SAND2019-6178C

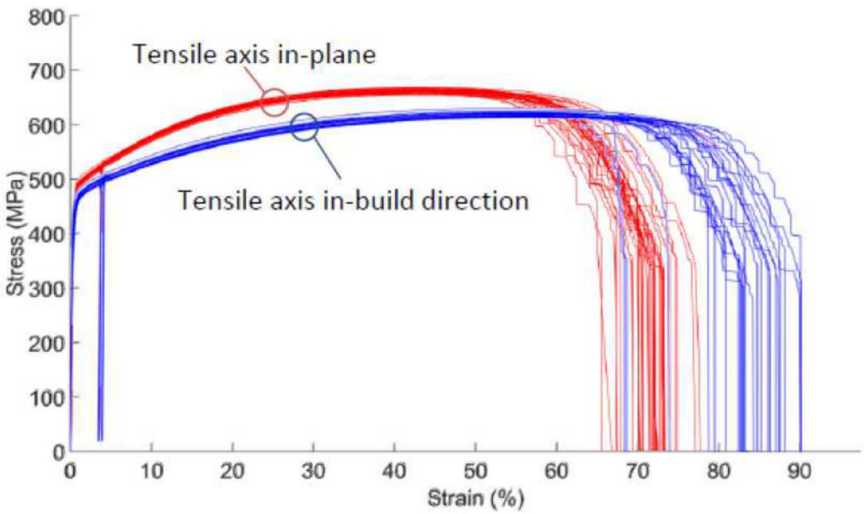
Twinning and Mechanical Anisotropy in Additively Manufactured 304L Stainless Steel

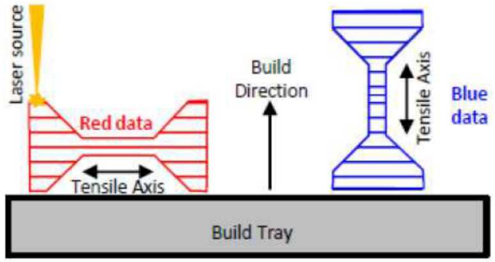
Philip Noell, Davis Wilson, Jeff Rodelas, Bradley Jared

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

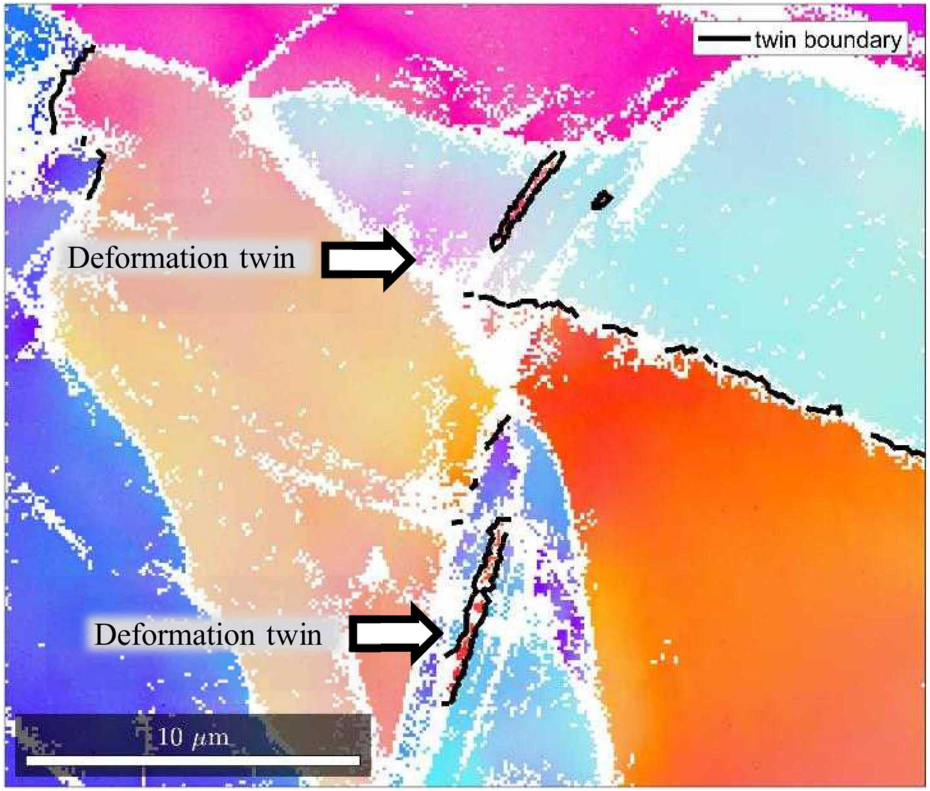
Compared to wrought 304L SS, AM 304L SS has two distinct characteristics:

1: Mechanical Property Anisotropy





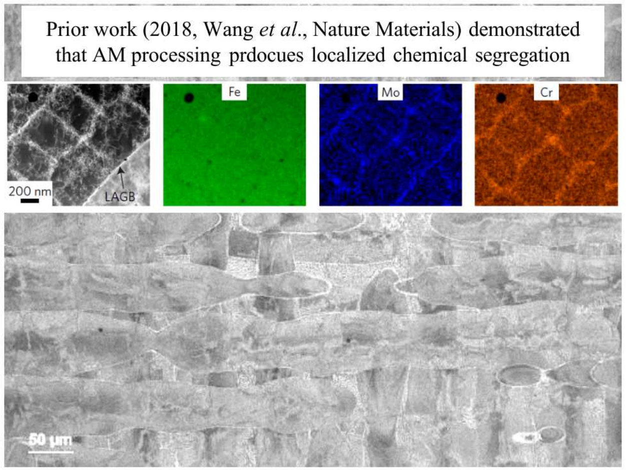
2: Deformation Twinning



- **Are these two related?**
- **When during deformation does twinning begin?**
- **What determines if twinning occurs in this material?**

Hypothesis: both anisotropy and twinning are controlled by the solidification substructure

