LA-UR-17-29732
Approved for public release; distribution is unlimited.

Title: Residual Stresses in Multiple Passes of Wire Arc Additively Manufactured Stainless Steel

Author(s): Clausen, Bjorn
Strantza, Maria
Brown, Donald William
Carpenter, John S.
Cooley, Jason Christopher
Losko, Adrian Simon

Intended for: Residual Stress Summit, 2017-10-23/2017-10-26 (Dayton, Ohio, United States)

Issued: 2017-10-24

Residual Stresses in Multiple Passes of Wire Arc Additively Manufactured Stainless Steel

Bjørn Clausen, Maria Strantza, Donald W. Brown,
John S. Carpenter, Jason C. Cooley and Adrian S. Losko

Los Alamos National Laboratory

Residual Stress Summit 2017

University of Dayton Research Institute

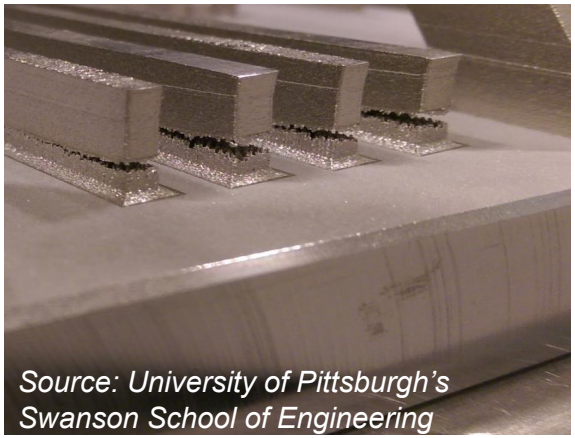
Dayton, OH, USA

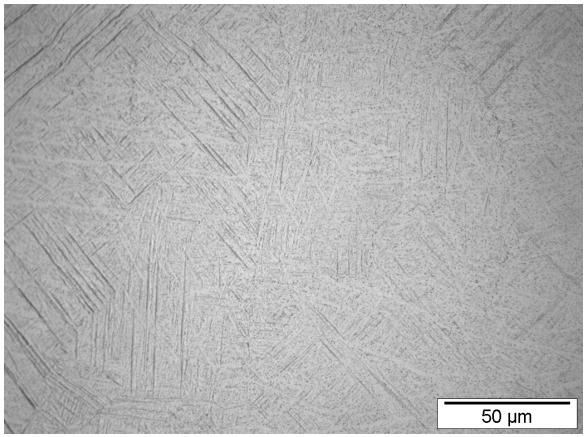
October 23-26, 2017

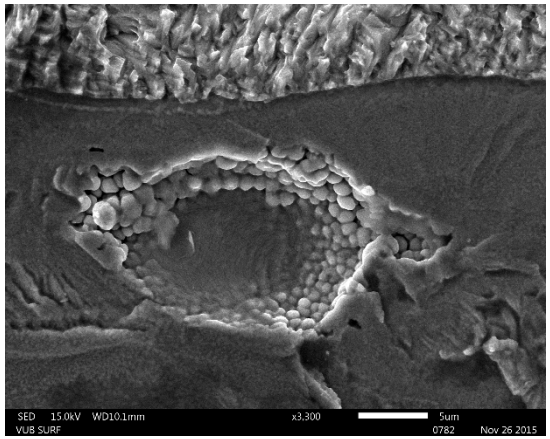
Additive manufacturing brings new possibilities while it poses unique material processing challenges

Challenges of the additive manufacturing process

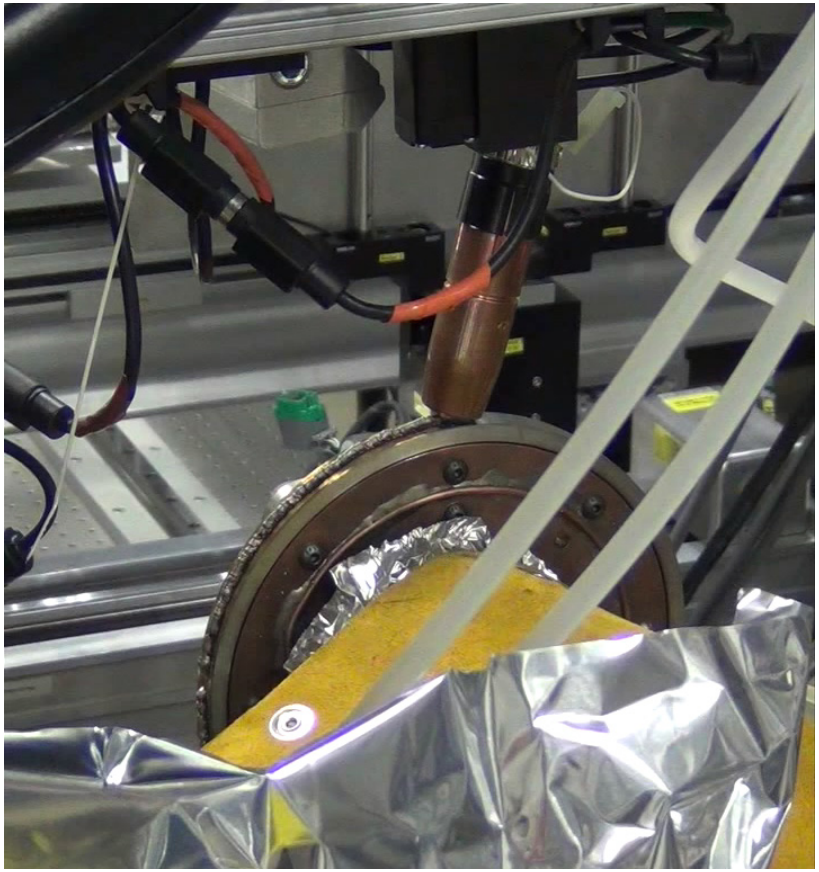
- Residual stresses
- Unique microstructure
- Internal defects







