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Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden

DRESDEN concept

Selective laser melting of 316L stainless steel and related composites: processing and properties

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Supervisors: **Prof. Dr. Jürgen Eckert**

Dr. Sergio Scudino

Additive manufacturing (AM)

- **What is AM ?**

AM a layer-based automated fabrication process for making scaled 3-dimensional physical objects directly from 3D-CAD data without using part-depending tools

- **Benefits**

 Design freedom
 Efficiency in materials use

T.S. Srivatsan, T.S. Sudarshan, Additive Manufacturing: Innovations, Advances, and Applications, 2015.

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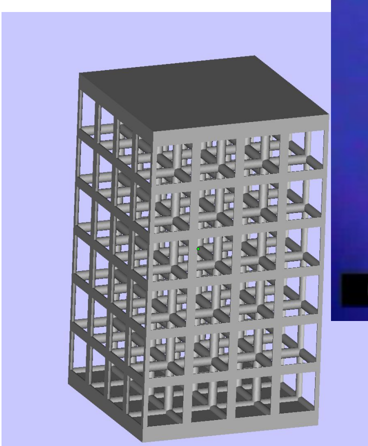
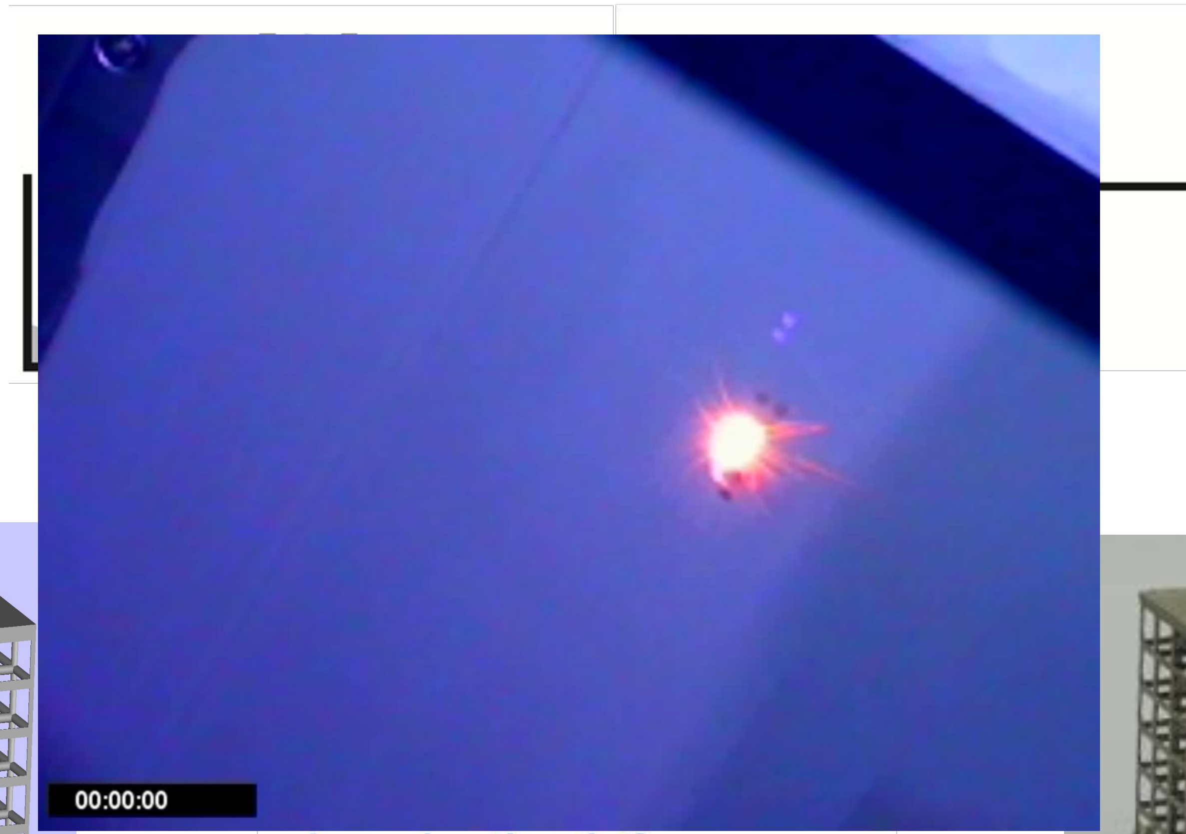
Principles of selective laser melting (SLM)



CAD



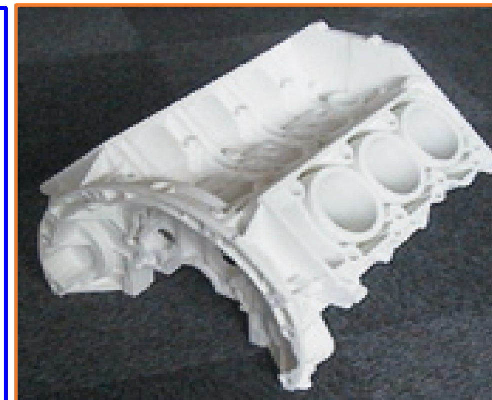
Lowering the platform

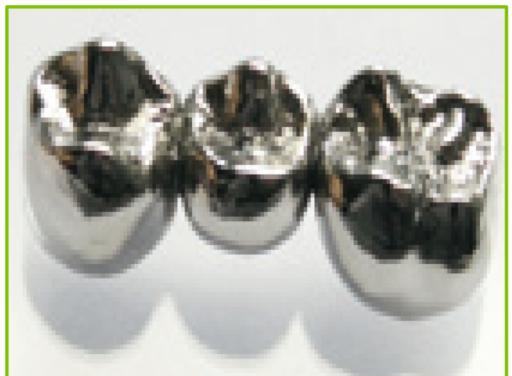
Final part

Potential applications

- **Advantages**
  - High relative density
  - High dimensional accuracy
    - Reduced post-machining
  - High cooling rates 10^5-10^7 K/s
    - Refined microstructure
      - High strength


Aerospace


Automotive


Medical


Electronics

D.I. Wimpenny et al., Advances in 3D Printing & Additive Manufacturing Technologies, Springer Singapore, 2017.
M.K. Thompson et al., CIRP Annals - Manufacturing Technology 65 (2016) 737-760.

Stainless steel

- **Properties** [1]
  - Excellent oxidation and corrosion resistance at moderate temperatures
  - Low costs
  - Good ductility
  - Relatively high strength
  - Biocompatibility


[2]

- **316L stainless steel**

Chemical composition of 316L powder (mass percent)

Fe	Cr	Ni	Mo	Mn	C
67.140 ±0.23	16.780 ±0.10	10.800 ±0.02	2.210 ±0.02	1.4 ±0.06	0.014 ±0.001


[3]

[1] R. Li et al, Applied Surface Science. 256 (2010) 4350–4356. [2] https://www.3dsystems.com
[3] https://www.tctmagazine.com.

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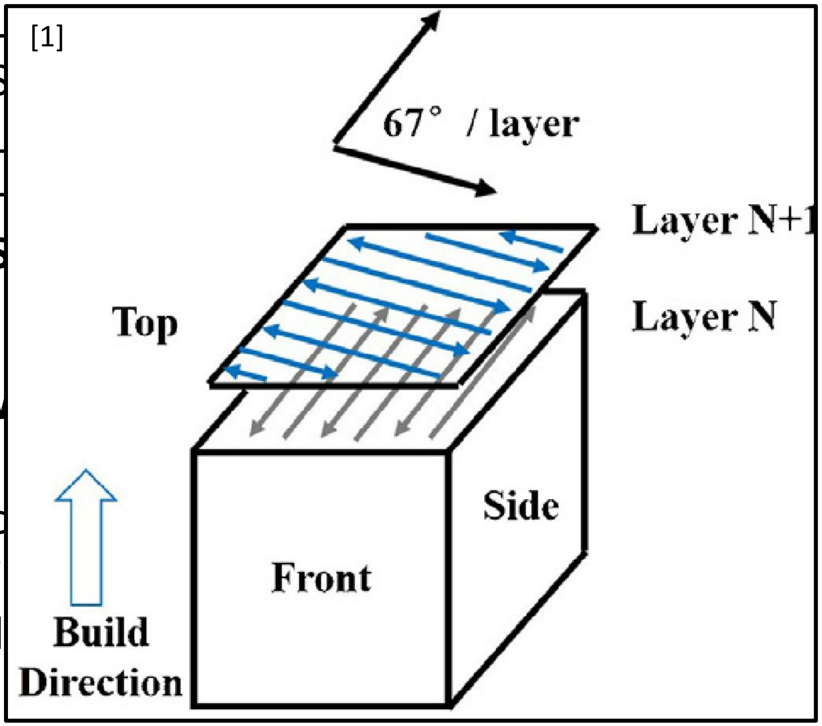
SLM processing parameters

