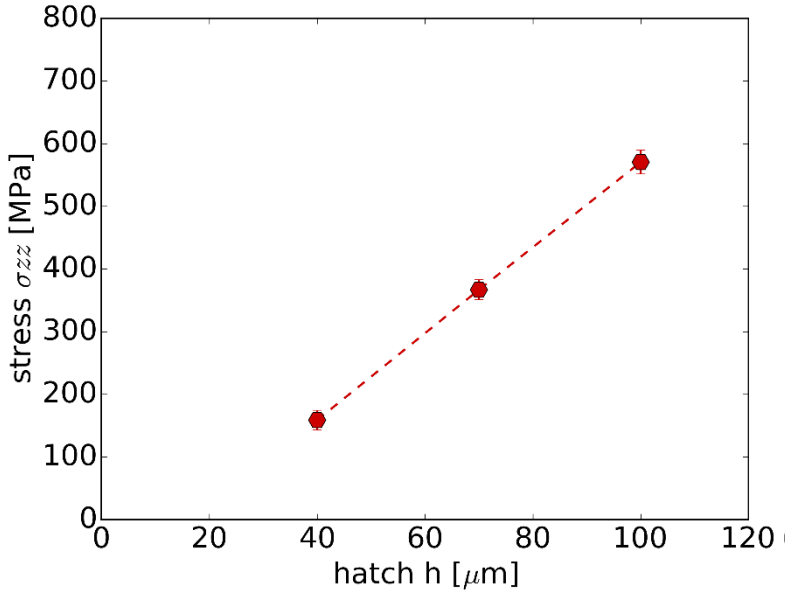


Mishurova, T., Artzt, K., Haubrich, J., Requena, G., & Bruno, G. (2019). Metals, *9*(2), 261

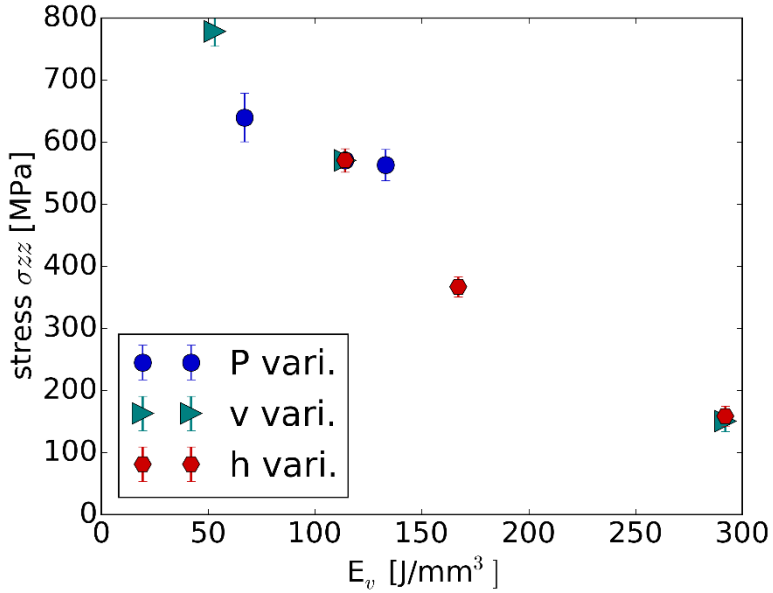
Optimization of Volume Process Parameters
Residual Stresses

Variation of

- Laser Power P
- Scanning Velocity v
- Hatch h



$$E_v = \frac{P}{hv}$$

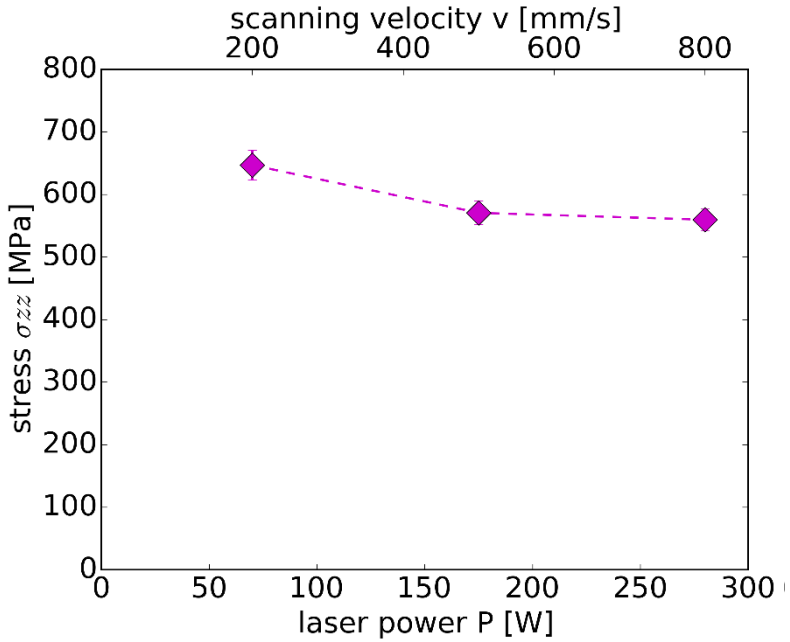


Mishurova, T., Artzt, K., Haubrich, J., Requena, G., & Bruno, G. (2019). Metals, *9*(2), 261

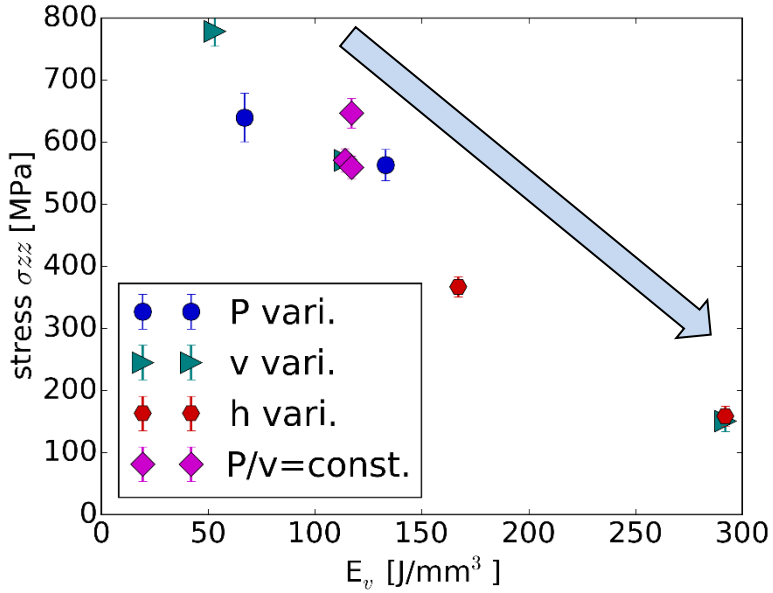
Optimization of Volume Process Parameters
Residual Stresses

Variation of

- Laser Power P
- Scanning Velocity v
- Hatch h
- P/v=const.



$$E_v = \frac{P}{hv}$$



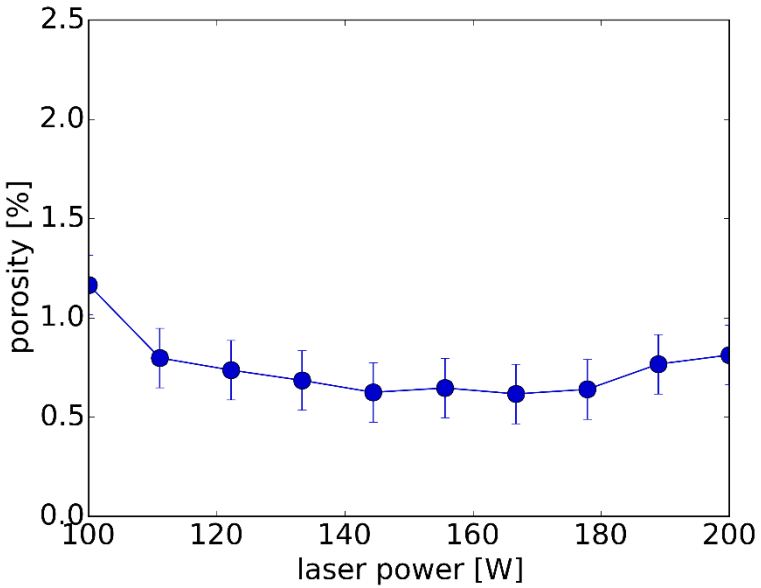
Optimization of RS for Volume Process Parameters: **High E_v → low residual stresses**

Mishurova, T., Artzt, K., Haubrich, J., Requena, G., & Bruno, G. (2019). Metals, *9*(2), 261

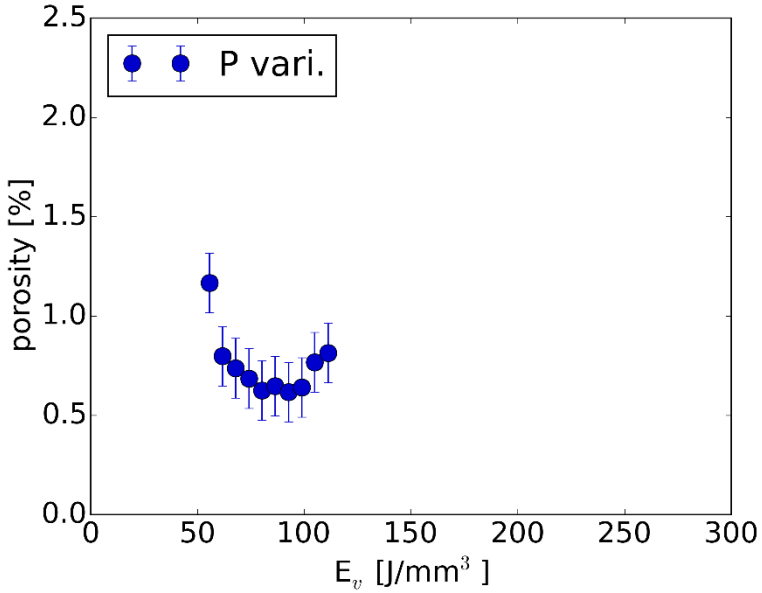
Optimization of Volume Process Parameters
Porosity

