Comparison of Residual Stress Measurements from Multiple Techniques in Die-forged 7085-T7452

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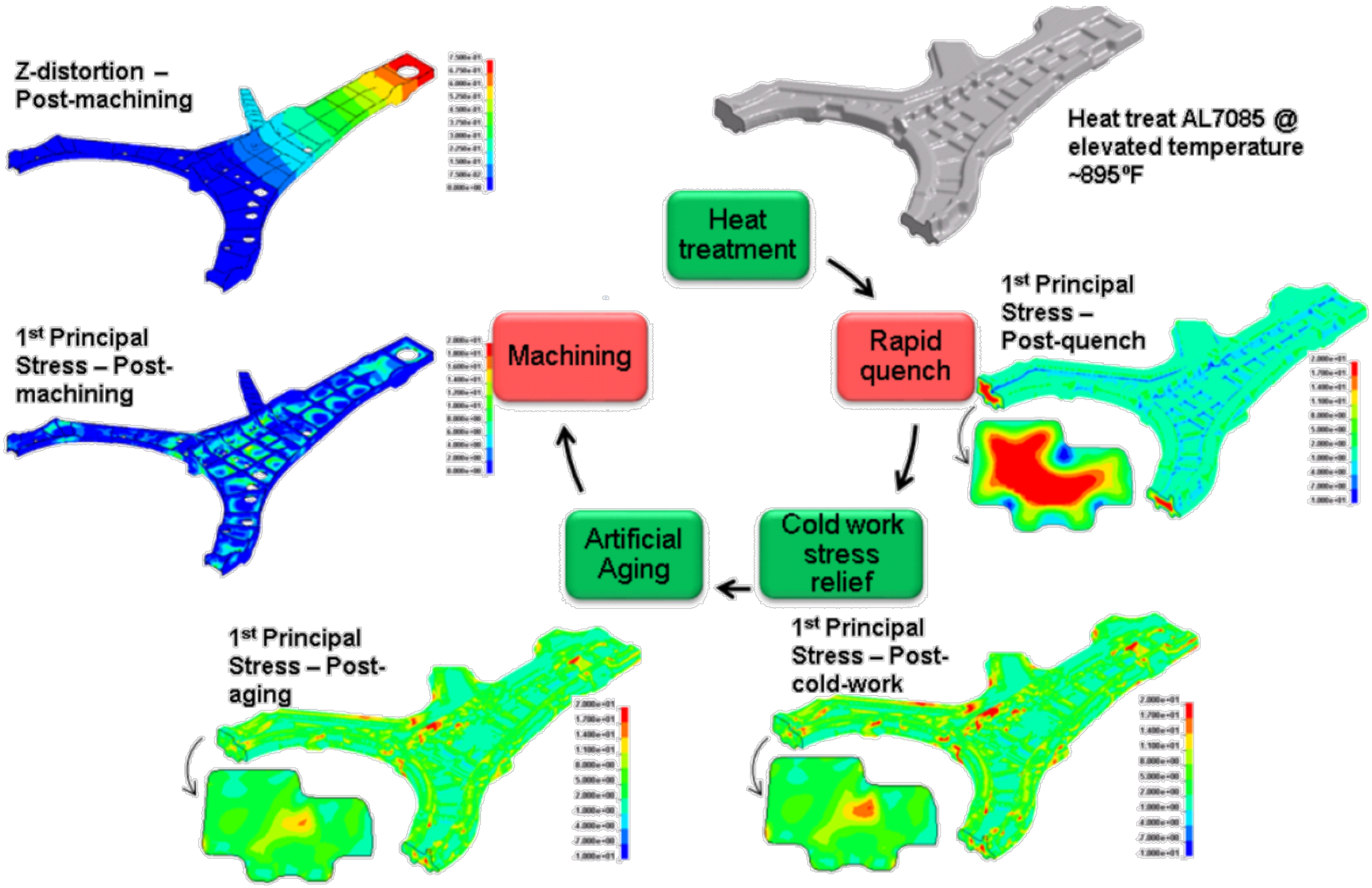
Overview

- Motivation
- Experiment Details
- Results & Discussion
- Conclusions

Motivation

- **Cold Working Effectivity**
  - **Ability to mitigate bulk residual stresses in monolithic-unitized forgings**
- **Integrated Computational Materials Engineering (ICME) Model Validation**
  - **Appropriate instrument/experiment for model validation**
    - **Required Information**
    - **Stress Gradient**
    - **Boundary Conditions**