- **Parameters**
  - L
  - S
  - L
  - H
  - **S**



- **V**

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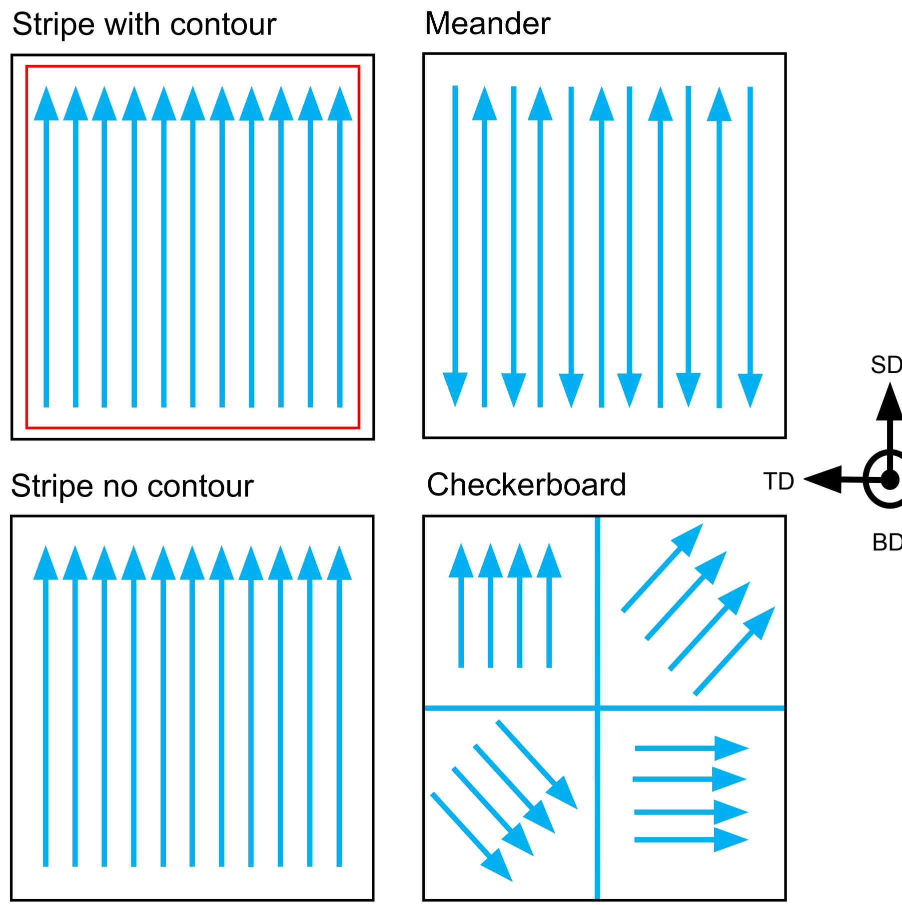

[1] Xin Zhou et al, Journal of Materials Processing Technology 222 (2015) 33–42

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Objectives

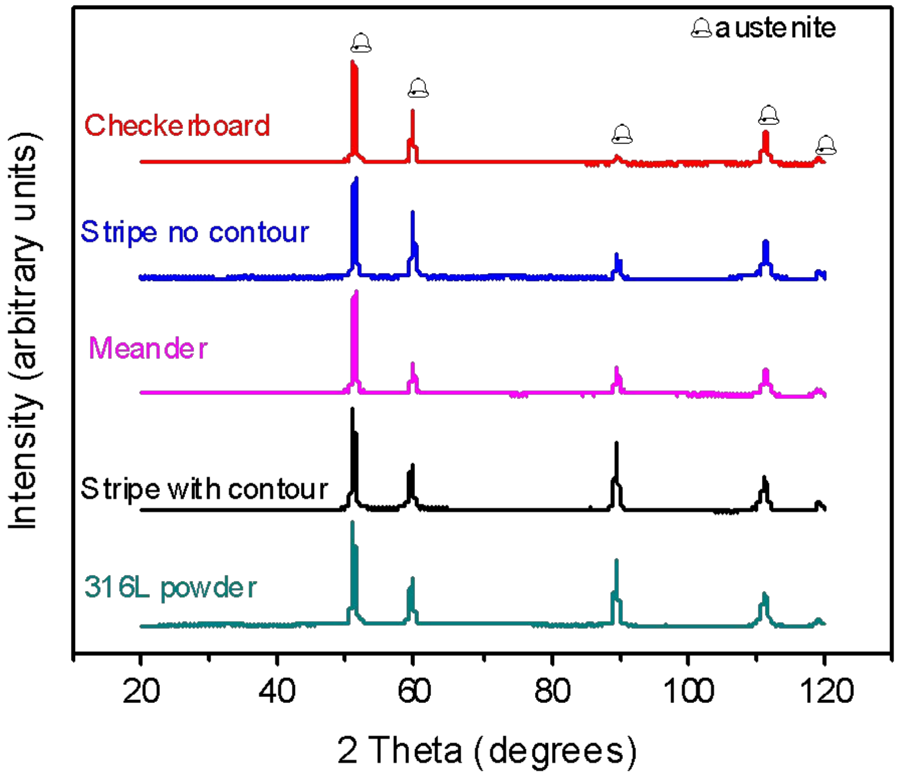
1. Investigate the effect of the scanning strategy on the mechanical behavior of 316L stainless steel
2. Understand the effect of annealing temperatures on the stability of phases, microstructure and mechanical properties
3. Strengthening the 316L stainless steel matrix by adding hard second phases: CeO_2 and TiB_2 particles

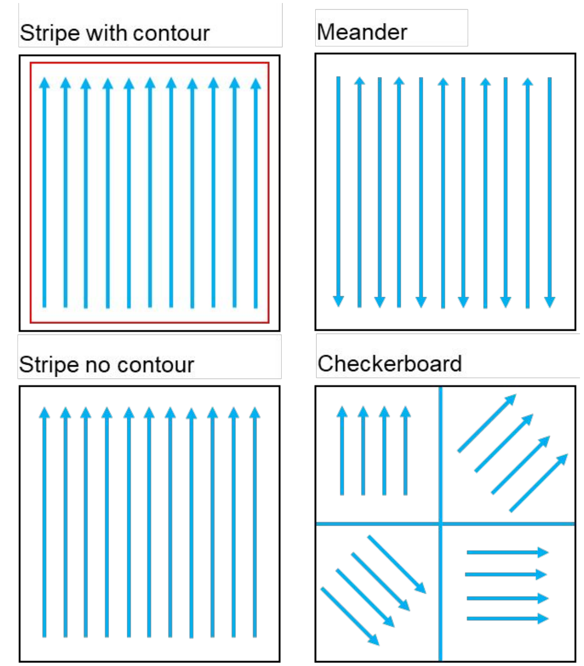
Characterization:

- Phase formation
- Microstructure at different length scales
  - SEM, EBSD, TEM
- Mechanical properties
  - tensile and compression

Effect of the scanning strategy

Phase analysis

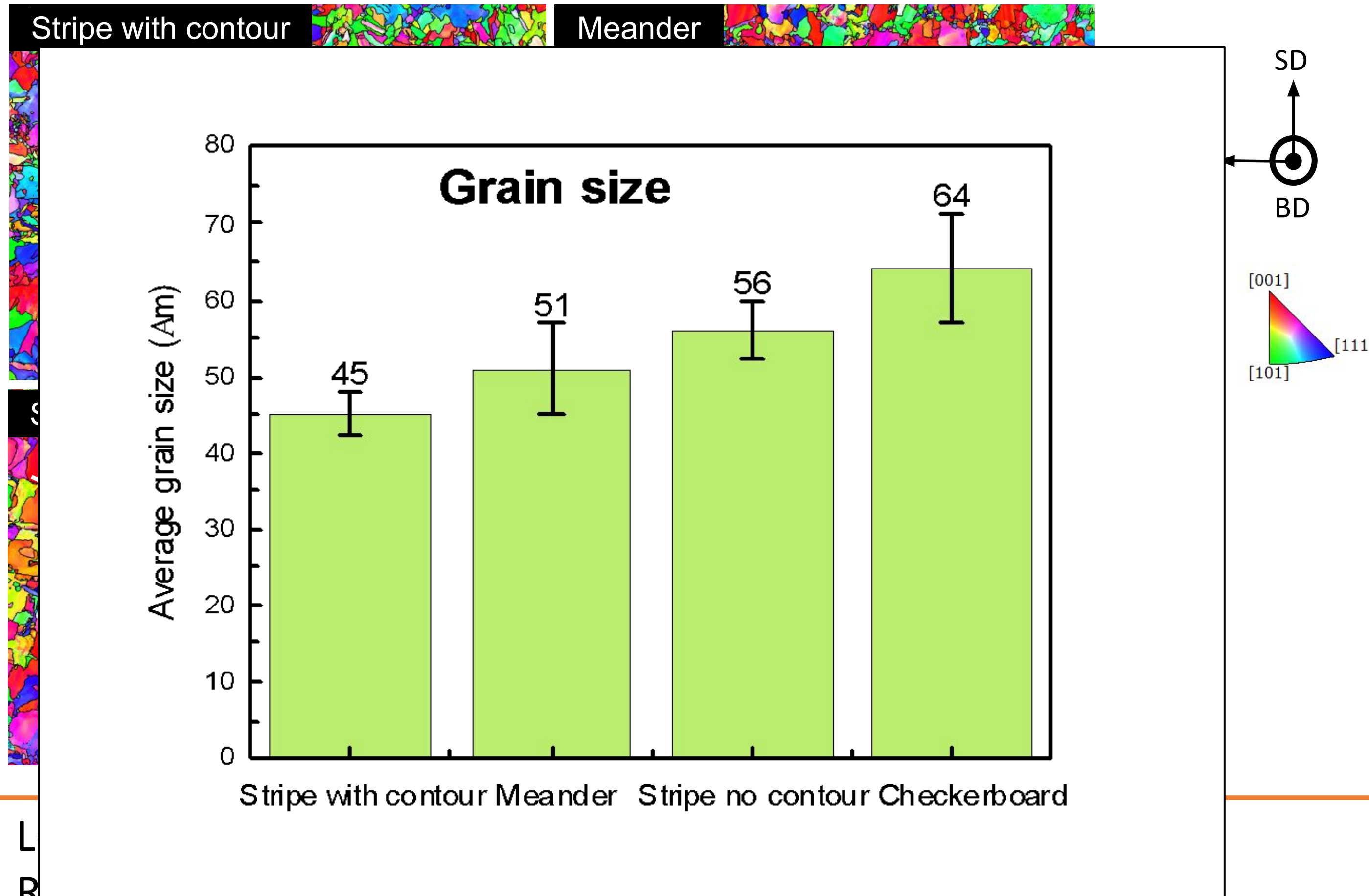




- Single-phase austenite
  - No influence of scanning strategy on phase formation