Variation of

- Laser Power P



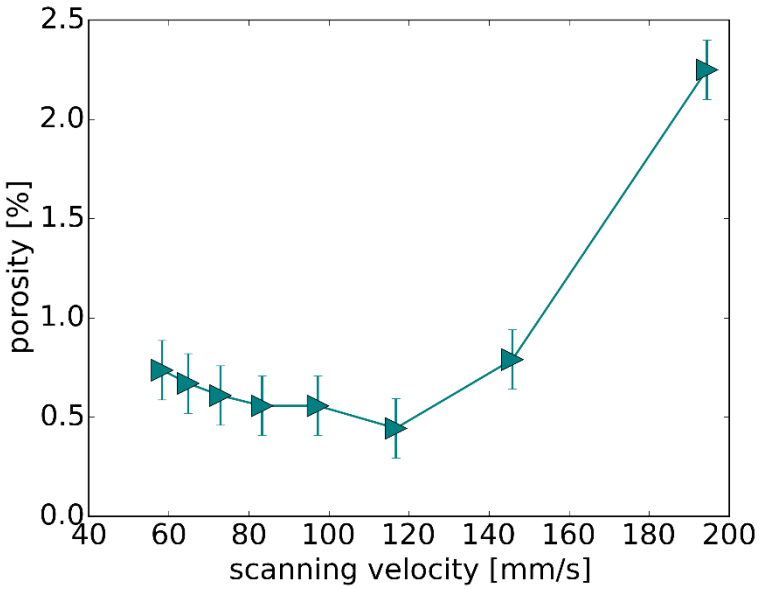
$$E_v = \frac{P}{hv}$$



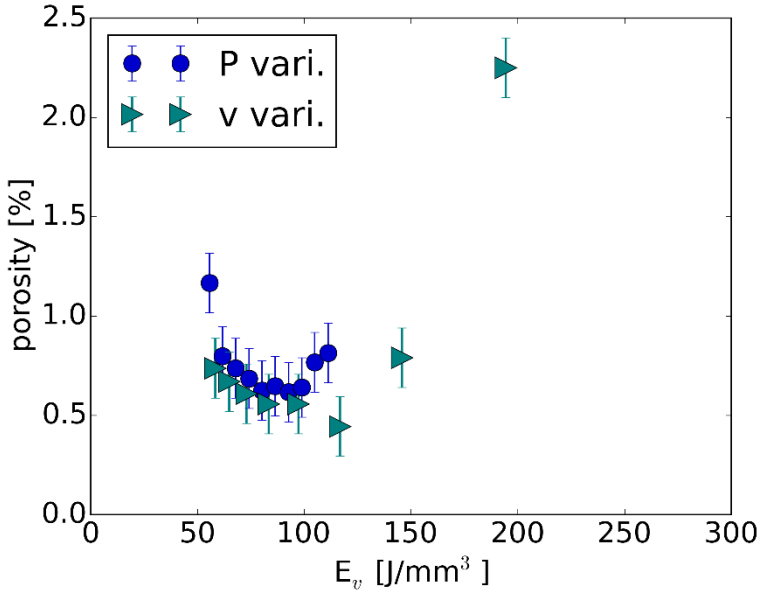
Optimization of Volume Process Parameters
Porosity

Variation of

- Laser Power P
- Scanning Velocity v



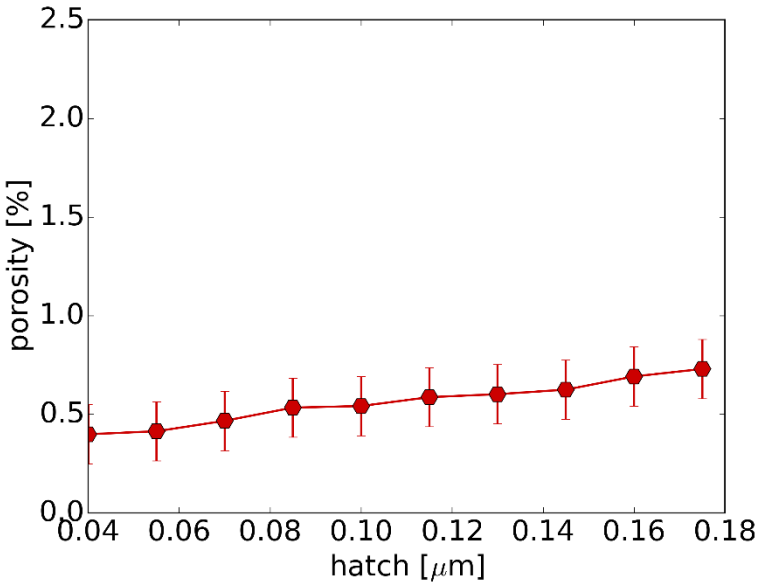
$$E_v = \frac{P}{hv}$$



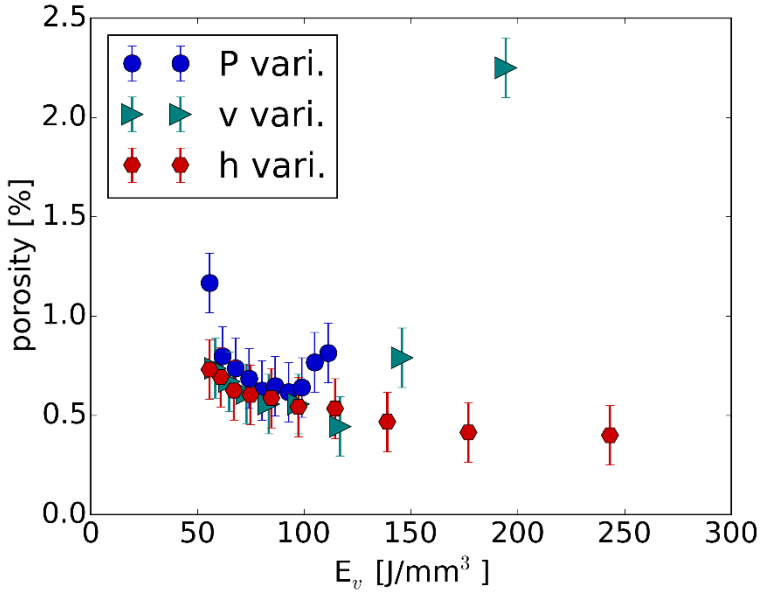
Optimization of Volume Process Parameters
Porosity

Variation of

- Laser Power P
- Scanning Velocity v
- Hatch h



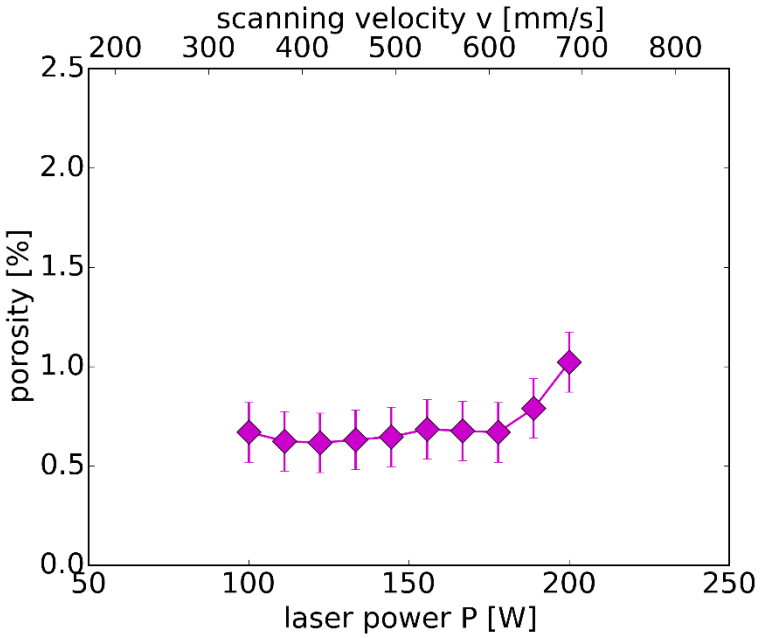
$$E_v = \frac{P}{hv}$$



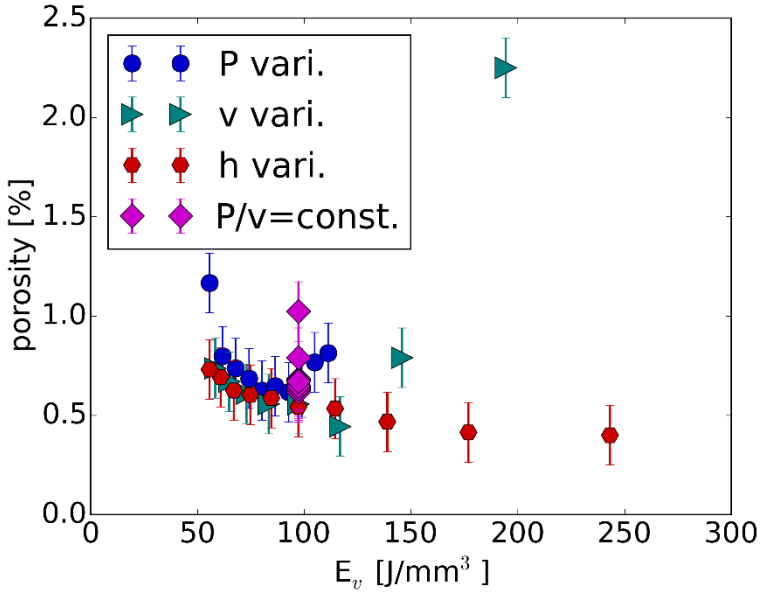
Optimization of Volume Process Parameters
Porosity

Variation of

- Laser Power P
- Scanning Velocity v
- Hatch h
- P/v=const.



$$E_v = \frac{P}{hv}$$



Optimization of Porosity for Volume Process Parameters:

- P & v: Optimum exists for E_v ~ 80-150 J/mm^3
- h: Porosity decreases with decreasing hatch distance (high E_v)

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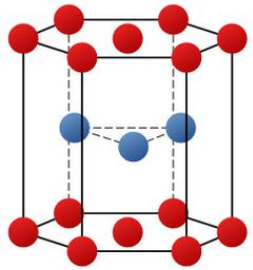
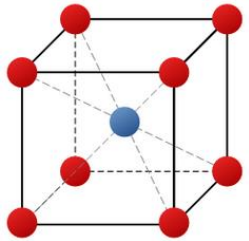
Optimization of Volume Process Parameters
Microstructure