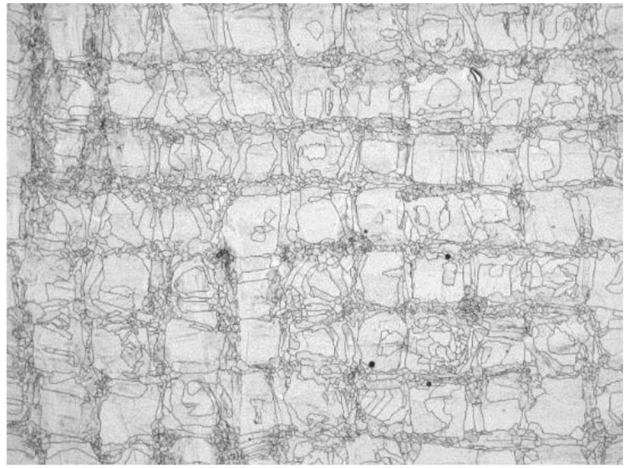
As printed



Key Features:

- Solidification substructure
  - Chemical microsegregation
  - Dislocation networks
  - Solidification grains

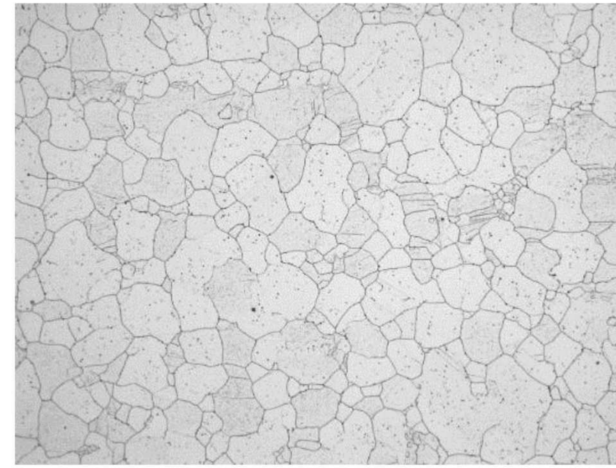
Low temperature anneal (900°C)



Key Features:

- Homogenization of most chemical microsegregation
- Maintains high angle solidification grain structure

High temperature anneal (1200°C)



Key Features:

- Elimination of dislocation networks
- High angle grain mobility (recrystallization)

By examining specimens from these three conditions, the effects of both chemical segregation and dislocation networks created by solidification can be assessed.

AM 316L annealing study (Susan *et al.*, 2018) – Microstructures shown as example

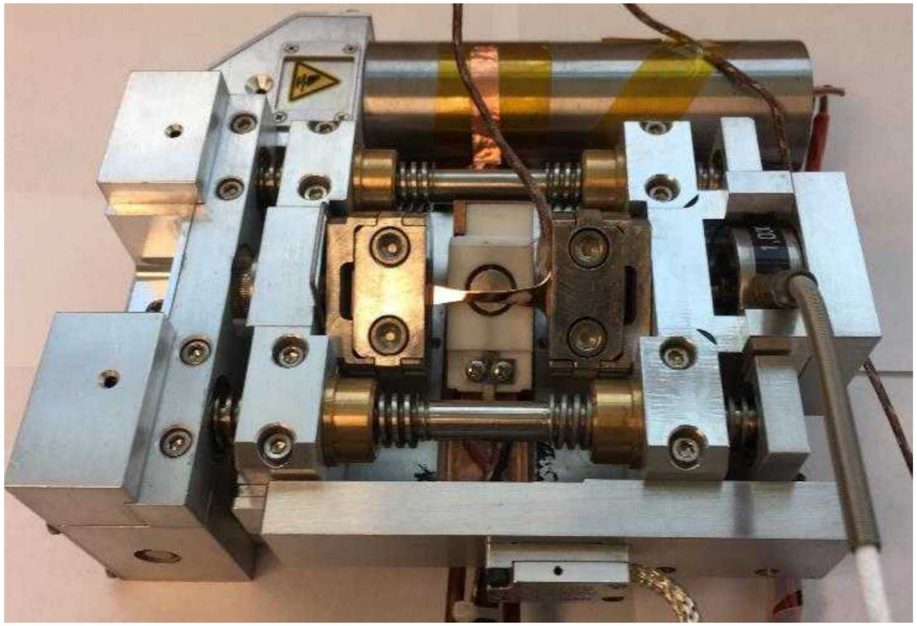
Project goal and experimental approach

The goal of this project is to investigate these behaviors by:

