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In situ characterization of deformation mechanisms in L-PBF 316L stainless steels

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San Antonio, TX, United States
March 10, 2019 through March 14, 2019

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In situ characterization of deformation mechanisms in L-PBF 316L stainless steels

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Lawrence Livermore National Laboratory, Livermore, CA

03/14/2019



Selective Laser Melting – SS 316L

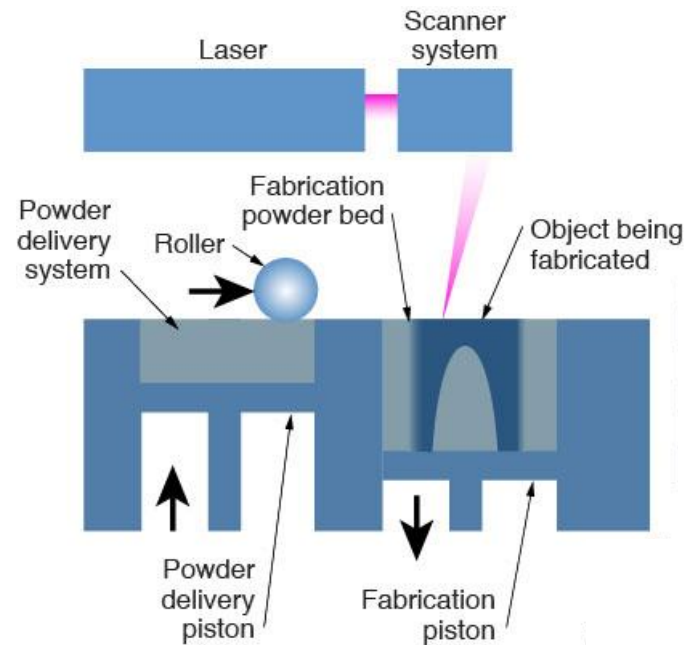


Concept Laser M2 Cusing

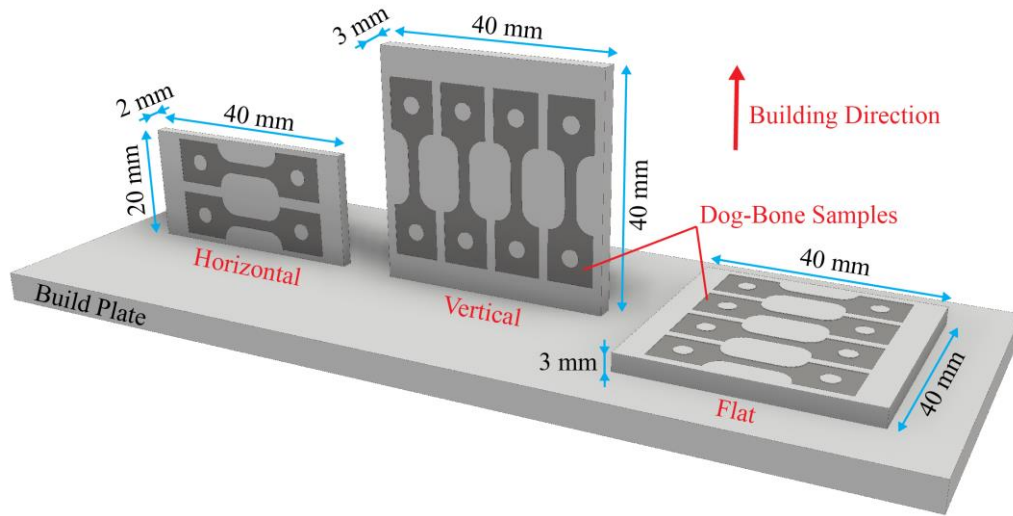


Open architecture Fraunhofer 3D printer

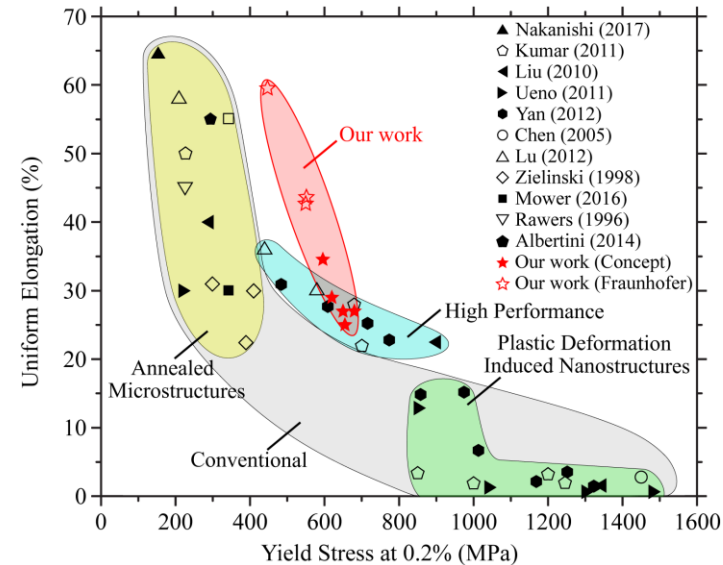
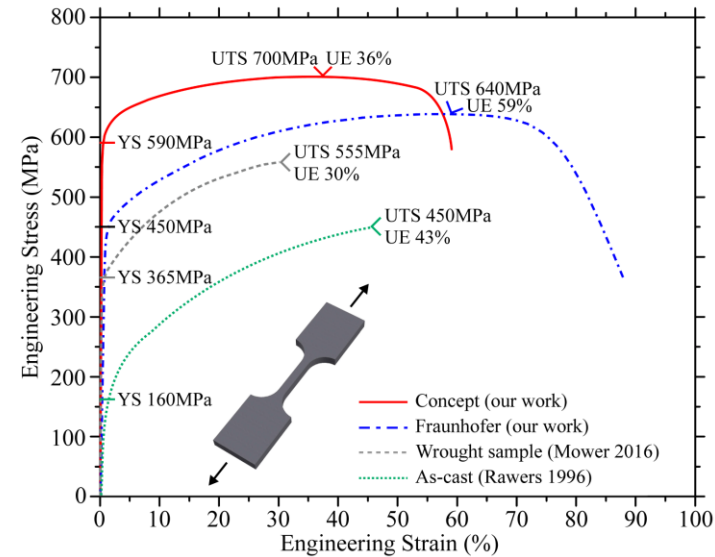
Powder Bed Fusion (PBF) Selective Layer Melting (SLM)



SLM SS 316L / Mechanical Properties



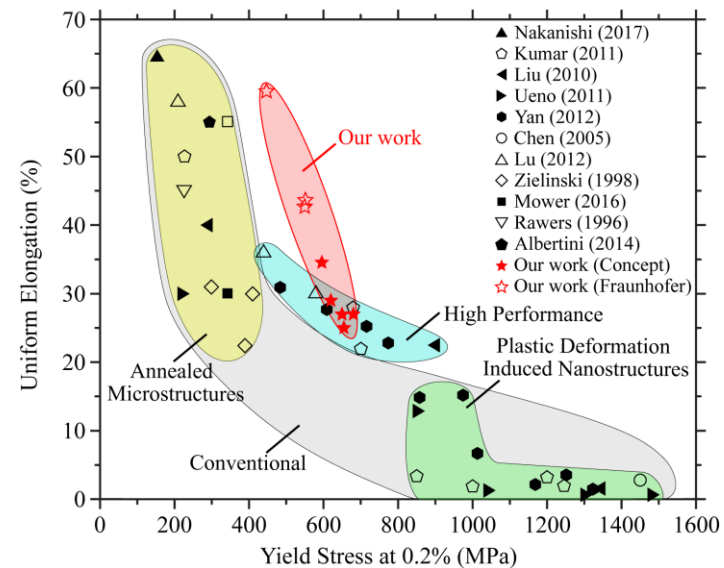
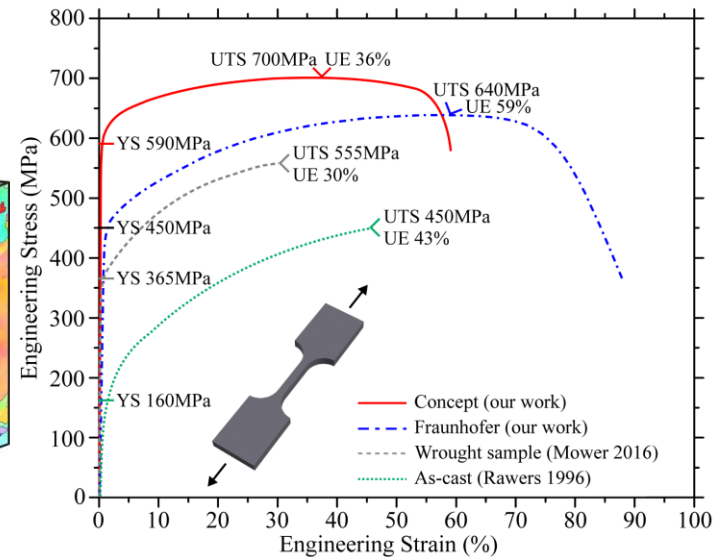
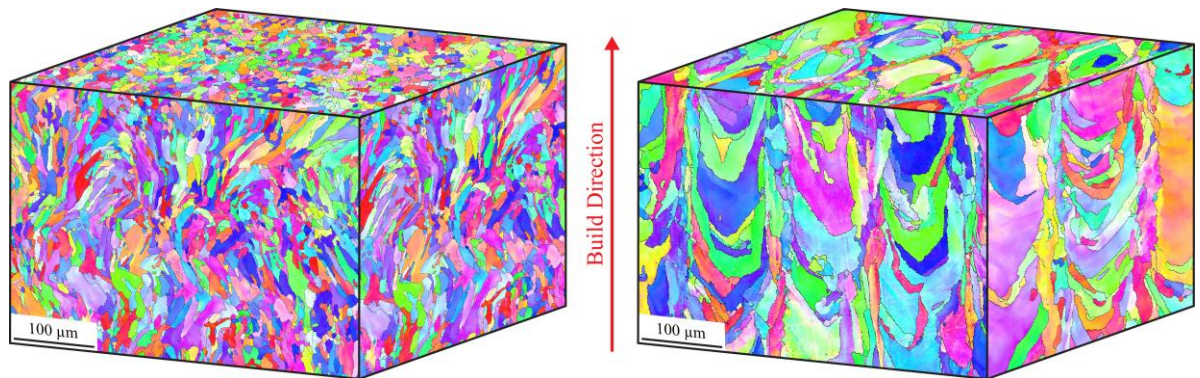
Laser power and speed optimization