α-phase /α‘ martensite:
hcp → brittle

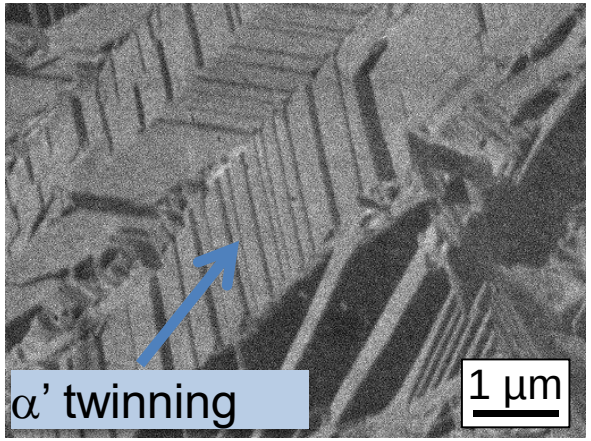


β–phase: bcc
→ ductile

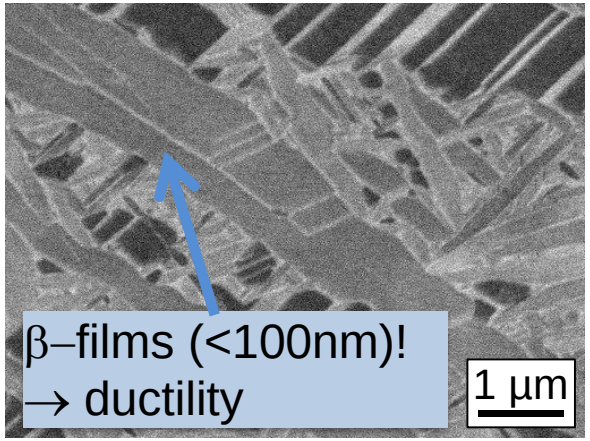


Lattice structures:
www.tec--science. com

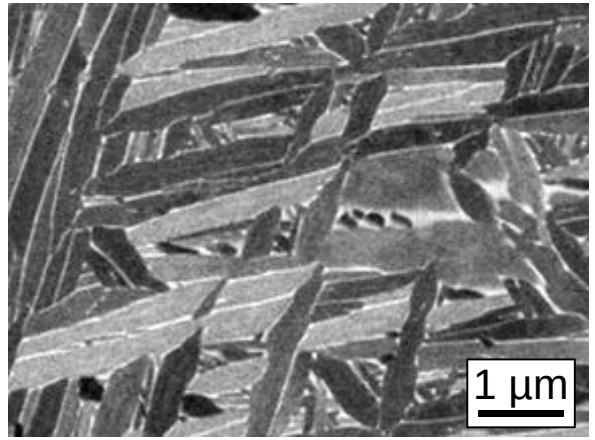
Low E_V (77 J/mm³)



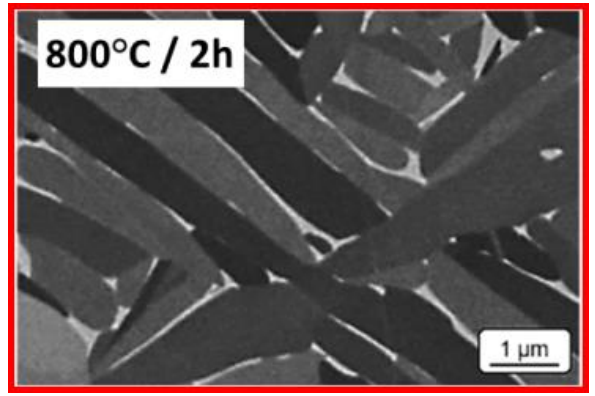
Intermediate E_V (145 J/mm³)



High E_V (243 J/mm³)



→ Microstructure dependent on E_v
→ E_V increase ⇒ increase in β volume fraction
→ stabilized α+β microstructure possible at high E_v
→ Post-Processing:
Heat treatment or Hot-Isostatic Pressing

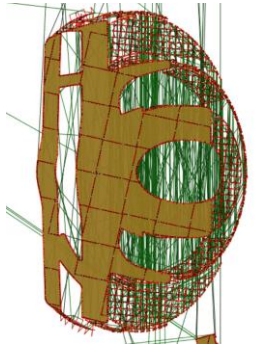


Optimization of Process Parameters
Summary I

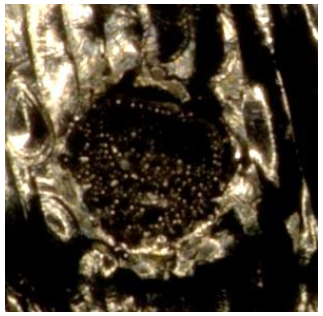
Recommendation – Volume Process Parameters:

- **Hatch distance↓ ⇨ Minimal stresses + porosity** (- higher build time)
- Post-processing: Heat treatment for ductile microstructure

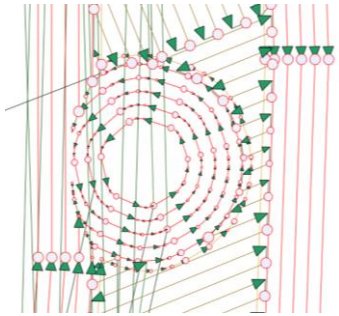
→ solution for the impeller?



Recommendation – Contour Process Parameters?
Solution for the injector element?



500µm



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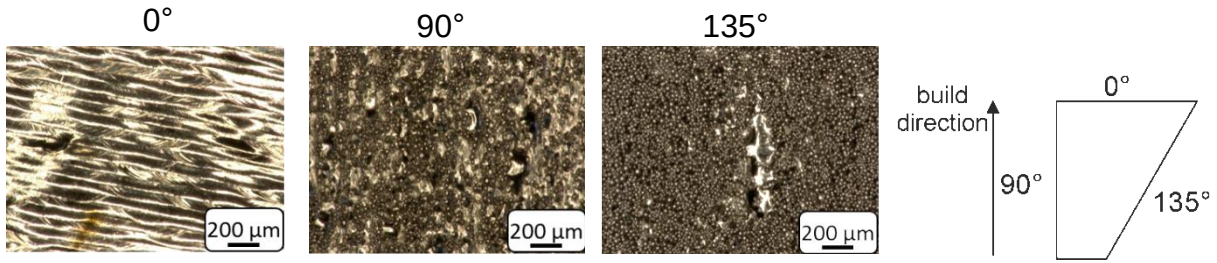
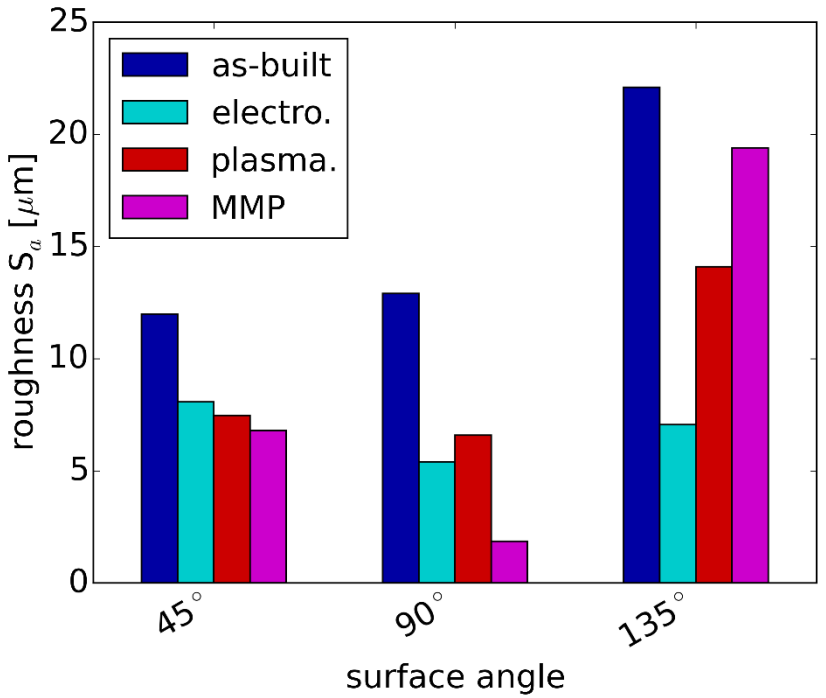
Optimization of Contour Process Parameters
Surface Roughness

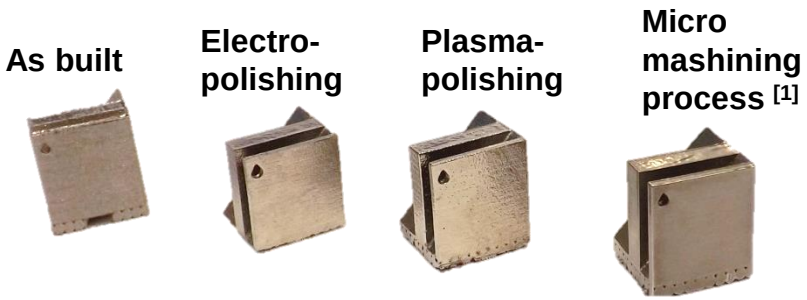
Roughness strongly dependent on orientation