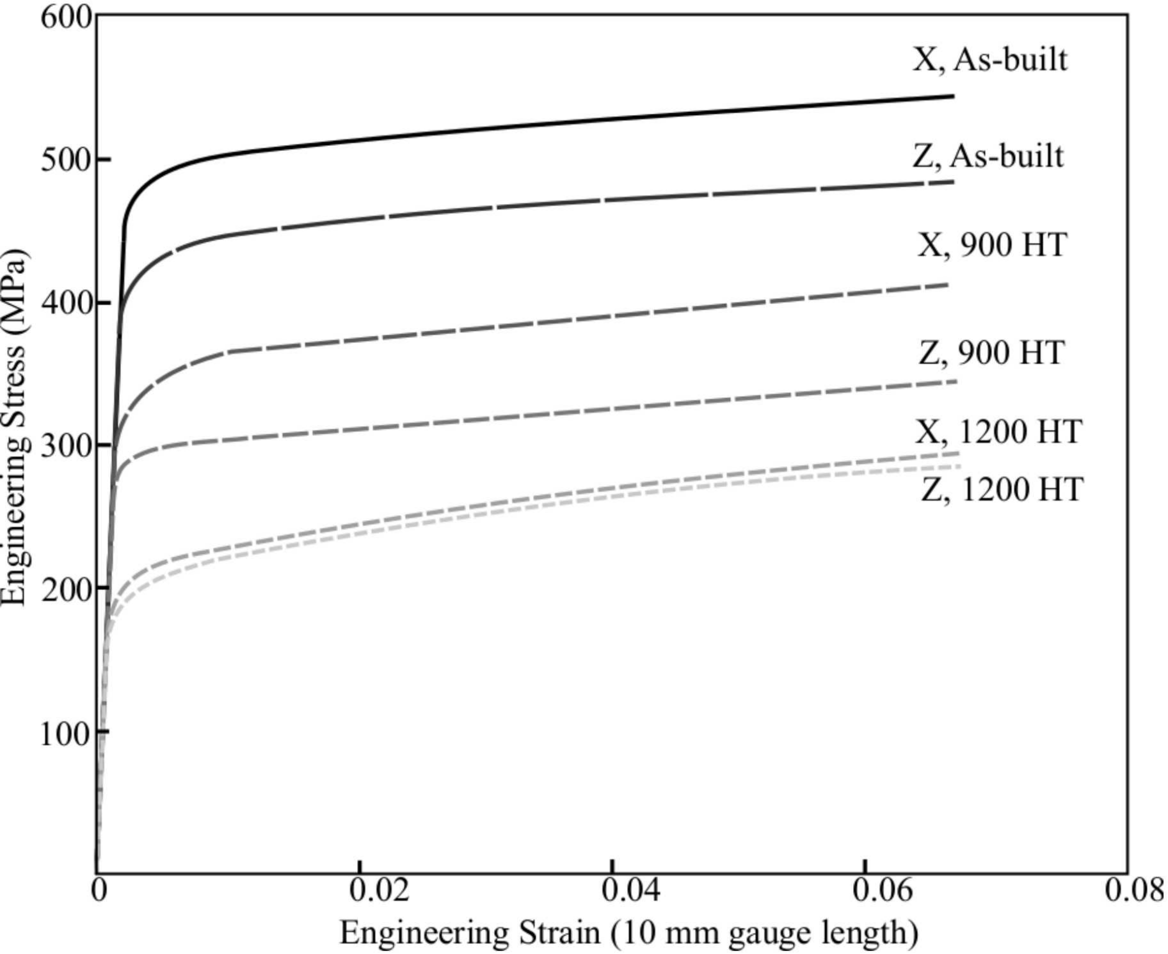
- Systematically varying AM microstructure *via* heat treatment, and
- Directly observing material deformation mechanisms via in-situ tensile testing

Experimental Approach:

- Micro-tensile specimens extracted in the as-built condition
  - Z-specimens: tensile axis parallel to the build direction.
  - X-specimens: tensile axis perpendicular to the build direction.
- As-built X and Z annealed at 900° C and 1200°C in argon for 120 minutes (900 HT and 1200 HT specimens).
- *In-situ* tensile tests performed in a SEM and interrupted for characterization using high-rate EBSD



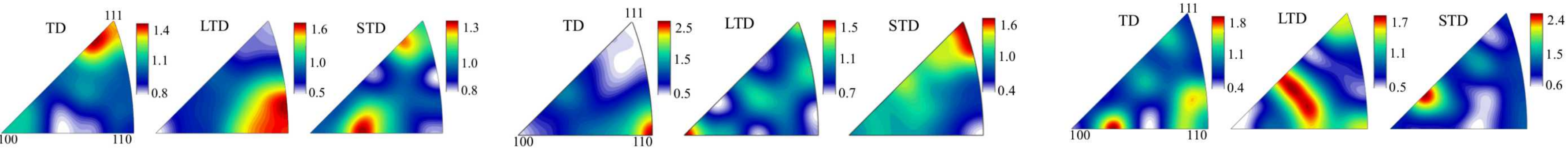
Mechanical testing data

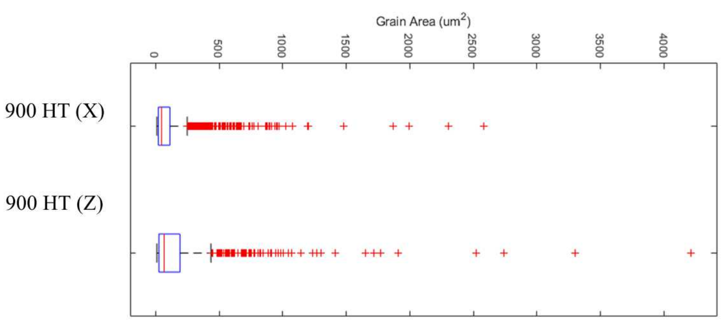


- Anisotropy observed between X and Z specimens in both As-built and 900 HT conditions
- Ratio of yield stresses, $\frac{\sigma_z}{\sigma_x}$, ≈ 0.85 for both conditions
- The mechanical properties of specimens annealed at 1200 C (fully recrystallized) are similar

