An assessment of subsurface residual stress analysis in SLM Ti-6Al-4V parts

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Kurzfassung

Synchrotron X-ray diffraction is a powerful non-destructive technique for the analysis of the material stress-state. High cooling rates and heterogeneous temperature distributions during additive manufacturing lead to high residual stresses. These high residual stresses play a crucial role in the ability to achieve complex geometries with accuracy and avoid distortion of parts during manufacturing. Furthermore, residual stresses are critical for the mechanical performance of parts in terms of durability and safety.

In the present study, Ti-6Al-4V bridge-like specimens were manufactured additively by selective laser melting (SLM) under different laser scanning speed conditions in order to compare the effect of process energy density on the residual stress state. Subsurface residual stress analysis was conducted by means of synchrotron diffraction in energy dispersive mode for three conditions: as-built on base plate, released from base plate, and after heat treatment on the base plate. The quantitative residual stress characterization shows a correlation with the qualitative bridge curvature method.

High tensile residual stresses were found at the lateral surface for samples in the as-built conditions. We observed that higher laser energy density during fabrication leads to lower residual stresses. Samples in released condition showed redistribution of the stresses due to distortion. A method for the calculation of the stress associated to distortion of the parts after cutting from base plate is proposed. The distortion measurements were used as input for FEM simulations.

Sicherheit in Technik und Chemie

Symposium Zerstörungsfreie Materialcharakterisierung
Charakterisierung additiv gefertigter Komponenten- 28.11.17

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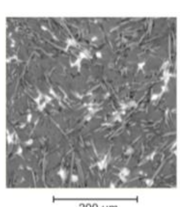
Residual stress

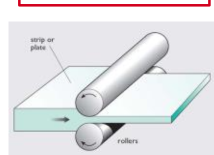
Stresses that ***remain*** *in a solid material even after the original cause has been removed*

Residual stress

Material



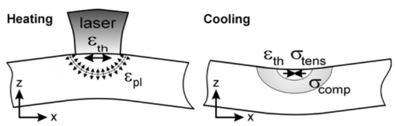
Material load



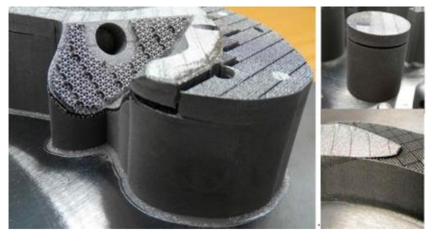
Material production

Residual stress
Selective Laser Melting (SLM)

Residual stress develops due to large temperature gradients → rapid heating of the top layers and relatively slow heat conduction



Temperature Gradient Mechanism [1]



Cracks in SLM Ti-6Al-4V parts due to residual stress [2]

[1] Peter Mercelis, Jean-Pierre Kruth, (2006),"Residual stresses in selective laser sintering and selective laser melting", Rapid Prototyping Journal, Vol. 12 Iss 5 pp. 254 - 265
[2] I. Yadroitsev, I. Yadroitsava (2015) Evaluation of residual stress in stainless steel 316L and Ti6Al4V samples produced by selective laser melting, Virtual and Physical Prototyping, 10:2, 67-76.

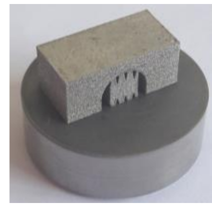
Motivation

- SLM promotes high residual stress. It leads to deformation and cracking of the part → an optimisation of process parameters is needed
- The residual stress in subsurface region has large impact on mechanical behaviour, especially during fatigue → crack propagation
- Laboratory/fast assessment of residual stress

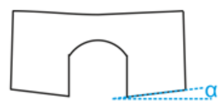
Sample Geometry

Ti-6Al-4V bridge samples:

- As-built on base plate (BP)
- Released (R) from base plate
- Heat treated (on the base plate) (TT): 650°C for 3h



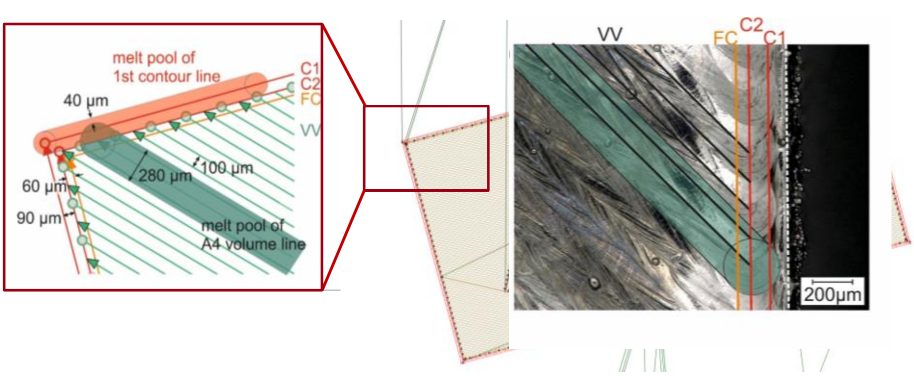
Why bridges? → Qualitative estimation of RS by Bridge curvature method [3]



[3] Kruth J.-P., Deckers J., Yasa E., Wauthle R. Assessing and comparing influencing factors of residual stresses in selective laser melting using a novel analysis method. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.