Example for S_a-values



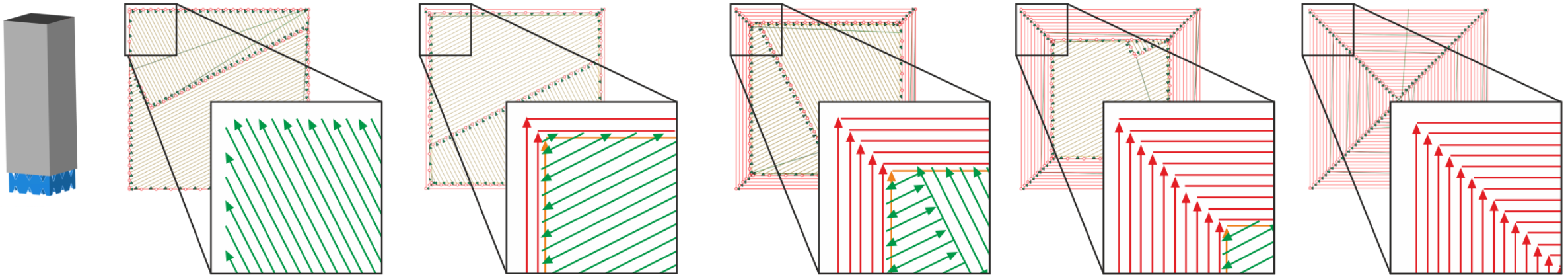
Post-Processing: surface finishing



[1] http://mmptechnology.com/

Optimization of Contour Process Parameters

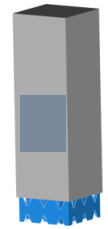
Scan Strategy



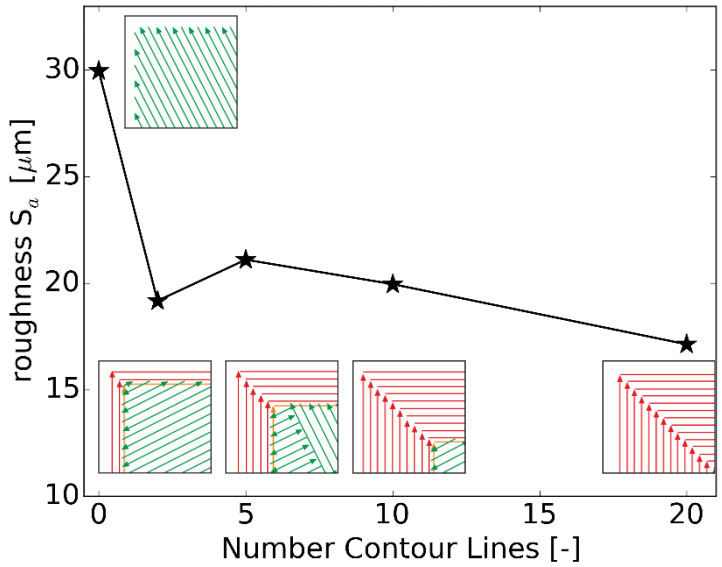
Standard Process:

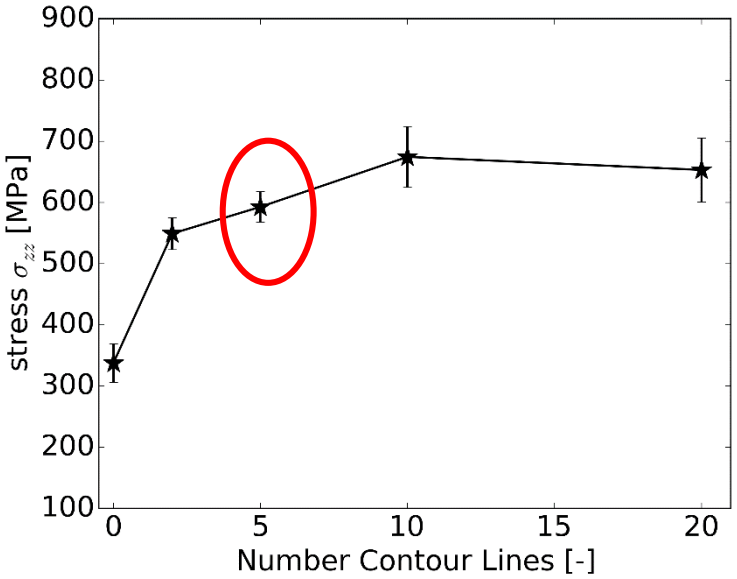
- 2 Contour Lines
- Scan order: Contour (out → in) → Volume

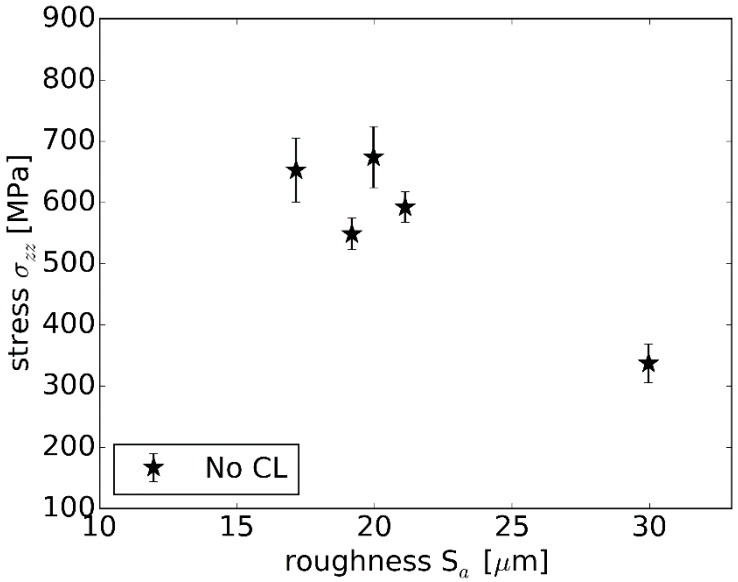
Optimization of Contour Process Parameters



Contour Line Number Variation







For Residual Stress Measurements:

- 5 Contour Lines; Standard Scan Order;
- Volume process parameters kept constant, contour parameters (P, h, v) are varied

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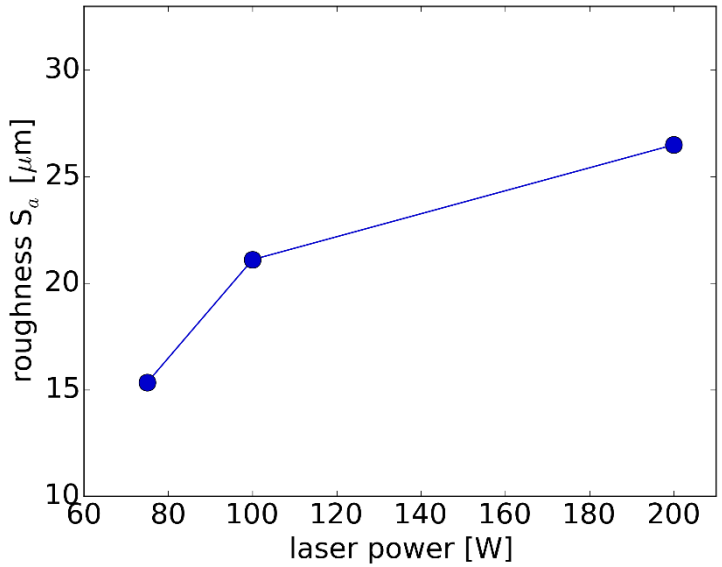
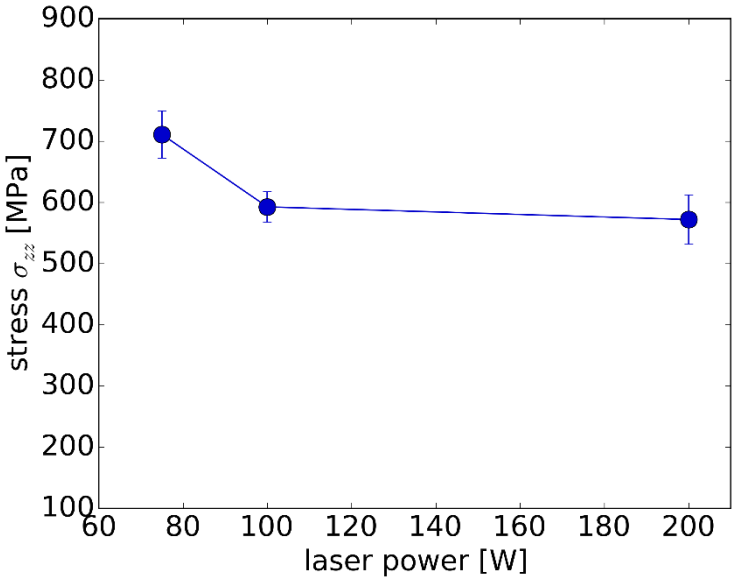
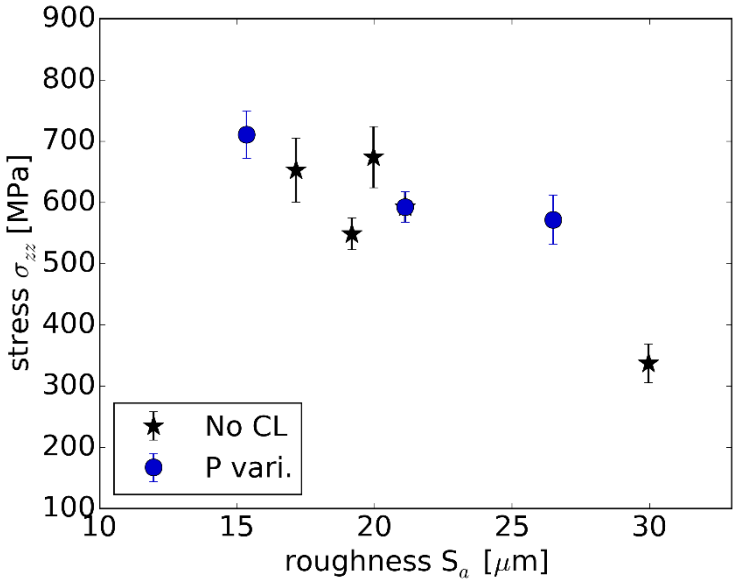
Artzt K. et al. (2020). Materials, 13
doi:10.3390/ma13153348