Microstructures: grain size and texture

Inverse pole figure (IPF) Maps colored with respect to the TD



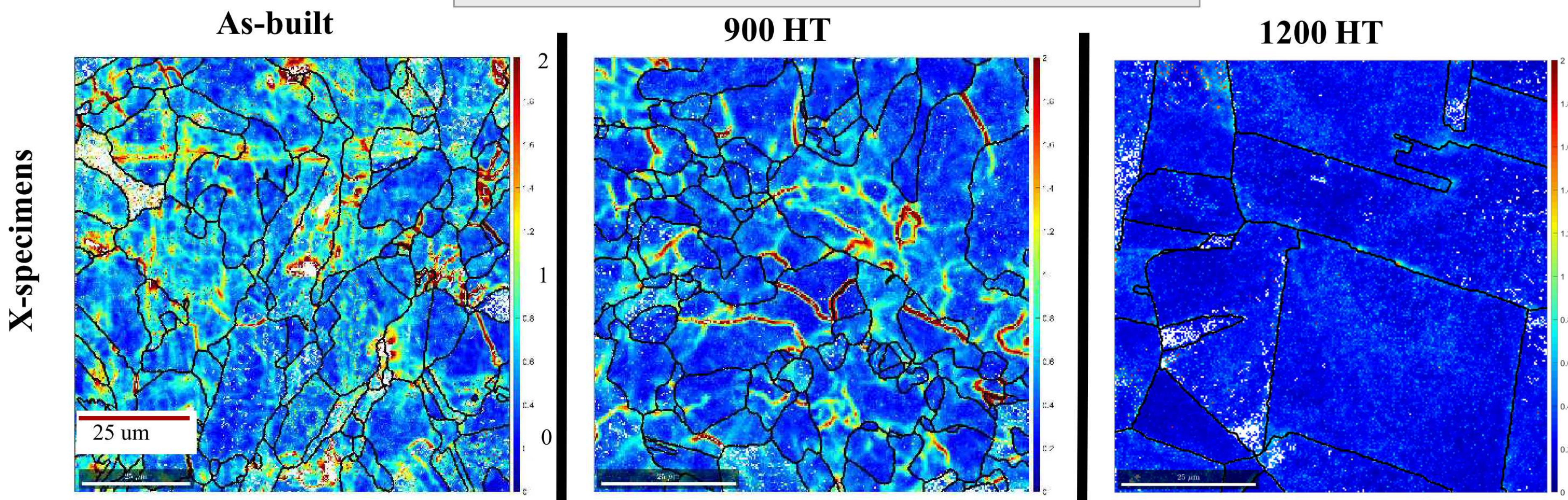


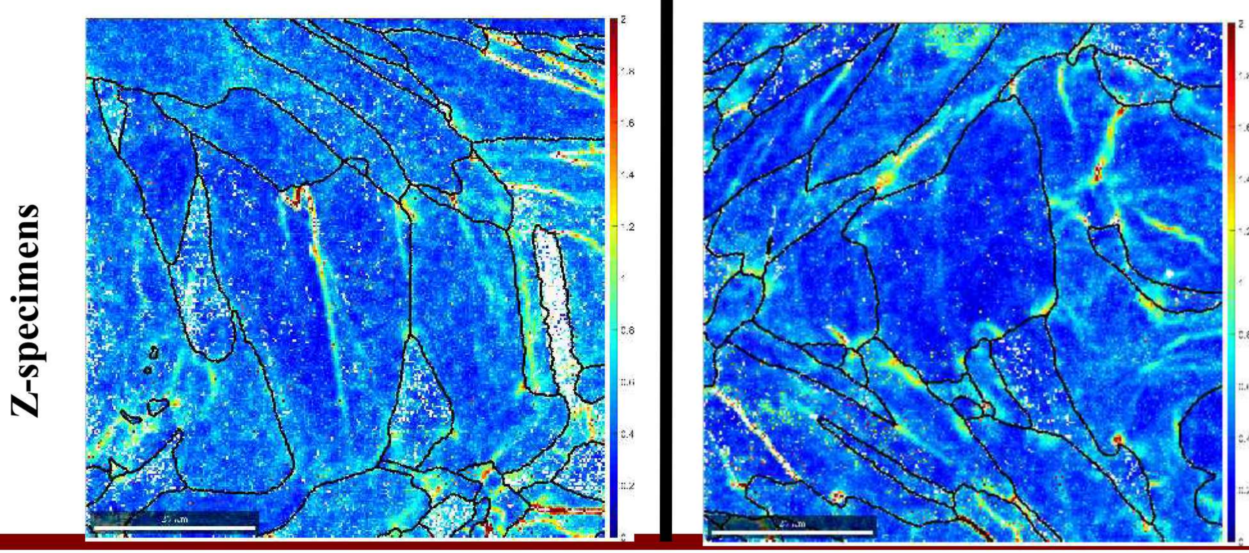
- Texture, grain size, and morphology were unaffected by 900 HT
- Differences in grain size and texture observed between X and Z specimens
- 1200 HT significantly changed texture, grain size, and morphology

Microstructures: dislocation substructures

Sandia National Laboratories

KAM maps of unstrained specimens

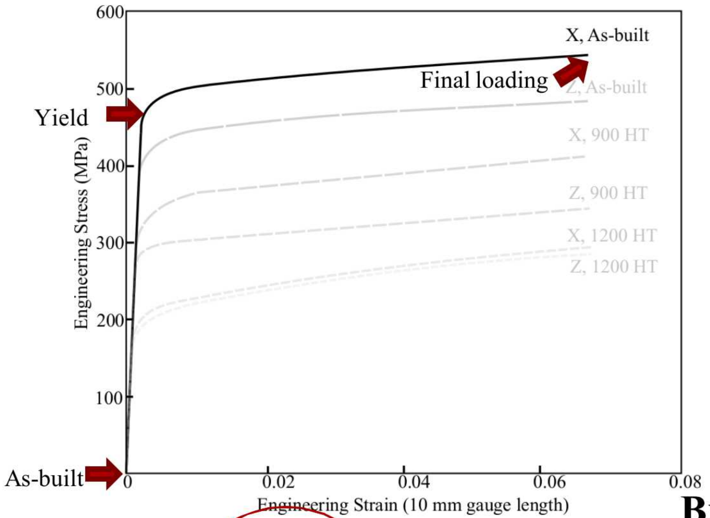


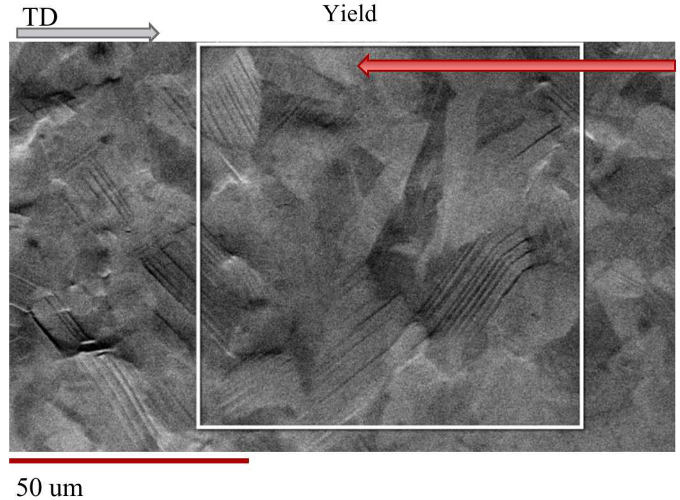


- No significant difference in dislocation substructure created by solidification observed in as-built specimens