In-situ WAAM: Captured Diffraction and Contrast Imaging



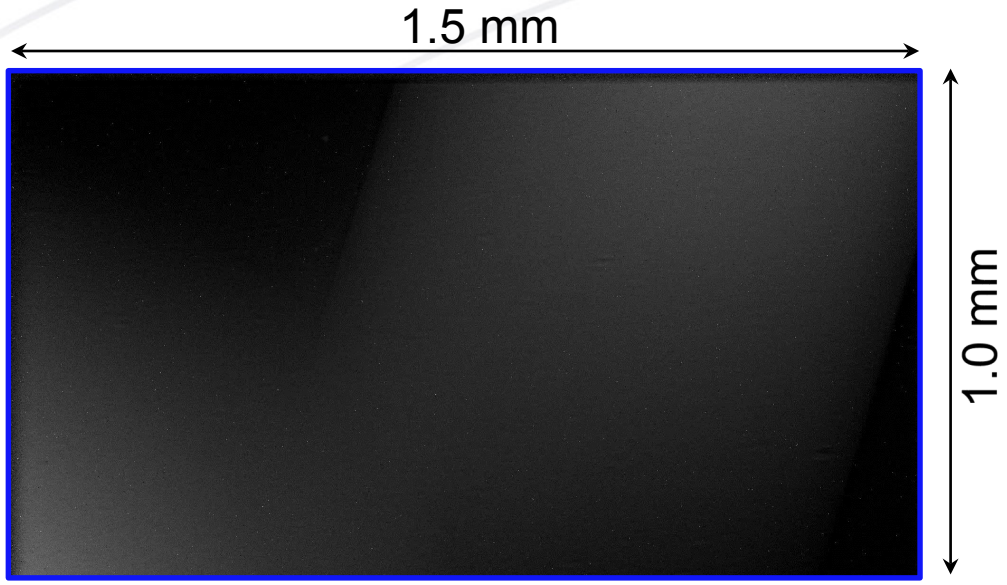
Imaging:

- Able to see weld pool wetting angle against substrate
- Able to see formation of voids during cooling

Diffraction:

- Able to determine temperature, cooling stresses and phase fraction changes during and after welding stopped

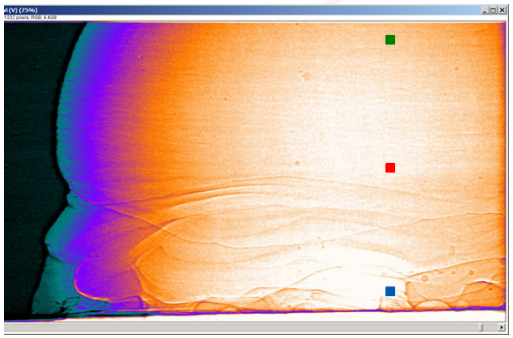
In-situ WAAM: Captured Diffraction and Contrast Imaging

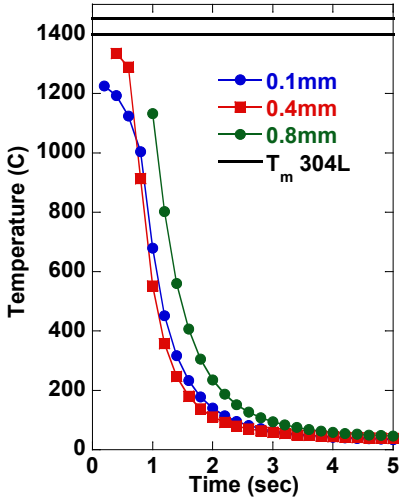


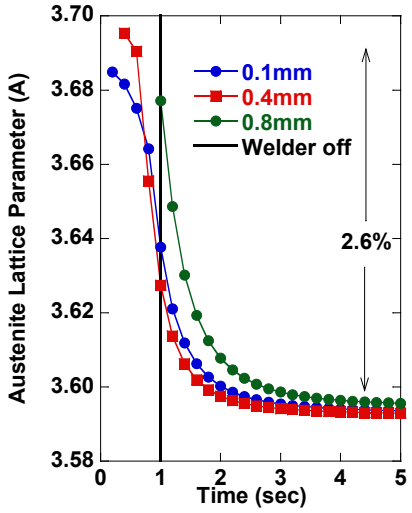
Imaging:

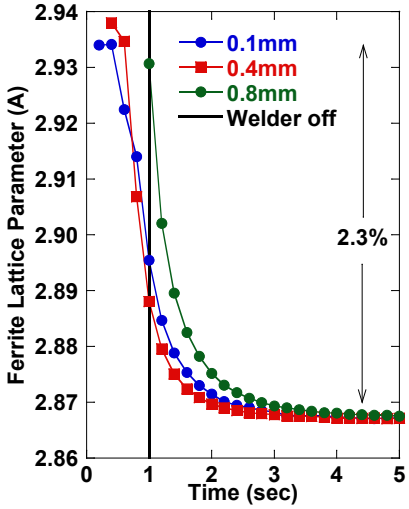
- Able to see weld pool wetting angle against substrate
- Able to see formation of voids during cooling

