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.
Residual stress

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

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]

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Scanning strategy

„Chess“ scanning strategy
One of the ways to reduce residual stress
**Samples and SLM 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 $E_v = \frac{P}{v \cdot h}$

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

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**Computed tomography**

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

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[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.
A closer look to pores

A10

- Defects aligned with the layers
- Homogeneous size
- Larger porosity corresponds also to larger pores
Residual Stress Analysis: Synchrotron X-Ray Diffraction

Bragg’s Law

\[ 2d^{(hkl)} \sin \theta = n \lambda \]

Lattice Strain

\[ \varepsilon^{(hkl)} = \frac{d^{(hkl)} - d^{0}}{d^{0}} \]

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

Detector

We can assume the normal and the shear components to vanish
Synchrotron X-ray diffraction

Stress gradients

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

E₁ < E₂ < E₃ ...

Only tensile stress

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

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

Residual stress

As-built condition

A decrease of energy density from A1 to A10 leads to an increase of (transversal) residual stress $\rightarrow$ good correlation with deflection angle measurements
Residual stress
Released and Heat treated

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

Transversal Residual stress, MPa

Distortion
FEM

\[ \tilde{\varepsilon}_{BP} = \tilde{\varepsilon}_{R} + (-\tilde{\varepsilon}_{D}) \]

\( \tilde{\varepsilon}_{D} \) 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
Comparison between FEM calculated and diffraction measured strains

→ Simulation needs to be improved
→ Diffraction as Benchmark

Summary

- 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!