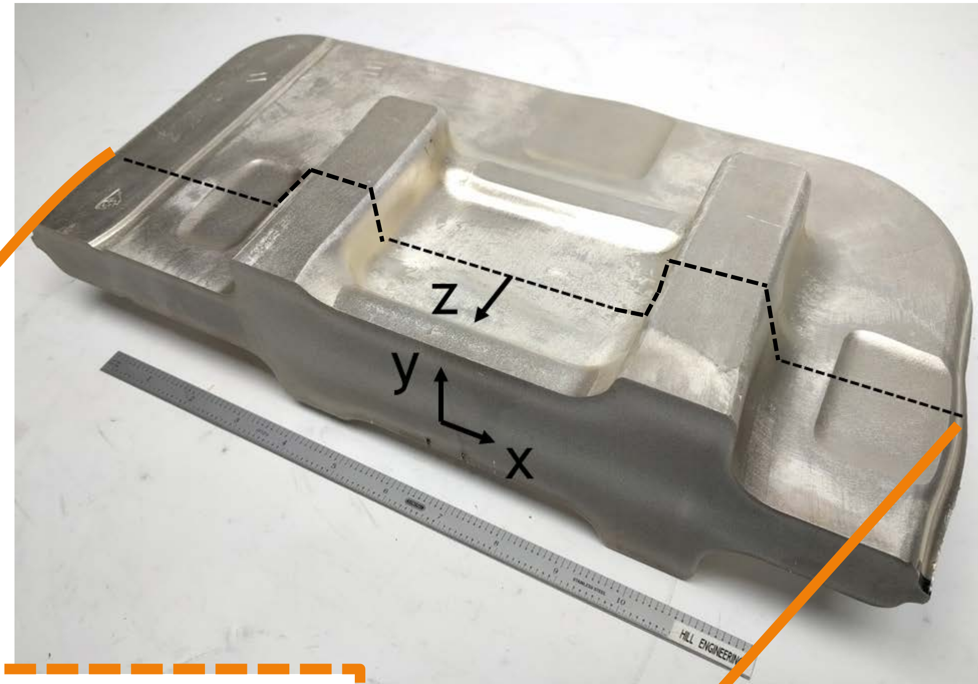
ICME: Residual Stress & Distortion

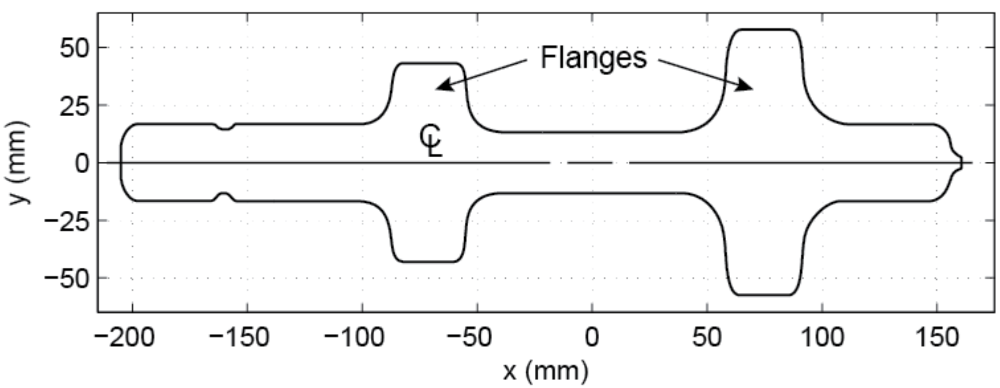


Ref: Watton, et. Al., USAF ASIP, December 2015

7085-T74/T7452 Die Forgings

- Both articles peak over-aged (-T74)
- One article left as tempered (0% cold work)
- Other article cold worked (3% cold work)
  - Achieved with a single die strike



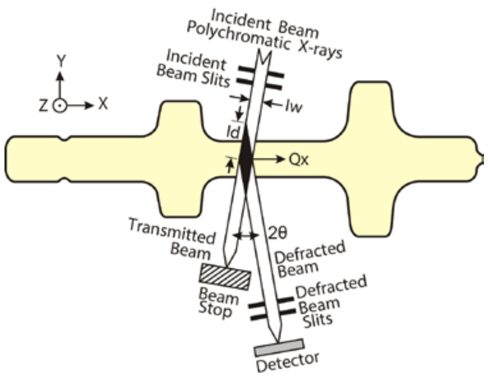


Al	Cu	Mg	Zr	Zn
89.8	1.6	1.5	0.1	7

Material Composition (% Weight)