In-situ WAAM: Captured Diffraction and Contrast Imaging







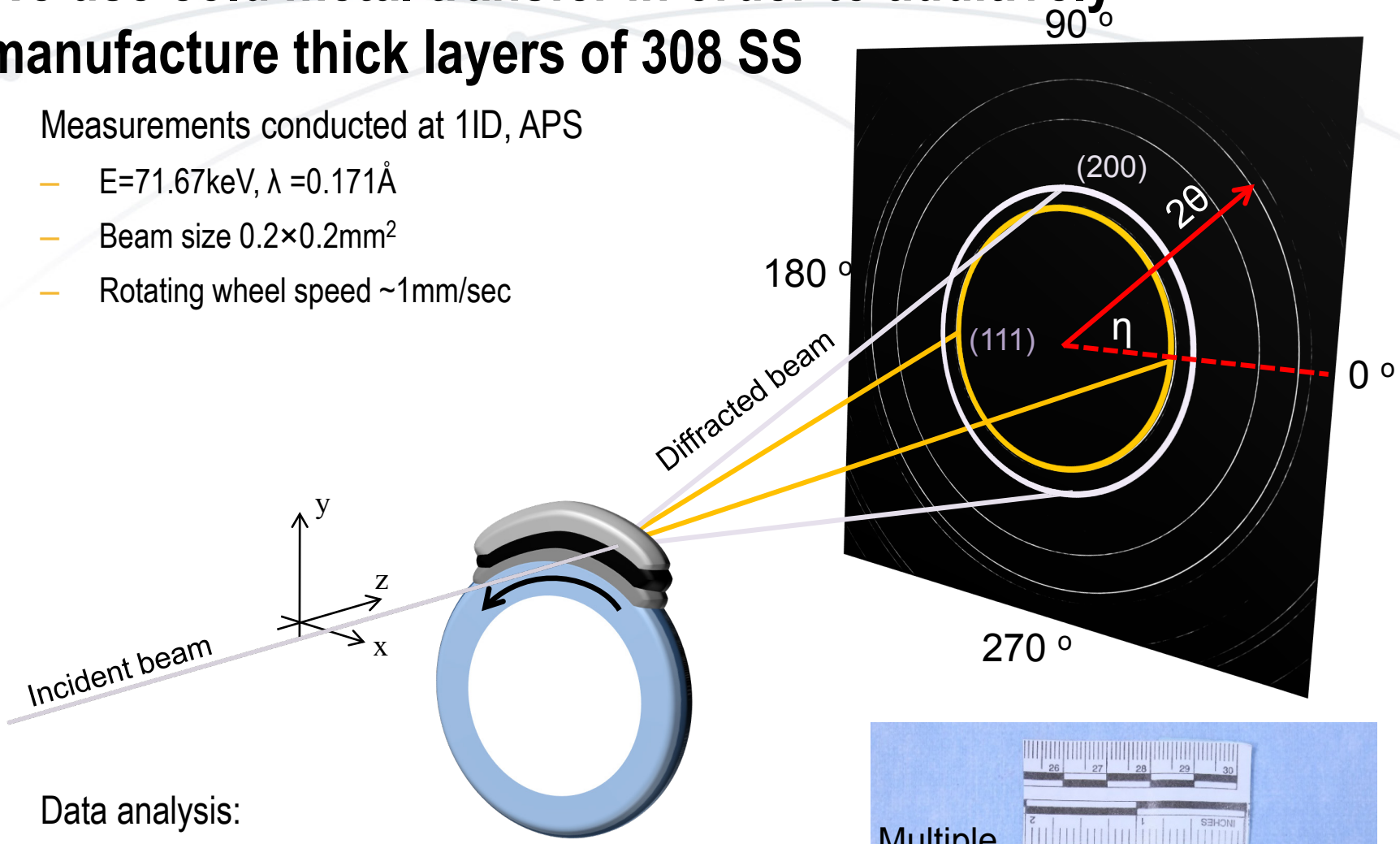


Diffraction:

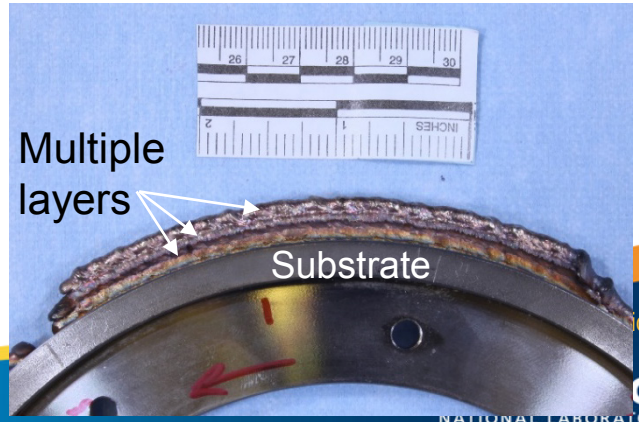
- Able to determine temperature, cooling stresses and phase fraction changes during and after welding stopped

We use cold metal transfer in order to additively manufacture thick layers of 308 SS

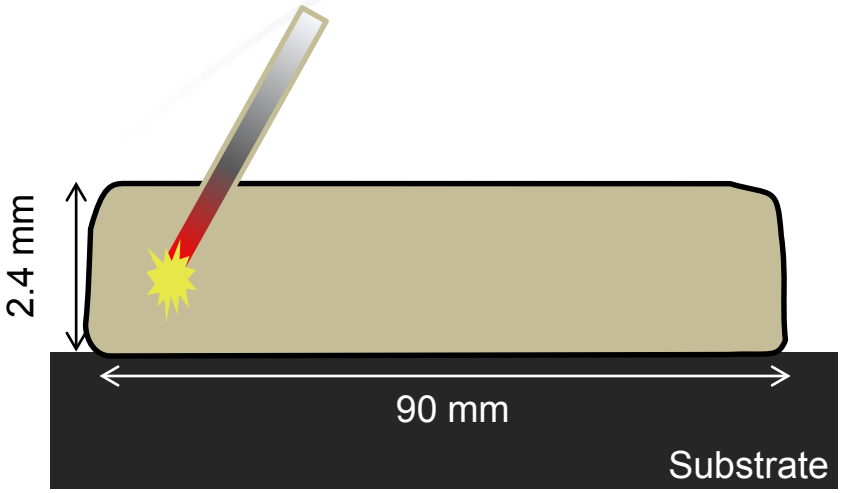
- Measurements conducted at 1ID, APS
  - E=71.67keV, λ =0.171Å
  - Beam size 0.2×0.2mm^2
  - Rotating wheel speed ~1mm/sec

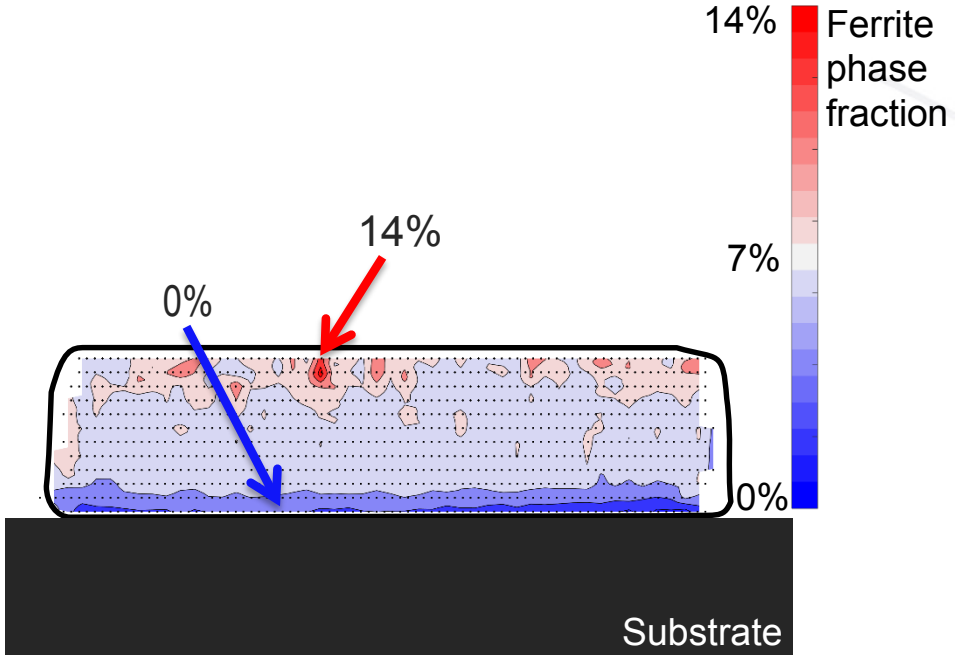


- Data analysis:
  - Data binning with GSAS-II: Cake'ing into 24 intervals (15°)
  - In-plane (x-y) strains were calculated using Rietveld analysis in GSAS and Mohr's circle analysis