Scanning strategy

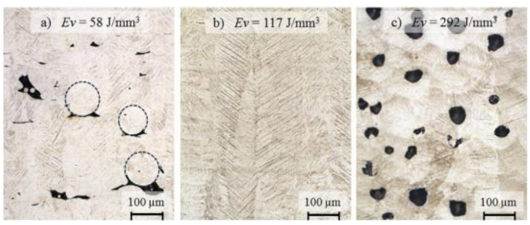
„Chess" scanning strategy
One of the ways to reduce residual stress



Samples and SLM parameters

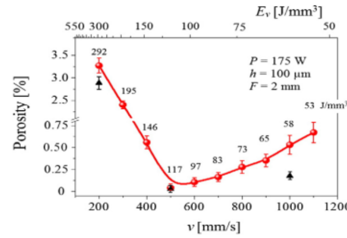
Scanning parameters:

Sample	Laser power, P (W)	Hatch, h (mm)	Velocity, v (mm/s)	Energy density, E_v* (J/mm³)	Porosity (vol%)
A1	175	0.1	200	291.7	3.3
A3	175	0.1	400	145.8	0.6
A4	175	0.1	500	116.7	0.1
A10	175	0.1	1100	53.0	0.7



Energy density

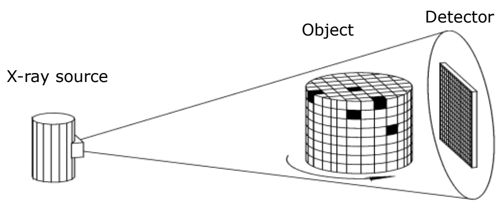
$$E_v = \frac{P}{v \cdot h \cdot x}$$



The dependence of porosity volume fraction on scanning velocity/energy density [4].

[4] Kasperovich, G.; Haubrich, J.; Gussone, J.; Requena, G. Correlation between porosity and processing parameters in TiAl6V4 produced by selective laser melting. *Mater. Des.* **2016**, *105*, 160–170.

Computed tomography

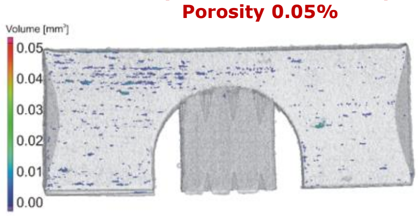


- **Characterization of defects**
  - Volume fraction
  - Shape
  - Spatial and angular distribution

Computed tomography

BAM

A4 (medium v, medium E)
Porosity 0.05%



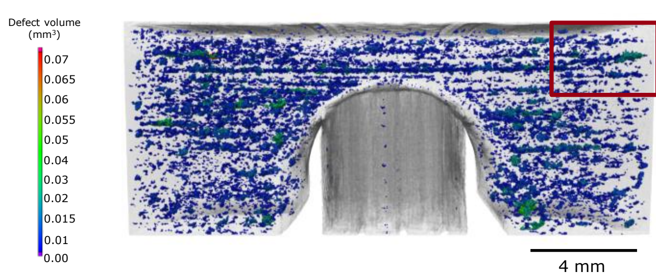
A10 (high v, low E)
Porosity 0.95%

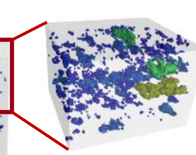
No stress relaxation due to porosity!

A closer look to pores

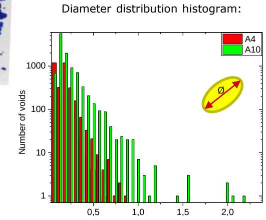
A10

BAM





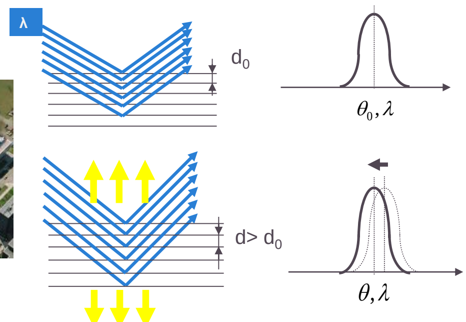
Diameter distribution histogram:



- Defects aligned with the layers
- Homogeneous size
- Larger porosity corresponds also to larger pores