SLM SS 316L / Microstructure

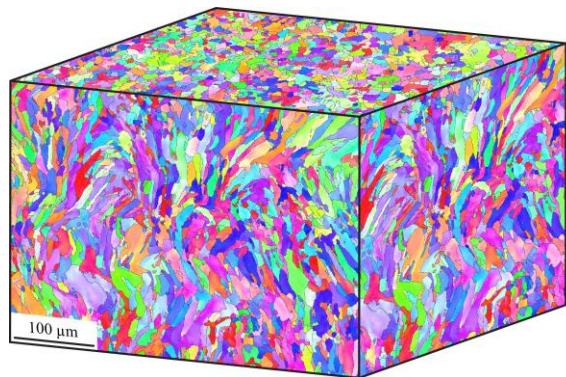
Sample 1

Sample 2

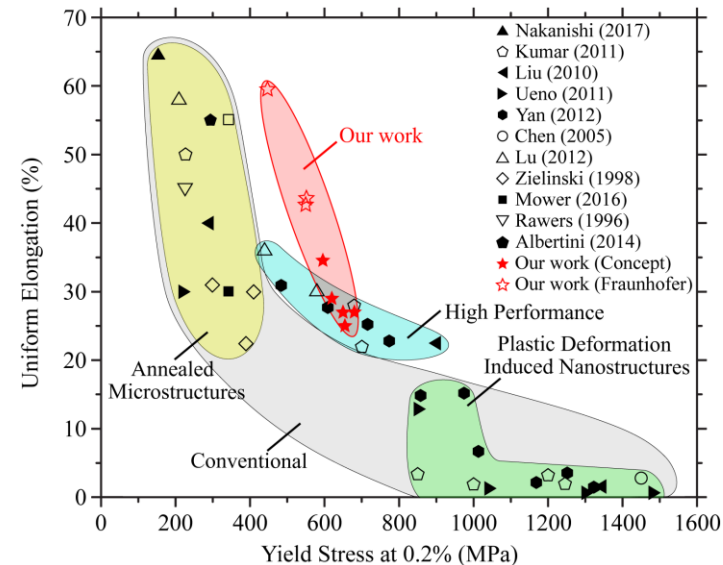
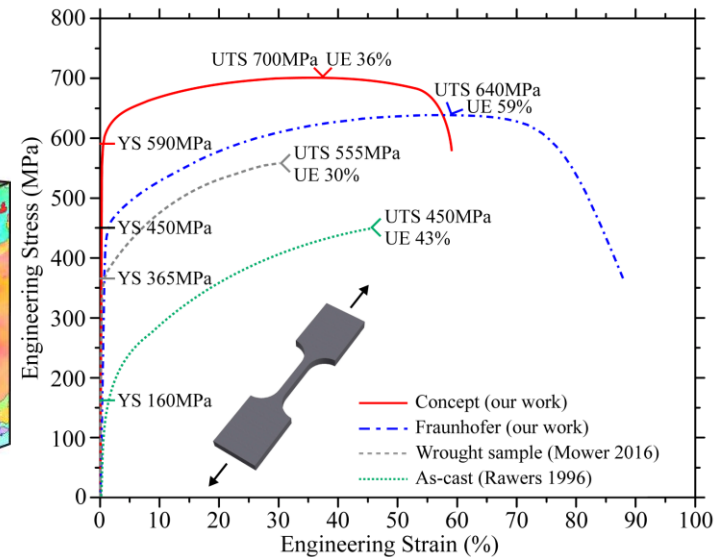
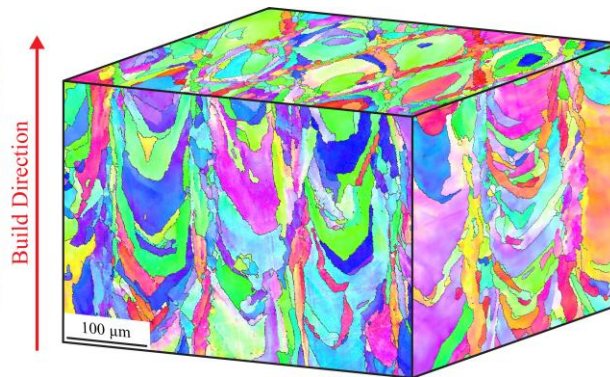


SLM SS 316L / Microstructure

Sample 1
Yield Strength = 450 Mpa
Strain-to-failure = 88%



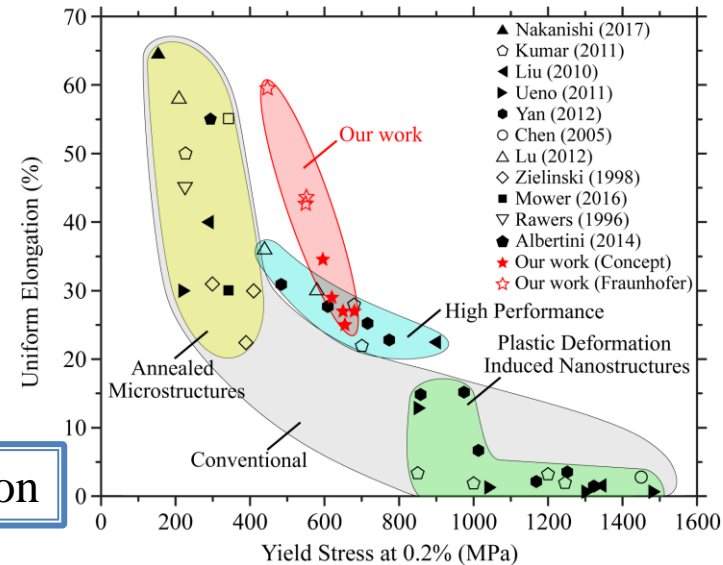
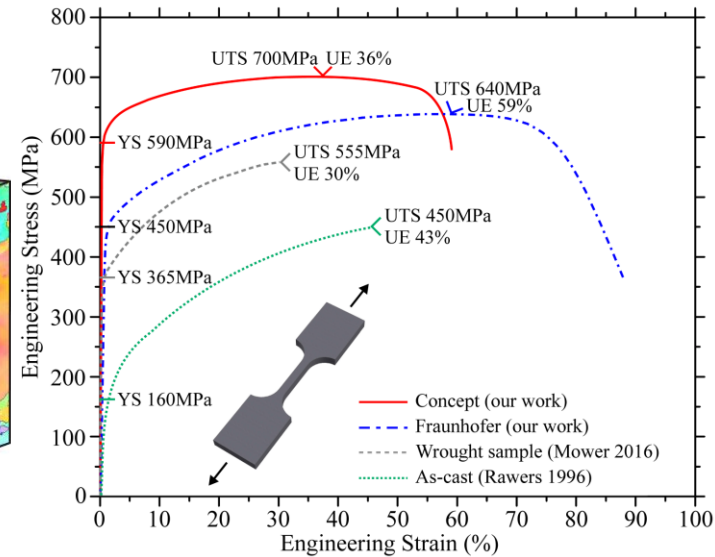
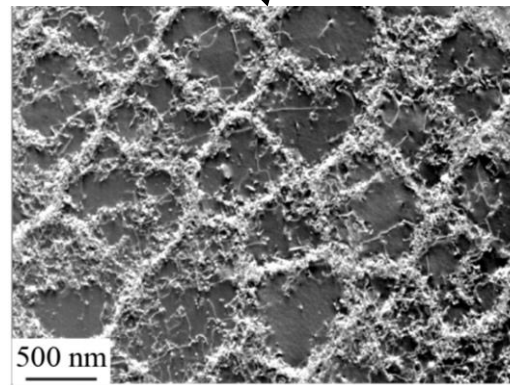
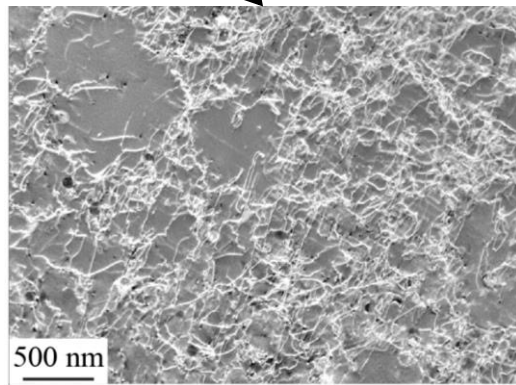
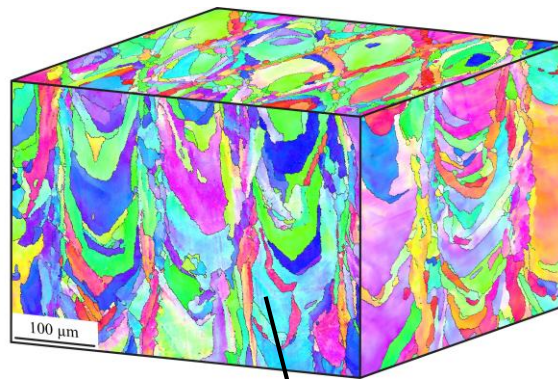
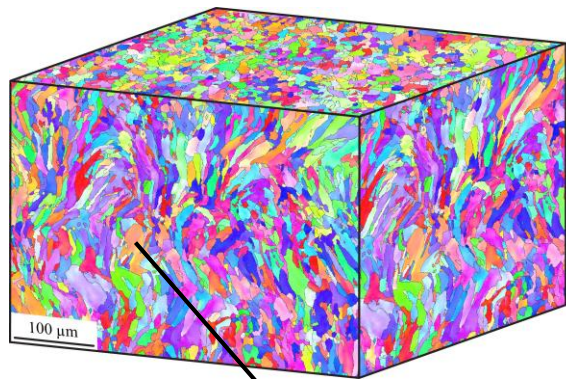
Sample 2
Yield Strength = 590 Mpa
Strain-to-failure = 58%