Increased ferrite content at the top of the layer

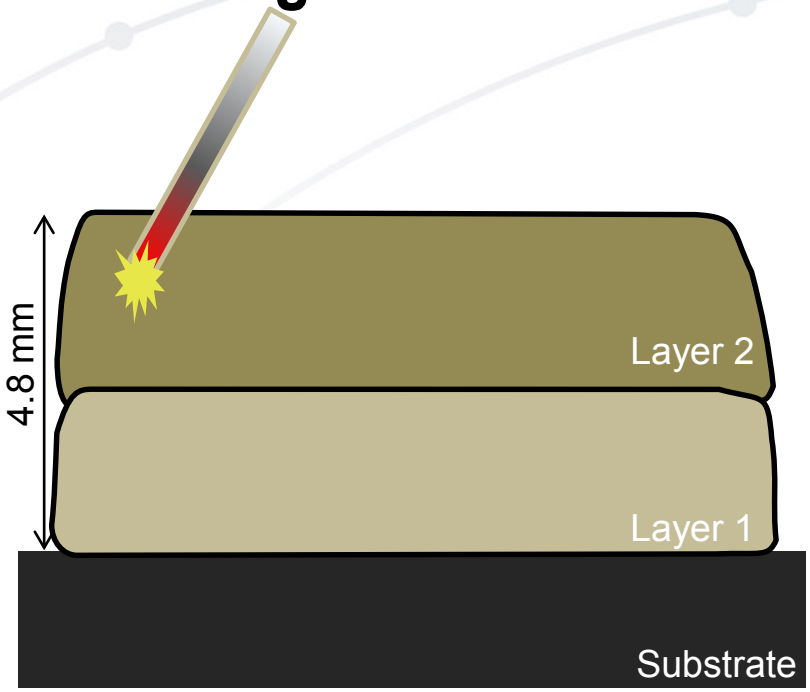


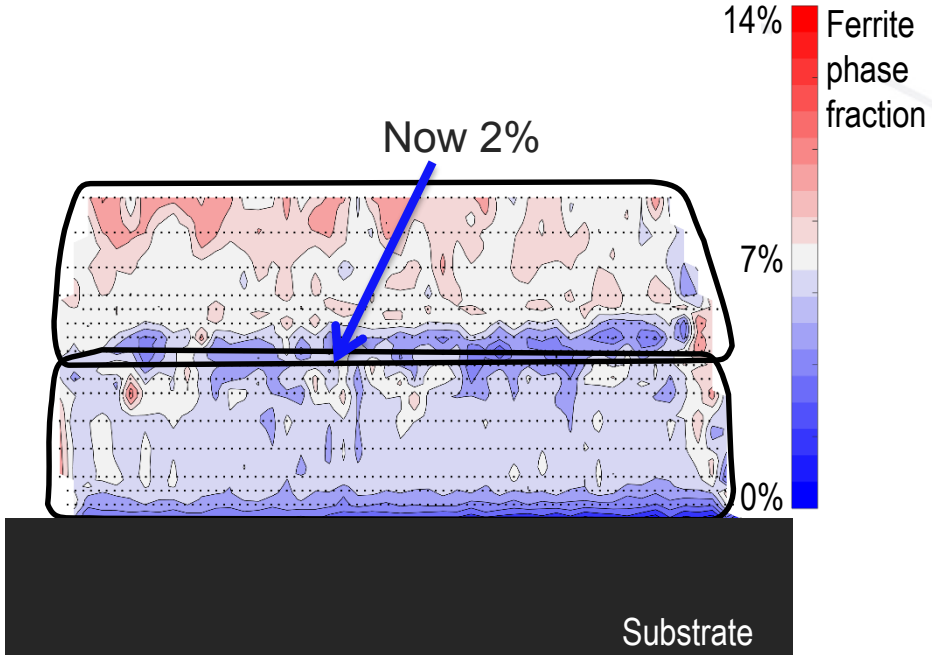


The ferrite content is minimum or zero close to the substrate

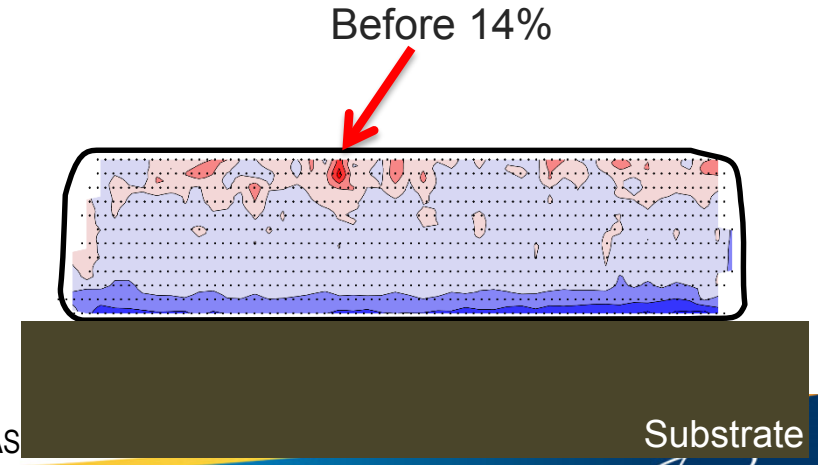
Ferrite is the minor phase in this stainless steel and can affect the mechanical properties