- This substructure was *not* eliminated by the 900 C heat treatment but was eliminated by the 1200 C heat treatment

Differentiating slip and deformation twinning





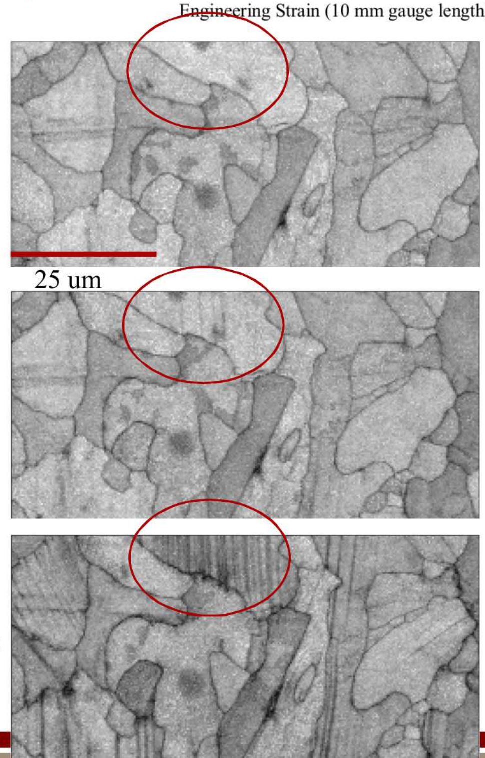
Are these lines slip traces or twins?
<u>We can't tell from crystallographic orientation data, even at 50 nm stepsize!</u>

<u>But we can differentiate between twins and slip lines from image quality maps!</u>