SLM SS 316L / Microstructure

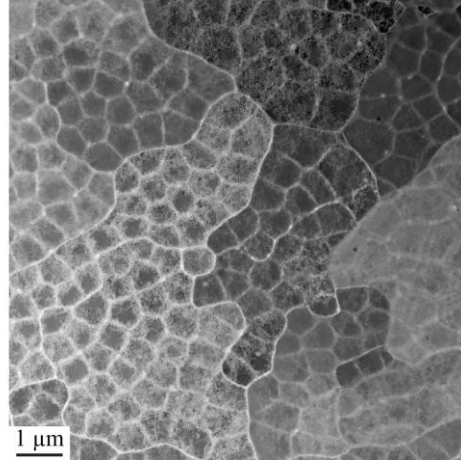
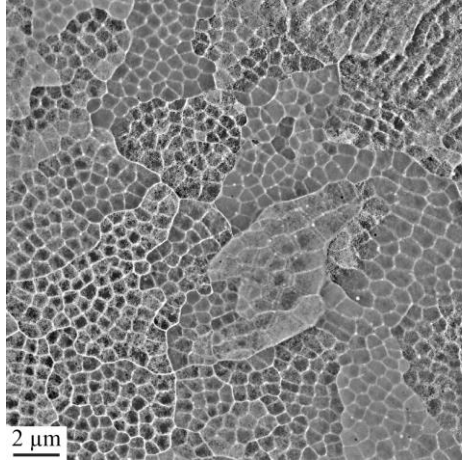
Sample 1
Yield Strength = 450 Mpa
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Sample 2
Yield Strength = 590 Mpa
Strain-to-failure = 58%

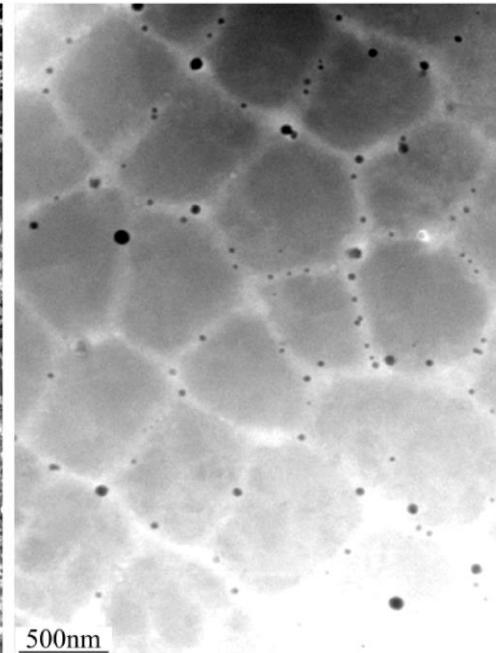
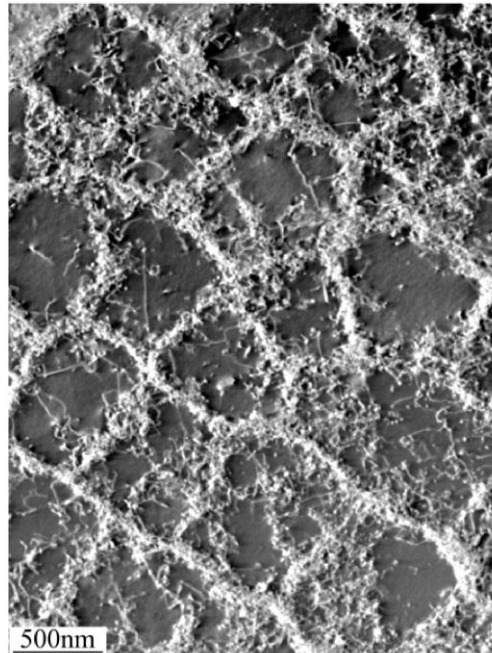
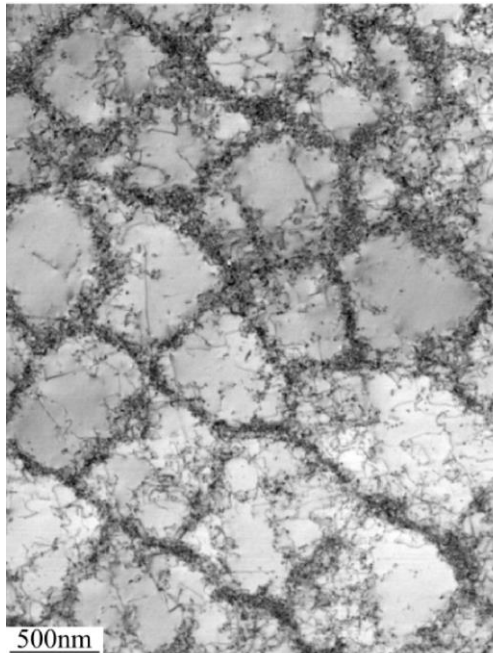


Features below the grain scale take control of the deformation

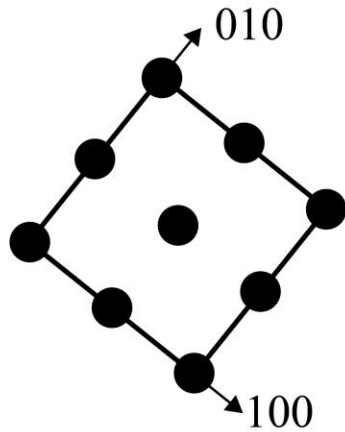
SLM SS 316L / Cellular Structure



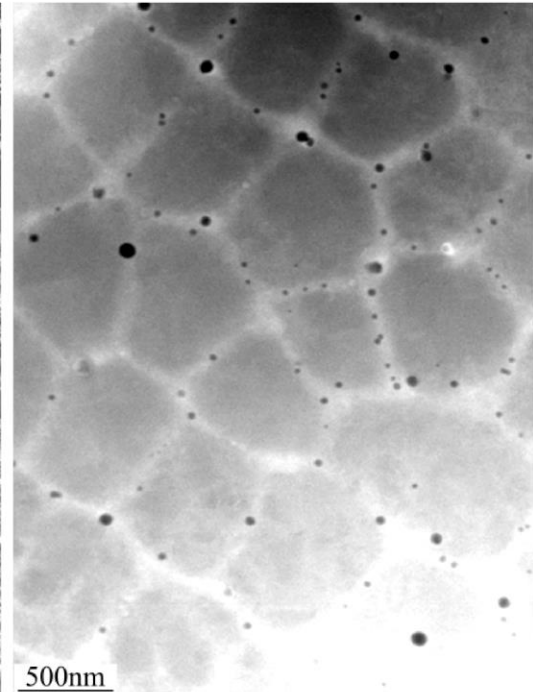
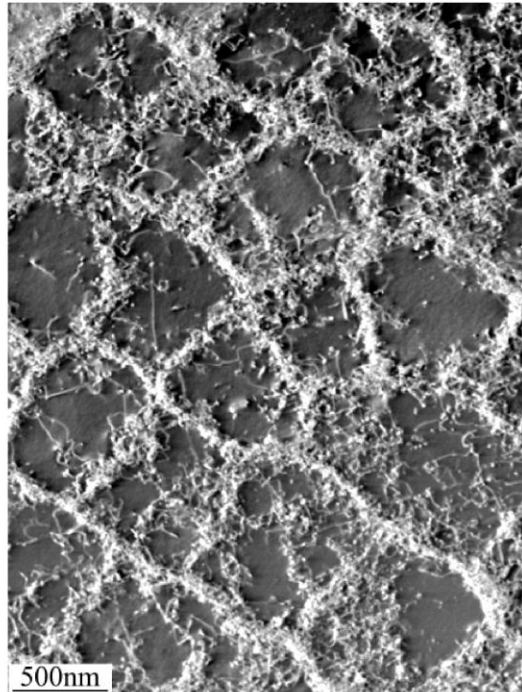
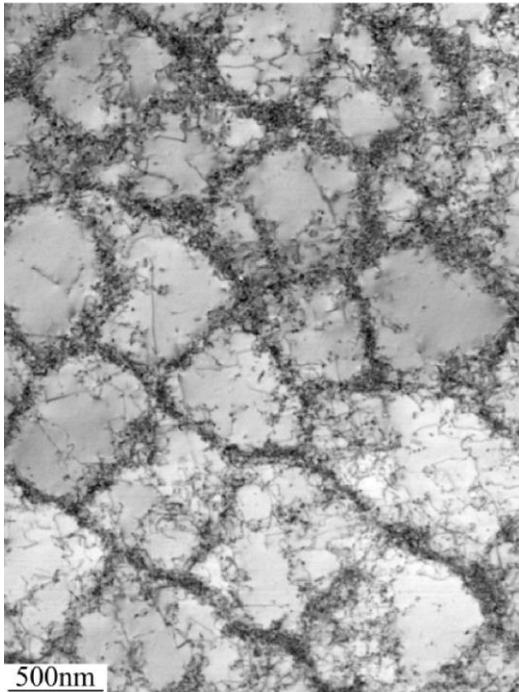
Solidification structure
Cell walls contain dislocations and
segregated elements