Cooling rates control the ferrite phase in stainless steel

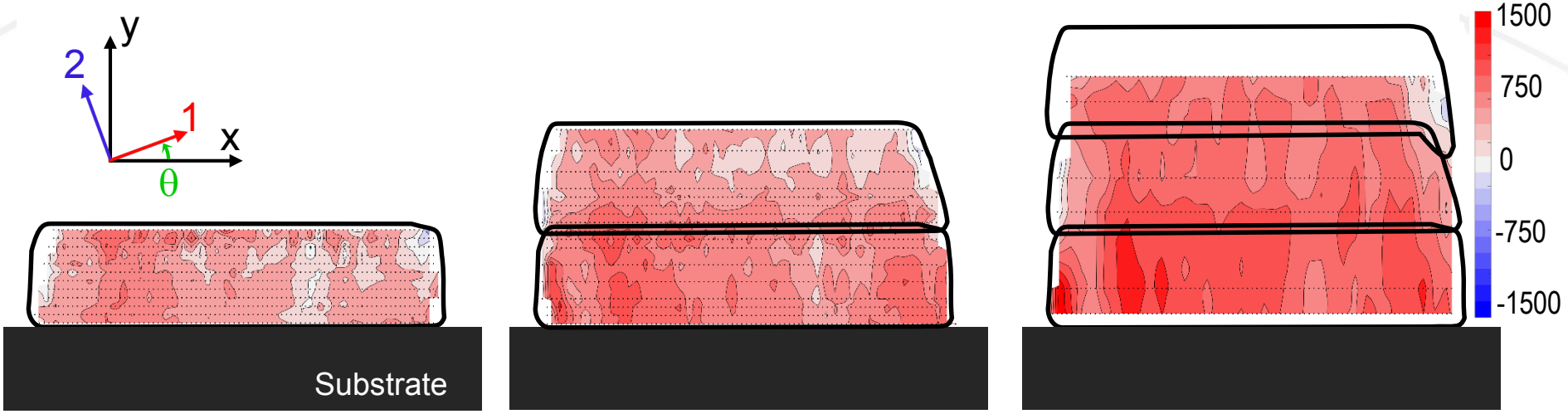


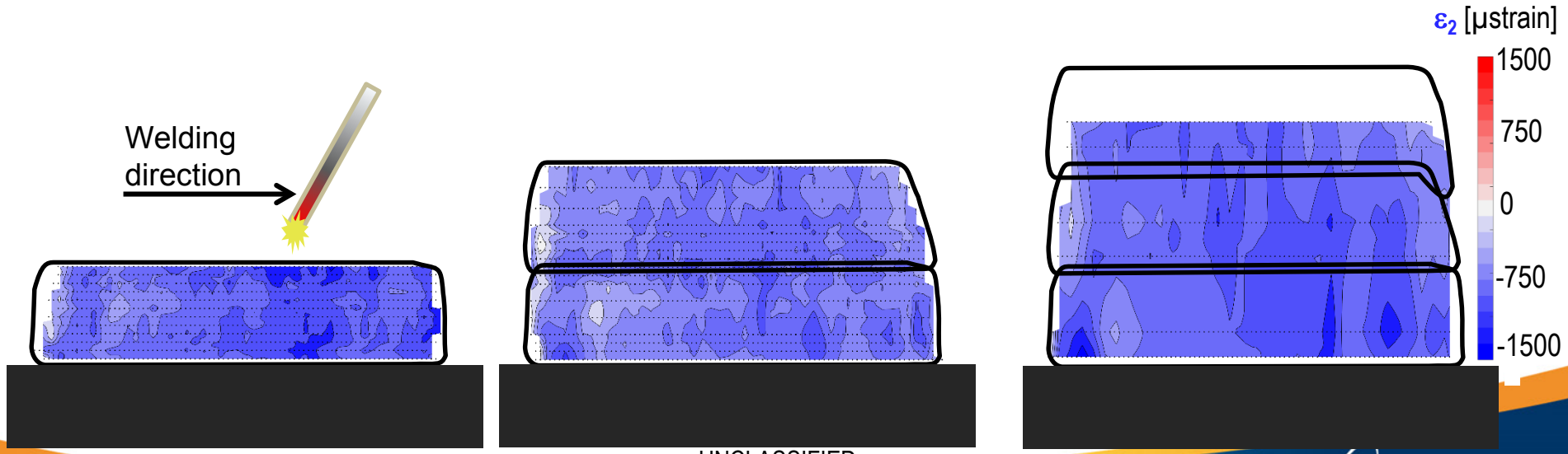


Significant change in ferrite fraction at the interface between layers



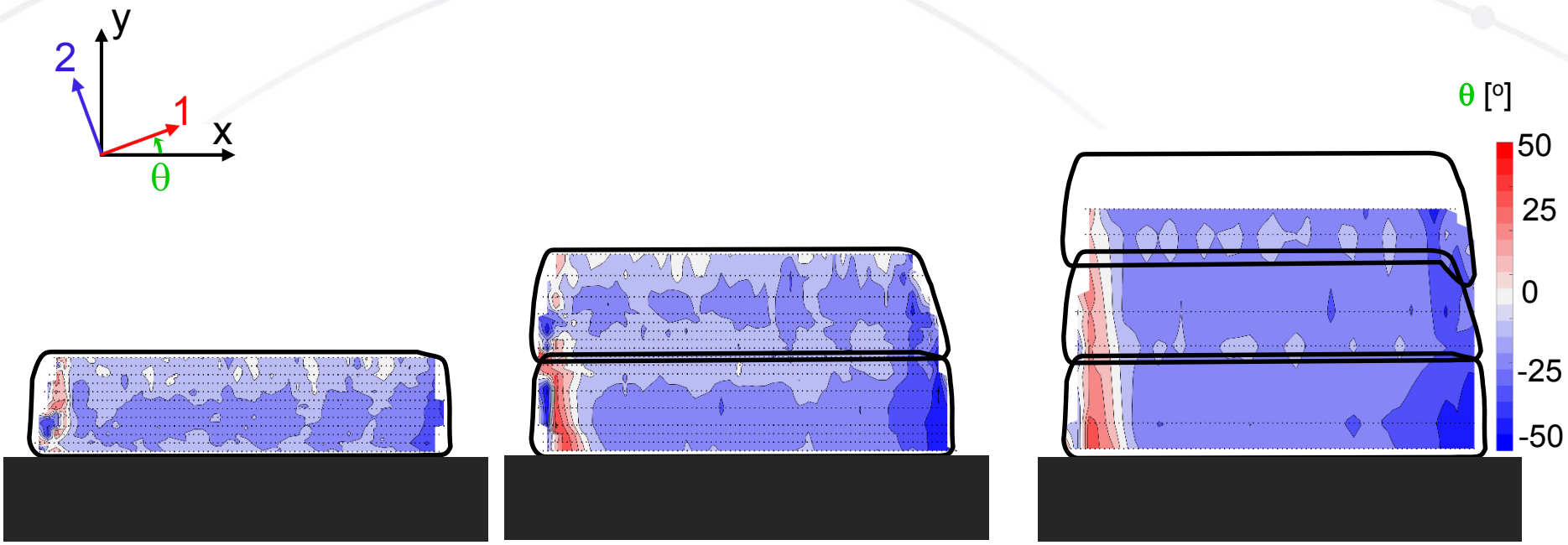
Principal strains increase slightly with adding layers and the general trends remain the same





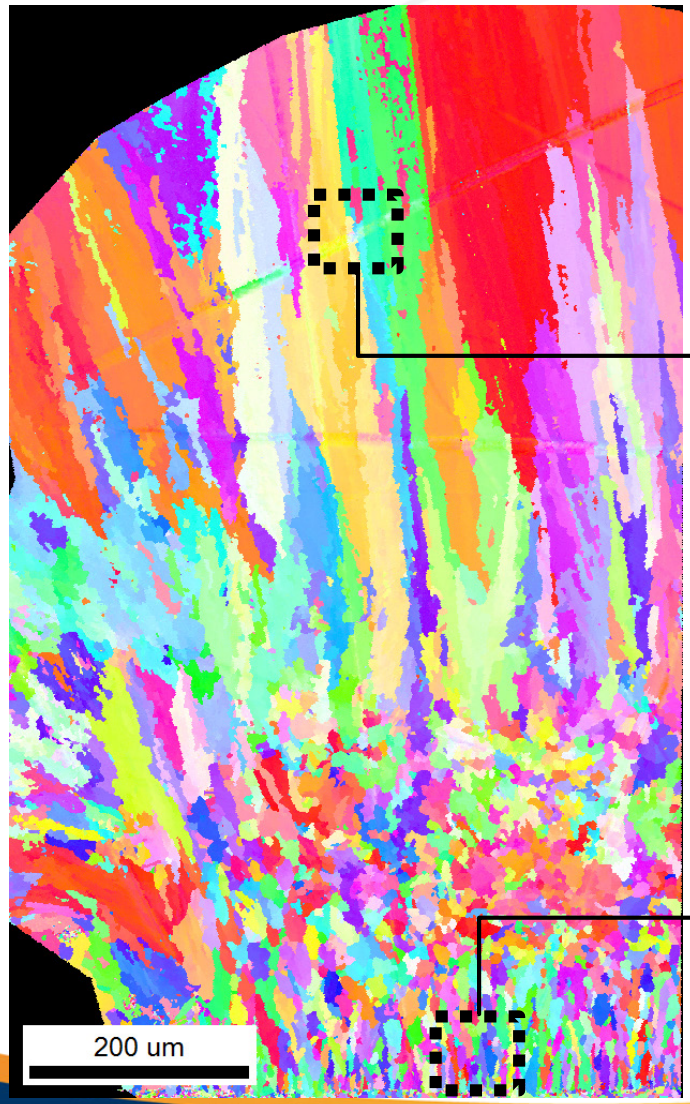
The min strain component is decreasing by increasing the number of layers