Optimization of Contour Process Parameters

Laser Power Variation





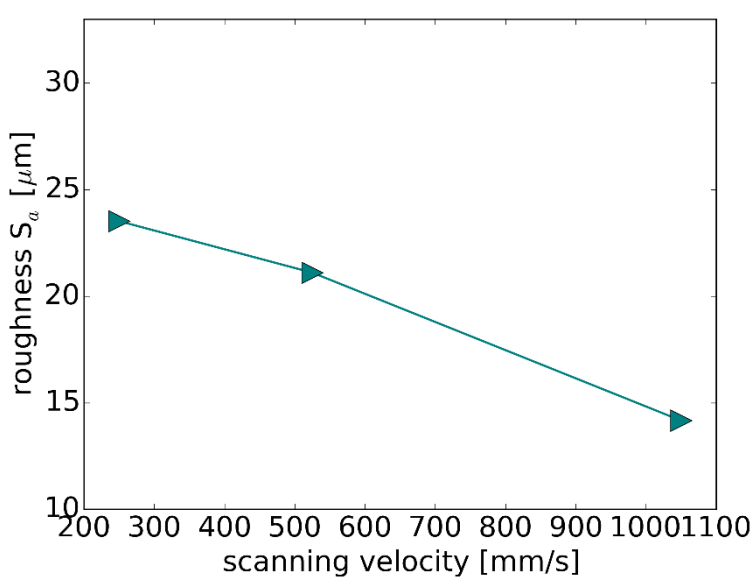


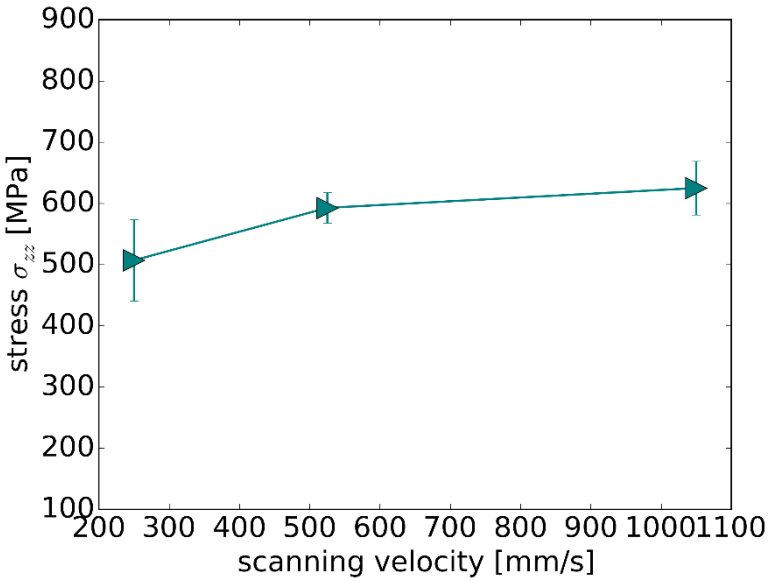
- Laser Power: P ↑ ⇨ S_a ↑, σ ↓

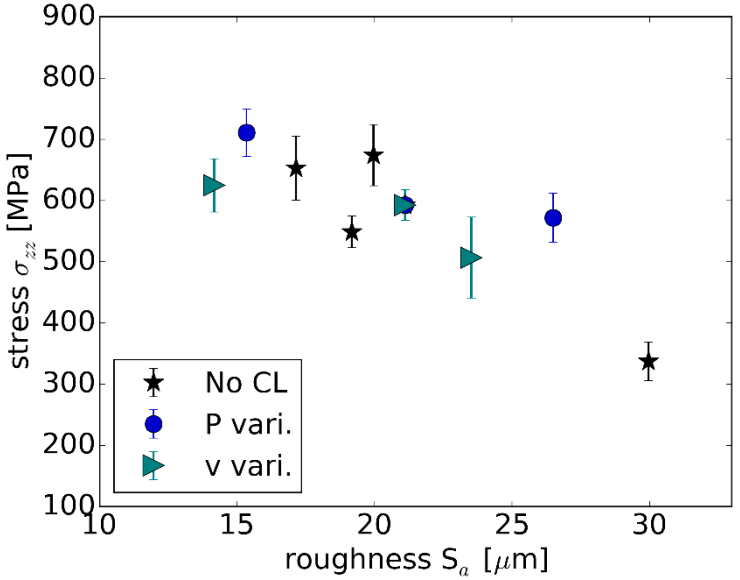
Artzt K. et al. (2020). Materials, 13
doi:10.3390/ma13153348

Optimization of Contour Process Parameters

Scanning Velocity Variation





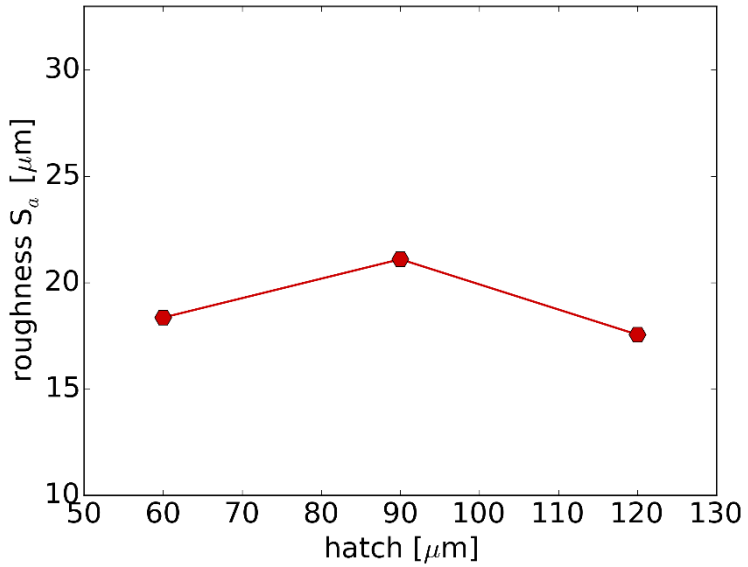


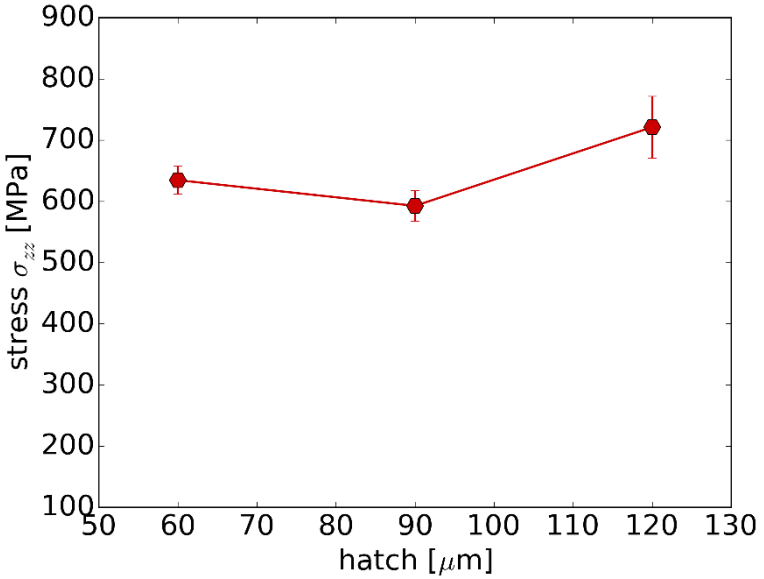
- Laser Power: P ↑ ⇨ S_a ↑, σ ↓
- Velocity: v ↑ ⇨ S_a ↓, σ ↑

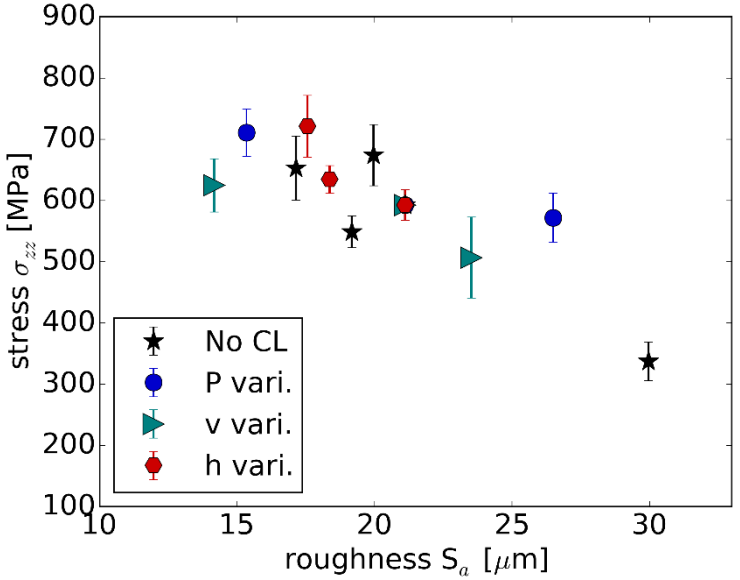
Artzt K. et al. (2020). Materials, 13
doi:10.3390/ma13153348

Optimization of Contour Process Parameters

Hatch Variation





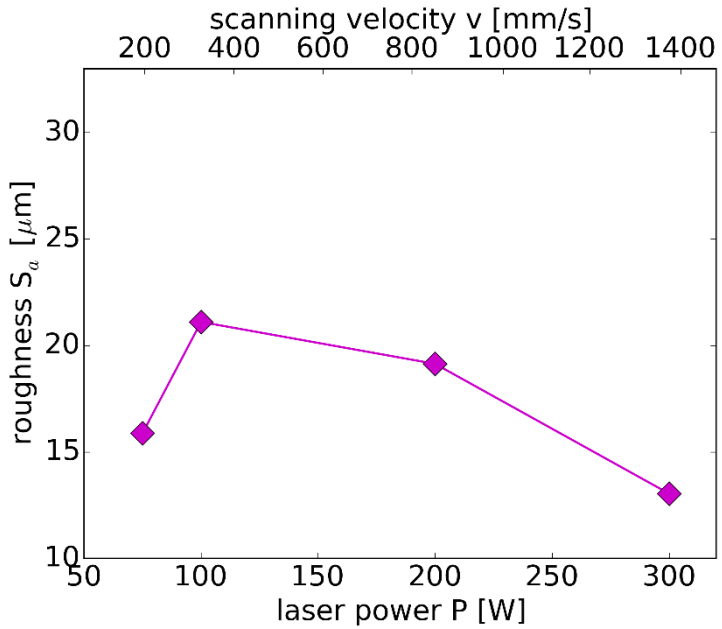


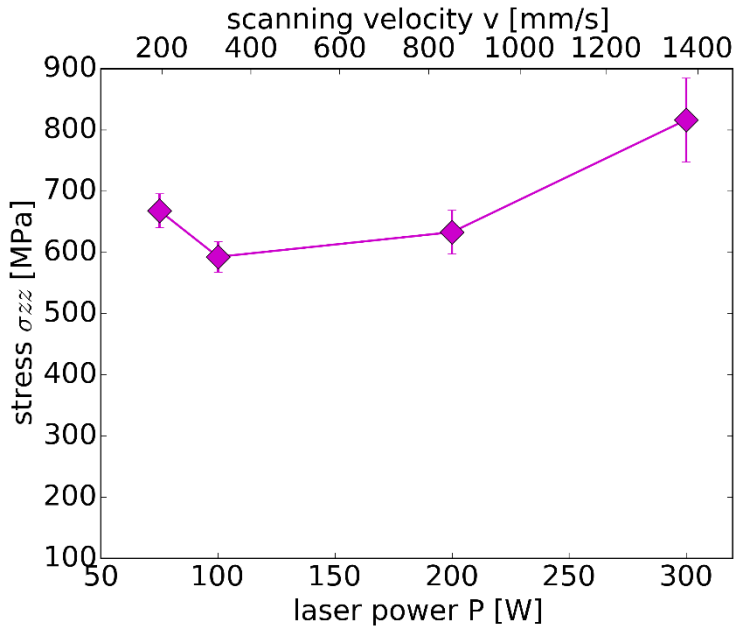
- Laser Power: P ↑ ⇨ S_a ↑, σ ↓
- Velocity: v ↑ ⇨ S_a ↓, σ ↑
- Hatch: h ↑ ⇨ no clear influence