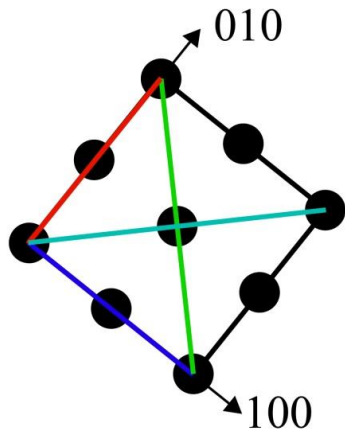
SLM SS 316L / Cellular Structure



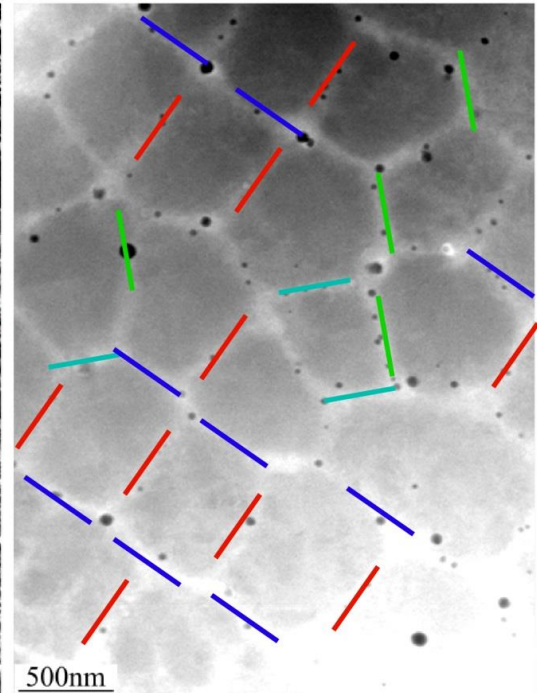
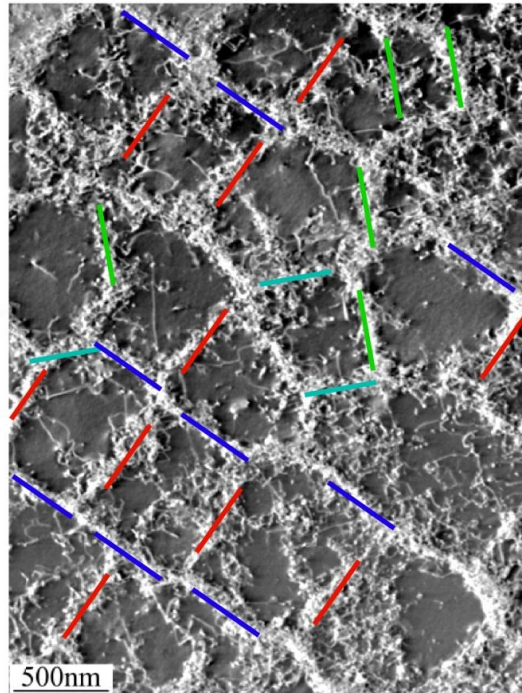
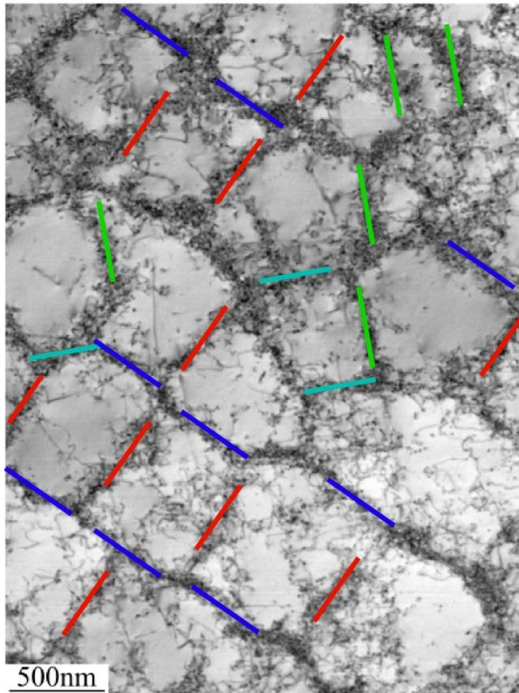
Solidification structure
Cell walls contain dislocations and segregated elements



SLM SS 316L / Cellular Structure



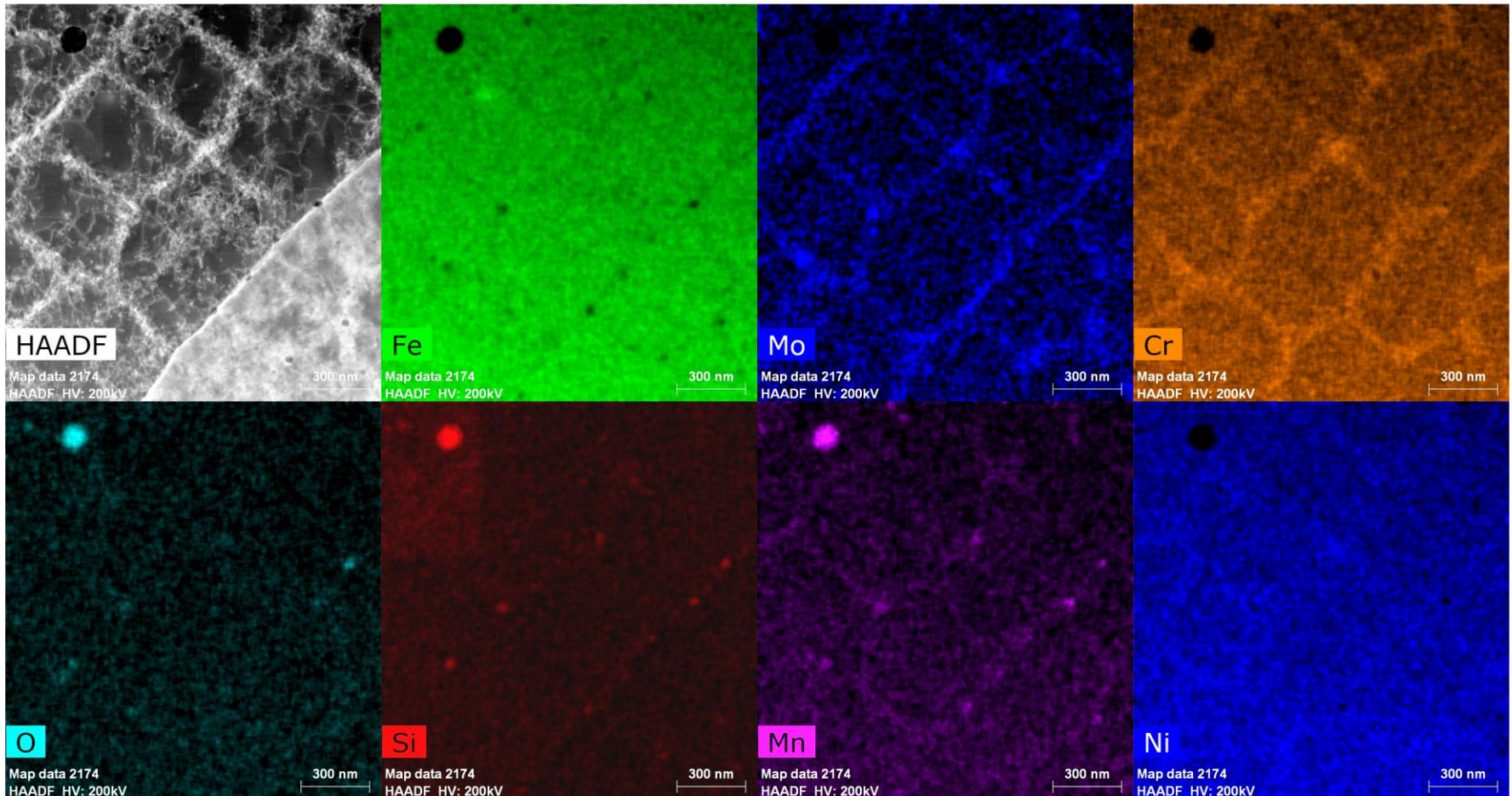
Cell walls line up along specific crystallographic directions