The angle of the principals strains varies significantly at the ends of the welds, but is fairly constant in the middle



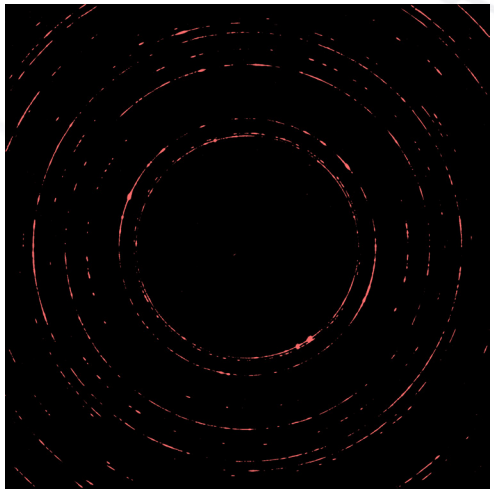
- In most of the material the rotation of the principal axes is about 10-15 degrees
  - Significant changes at the starting end and more moderate change at the finishing end

The 2D diffraction images can provide information about the microstructure; grain size and texture



Large elongated grains

"Spotty" pattern

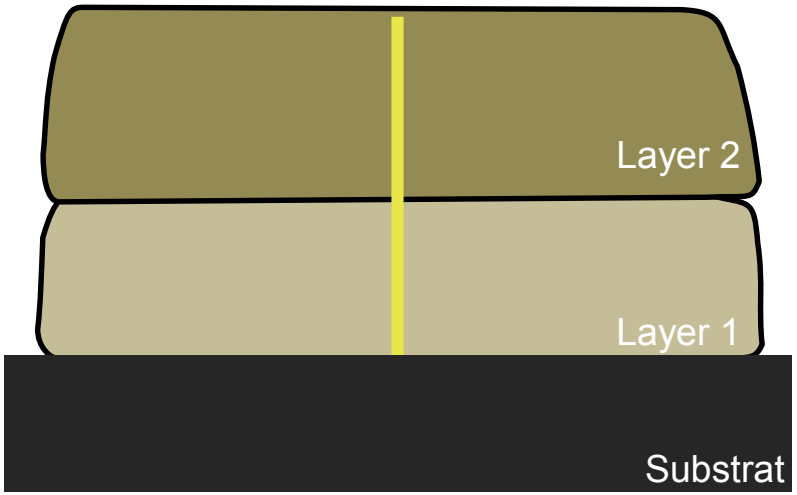


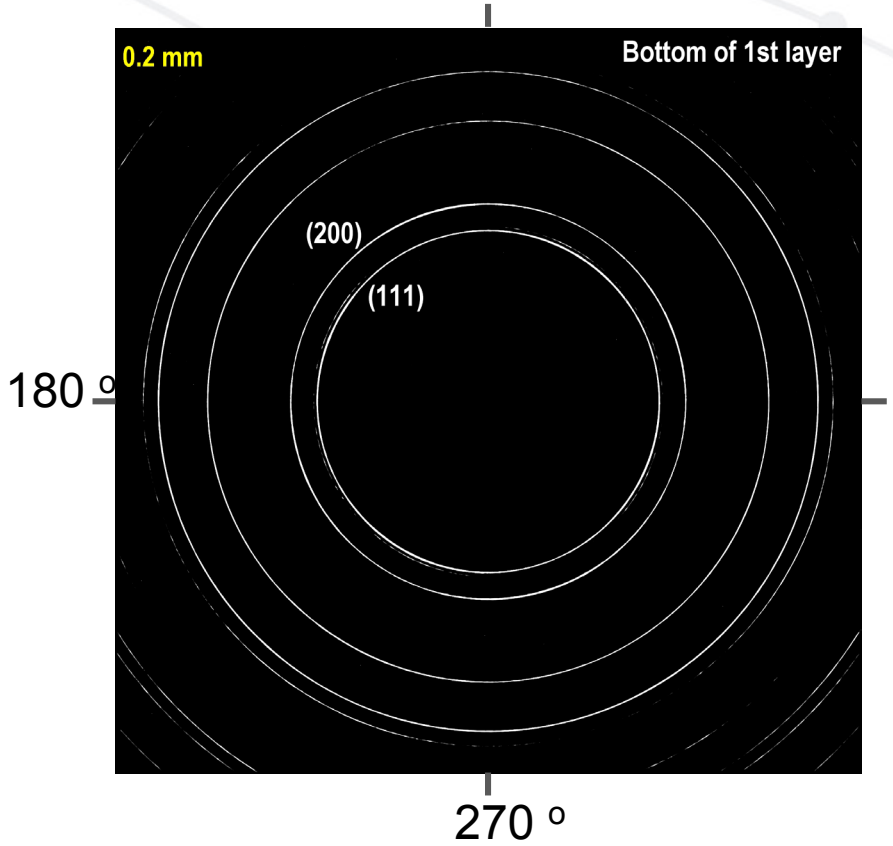
Small grains