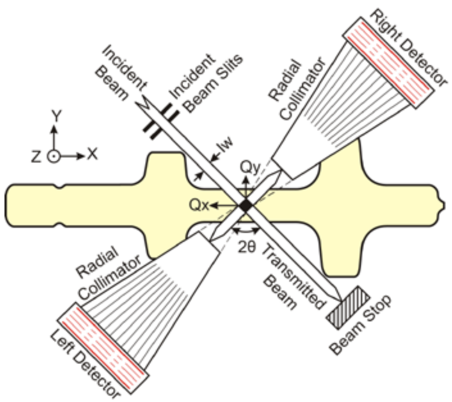
Experimental Setup: Methods

Energy Dispersive X-Ray Diffraction (EDXRD)



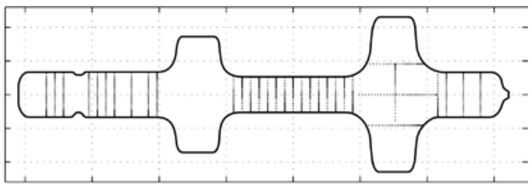
- **<u>Facility:</u>** Argonne National Laboratory: Advanced Photon Source (APS)
- **<u>Diffraction Angle:</u>** 2θ = 7˚
- **<u>{*hkl*}:</u>** {311} Peak Used for Strain Calculation
- **<u>Note:</u>** Out-of-plane (dyy) component not measured due to part geometry

Neutron Diffraction (ND)



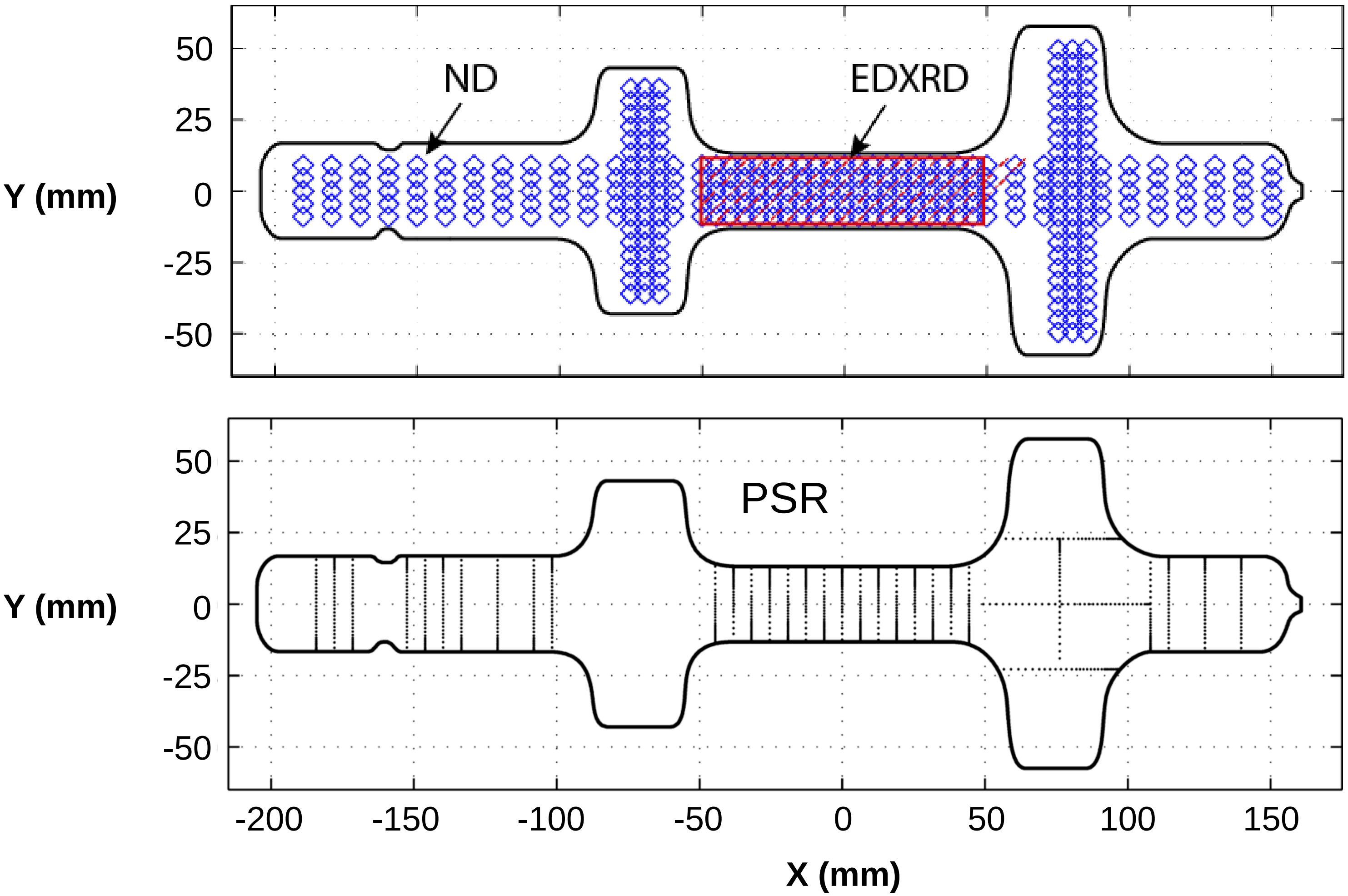
- **<u>Facility:</u>** Oak Ridge National Laboratory: VULCAN
- **<u>Diffraction Angle:</u>** 2θ = 45˚
- **<u>{*hkl*}:</u>** Multiple {*hkl*} Peaks Used for Strain Calculation due to peaks missing in some locations