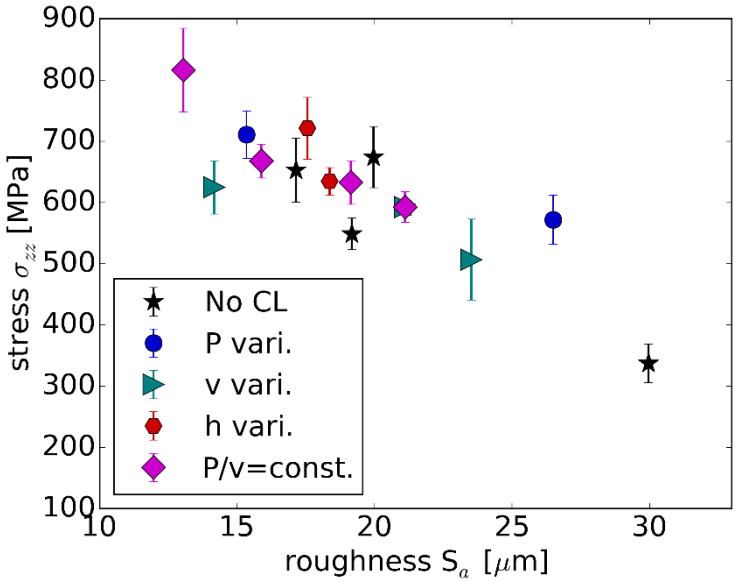
Artzt K. et al. (2020). Materials, 13
doi:10.3390/ma13153348

Optimization of Contour Process Parameters

P/v=const.





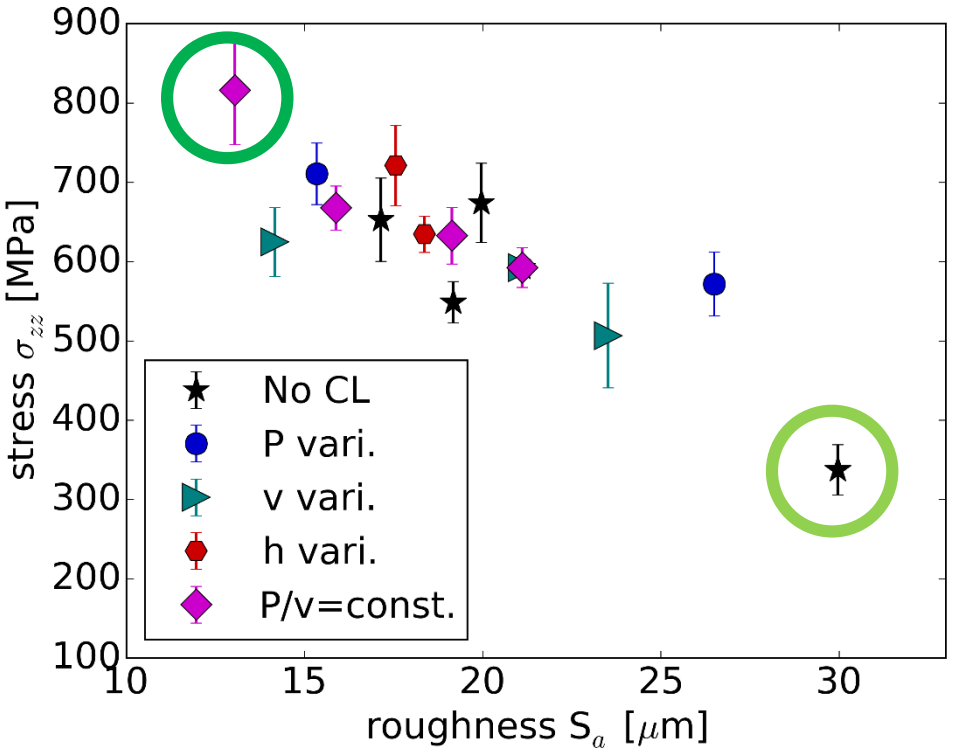


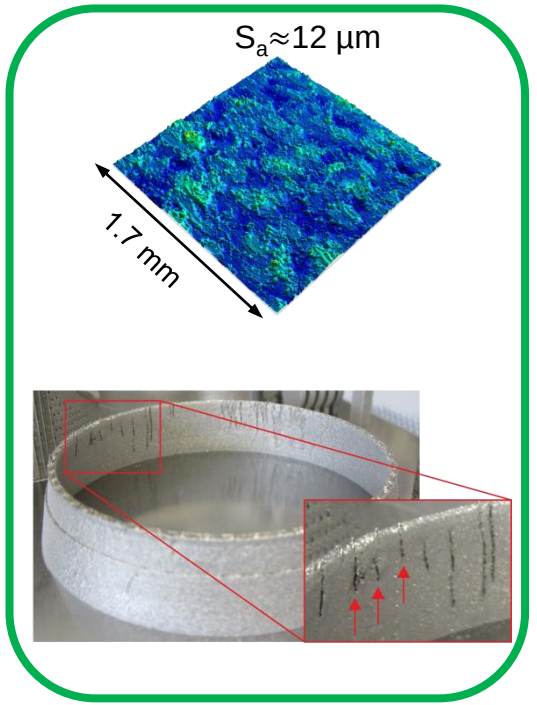
- Laser Power: P ↑ ⇨ S_a ↑, σ ↓
- Velocity: v ↑ ⇨ S_a ↓, σ ↑
- Hatch: h ↑ ⇨ no clear influence
- P/v=const: P+v ↑ ⇨ S_a maximum, σ minimum

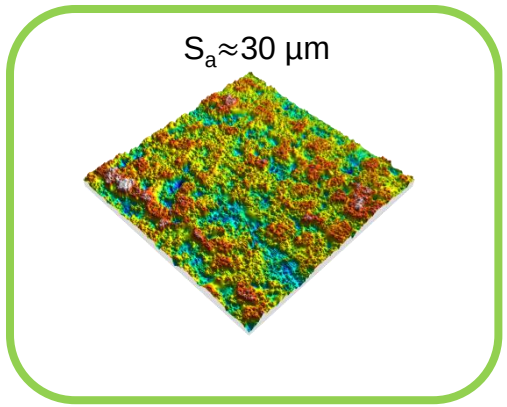
Artzt K. et al. (2020). Materials, 13
doi:10.3390/ma13153348

Optimization of Contour Process Parameters

Correlation between residual stresses and roughness







It is not possible to optimize RS and roughness the same time → compromise necessary

Artzt K. et al. (2020). Materials, 13
doi:10.3390/ma13153348

Optimization of Process Parameters
Summary II

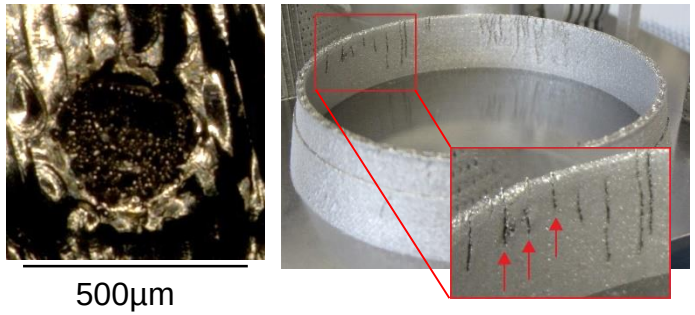
Recommendation – Volume Process Parameters:

- **Hatch distance↓ ⇨ Minimal stresses + porosity** (- higher build time)
- Post-processing: Heat treatment for ductile microstructure

  → solution for the impeller?

Recommendation – Contour Process Parameters:

- Low RS: low velocity, low laser power
- Low surface roughness: high velocity
- ⇨ Residual stresses and surface roughness cannot be simultaneously optimized → compromise needed



Outline

Part I – Cuboids (Ti-6Al-4V)

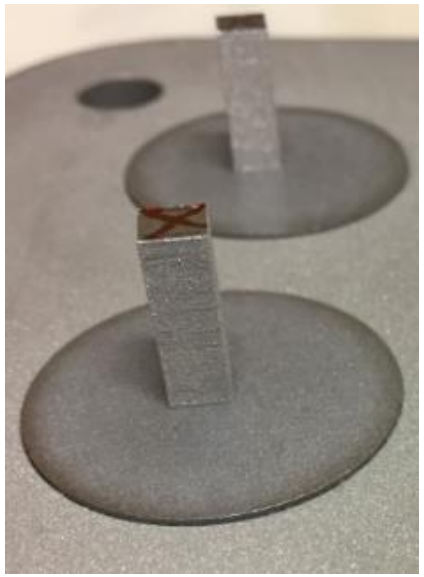
- Influence Factors for Parameter Optimization
- Residual Stress Measurement – Method
- Optimization of Volume Process Parameters
- Optimization of Contour Process Parameters

Part II – Outlook: Components (Ti-6Al-4V)

- Transferability: from Coupon to Component

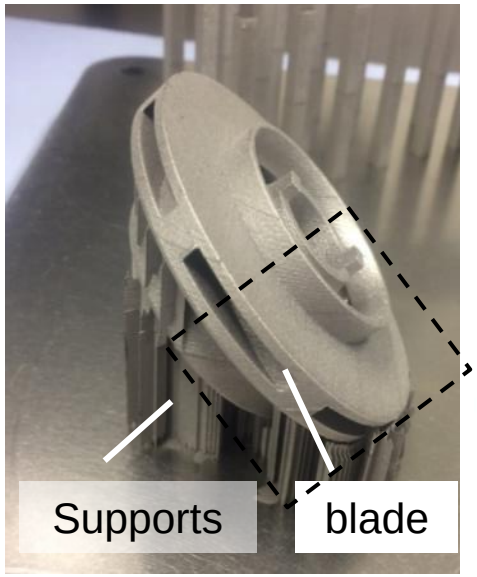
Transferability: from coupon to component