Continuous pattern

Brown et al. 2017

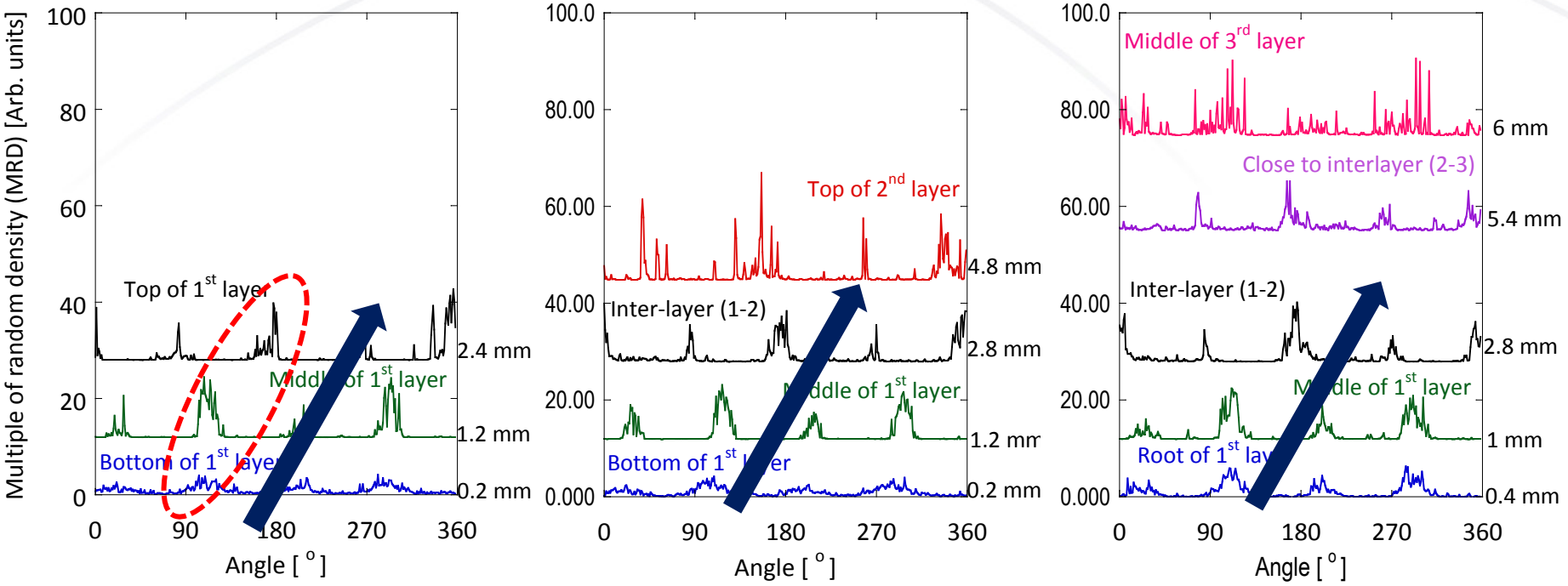
Microstructure development: Small grains turns into bigger grains at the top of the layers





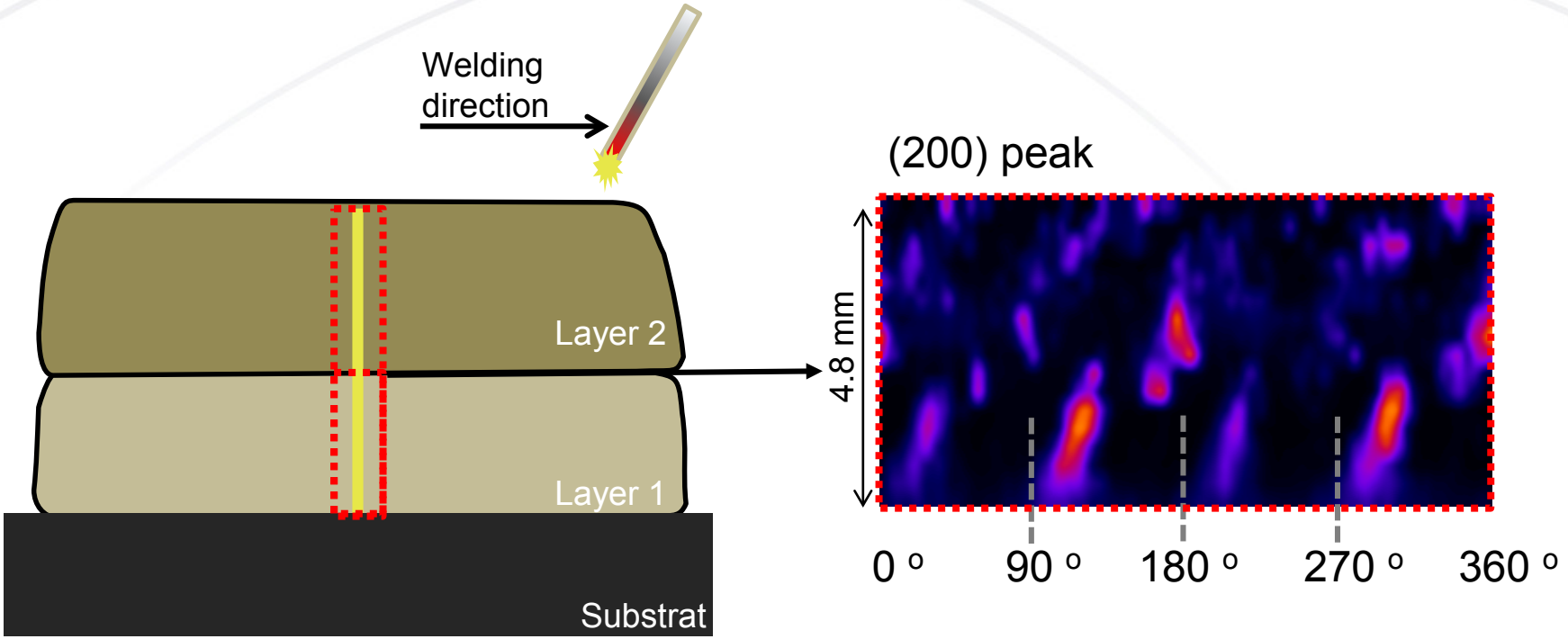
- There are small mosaic grains at the bottom of the sample and at the interlayer
- 'Rotation' of the texture of the (200) peak –epitaxial growth relationship?

The texture of the first layer is not affected by adding more layers on the top



- The texture is stronger at the top of the layers
- The texture of the first layer is not affected by adding more layers on the top

