Cornell Engineering

Not all defects are bad defects: *Designing superior microstructures in Additive Manufacturing*

L A M M — Lab Advanced Materials Manufacturing

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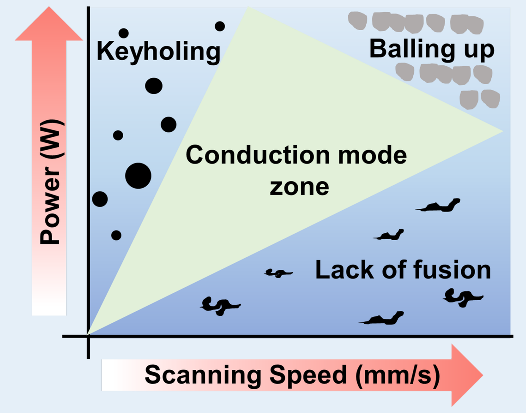
Highlights

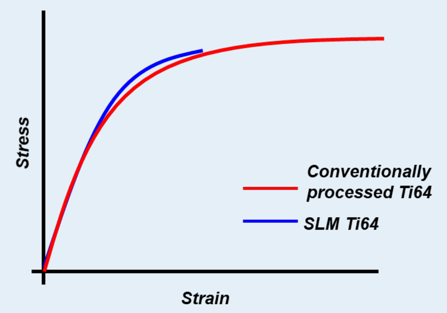
- Exploiting lack of fusion defects to design printed duplex microstructure
- Breakdown of columnar prior β-grains in printed Ti alloys
- α-globular and α-lath grains enable high strength and ductility in printed Ti alloy

What is holding us back?

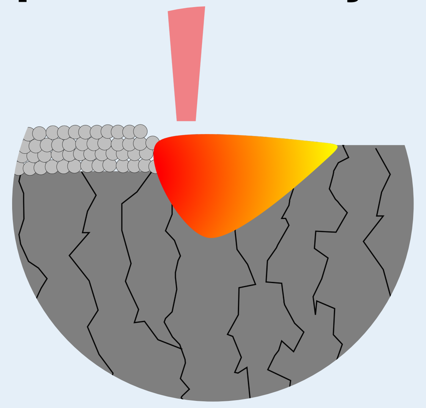
Porosity and fusion defects



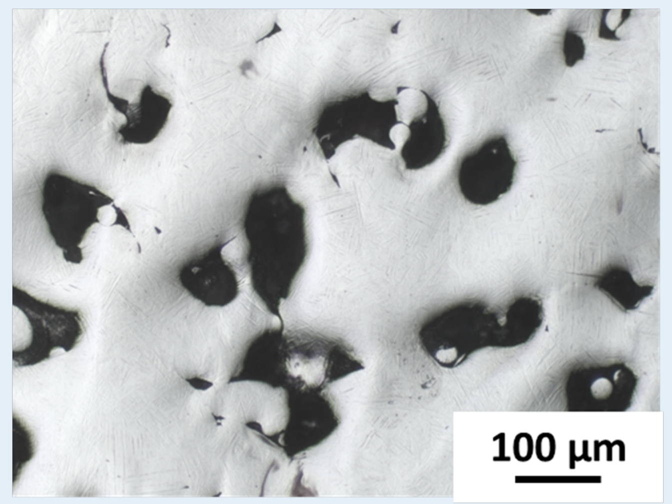
Directional grain growth



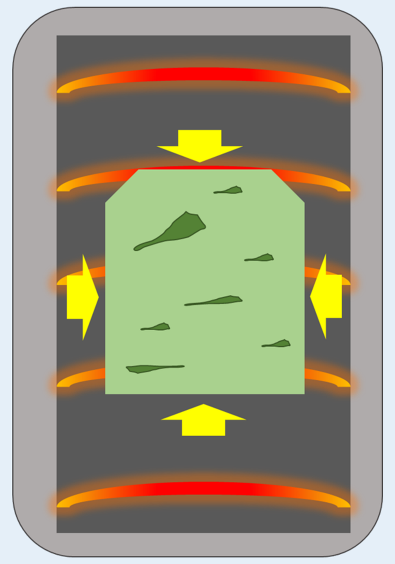
Anisotropy and poor ductility



Materials & methods



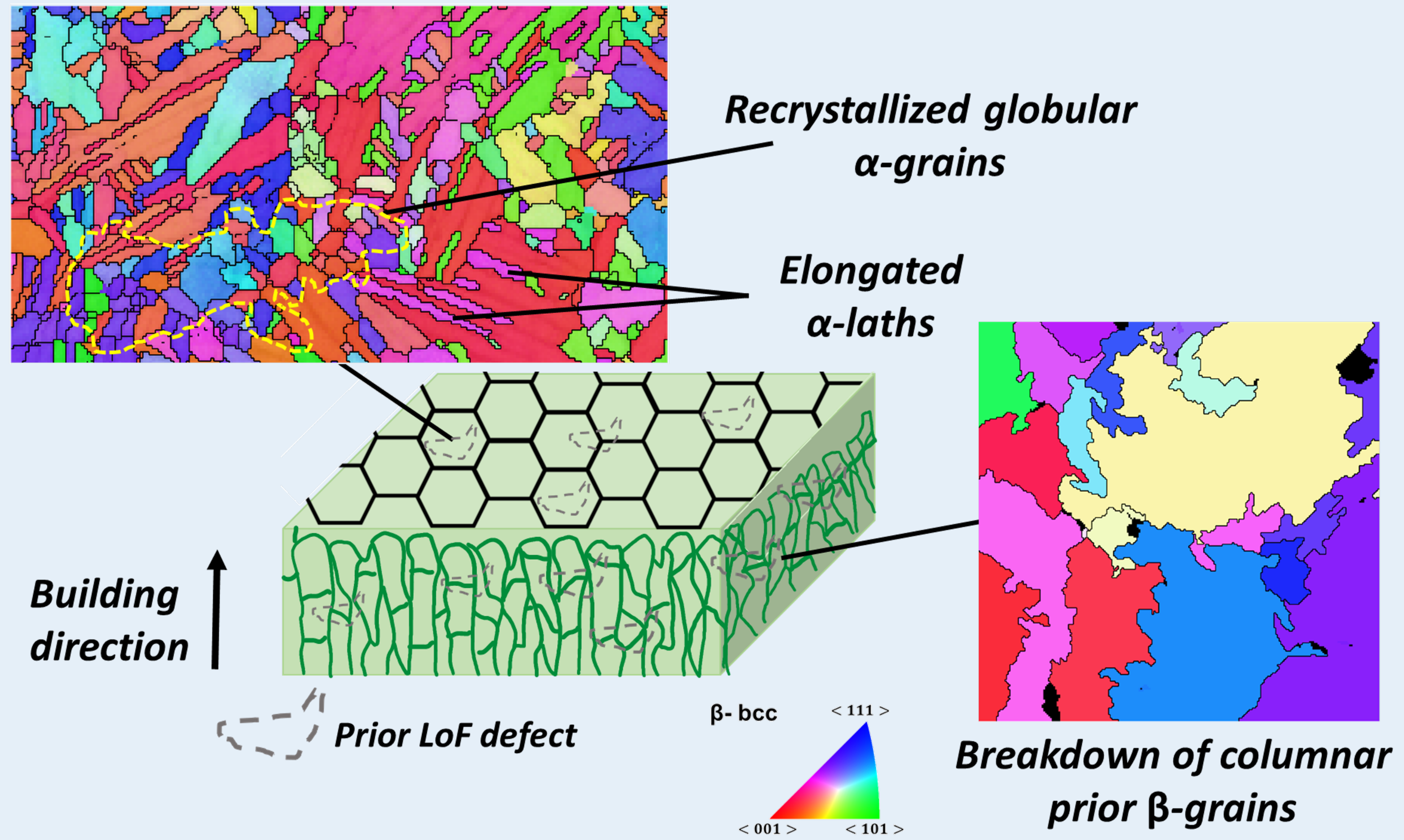
Printing defective parts
Low energy densities
Defects (up to 500 µm)