Coupon level



Columnar prior β-grains
parallel to building direction

Component

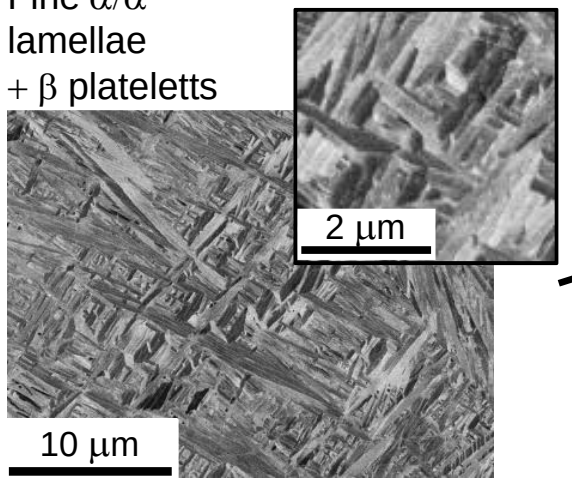


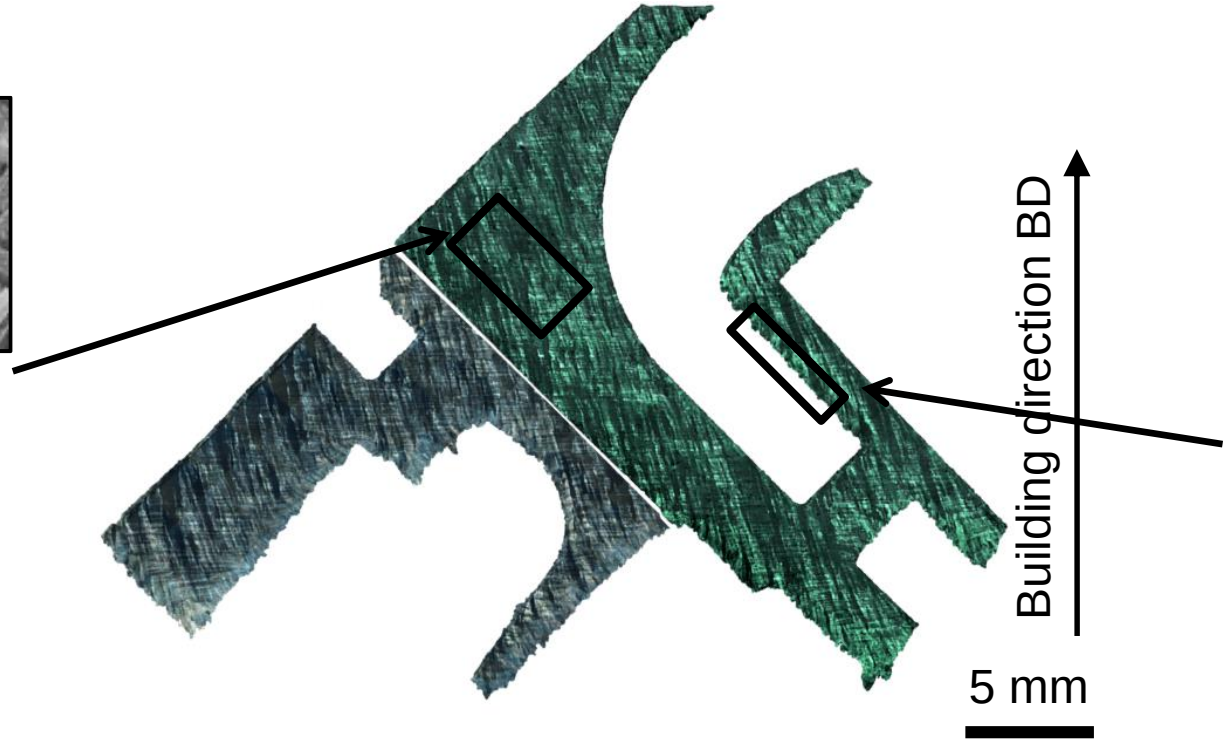
Columnar prior β-grains
not parallel to building direction

Transferability: from coupon to component

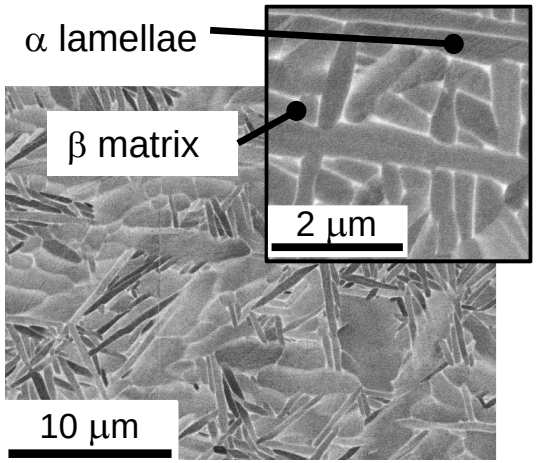
Component bulk:

Fine α/α´ lamellae + β plateletts



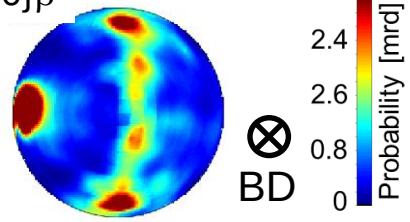


Dowskin regions (<< 1 mm):



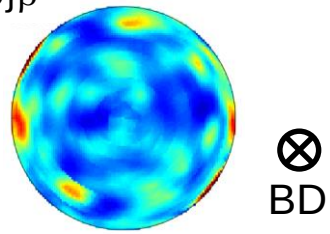
Pronounced texture:

{200}β



Less textured:

{200}β



Microstructures and textures different from cuboids with same parameters!

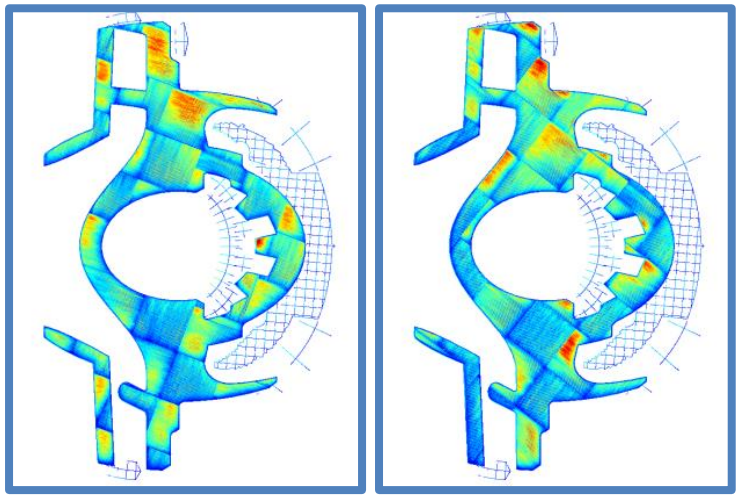
⇒ Strong **geometry influence**!

Barriobero-Vila P. et al. (2020). Scripta Materialia, 182, pp 48-52. https://doi.org/10.1016/j.scriptamat.2020.02.043

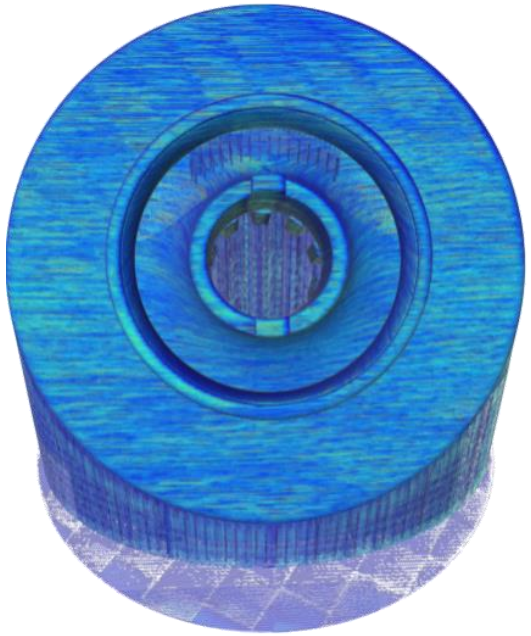
Transferability: from coupon to component

Melt Pool Monitoring (MPM)

- SLM 280^{HL} with Melt Pool Monitoring system (2 photodiodes)
- Layerwise data acquisition of emitted melt pool intensity