SLM SS 316L / Cellular Structure

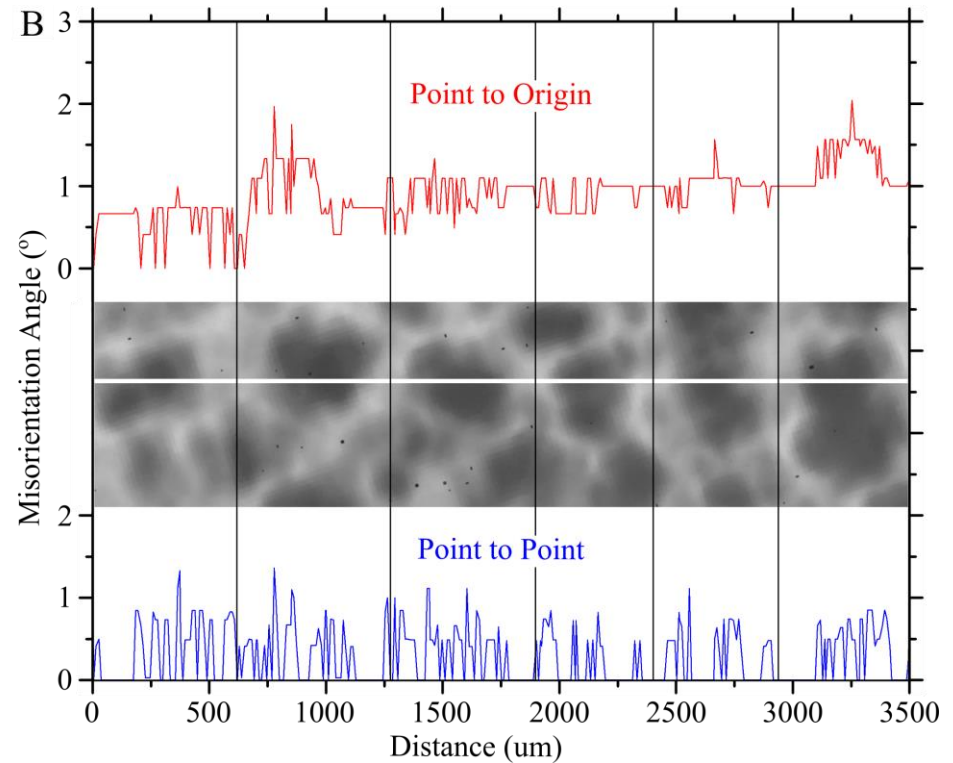
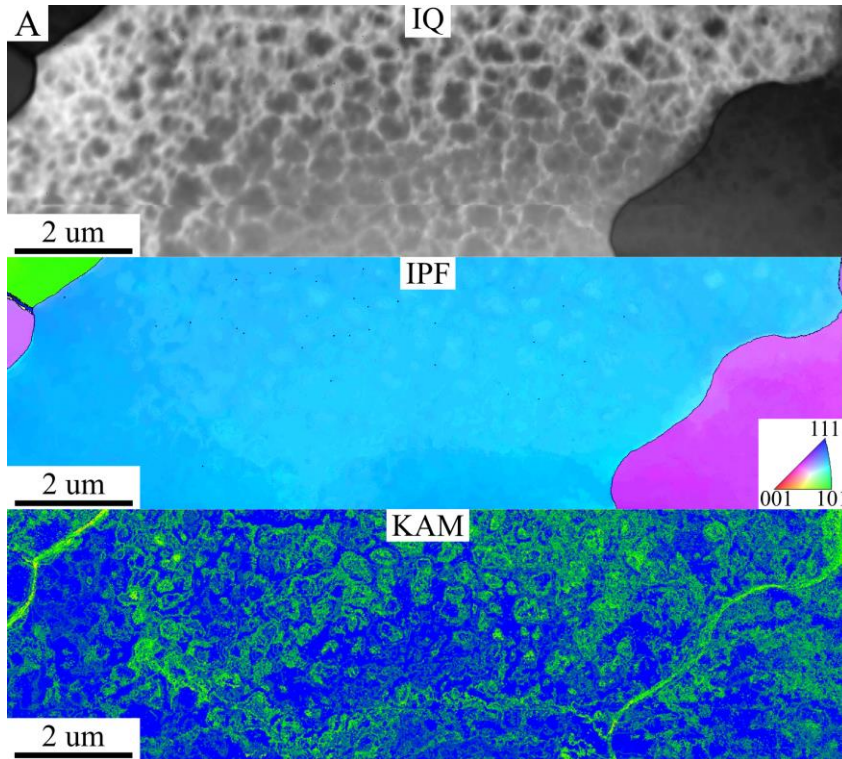
Mo and Cr segregation in cell walls

Presence of particles inside walls



SLM SS 316L / Cellular Structure

Orientation Mapping in a TEM (probe size 5nm)

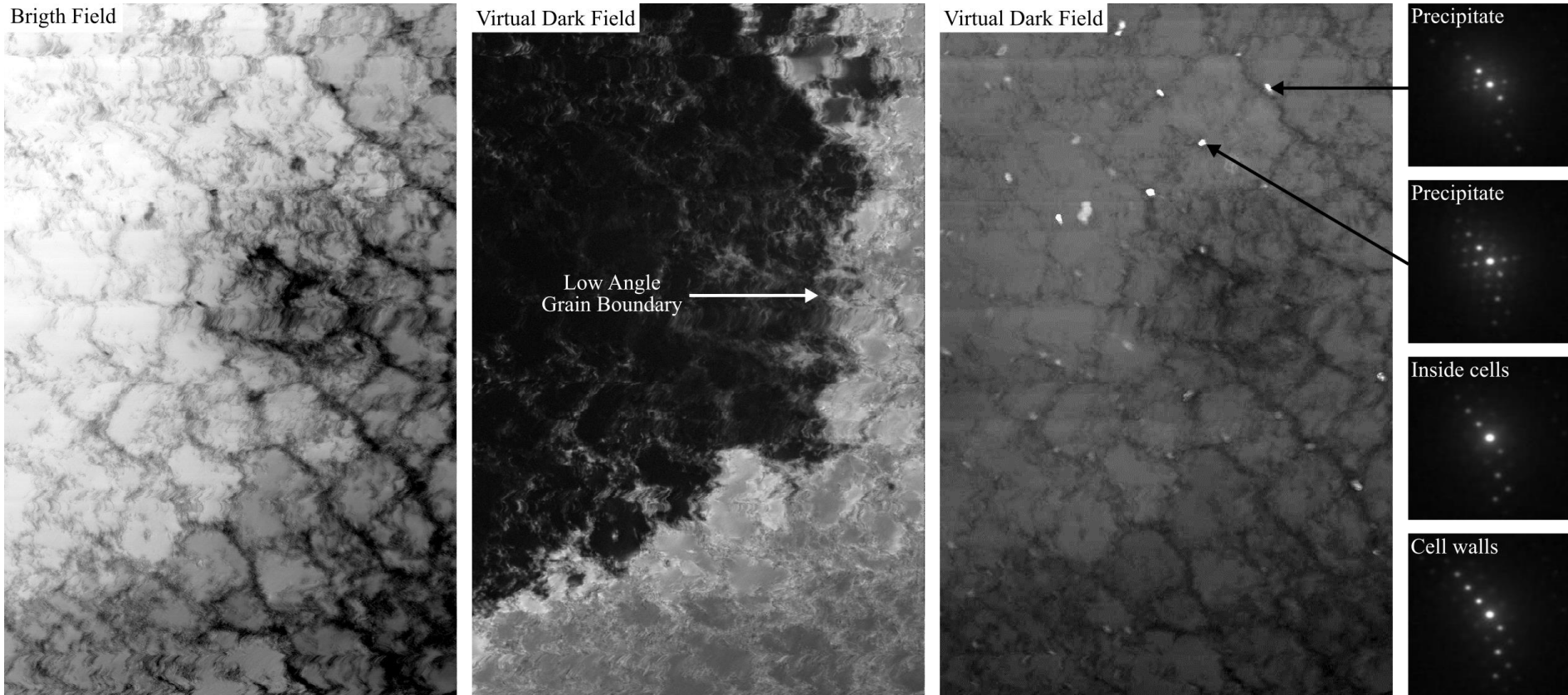


Very low misorientations related to the cell structure

- Different from conventional dislocation cells
- In agreement with solidification structure