Post-process via hot isostatic pressing

Local recrystallization and defect closure

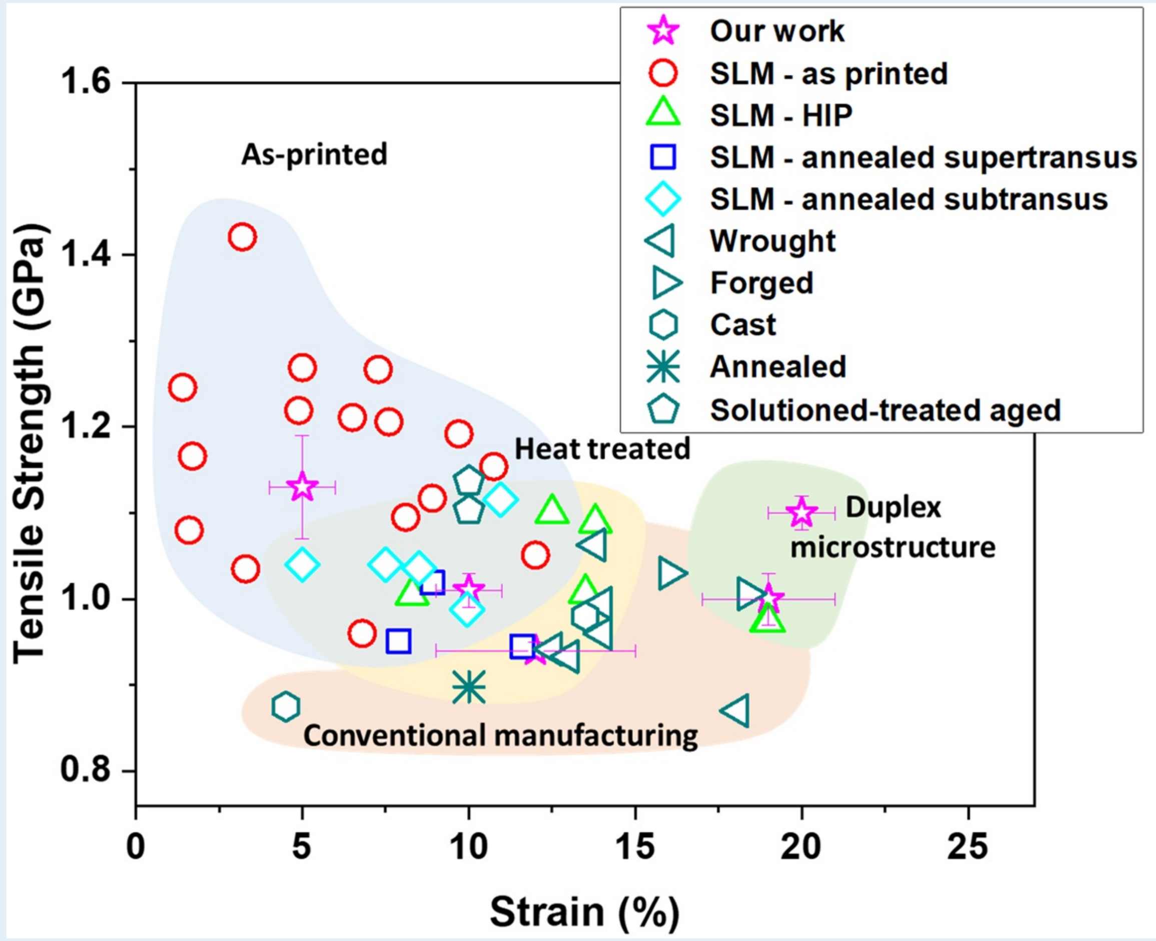
Exploiting lack of fusion defects



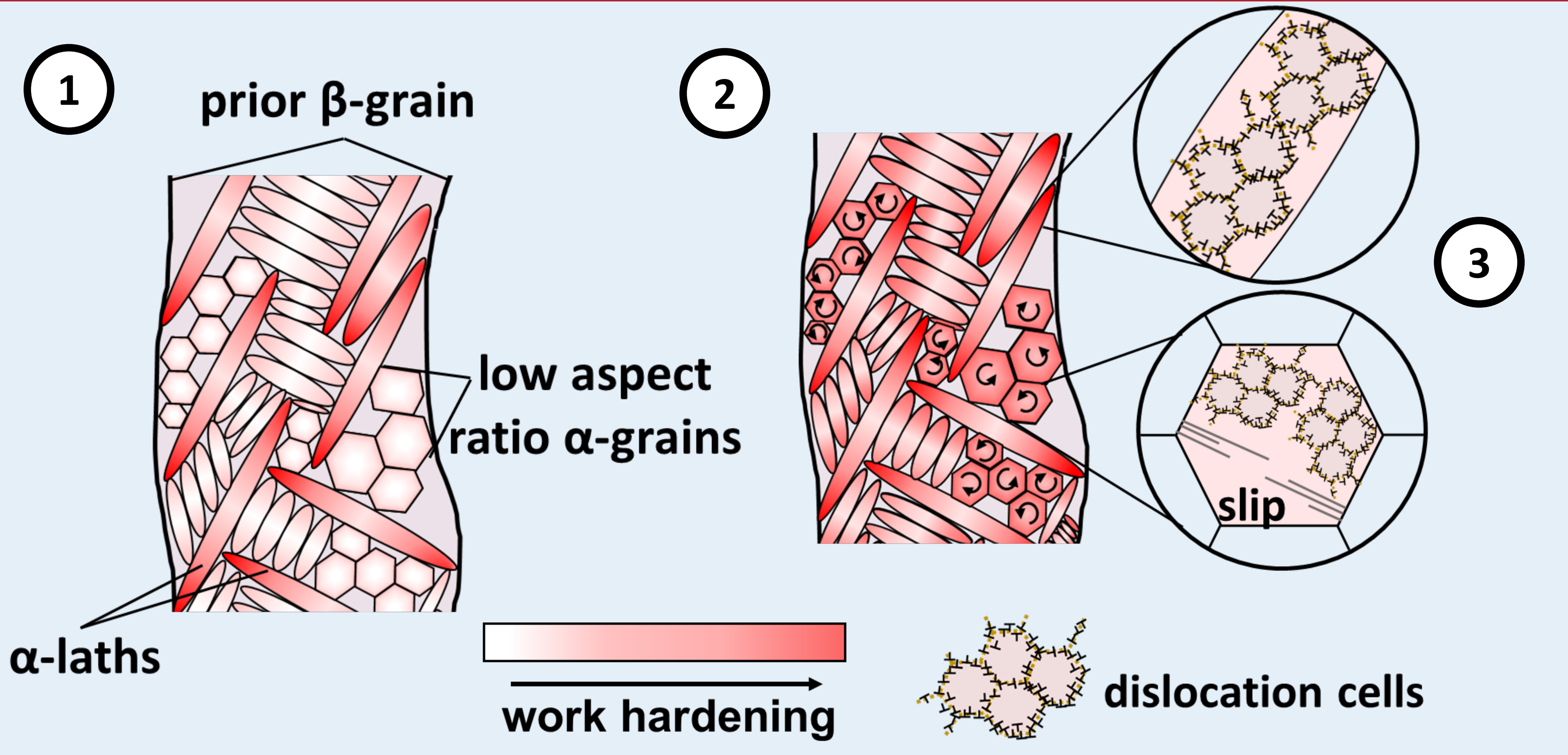
✓Enhanced ductility by up to 90% as compared to the baseline (FD-HIP 1)

✓Ductility was achieved at no loss of strength

Mechanically superior to conventional manufacturing routes



Results & Discussion



Co-existence of α-laths and dislocation-free α-globules enable the effective strain transfer to accommodate extended deformation

Conclusions

- Universal method to engineered AM microstructures
- Duplex microstructure derived from recrystallization and reduction of surface energy
- Mechanically superior microstructure vs. as-printed, HIP-ed, forged, annealed and STA alloys