Residual Stress Analysis: Synchrotron X-Ray Diffraction

Synchrotron - BESSY II



Bragg´s Law

$$2d^{hkl}\sin\theta = n\lambda$$

Lattice Strain

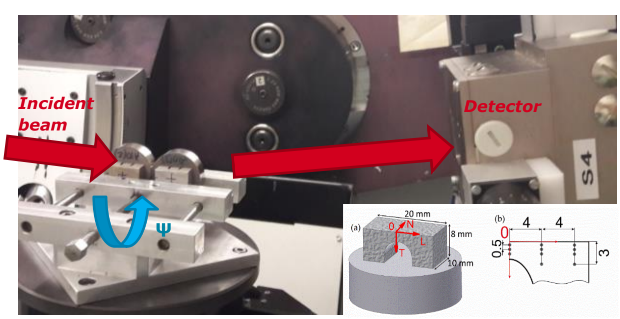
$$\varepsilon^{hkl} = \frac{d^{hkl} - d_0^{hkl}}{d_0^{hkl}}$$

Hooke´s Law

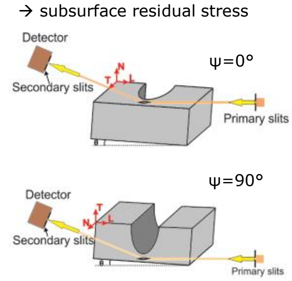
$$[\sigma] = [C][\varepsilon]$$

Synchrotron X-ray diffraction

Sample mount on the beamline EDDI, HZB



Reflection set-up // sin²ψ method
→ subsurface residual stress



Transversal component

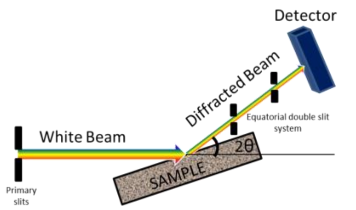
We can assume the normal and the shear components to vanish

Synchrotron X-ray diffraction

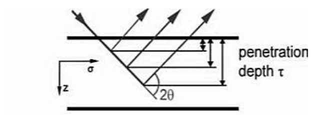
BAM

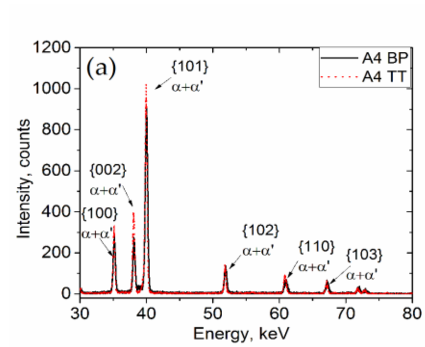
Stress gradients

Energy dispersive diffraction allows obtaining residual stress depth profile near the surface (each peak corresponds to a different penetration depth)



$E_1 < E_2 < E_3 \ldots$





Synchrotron X-ray diffraction

BAM

Stress gradients

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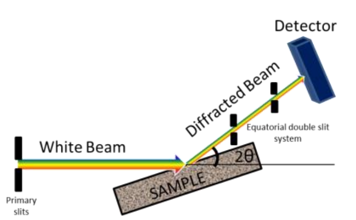
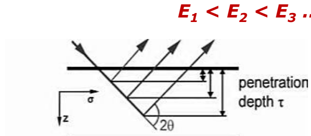
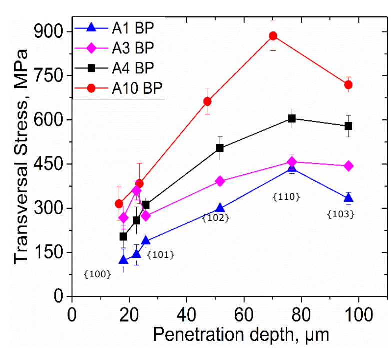


$E_1 < E_2 < E_3 \ldots$





Only tensile stress

Bridge curvature method

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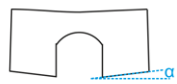
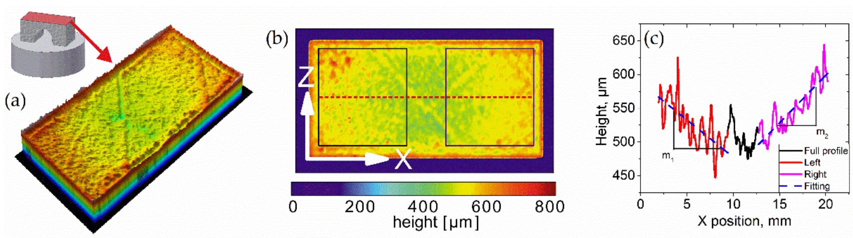
Deflection angle α was measured by confocal microscopy on top surface and in the bottom on pillar. Distortion *maps* were acquired.