Effect of the scanning strategy

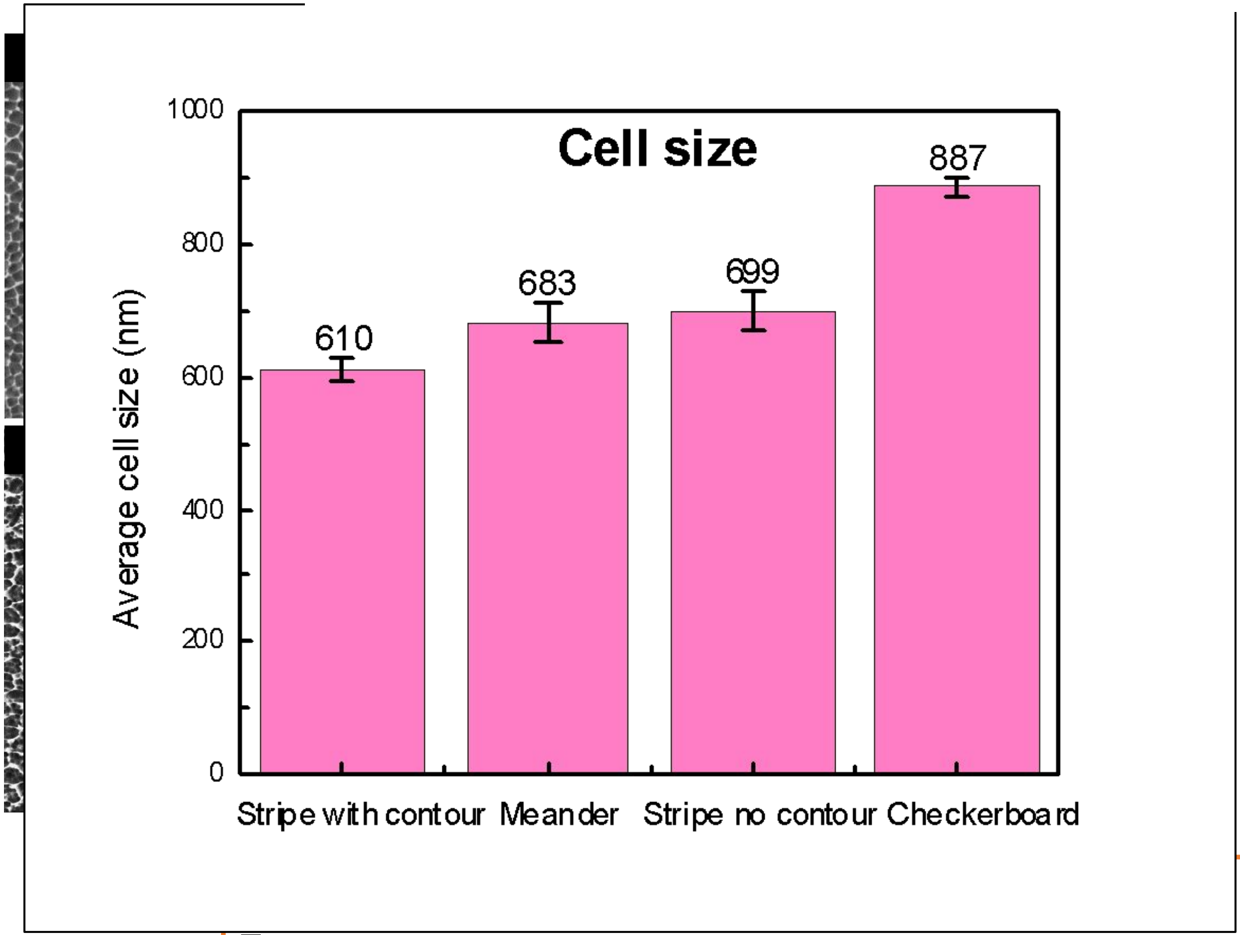
EBSD maps



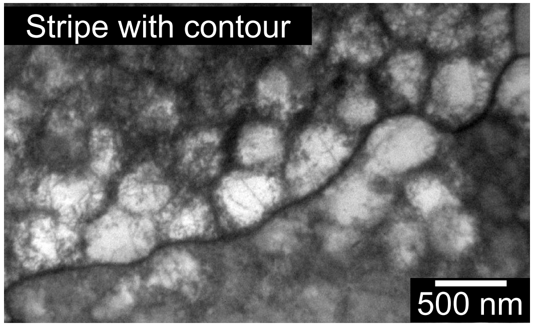
- L
- Random texture
- Smallest average grain size (45 ± 3 µm) for stripe strategy with contour
- Largest grain size (64 ± 7 µm) for checkerboard strategy

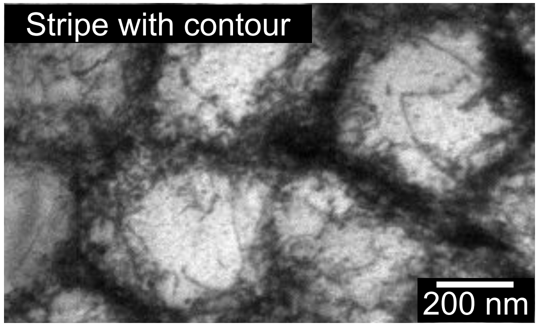
Effect of the scanning strategy

Microstructure



Cr-Si rich cell boundaries
Cell size about 500 nm
Dislocations at cell walls

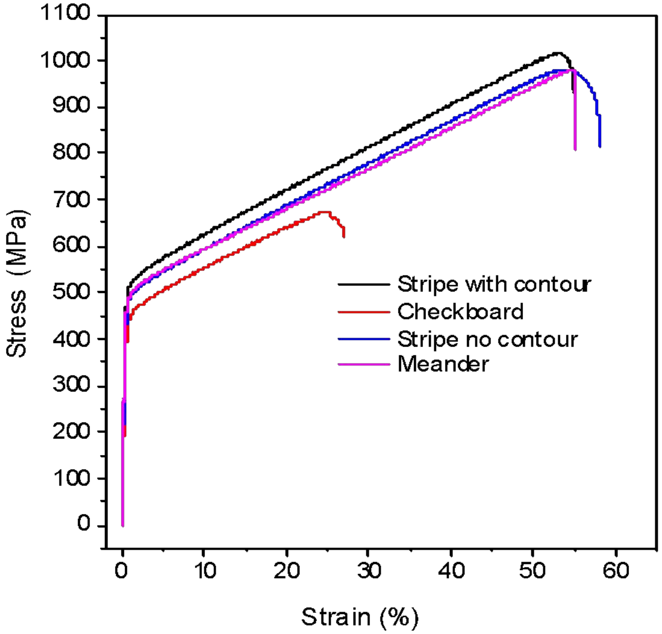


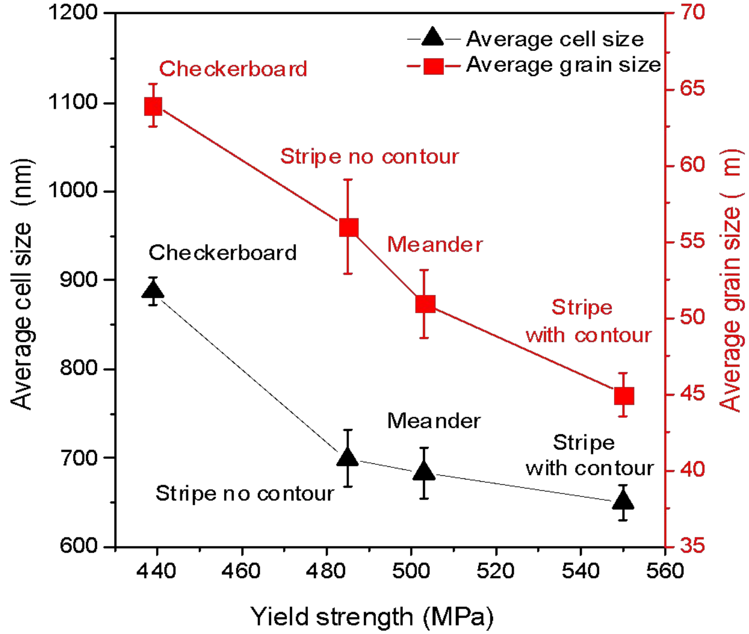


- Average cell size is affected
  - smallest (610 ± 19 nm) for stripe strategy with contour
  - largest (887 ± 15 nm) for checkerboard