References

Moridi et al. Mate Sci & Eng A, 2019
J Bustillos, J Kim, A Moridi, Additive Manufacturing, 48, (2021), 102399
Zhang, D. et al., Nat. 576, (2019)
Todaro, C.J et al., Nat. Commun. 11, (2020)
Zhang, D. et al., Advanced Engineering Materials, 2018, 20
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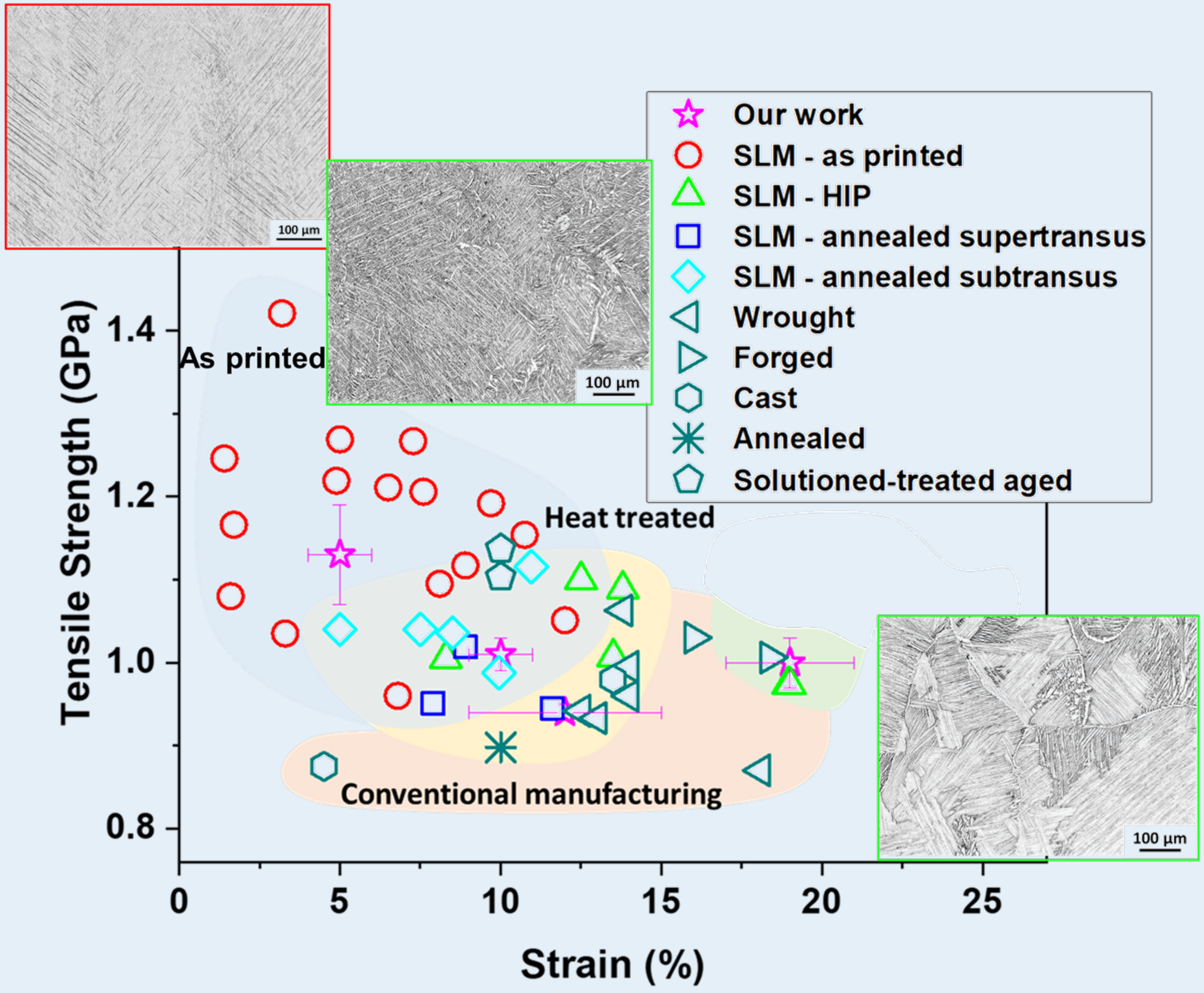
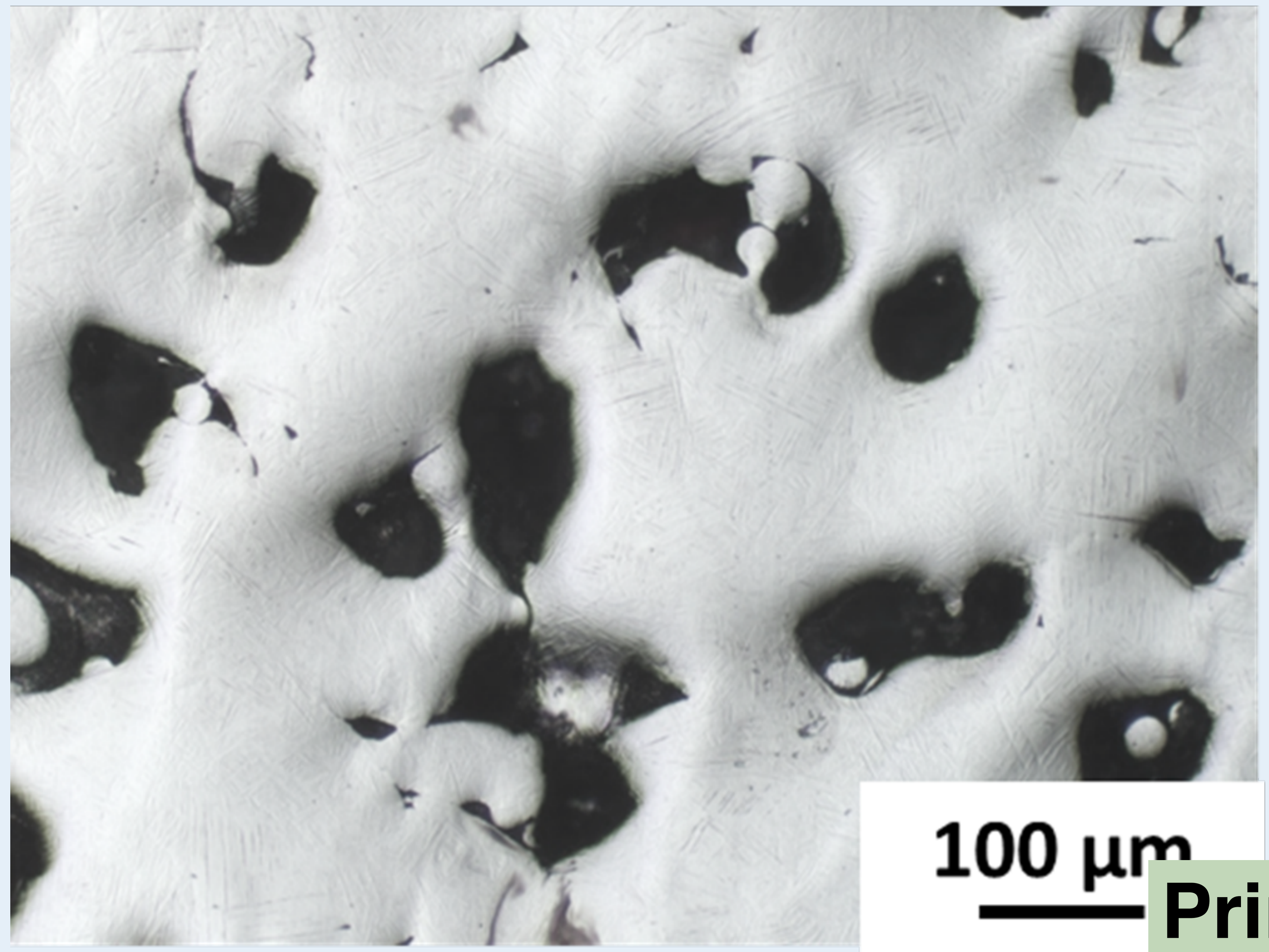
What is holding us back?