The texture of the first layer is not affected by adding more layers on the top

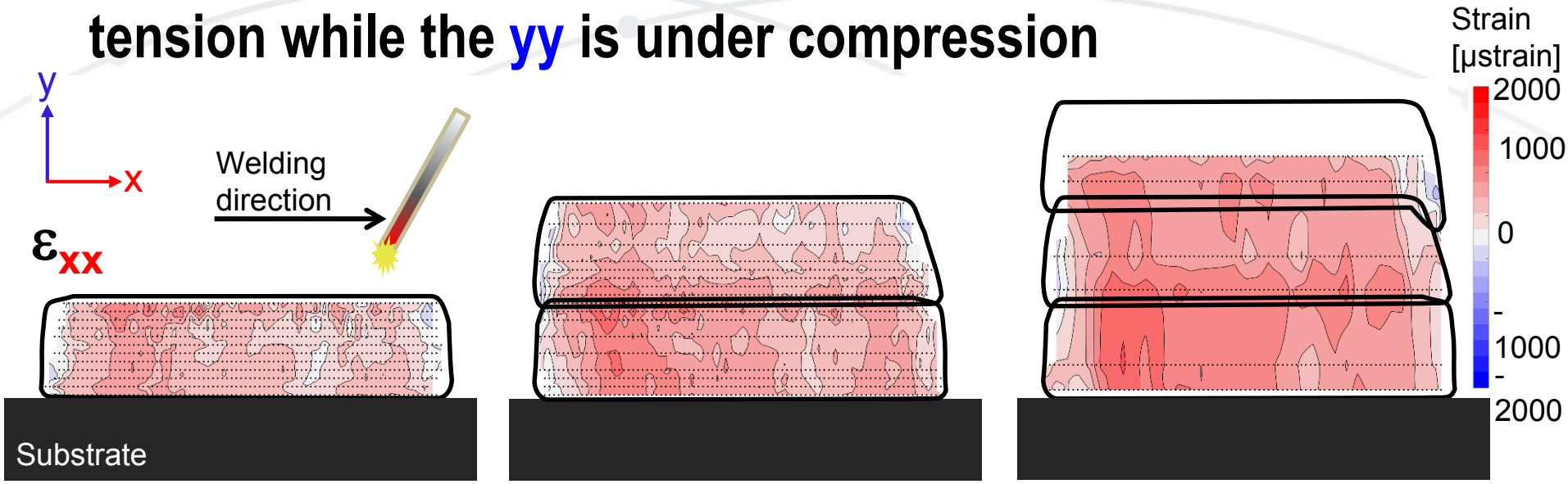


- The orientation of the texture could be associated with the grain growth direction and/or tilt of the welding torch

Conclusions

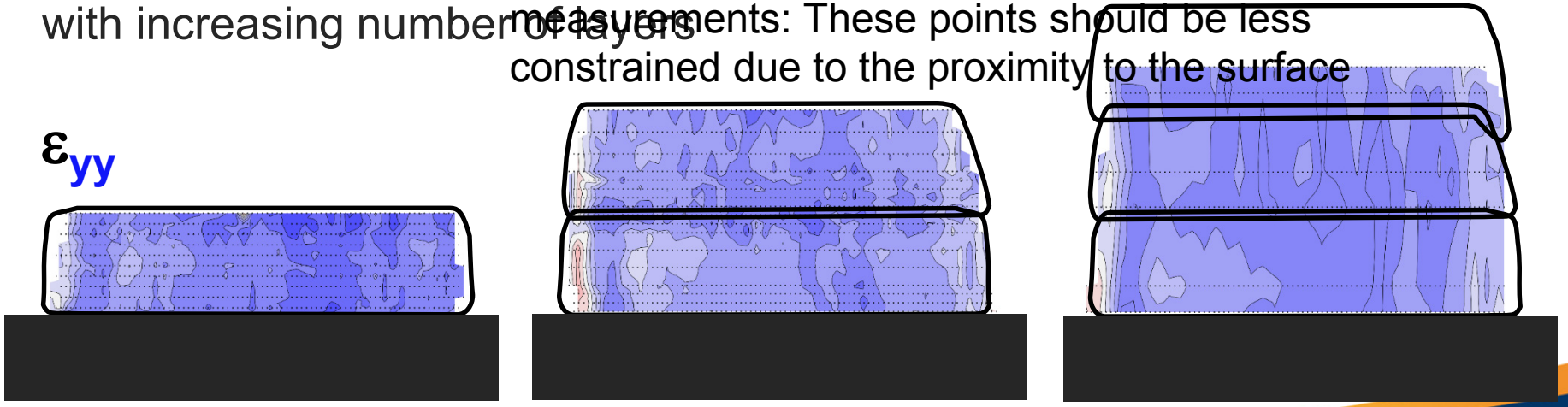
- The ferrite fraction is related to the cooling rates; fast cooling rate results in lower ferrite fraction
  - At the top of a layer the ferrite fraction is increased while it is lower at the bottom and within the interlayer; Adding another layer changes the ferrite fraction at the interlayer from high to low
- The variation of the principal strains along x is not changing significantly by adding layers
- The rotation of the principal axes is strong at the start of the weld
  - Variation through the layer is washed out by adding layers on top
- A cube texture is developing within each layer.
  - Weaker texture close to the substrate and at the interlayer/re-solidified region
  - The orientation of the cube texture changes through the layers

The Cartesian xx strain component (Austenite) is in tension while the yy is under compression



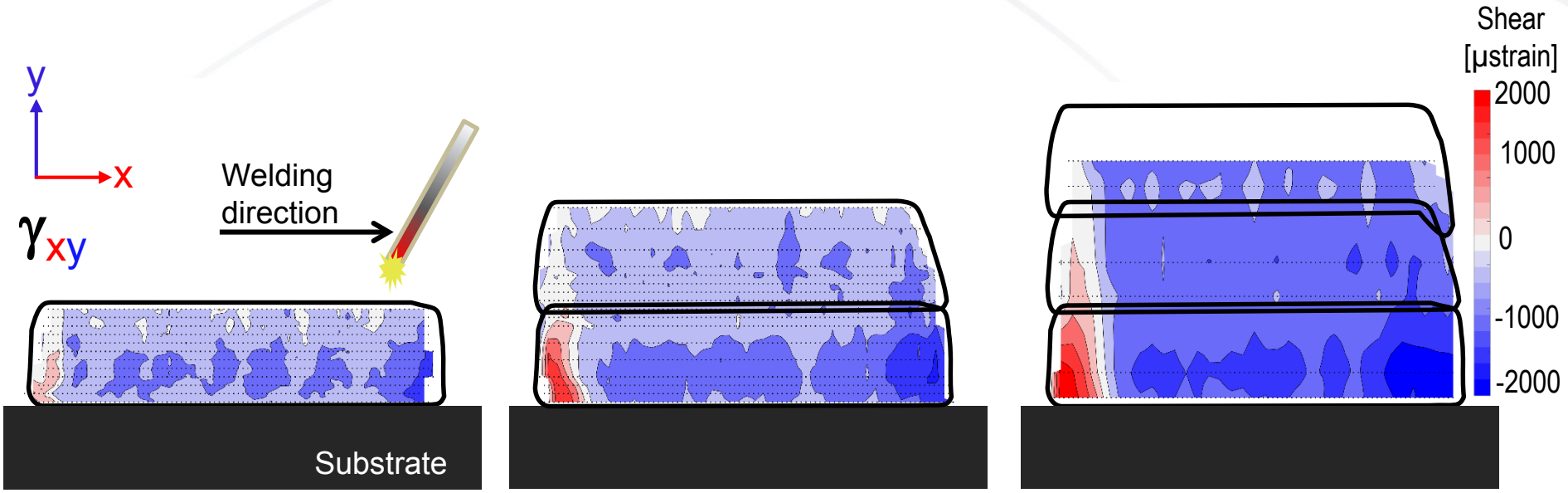
The xx strain component is increasing with increasing number of layers

Reference: Average lattice parameter of the top measurements: These points should be less constrained due to the proximity to the surface



The yy strain component is decreasing with increasing number of layers

The shear strain component (Austenite) is increasing in an absolute sense with increasing number of layers



- The shear is close to zero at the top of layers not restricted by another layer
- Shear is getting more extreme by adding more layers at the top