SLM SS 316L / Second Phase

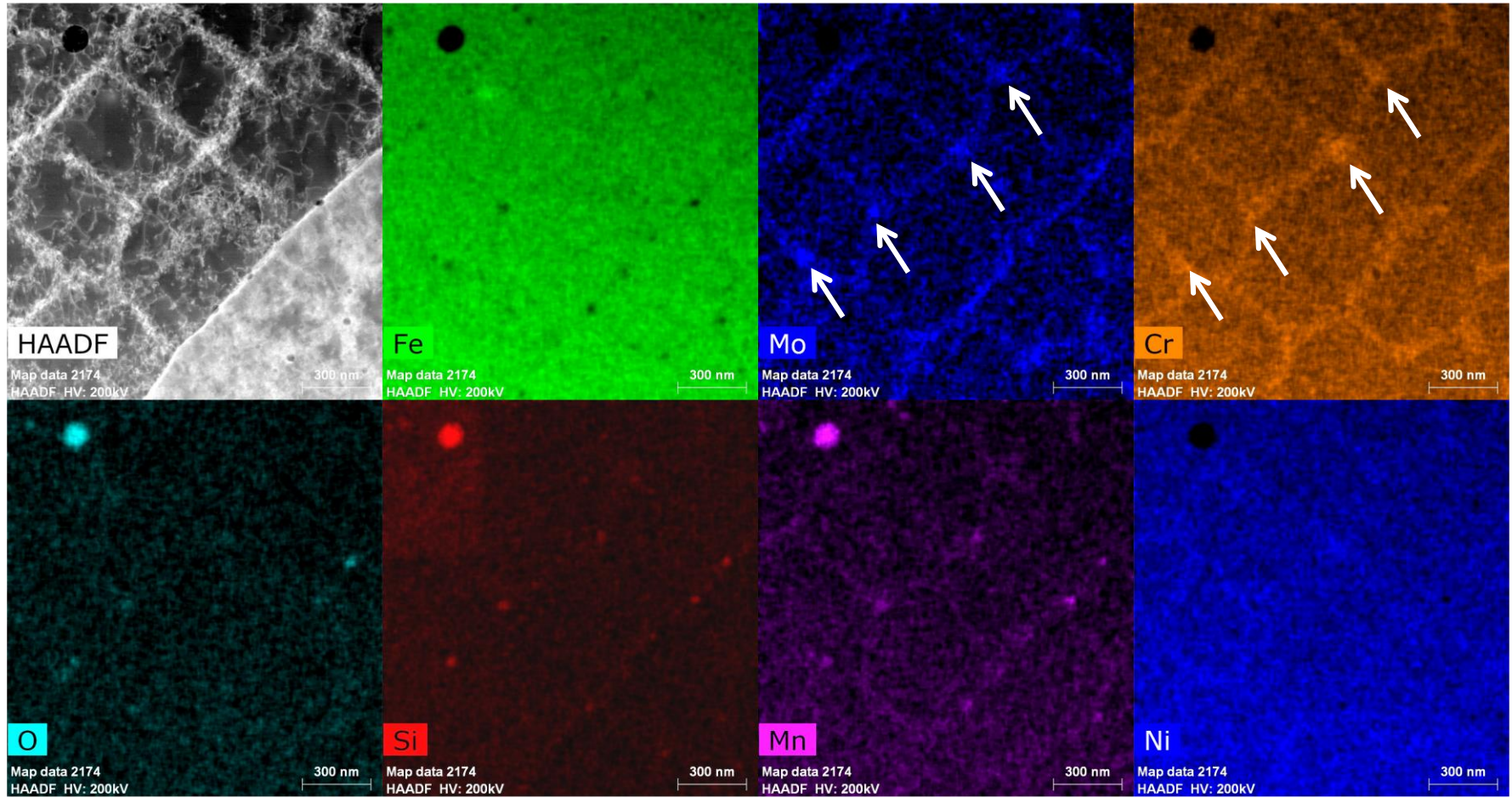
Orientation Mapping in a TEM (probe size 5nm)



Revealing second phase particles

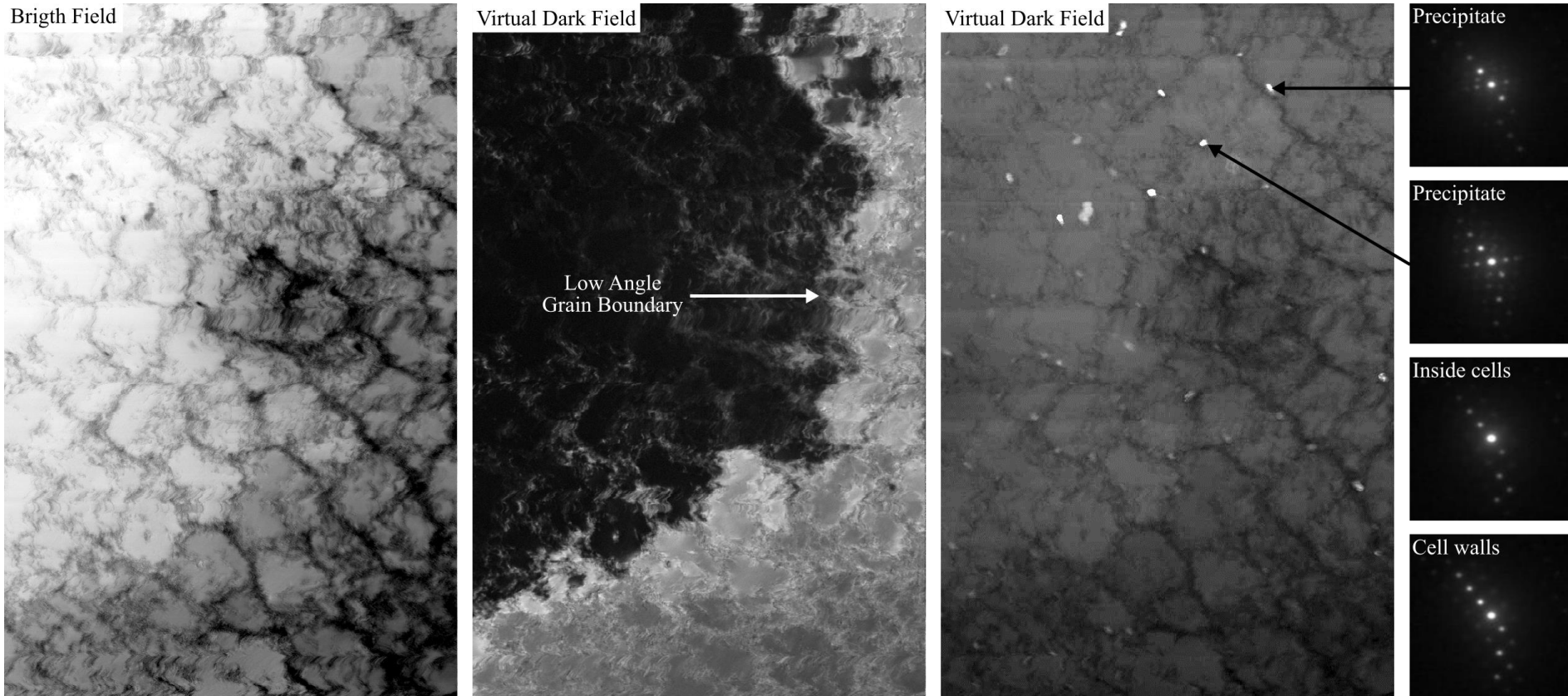
SLM SS 316L / Second Phase

Second phase particles may correspond to local Mo-Cr segregations



SLM SS 316L / Second Phase

Orientation Mapping in a TEM (probe size 5nm)

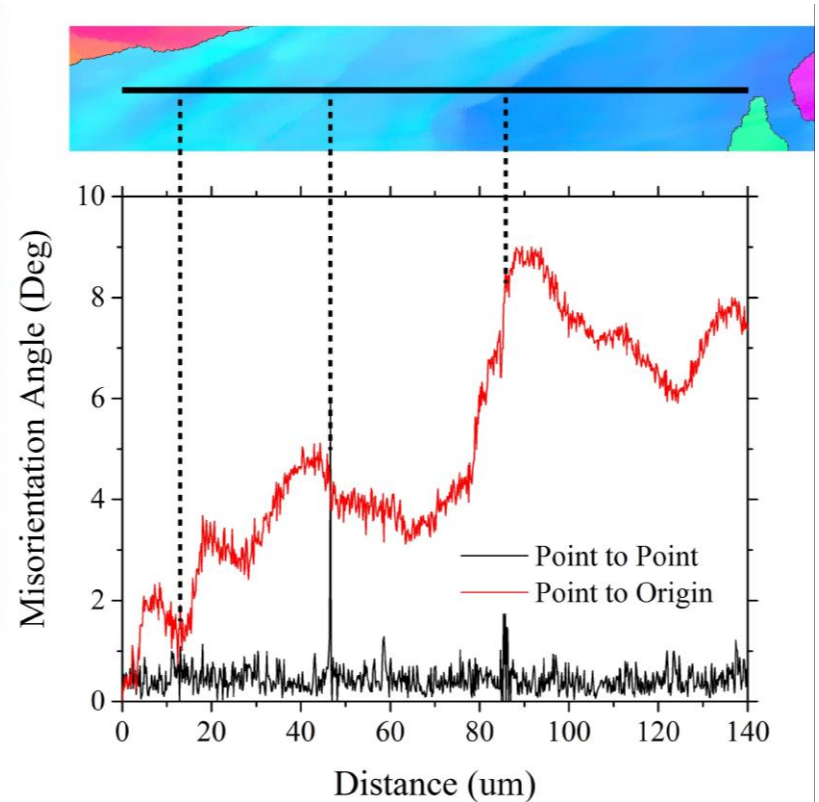
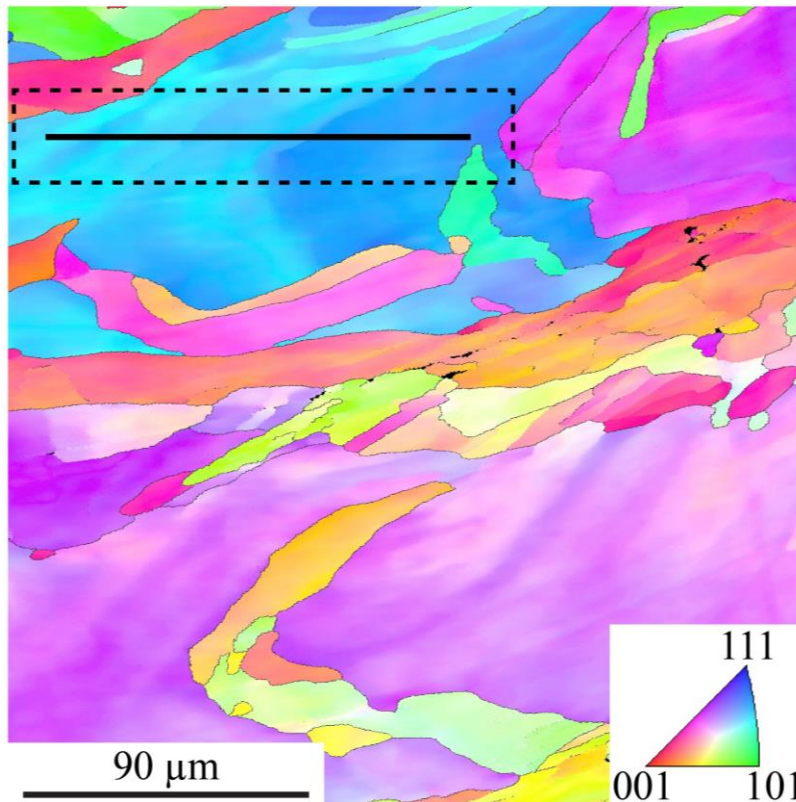