Materials & methods



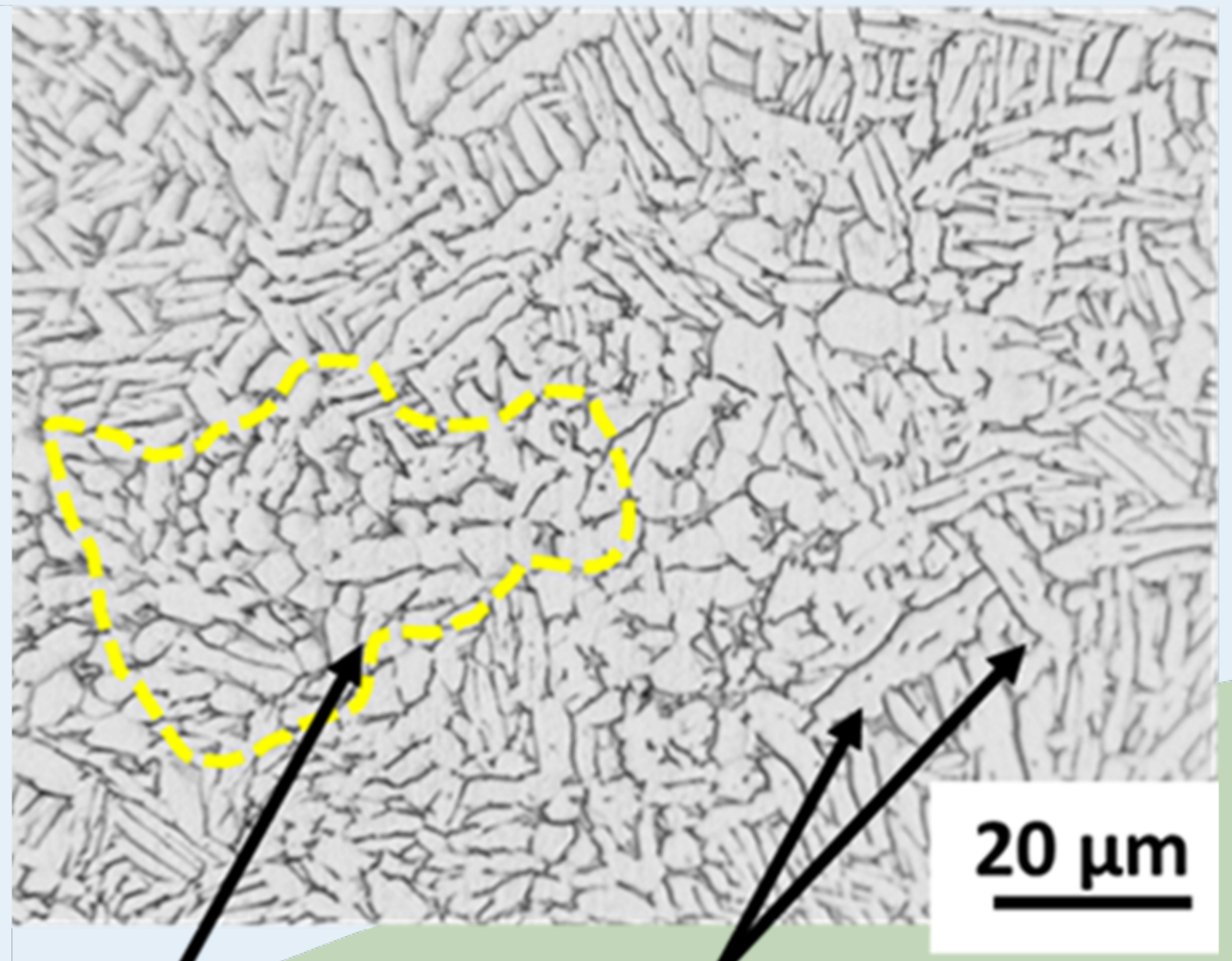
Printing defective parts

Low energy densities

Defects (up to 500 µm)

Post-process via hot isostatic pressing

900°C – 2 h - 100 MPa



Low aspect ratio α-grains

α-laths

Local recrystallization and defect closure

Results & Discussion

Proposed mechanisms for the evolution of duplex microstructures

1. **Recrystallization driven process**