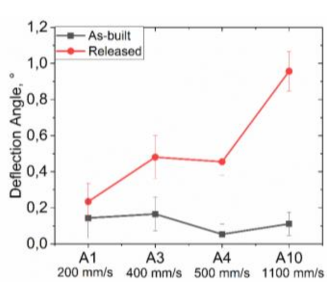


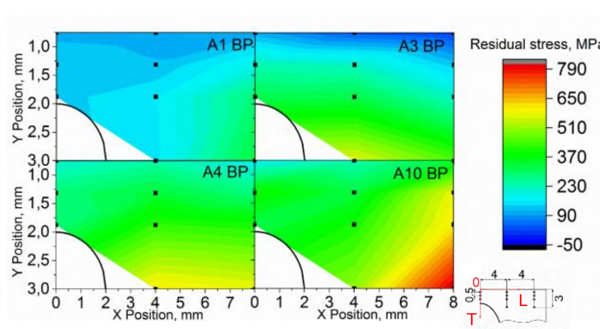
Residual stress

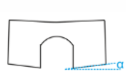
BAM

As-built condition

A decrease of energy density from A1 to A10 leads to an increase of (transversal) residual stress → good correlation with deflection angle measurements





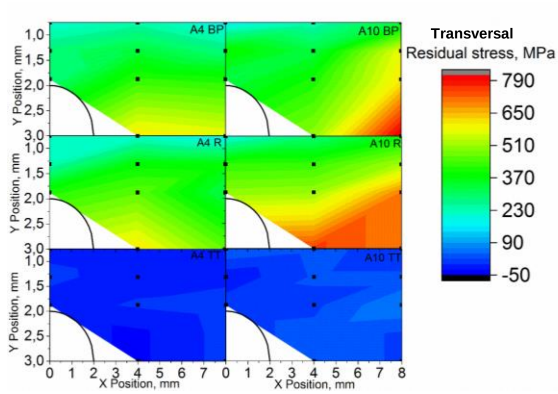


Residual stress

BAM

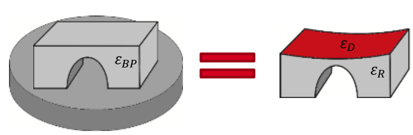
Released and Heat treated

- Redistribution of stresses after releasing from base plate due to distortion
- Stress relief takes place after heat treatment



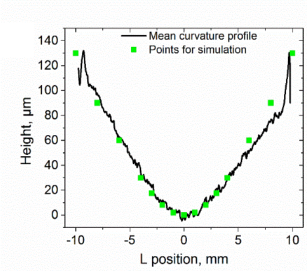
Distortion FEM

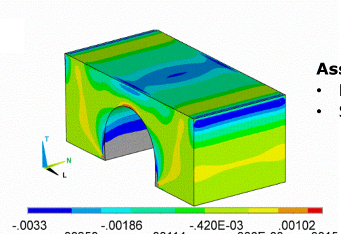
BAM



$$\bar{\bar{\varepsilon}}_{BP} = \bar{\bar{\varepsilon}}_R + (-\bar{\bar{\varepsilon}}_D)$$

$\bar{\bar{\varepsilon}}_D$ can be estimated from distortion measurement of top surface of specimen after realising and used as input for FEM.





Assumptions

- Linear elastic isotropic material
- Symmetric deformation

Quantitative use of the Bridge Curvature

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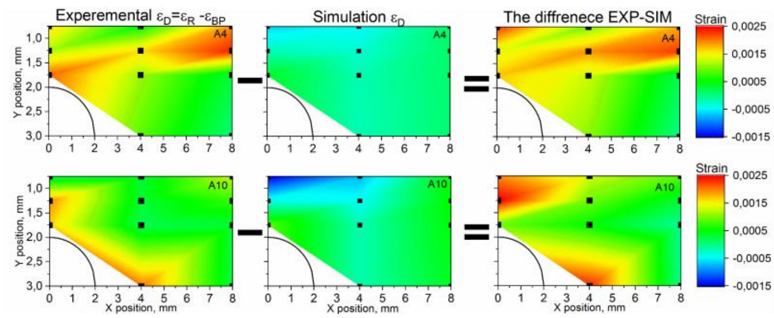
Comparison between FEM calculated and diffraction measured strains



→Simulation needs to be improved
→Diffraction as Benchmark

Summary

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- An increase of scanning velocity leads to an increase of residual stress due to increase of thermal gradient during scanning
- Tensile residual stress in subsurface region → reduced mechanical performance
- Stress relief occurs after heat treatment but RS should be controlled during/ after manufacturing anyway (shape changes, cracking)

Thank you!

Mishurova, T., Cabeza, S., Artzt, K., Haubrich, J., Klaus, M., Genzel, C., Requena, G., Bruno, G., 2017. An Assessment of Subsurface Residual Stress in SLM Ti-6Al-4V. Materials 10, 348.