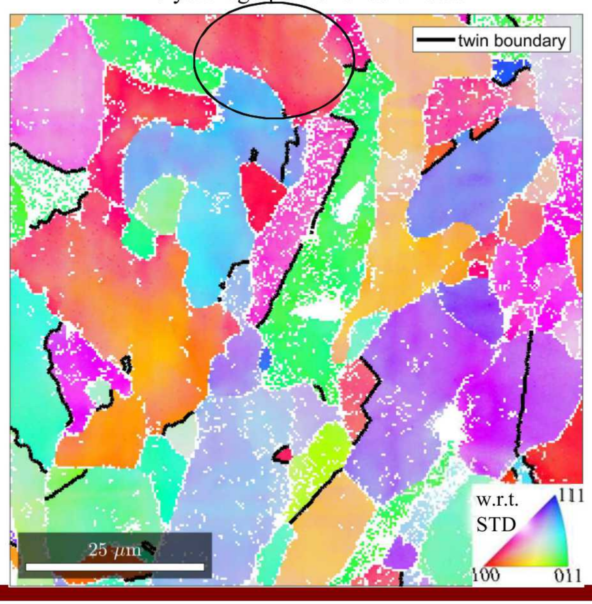
As-built

Yield

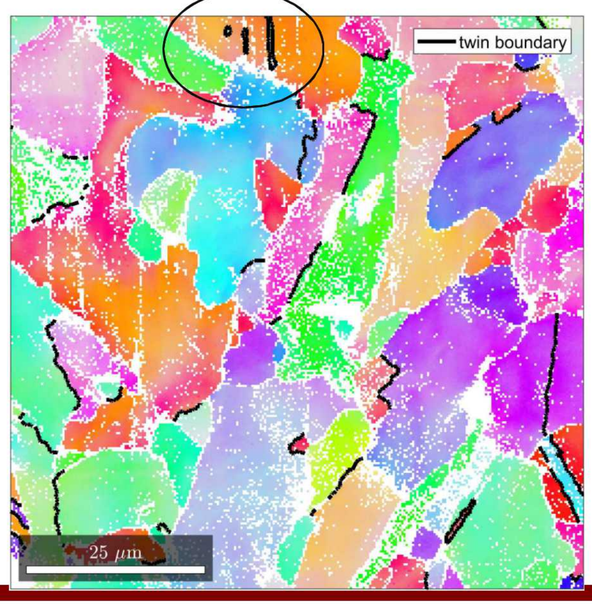
Final loading



Yield – twins do not appear in crystallographic orientation data

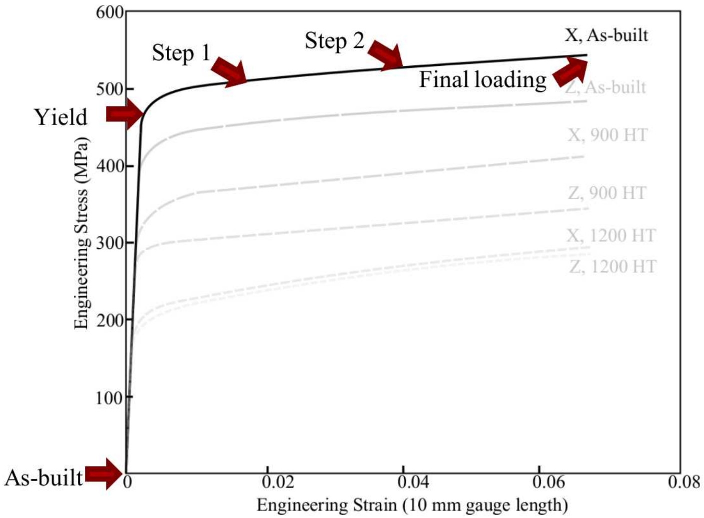


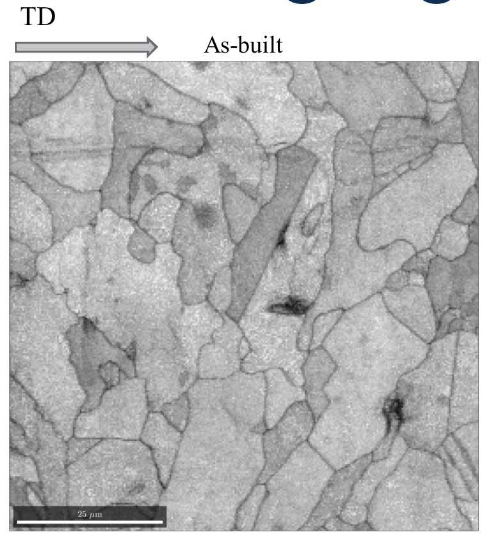
Final loading: largest twins finally appear in orientation data



When did twinning begin?

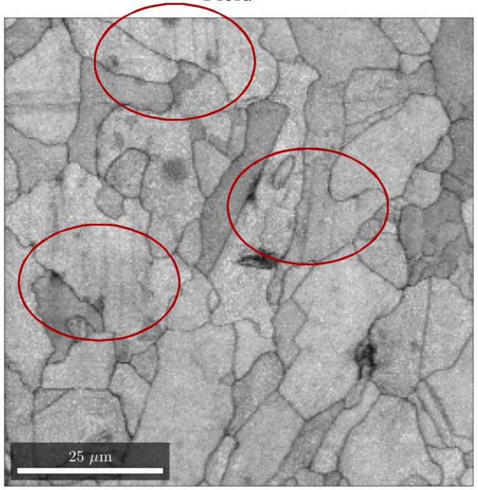
Sandia National Laboratories



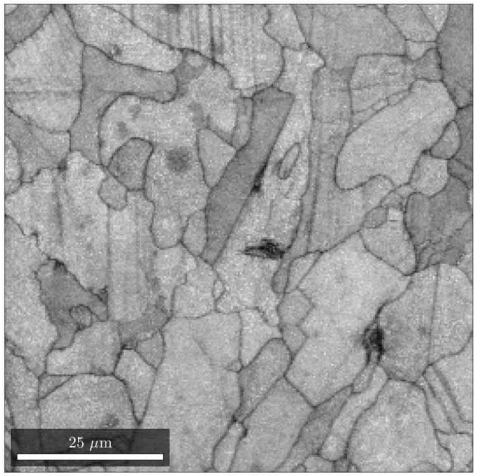


As-built

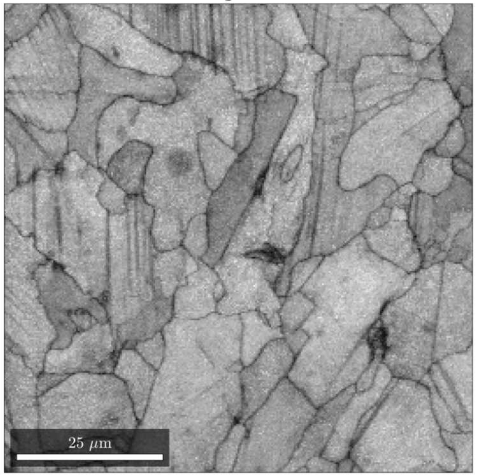
Yield



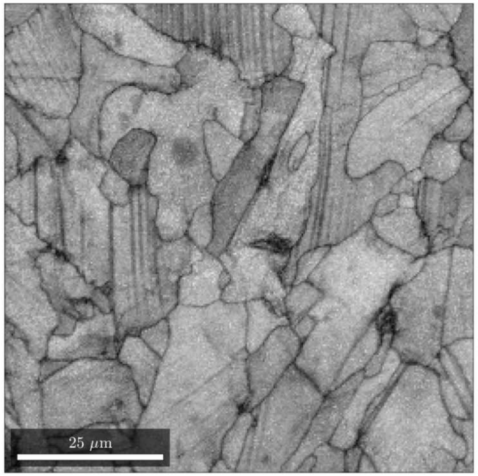
Step 1



Step 2

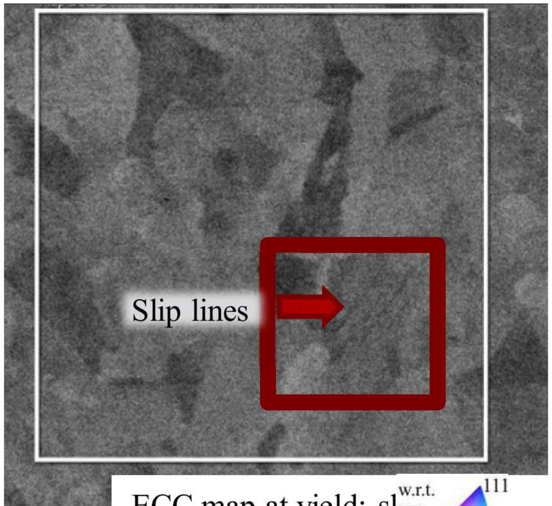


Final loading

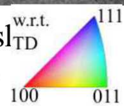


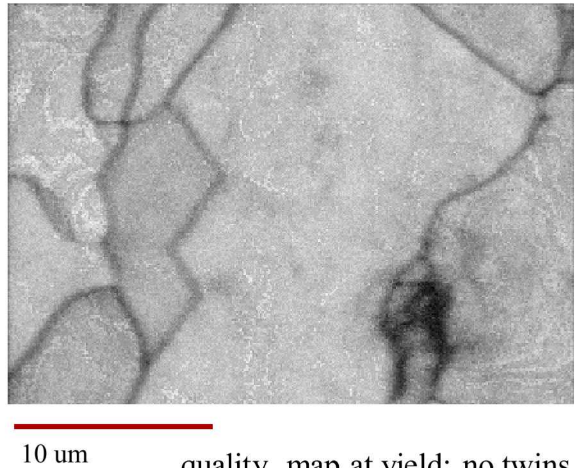
In both as-built conditions (X and Z) twins nucleated at yield in some grains