   - ✓Takes advantage of highly dislocated nature of as-printed microstructures
   - ✓Intensification of stress states at defect zones

2. **Reduction of free surface energy**

   Elimination of a fusion defect (free surface) = release of excess free energy (ΔG_d)

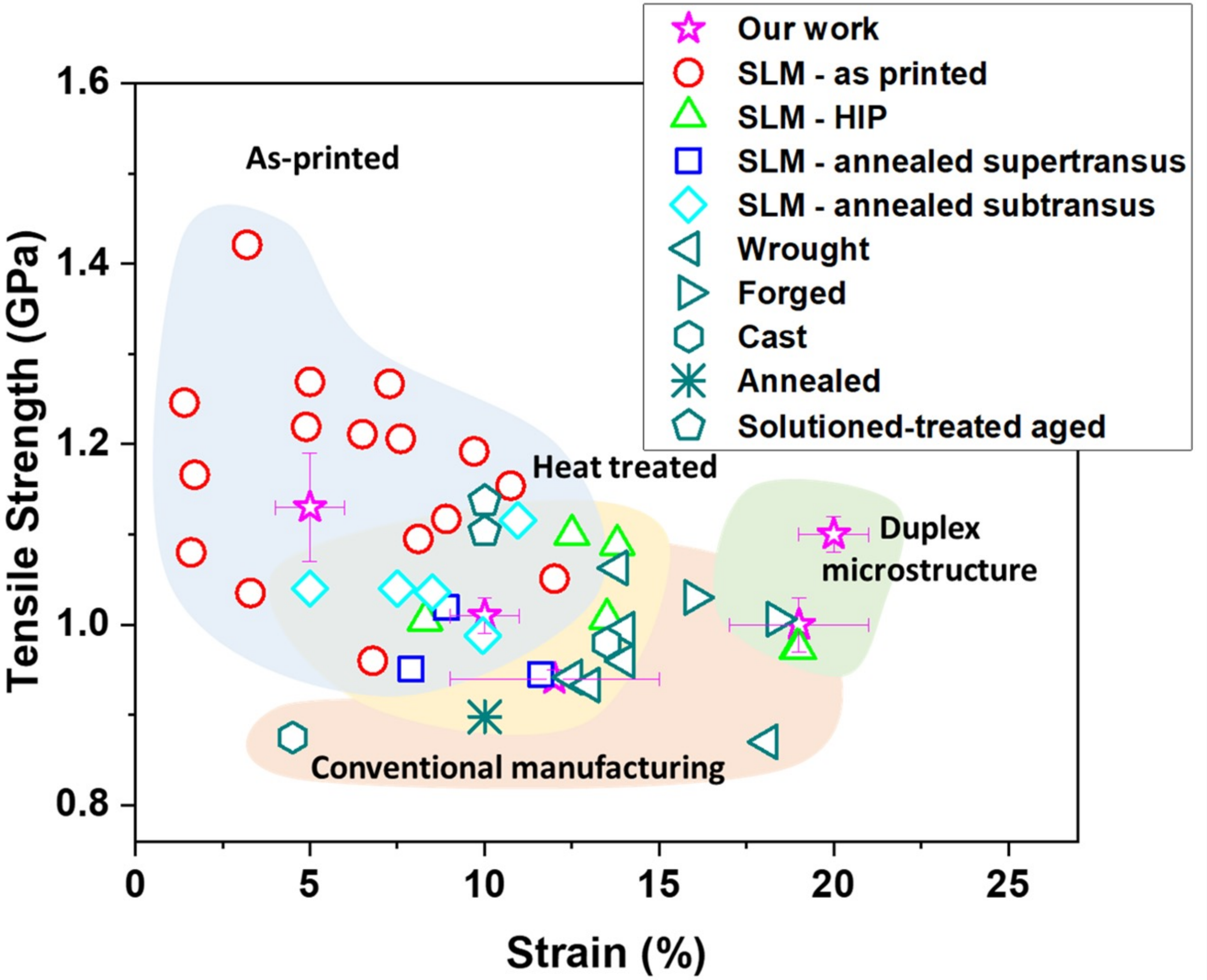
$$\Delta G_{het} = -V(\Delta G_V - \Delta G_s) + A\gamma - \Delta G_d$$