Revealing second phase particles

SLM SS 316L / Low Angle Grain Boundaries

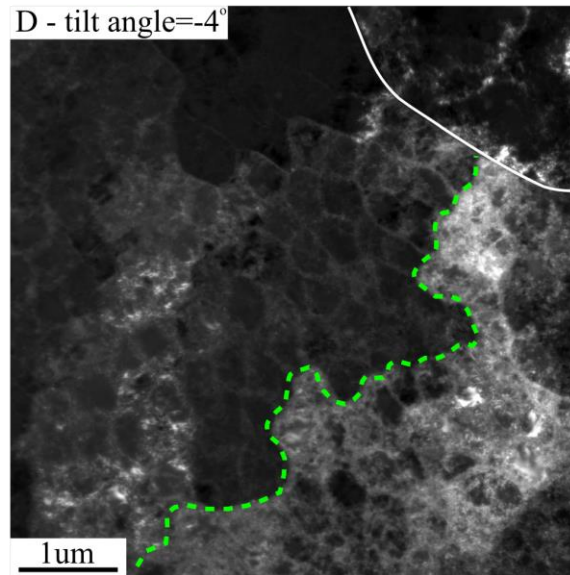
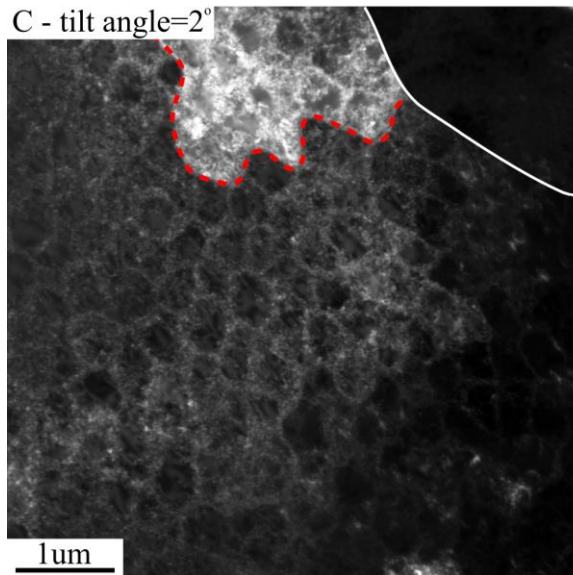
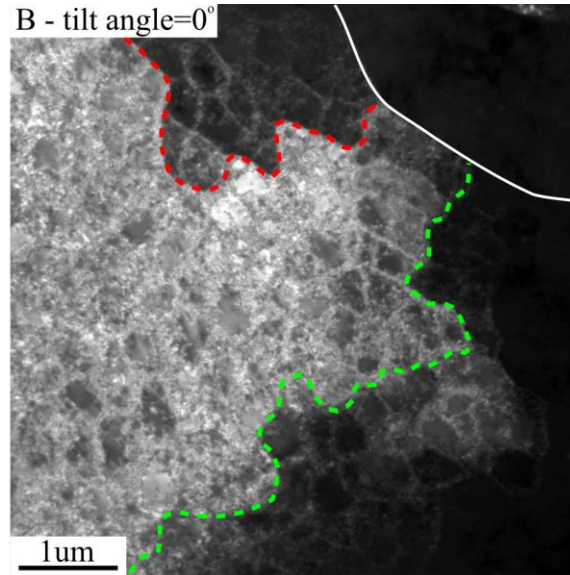
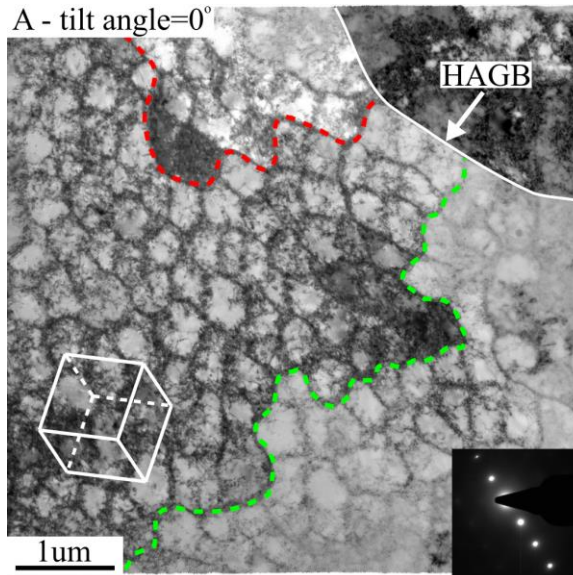
LAGB by EBSD

Build Direction
→



High Angle Grain Boundaries ($>10^\circ$) = 48%
Low Angle Grain Boundaries (1- 10°) = 52%

SLM SS 316L / Low Angle Grain Boundaries



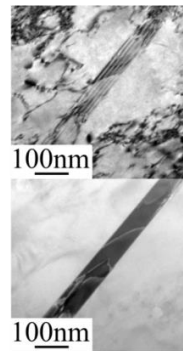
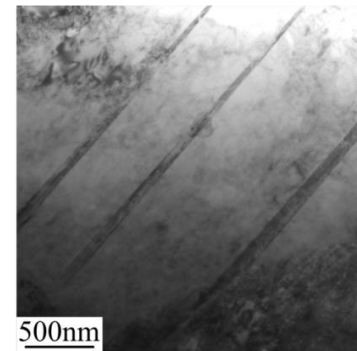
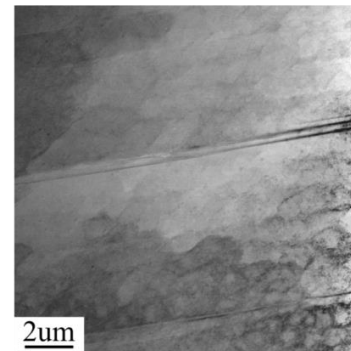
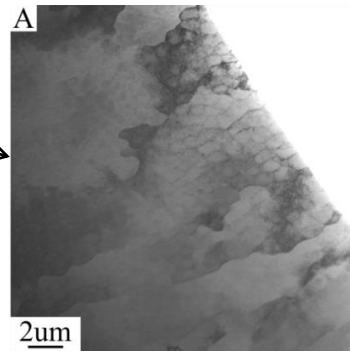
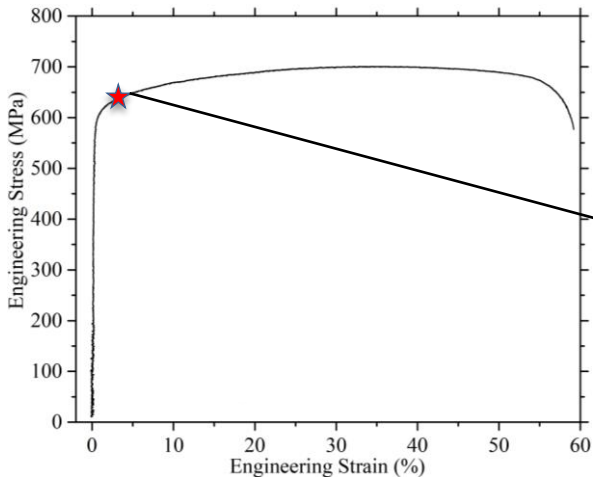
LAGB by TEM

LAGB follow cell walls.