Competition between slip and twinning



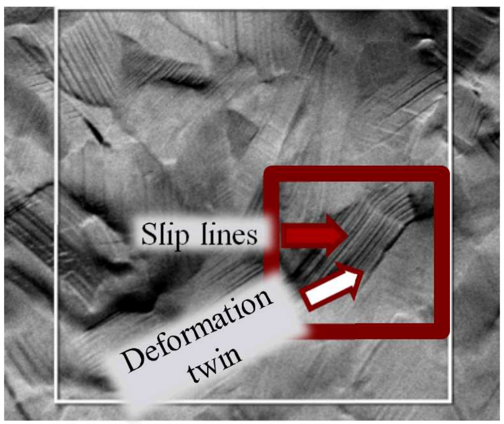
ECC map at yield: sl observed on surface





quality map at yield: no twins identified

- Some grains initially deformed only by slip, while others only deformed by twinning.
- The grain highlighted here initially deformed by slip but, a deformation twin nucleated later in loading.



ECC map at final loading increment after significant plastic strain

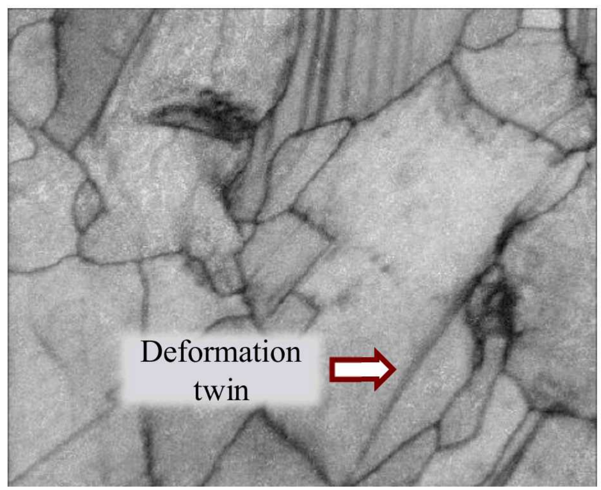
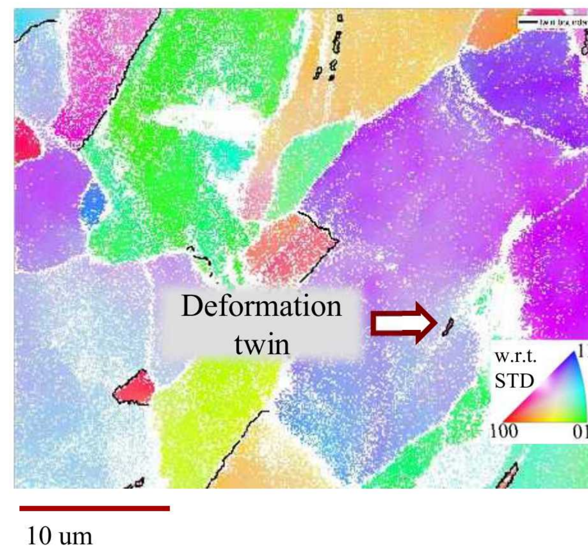
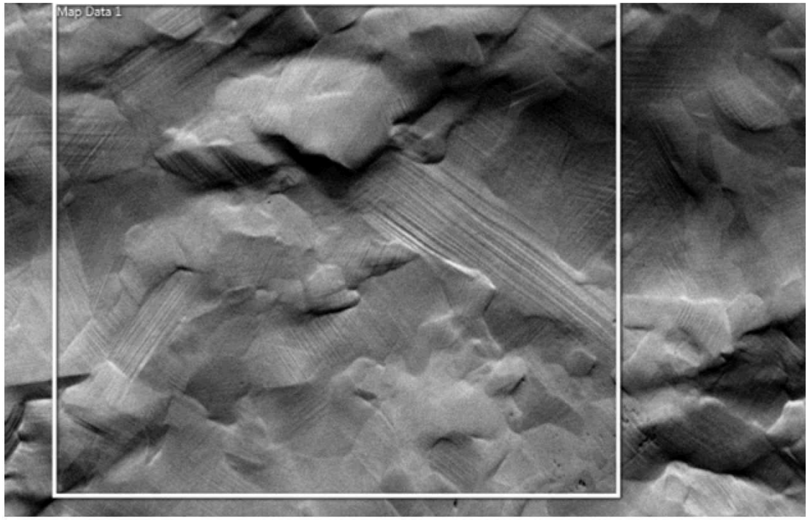


Image quality map at final loading increment



Did twinning occur in the heat-treated samples?

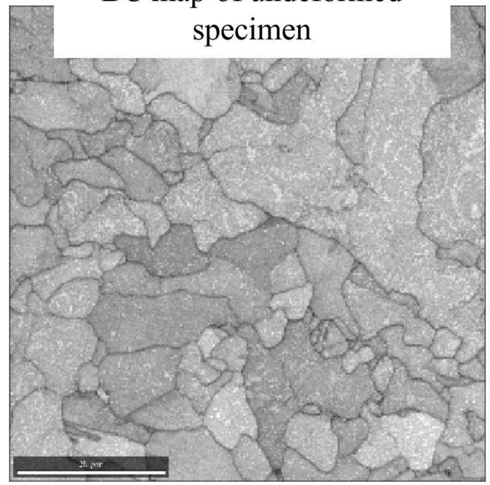


50 um

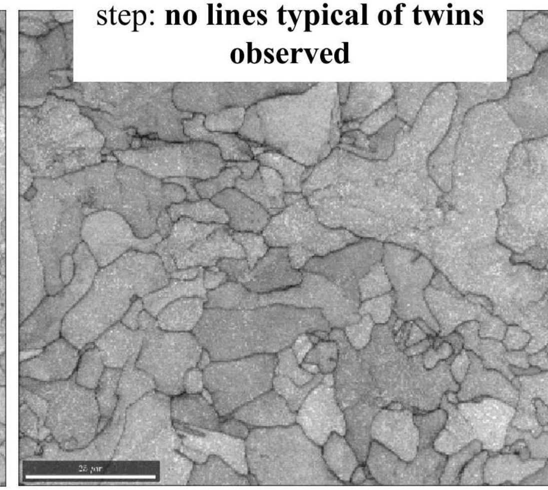
ECC map at final loading increment.