Results & Discussion

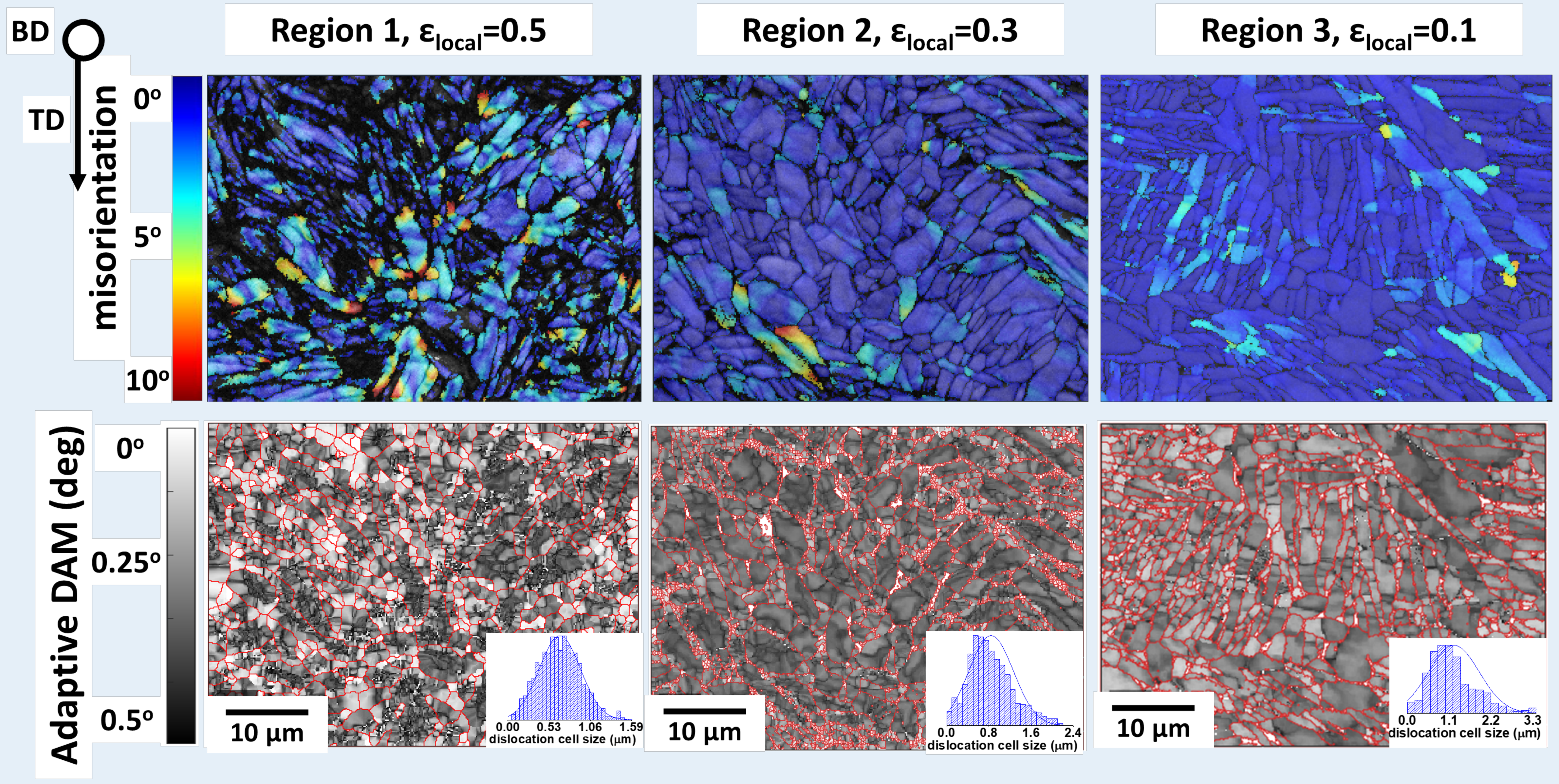
<u>Mechanically robust and ductile microstructures</u>

- ✓**Universal approach** for engineering microstructures during AM
- ✓**Not limited** to material system
- ✓**Ductility and strength** of the designed duplex microstructure surpassed that of the wrought and cast, forged, ST&A alloy