Important for the stability of
the microstructure

SLM SS 316L / Deformation Mechanisms

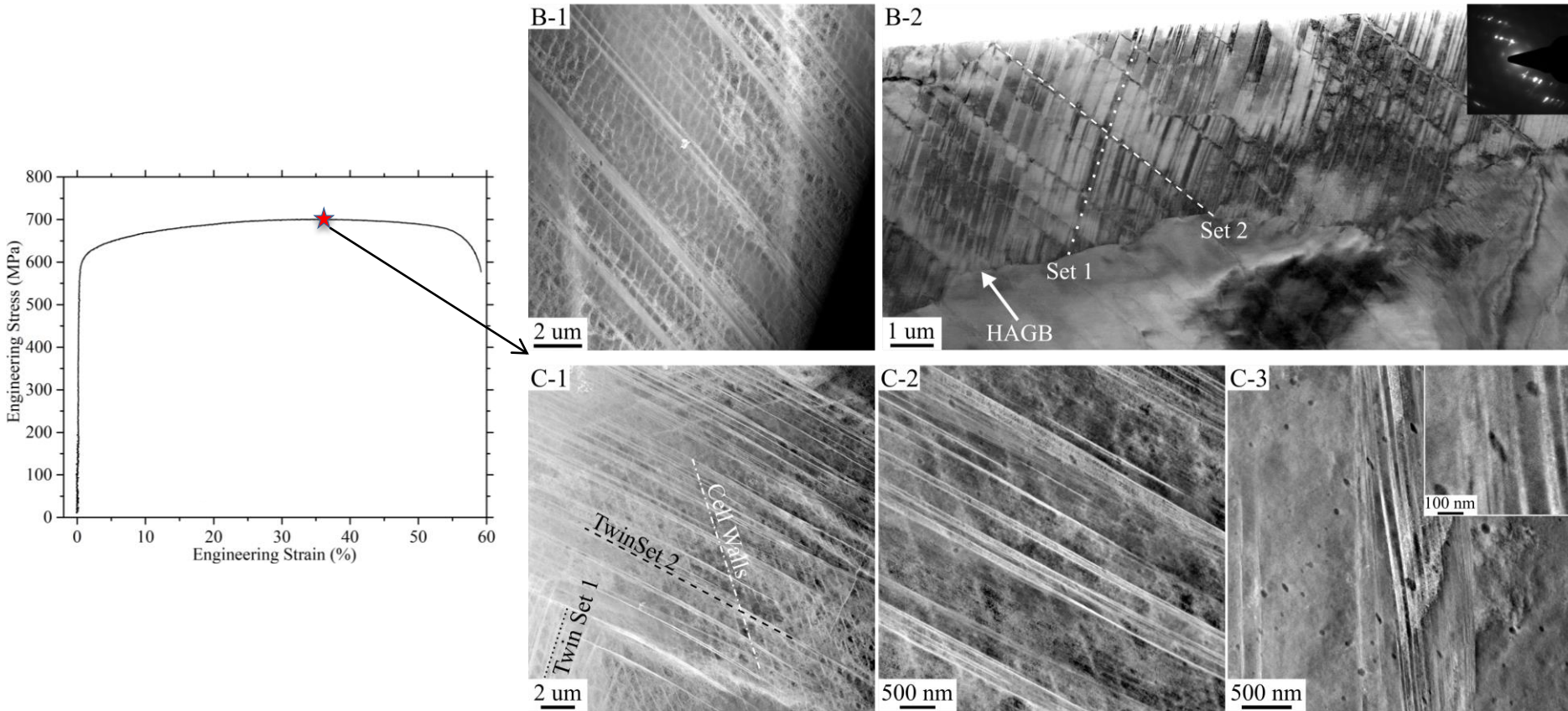
TEM after a few % of strain



Onset of twinning around 3% of plastic strain

SLM SS 316L / Deformation Mechanisms

TEM in uniformly deformed region after fracture

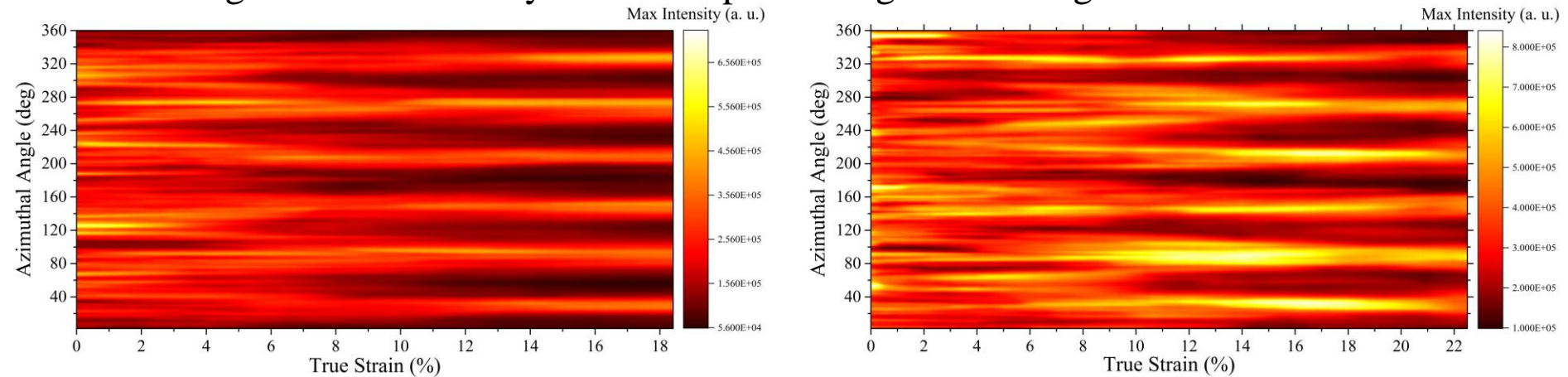


- Elongated dislocation cells still present
- Twinning everywhere with 2 twinning systems activated in many grains
- Silicate particles sheared by twins

SLM SS 316L / Deformation Mechanisms

Insight from synchrotron XRD

Changes in max intensity of the 111 peak along the full ring as a function of strain

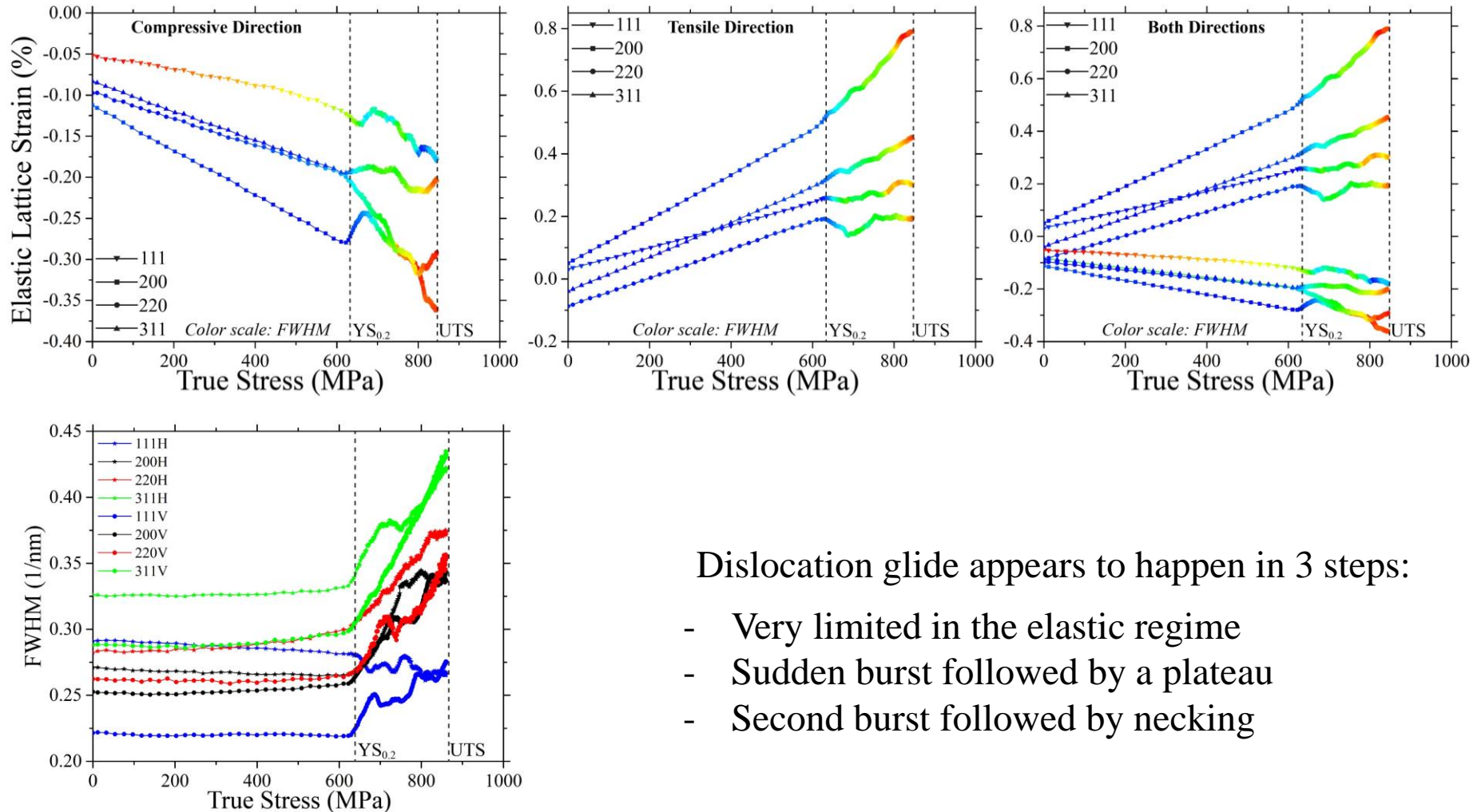


60° angle between peaks: signature of twinning

Twinning starts in the early stage of plastic deformation as observed by TEM

SLM SS 316L / Deformation Mechanisms

Insight from synchrotron XRD



Dislocation glide appears to happen in 3 steps:

- Very limited in the elastic regime
- Sudden burst followed by a plateau
- Second burst followed by necking

SLM SS 316L / Conclusion

- ★ Out of equilibrium microstructure with multi-scale features influencing mechanical properties
 - HAGB
 - LAGB
 - Cellular structure
 - Particles
 - Initial dislocations density
- ★ Cellular structure still present after fracture: thanks to chemical segregation?
- ★ Twinning: an important mechanism that may not be influenced by cellular structure or LAGB

In situ TEM tensile testing to determine the interaction between defects (dislocations and twins) and cellular structure

Thank you! Any questions?

Acknowledgments: Ibo Matthews, Joe Mckeown, Phil Depond, Gabe Guss, for their experimental assistance and discussion.



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