Effect of the scanning strategy

Mechanical properties



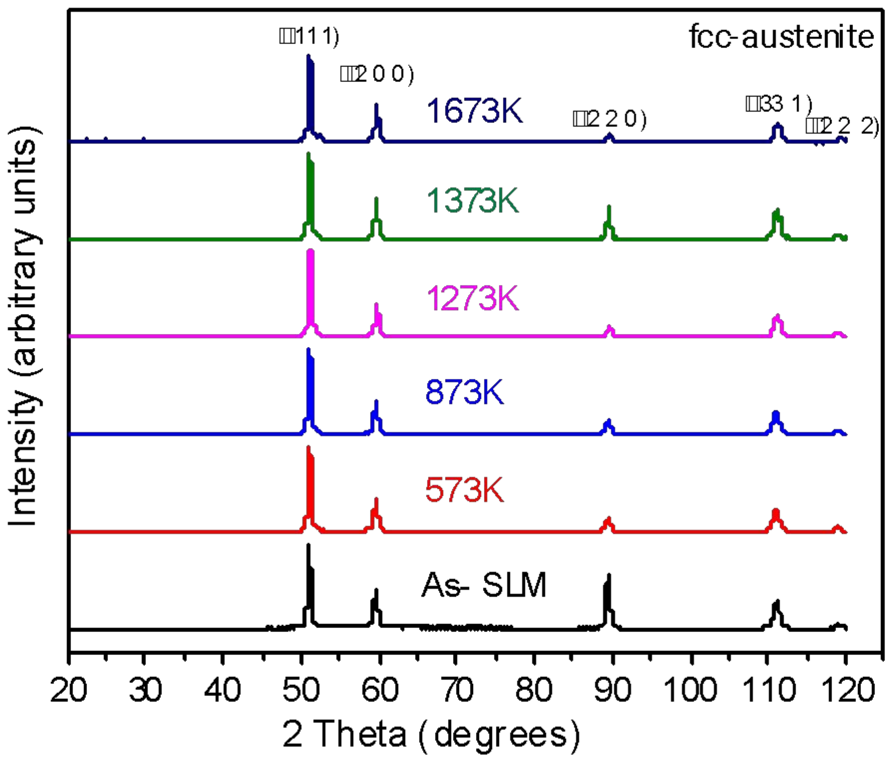


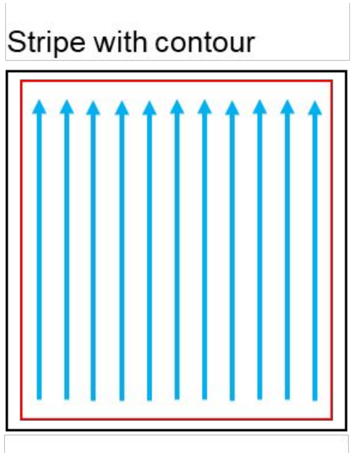
Mechanical properties depend on grain and cell size

Highest strength for stripe with contour strategy

Influence of annealing temperature

Phase analysis





- Single-phase austenite
  - No influnce of annealing on phase formation

O.O. Salman et al, Materials Science & Engineering A 748 (2019) 205–212.

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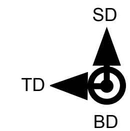
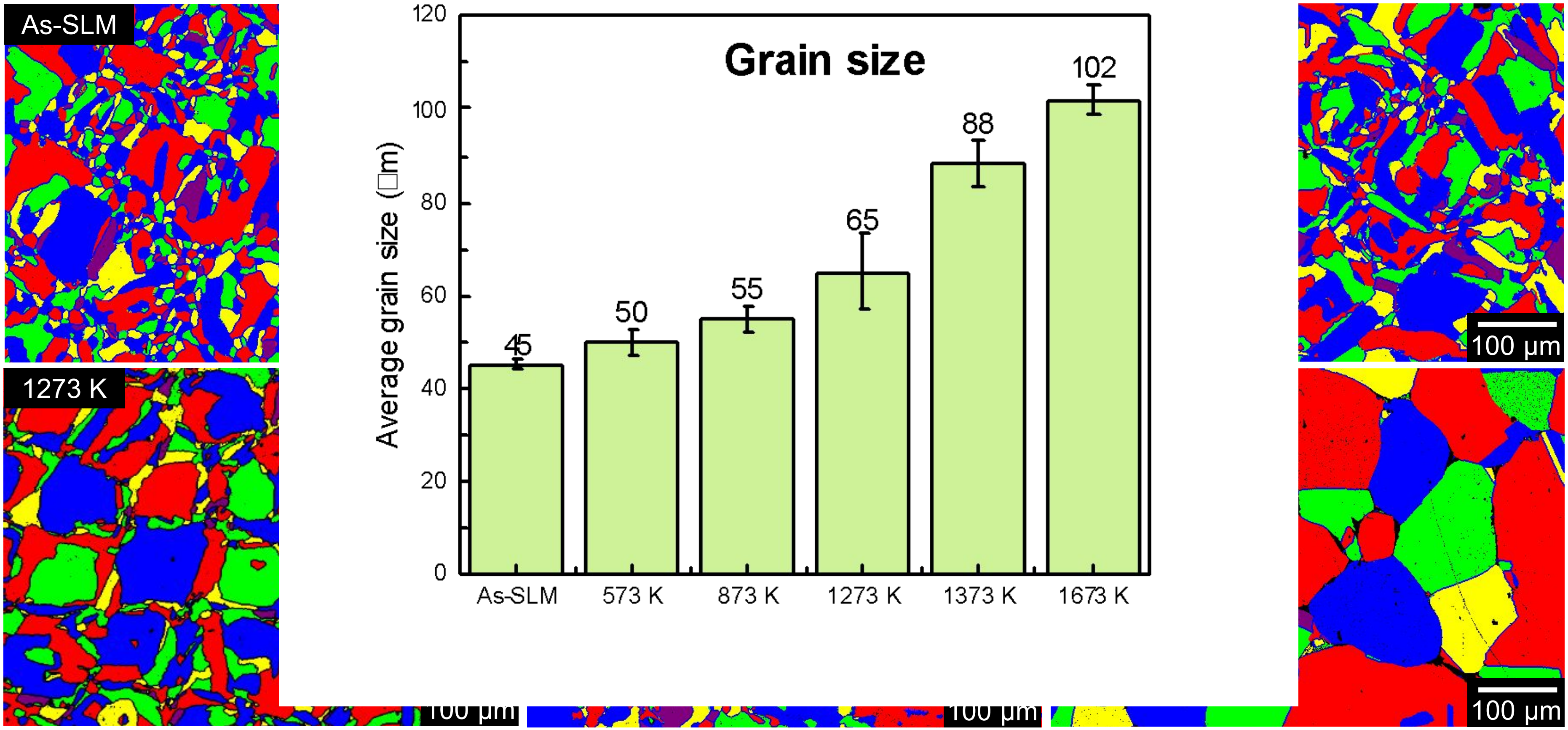
Influence of annealing temperature

EBSD maps

- Annealing plays no role in texture formation
- Grain growth





O.O. Salman et al, Materials Science & Engineering A 748 (2019) 205–212.