No deformation twinning was observed in either heat-treated condition (900 or 1200 C)

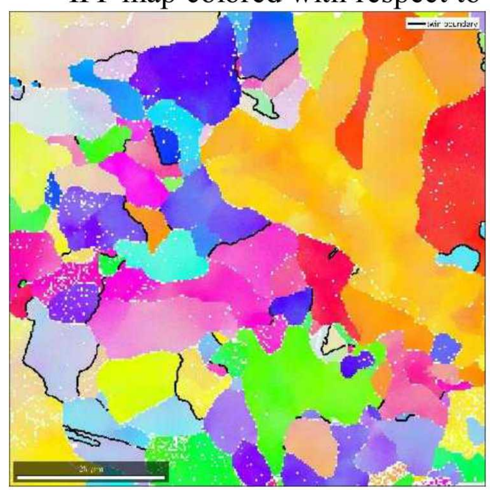
BC map of undeformed specimen

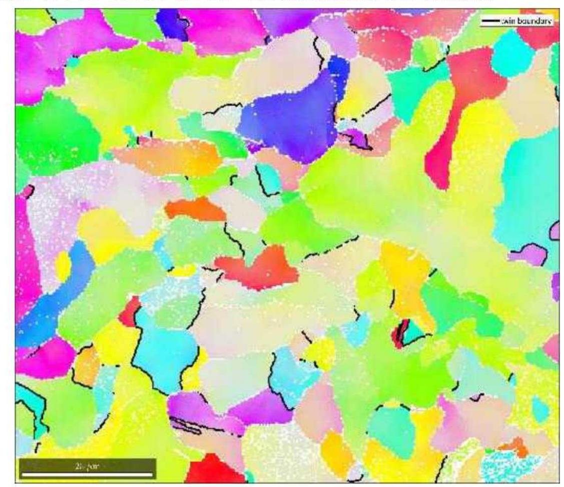


BC map after final loading step: **no lines typical of twins observed**



IPF map colored with respect to the STD with twin boundaries overlaid





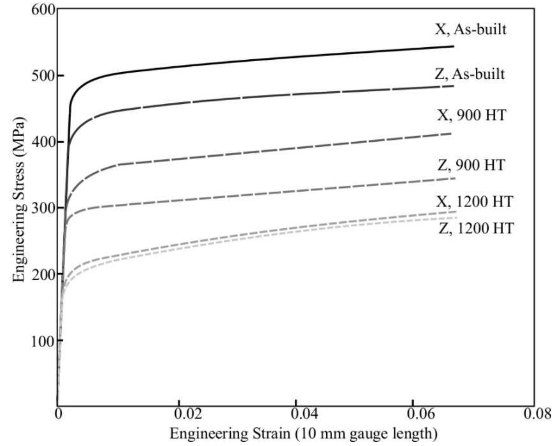
Typical data from 900 HT X specimen is provided.

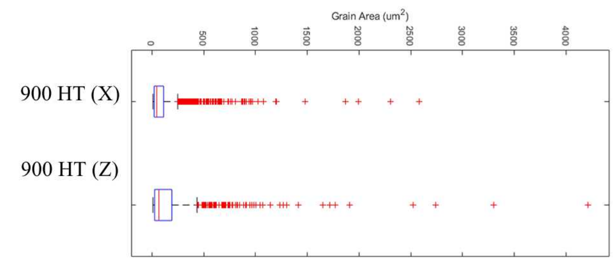
What do these observations tell us?

- Deformation twinning is not responsible for anisotropy between X and Z specimens

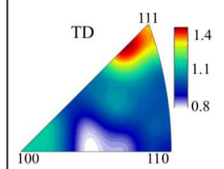
- What leads to twinning:
  - Many factors affect the competition between slip and twinning, including grain size, orientation, temperature, strain rate, dislocation substructure, and stacking fault energy
  - All of these were approximately the same for the as-built and 900 HT specimens except localized chemical segregation
  - ***<u>We propose that, by changing the local SFE, this segregation allows deformation twinning to occur</u>***

- Can we explain mechanical anisotropy from differences in grain size and texture between X and Z specimens?

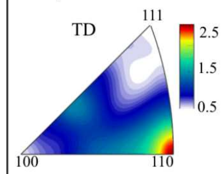


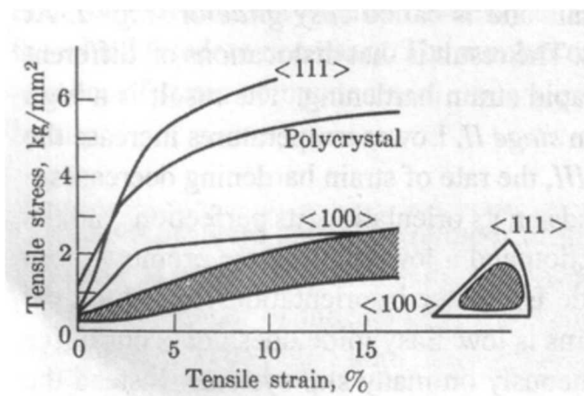


X, 900 HT



Z, 900 HT





Mechanical Behavior of Materials – W.F. Hosford

Question