<u>Mechanically superior to conventional manufacturing routes</u>



Results & Discussion



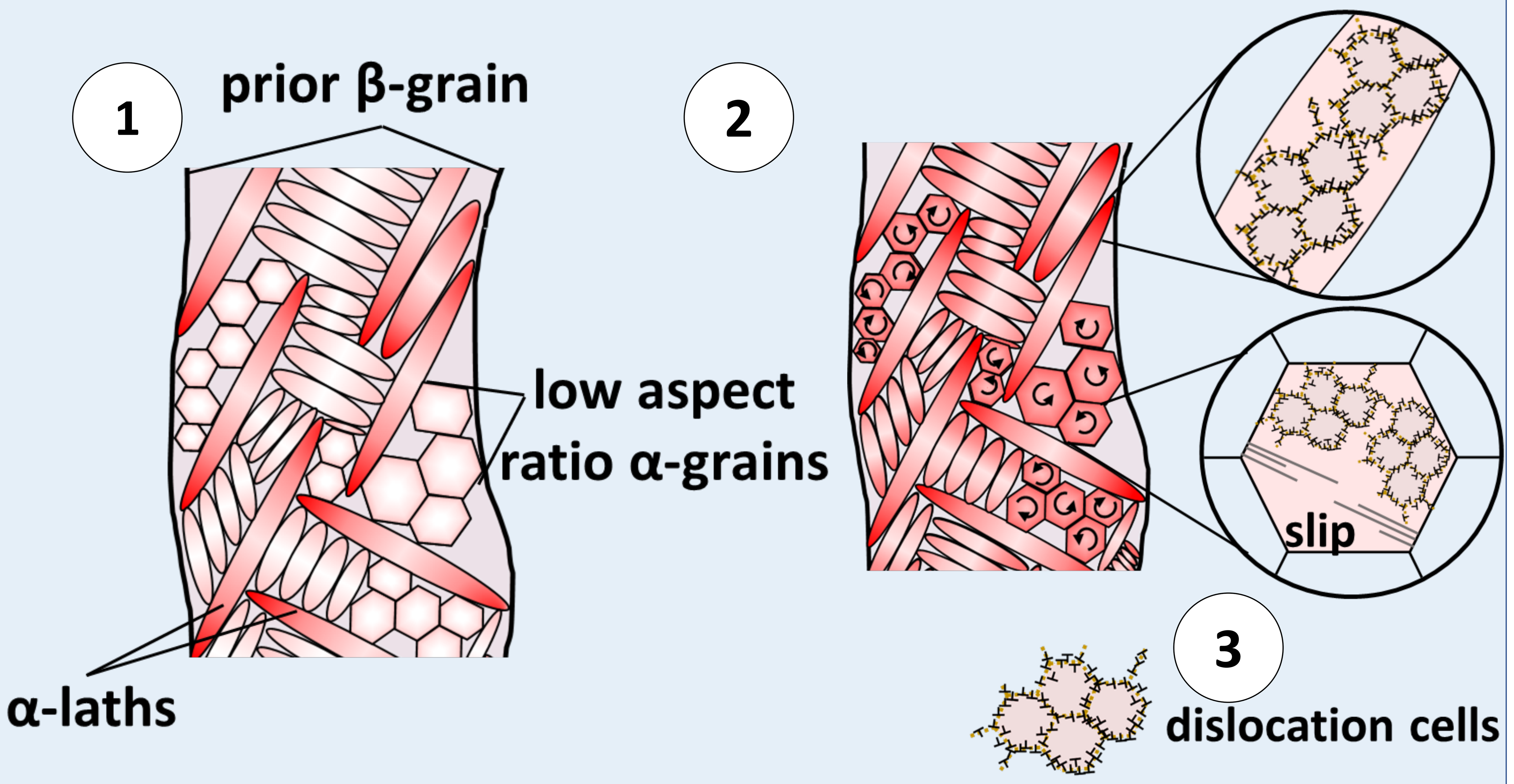
✓ ***Deformation via lattice rotation*** **(intragranular misorientation gradients)**

✓ **Adaptive domain misorientations (DAM) show high density of dislocations in the form of substructures *(cell walls to reduce strain energy)***

✓ ***LoF-HIP has an average cell size of 0.67 ± 0.3 μm as compared to FD-HIP with 1.25 ± 0.5 μm.***

Deformation pathways

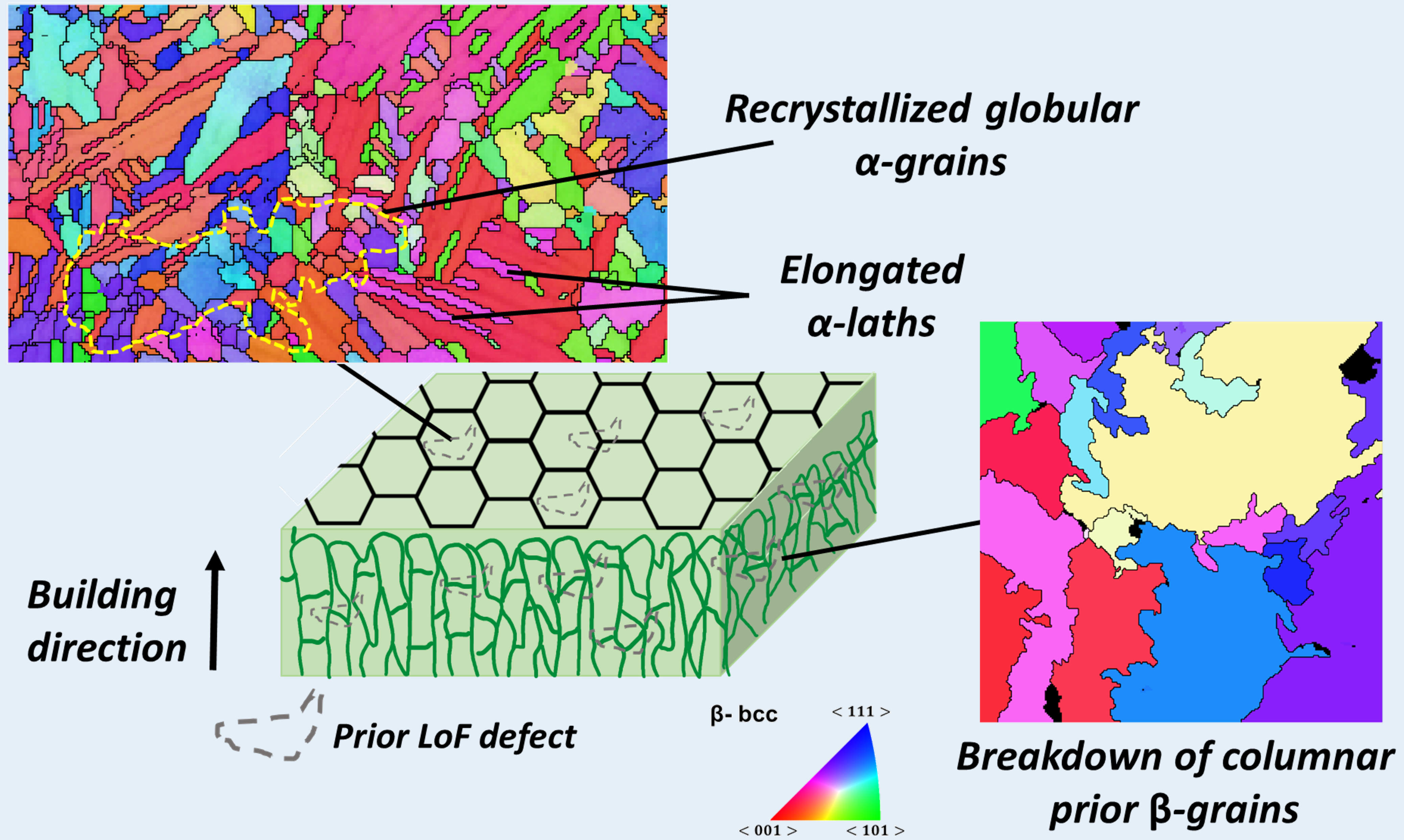
1. **Selective deformation of primary α-laths with soft configurations**
2. **Dislocation cell formation: reduction of the dislocation mean free path.**
3. **Low aspect ratio grains: experience rotation towards soft crystallographic orientations for easy slip due dislocation-free nature**