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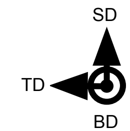
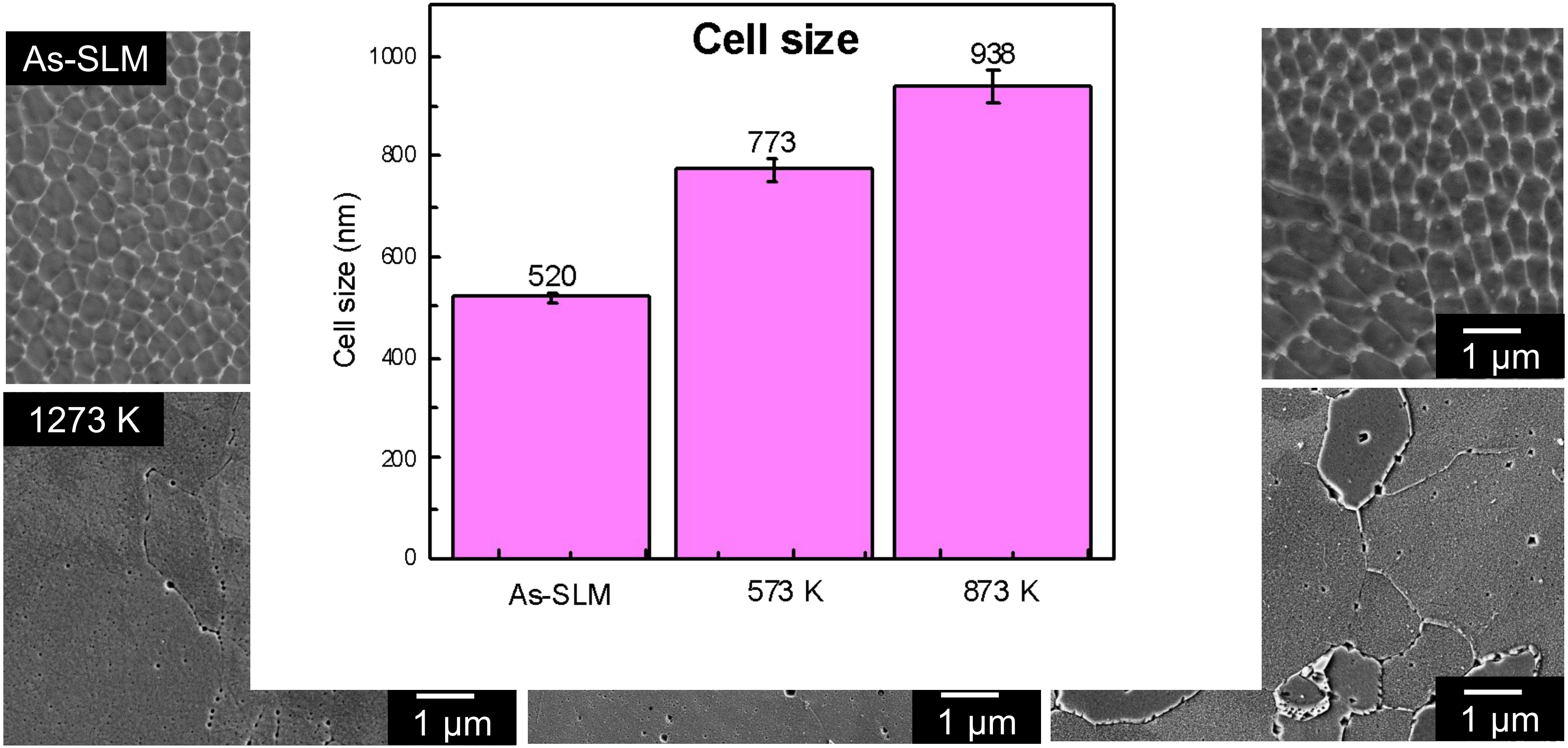
Influence of annealing temperature

Microstructure

- No cells above 1273 K
- Average cell size increases with annealing temperature

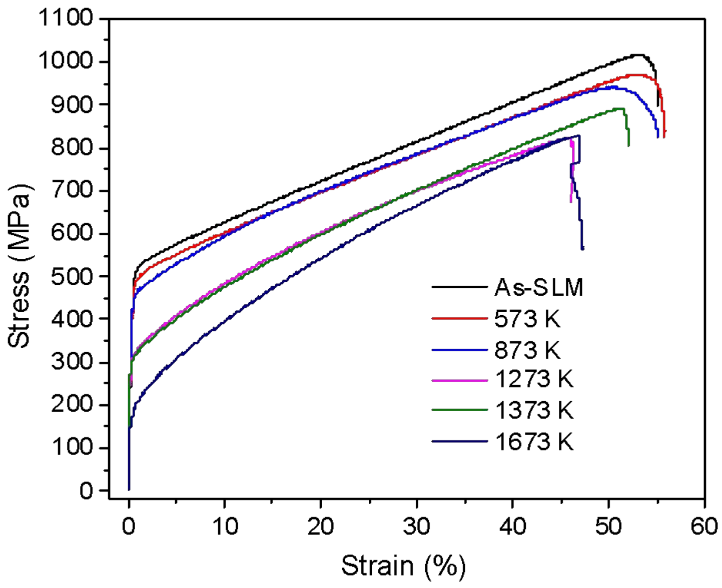


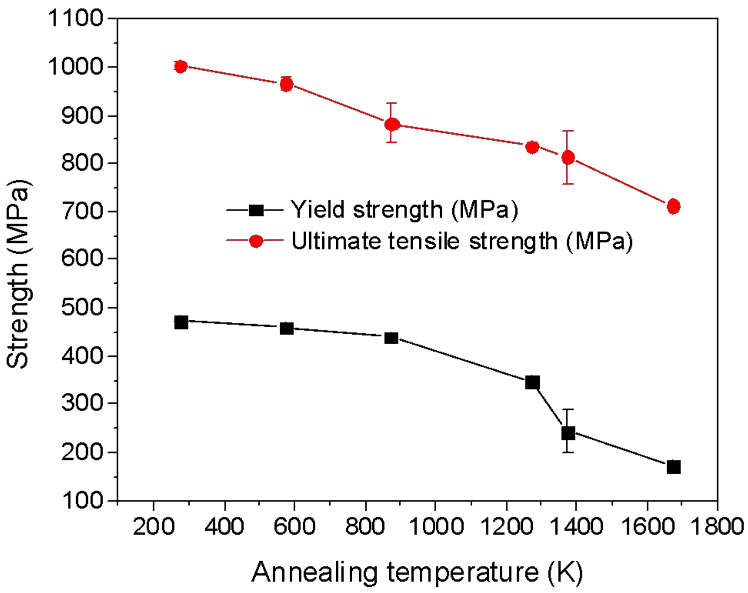


O.O. Salman et al, Materials Science & Engineering A 748 (2019) 205–212.

Influence of annealing temperature

Mechanical properties





Mechanical properties depend on grain and cell size

Highest strength for as-SLM material

O.O. Salman et al, Materials Science & Engineering A 748 (2019) 205–212.

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Strengthening the matrix

- Best mechanical properties for stripe with contour strategy
- Microstructure and mechanical properties stable up to 873 K

- How can 316L matrix be strengthened?

- By the addition of hard second phase particles

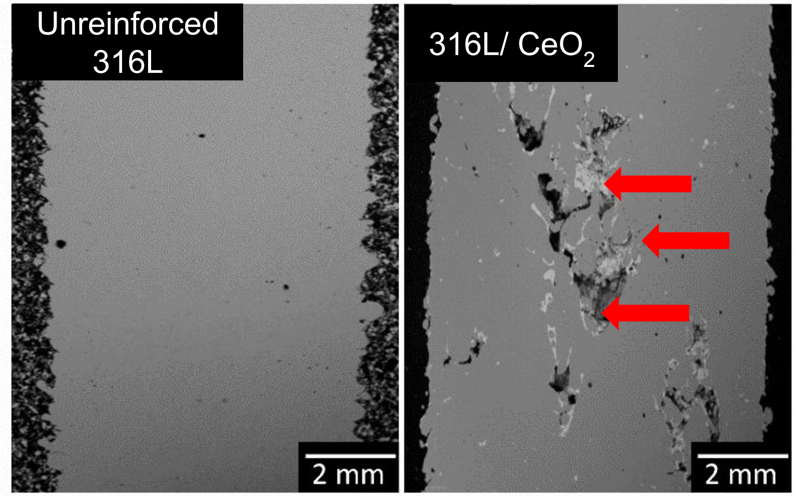
↓

- Stainless steel matrix composite (SMCs)
  - ✔ High thermal stability
  - ✔ High strength and excellent wear resistance at elevated temperatures
  - ✔ Excellent creep resistance

Strengthening 316L steel with CeO_2

- High melting temperature
- Good resistance against radiation
- Grain refinement
- Good mechanical properties

316L/CeO_2



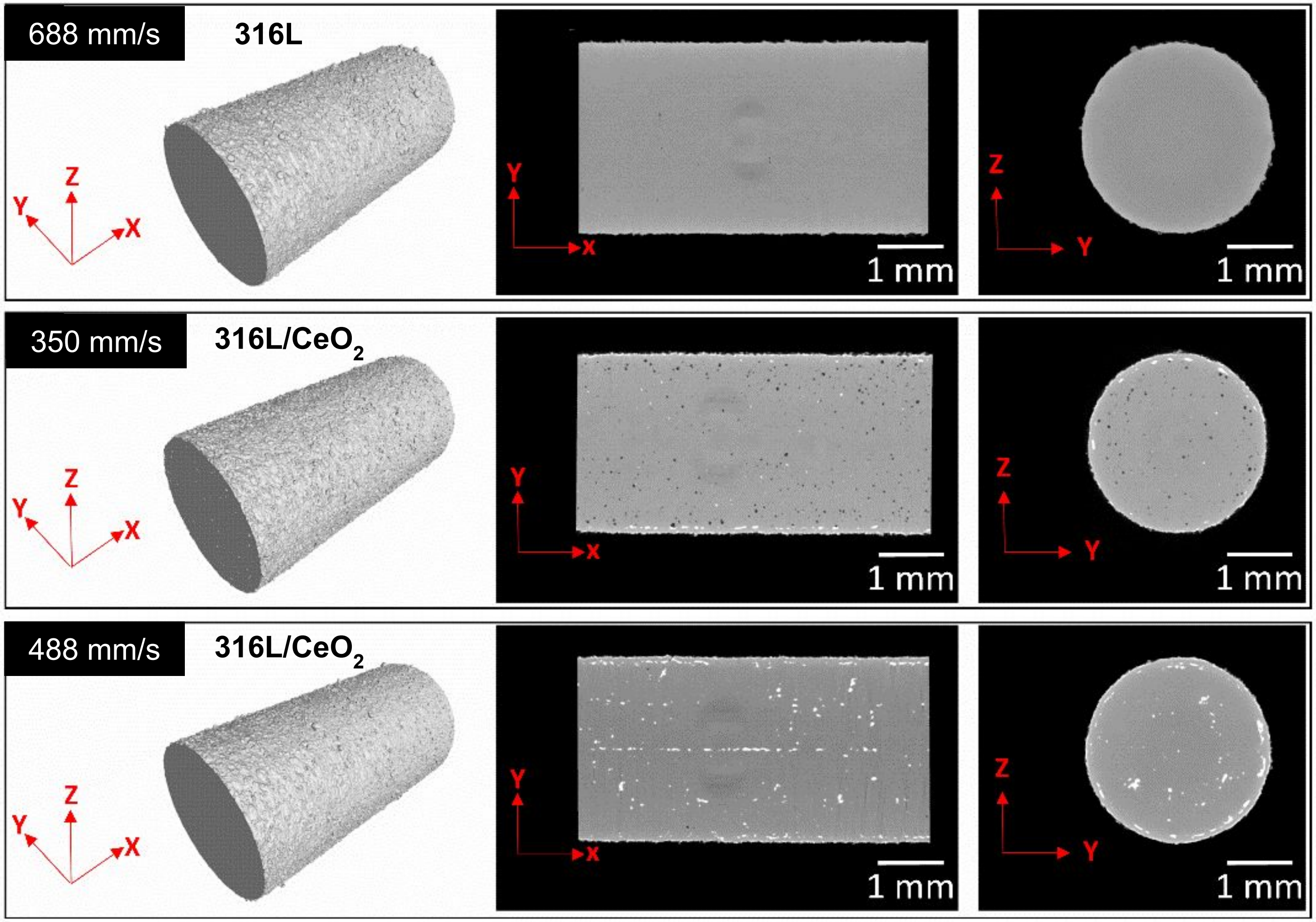
- Fabrication 316L/CeO_2 matrix composites requires the optimization of processing parameters