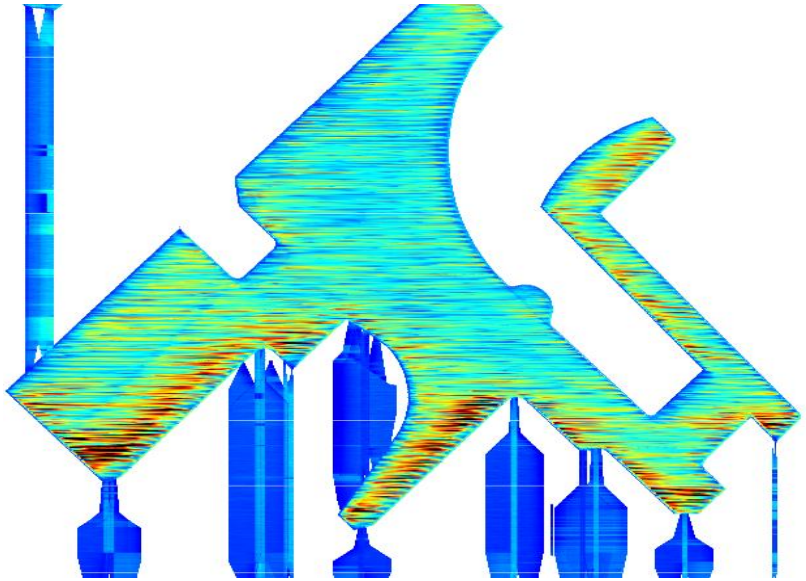


Layer n **Layer n+1**

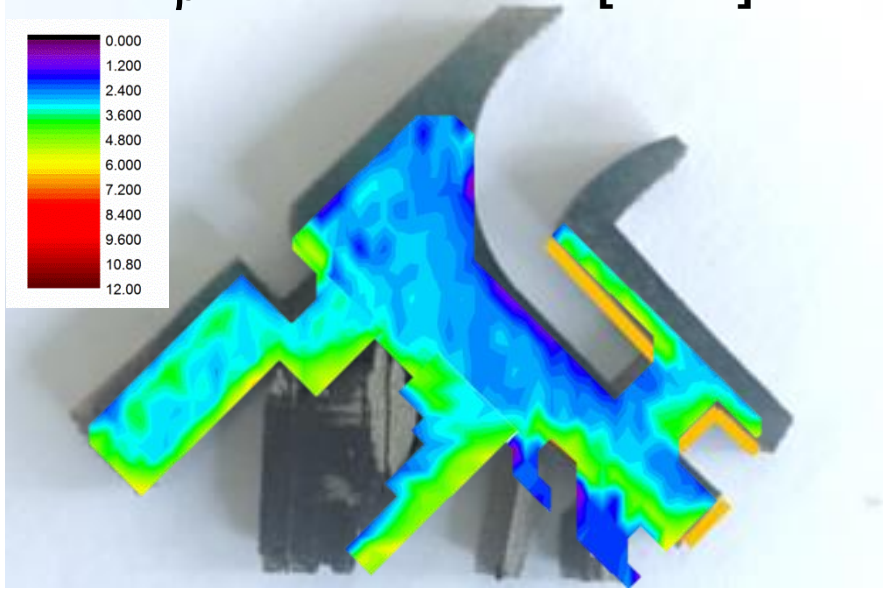


Transferability: from coupon to component

In situ Melt-pool Monitoring (MPM):



HEXRD β–volume fraction [vol.%]:



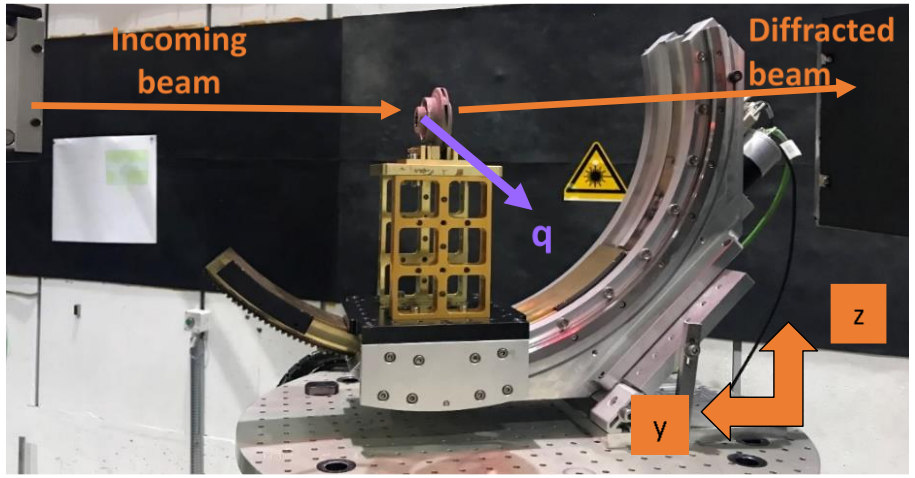
⇒ Strong **geometry influence**

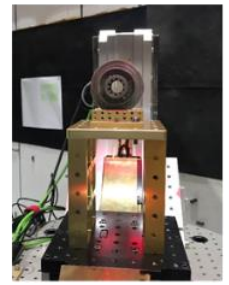
⇒ β–volume fraction is reflected in Melt Pool Monitoring data

Barriobero-Vila et al. Scripta Mat. 182 (2019) 48.

Transferability: from coupon to component

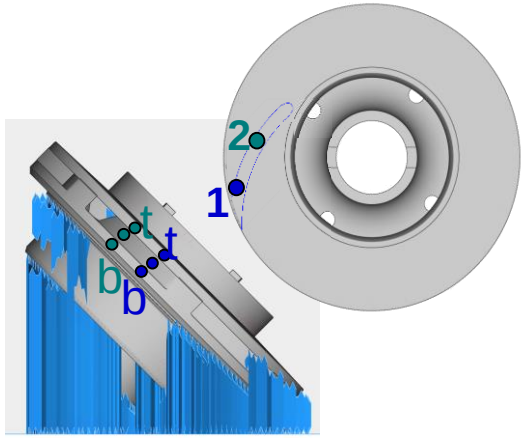
Neutron Diffraction

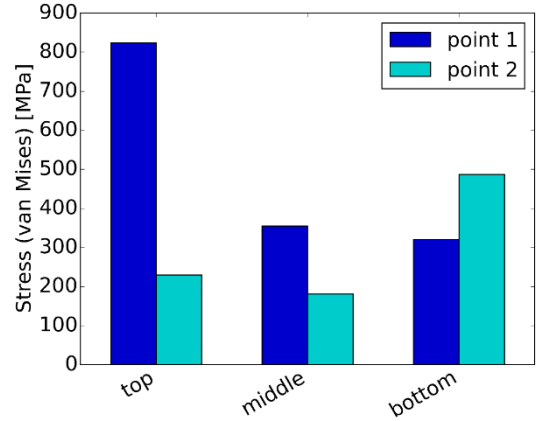




- SALSA strain diffractometer at ILL
- Neutron beam: 1.62Å (Ti-103 at 2θ=78°)
- Full Tensor analysis:
  6 different angular conditions i.e. strain components
- LAMP software (ILL) for peak fitting (Gaussian model)
- Unstrained reference measurements

⇒ Complex stress state, further analysis required

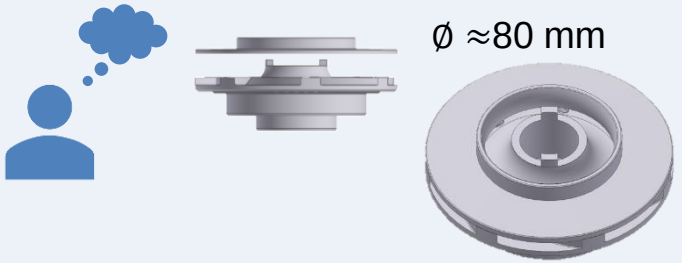




ILL: S. Cabeza, A. Cabrera, T. Pirling

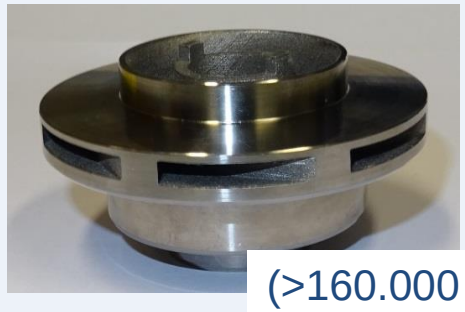
Motivation – „easy printing“?!

Rocket Turbo-Pump Impeller*



Idea: printed as a single part

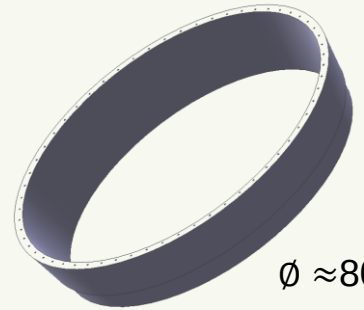
First result:
support cracks, deformation



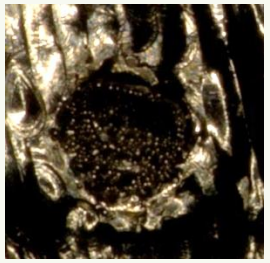
(>160.000 rpm)

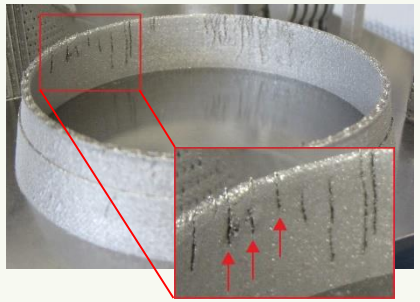
Optimized Result:
burst test - no failure

Injector element**



Idea: small channels (ø ≈300-400µm)



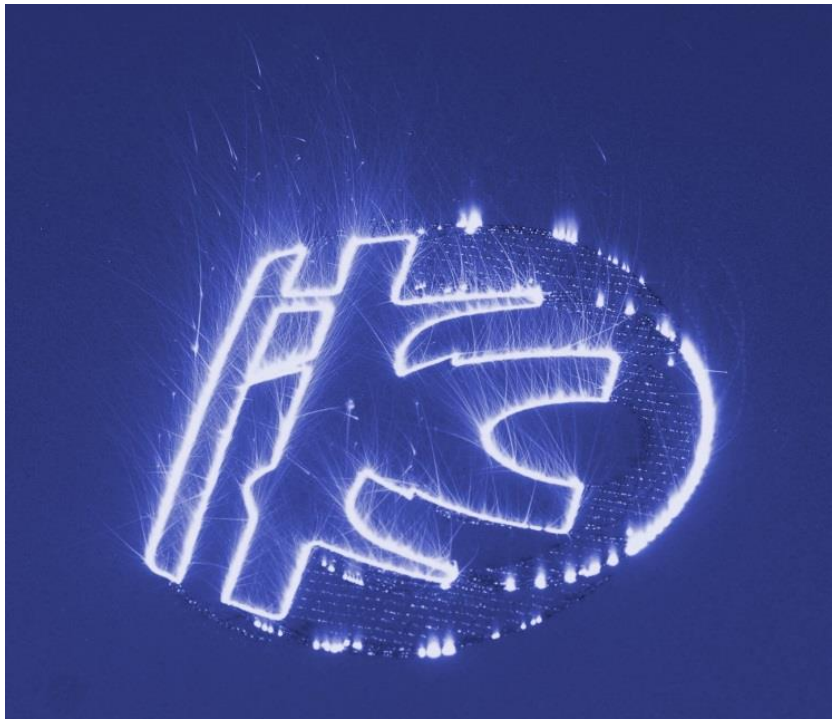


First result:
blocked channels or cracks

Optimized Result:
successful spray test

*Design: W. Kitsche, DLR-RA Lampoldshausen, **Design: M.Ortelt, DLR-BT Stuttgart

Thank you for your attention!!!



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