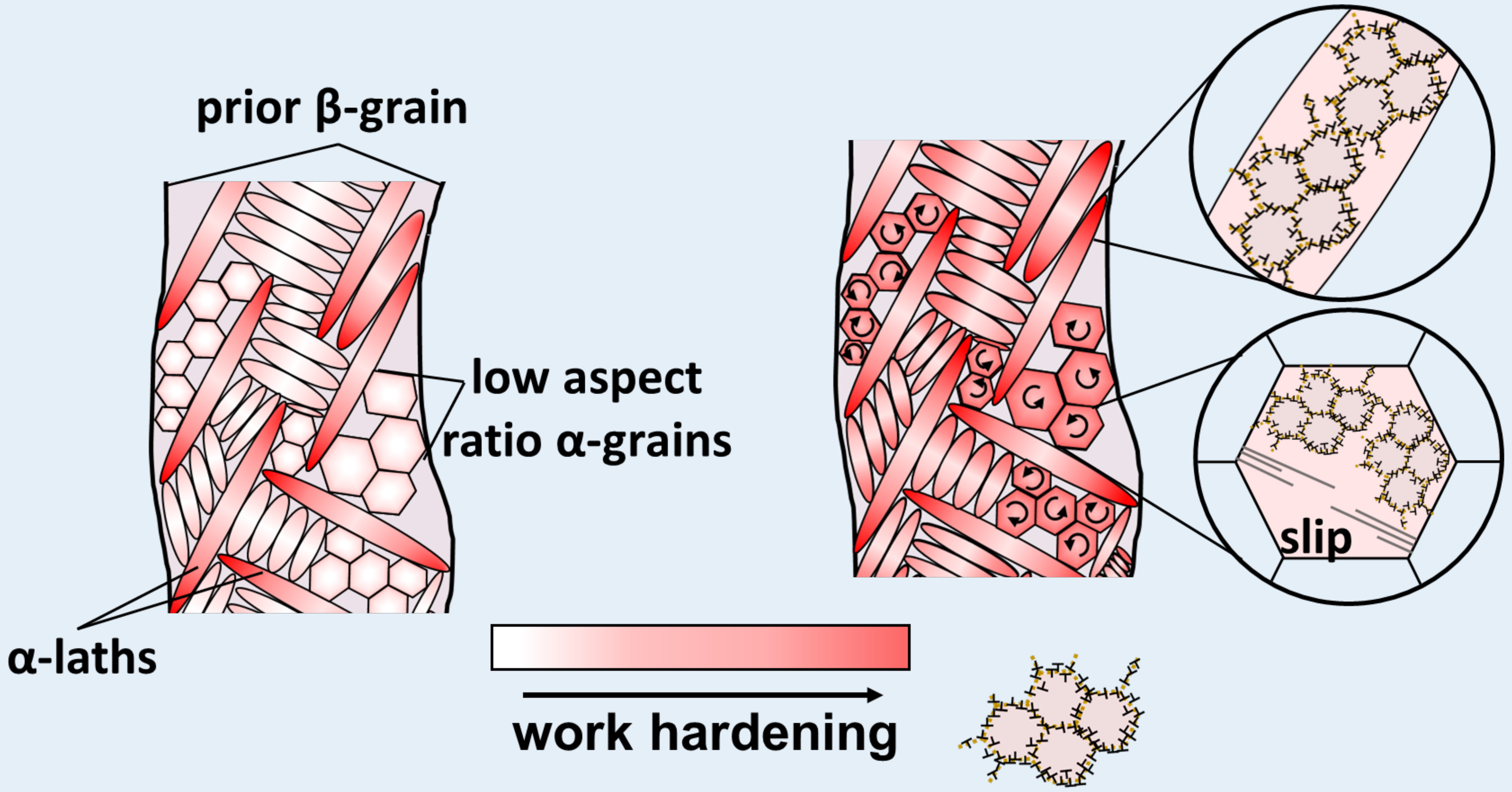


In FD-HIP, the energy required for dislocation climb/glide is too high leading to fracture

Conclusions

- Universal method for the engineering of AM microstructures via lack of fusion introduction and subsequent closure
- Duplex microstructure results from dislocation-induced recrystallization and reduction of surface energy
- Engineered microstructure shows unprecedented plasticity as compared to as-printed, HIP-ed, forged, annealed and STA alloys
- Recrystallized α-grains experience lattice rotations to preferential slip orientations with excellent work hardenability via dislocation substructures.





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