Varying the scanning speed can be used to improve the quality of the specimens[1]

[1] Simchi, A.; Pohl, *Mater. Sci. Eng. A* **2003**, *359*, 119–128

Strengthening 316L steel with CeO_2

Optimization of the laser scanning speed



488 mm/s optimized scanning speed

O.O. Salman et al, Technologies 2018, 6, 25; doi: 10.3390/technologies6010025.

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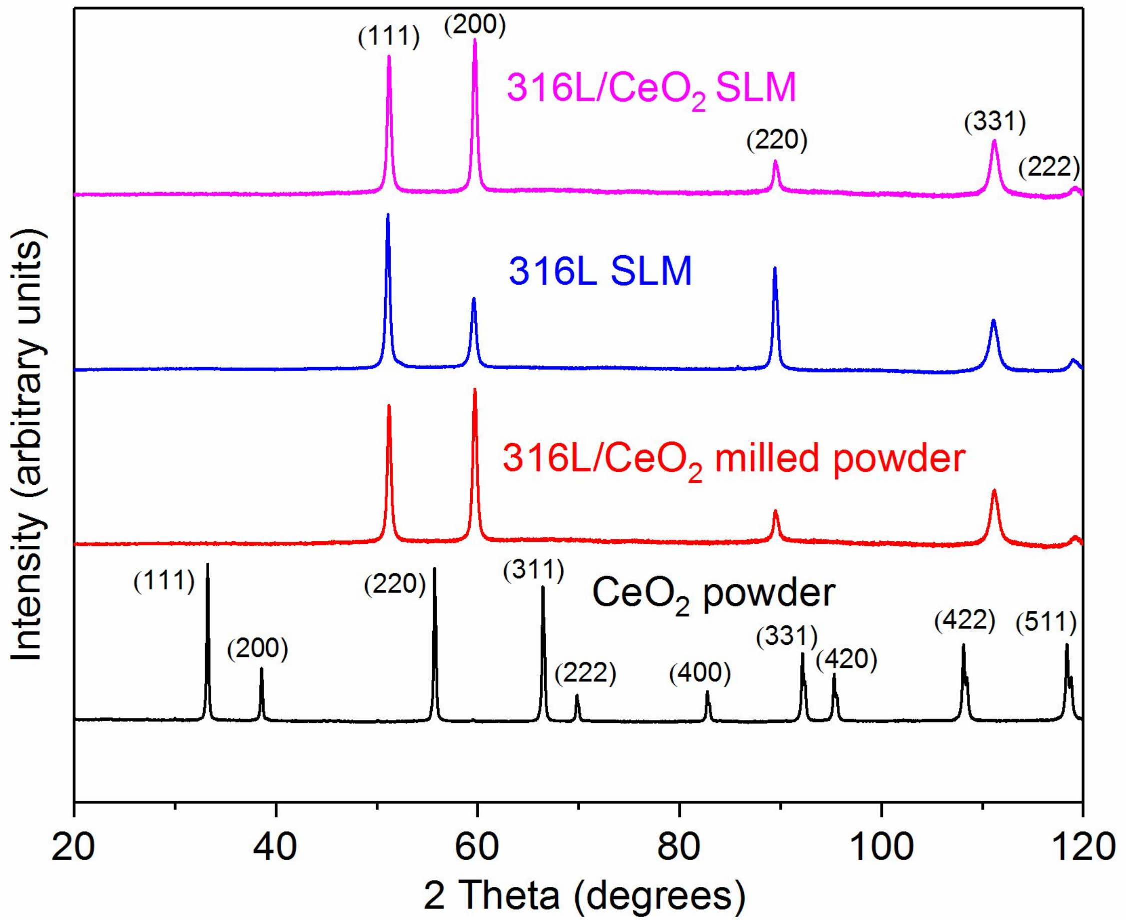
Strengthening 316L steel with CeO_2

Phase analysis

- Matrix : single-phase austenite structure



O.O. Salman et al, Technologies 2018, 6, 25; doi: 10.3390/technologies6010025.

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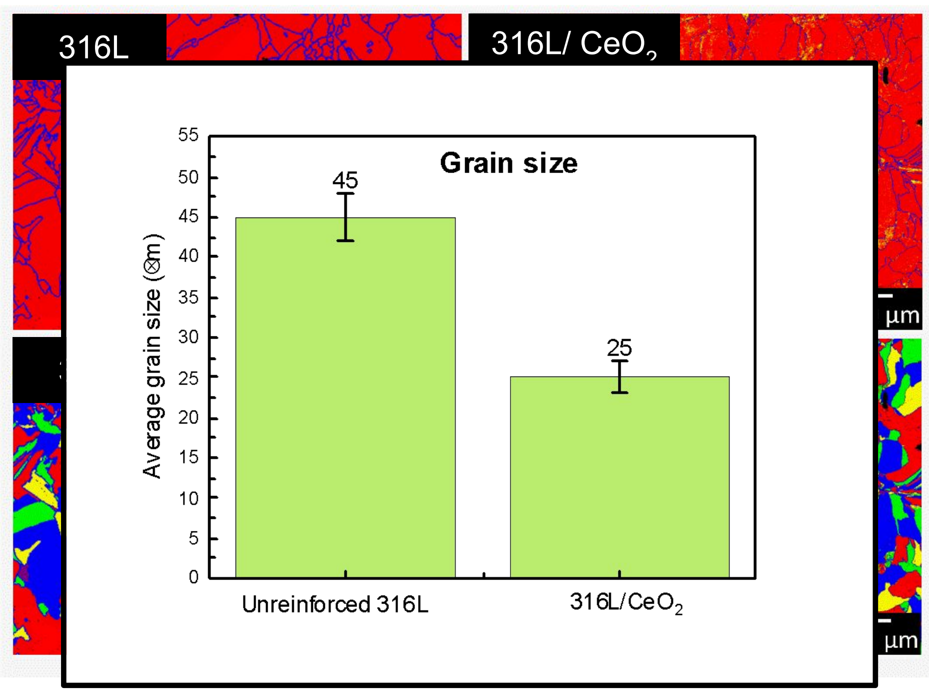
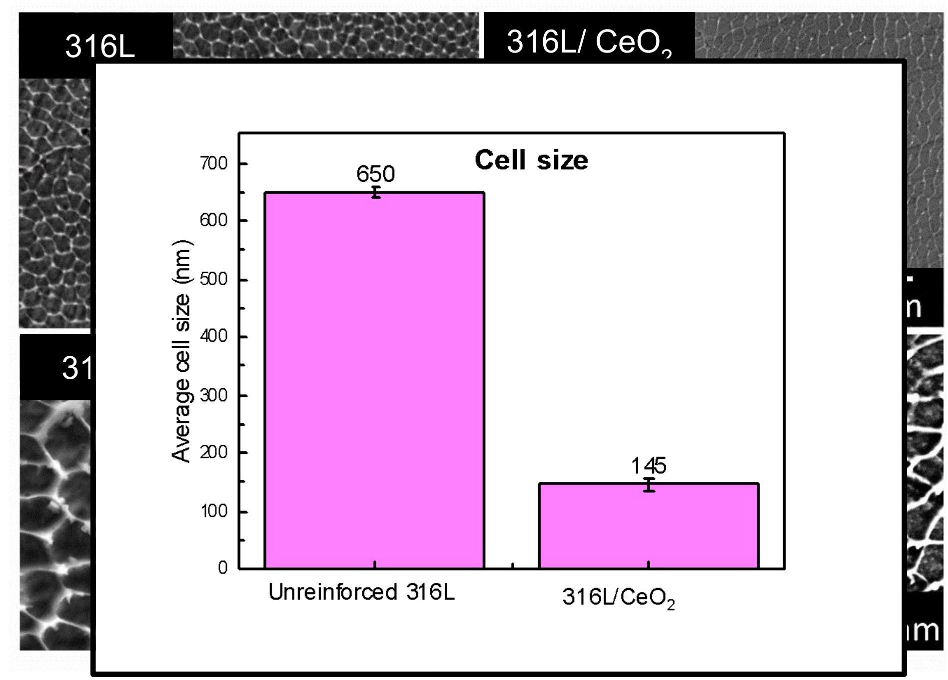
Strengthening 316L steel with CeO_2

Microstructure

- CeO_2 induces microstructural refinement
  - ✔ Cellular refinement
  - ✔ Grain refinement



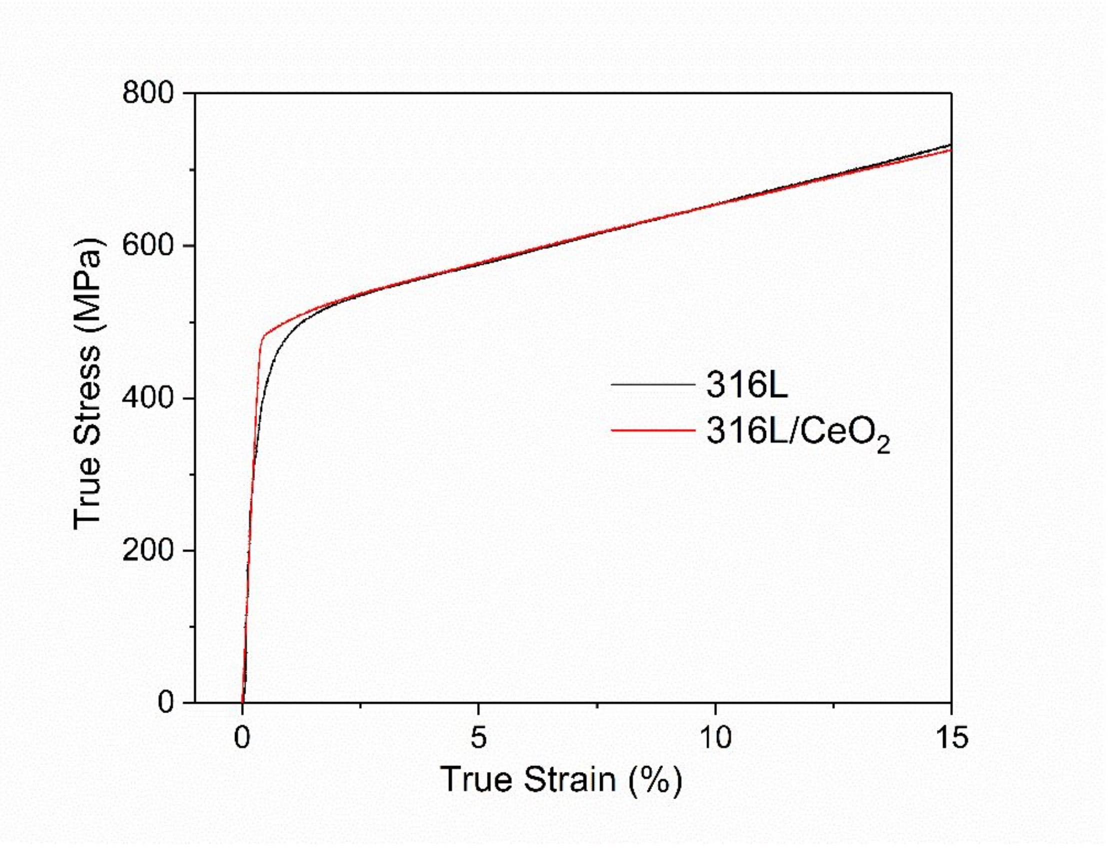


O.O. Salman et al, Technologies 2018, 6, 25; doi: 10.3390/technologies6010025.

Strengthening 316L steel with CeO_2

Mechanical properties

Yield strength unreinforced 316L: **412 ± 7** MPa
Yield strength 316L/CeO_2 composite: **485 ± 4** MPa



O.O. Salman et al, Technologies 2018, 6, 25; doi: 10.3390/technologies6010025.

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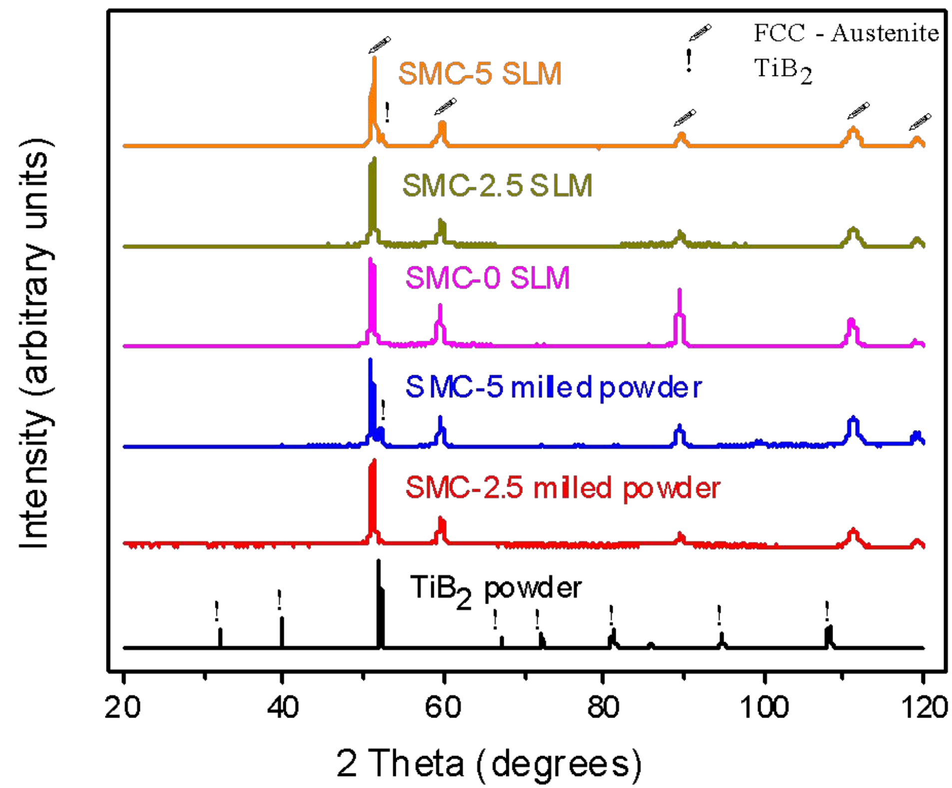
Strengthening 316L steel with TiB_2

316L/TiB_2

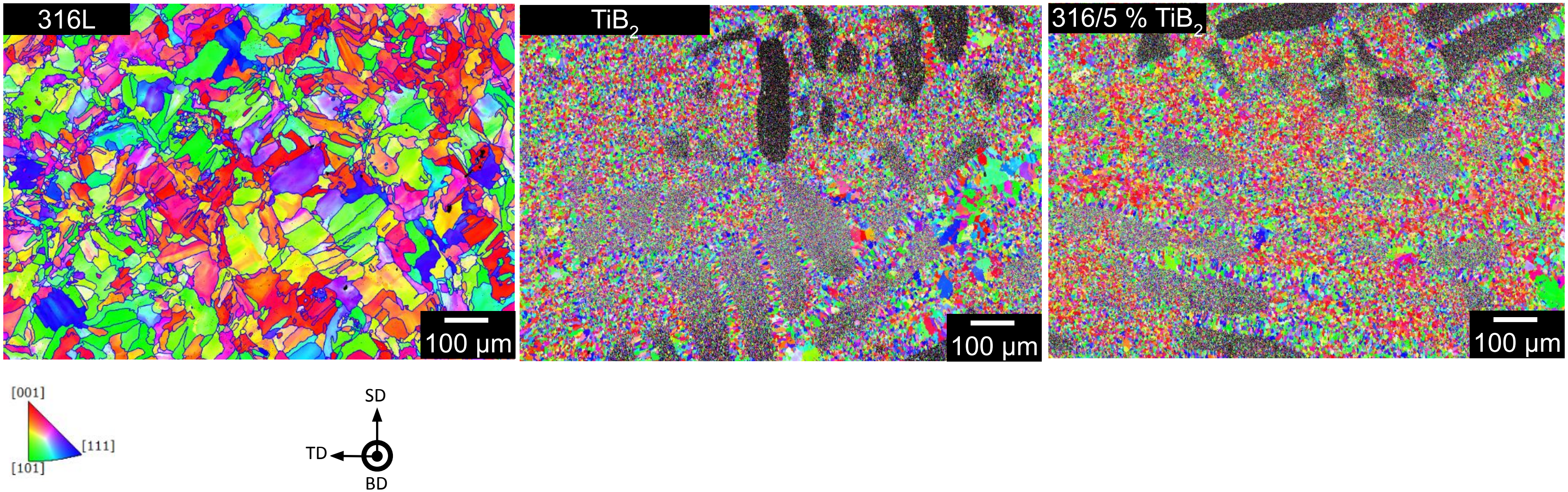
- **High melting temperature and strong grain refinement**
- **Good stability and wettability in steel matrix**
- **Low density 4.52 g/cm³**
- **High hardness**

- Matrix : single-phase austenite structure



Strengthening 316L steel with TiB_2

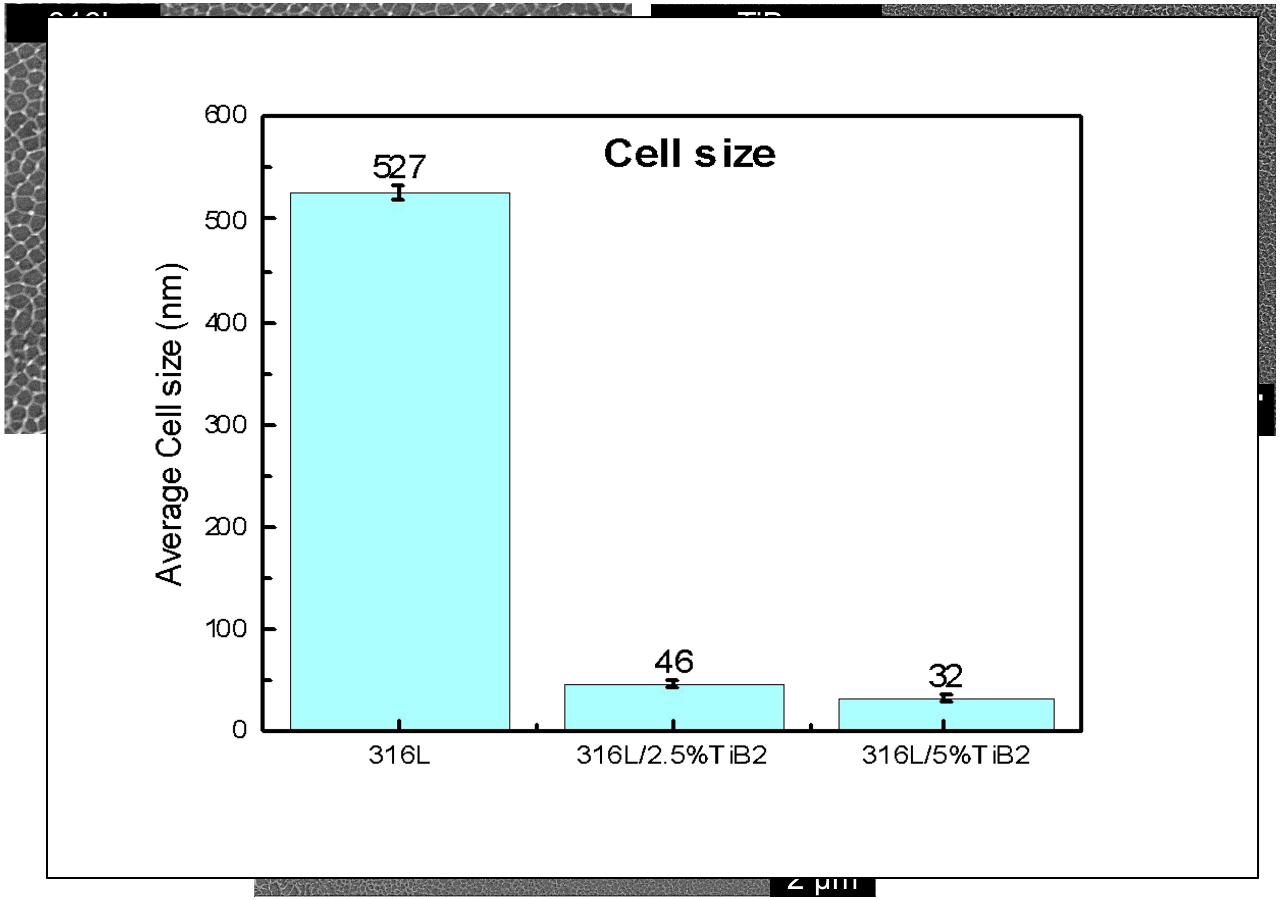
Microstructure



- Strong grain refinement
  - Unreinforced 316L = 45 ±3 µm
  - 316L/2.5%TiB_2= 6 ± 2 µm
  - 316L/5%TiB_2= 2 ± 1 µm

Strengthening 316L steel with TiB_2

Microstructure



- Strong cell refinement

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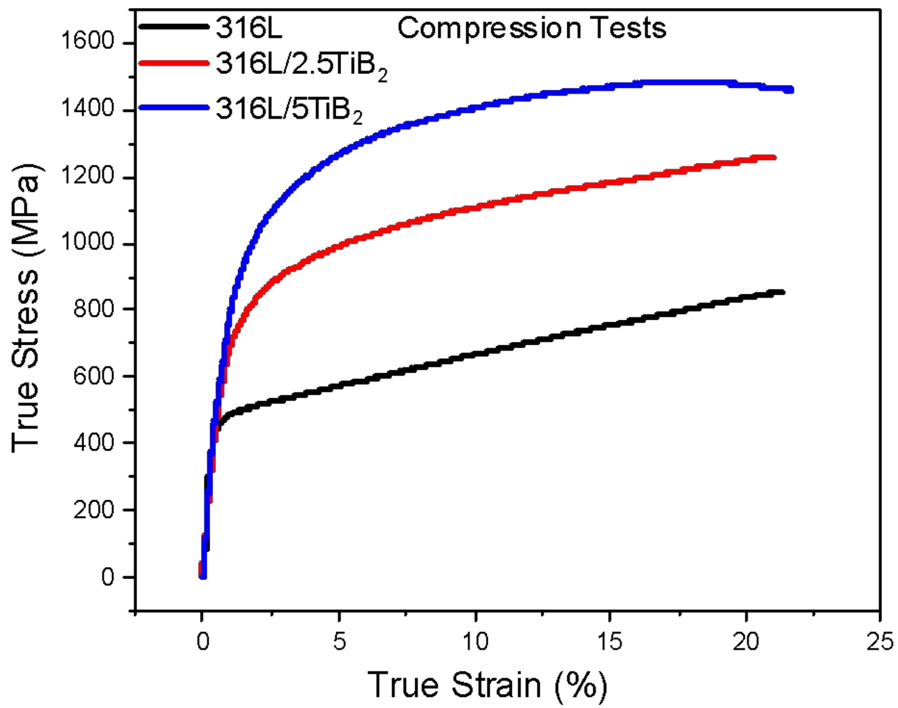
Strengthening 316L steel with TiB_2

Mechanical properties



- TiB2 very affective for enhancing the yield strength
    - 316L = 412 ± 7 MPa
    - 316L/2.5%TiB_2 = 600 ± 3 MPa
    - 316L/5%TiB_2 = 845 ± 5 MPa

Summary

Phase formation:

A single-phase austenite structure is formed regardless of the scanning strategy, annealing temperature or addition of second phase

Microstructure:

The smallest cell and grain sizes for stripe with contour strategy. The cellular microstructure is stable up to 873 K.

Further strong grain and cell refinement by the addition of CeO_2 and TiB_2.

Mechanical properties:

Strength depends on grain and cell size.

Highest strength for stripe with contour strategy.

The addition of CeO_2 and TiB_2 and related microstructural refinement enhances yield strength of 316L matrix.

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DRESDEN concept

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THANK YOU
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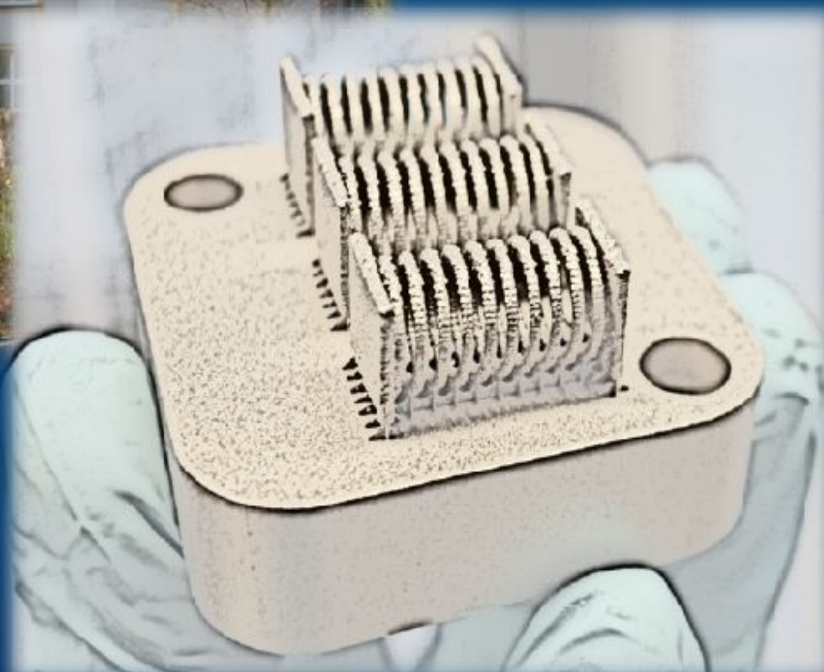

„Was wir wissen, ist ein Tropfen;
was wir nicht wissen, ein Ozean.“

Isaac Newton