Primary Slice Removal (PSR)



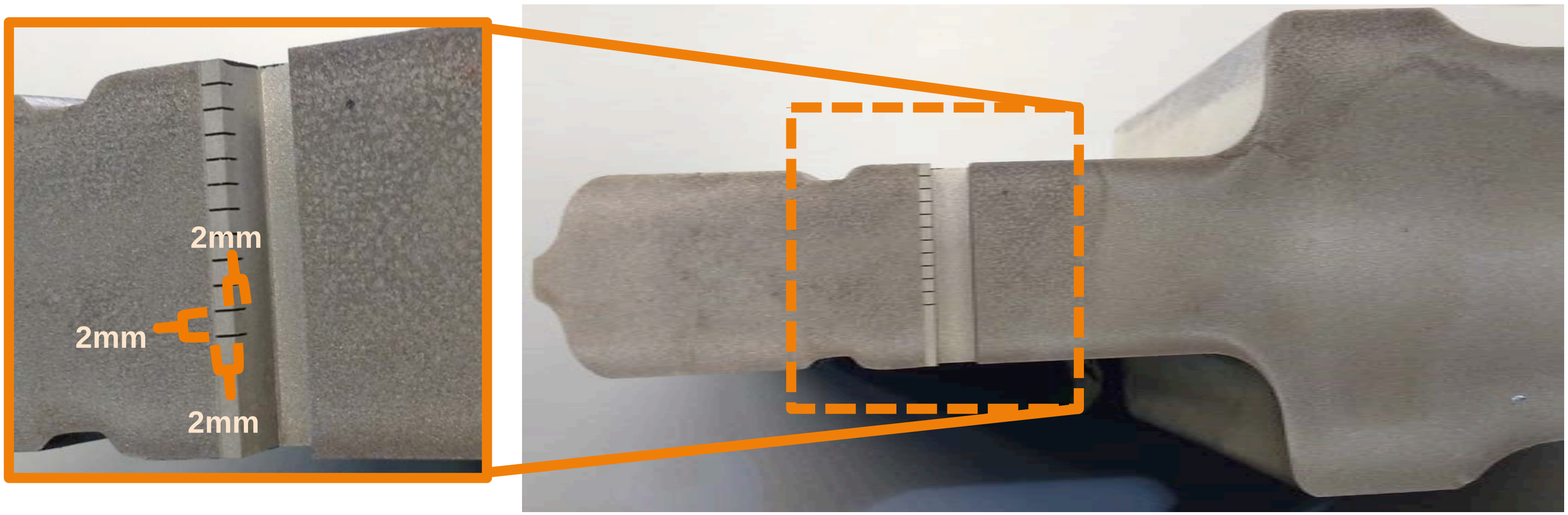
- **<u>Facility:</u>** Hill Engineering, LLC: AFRL SBIR Result
- **<u>Note:</u>** Primary plane measured using contour method followed by several slitting measurements where feasible

Measurement Locations

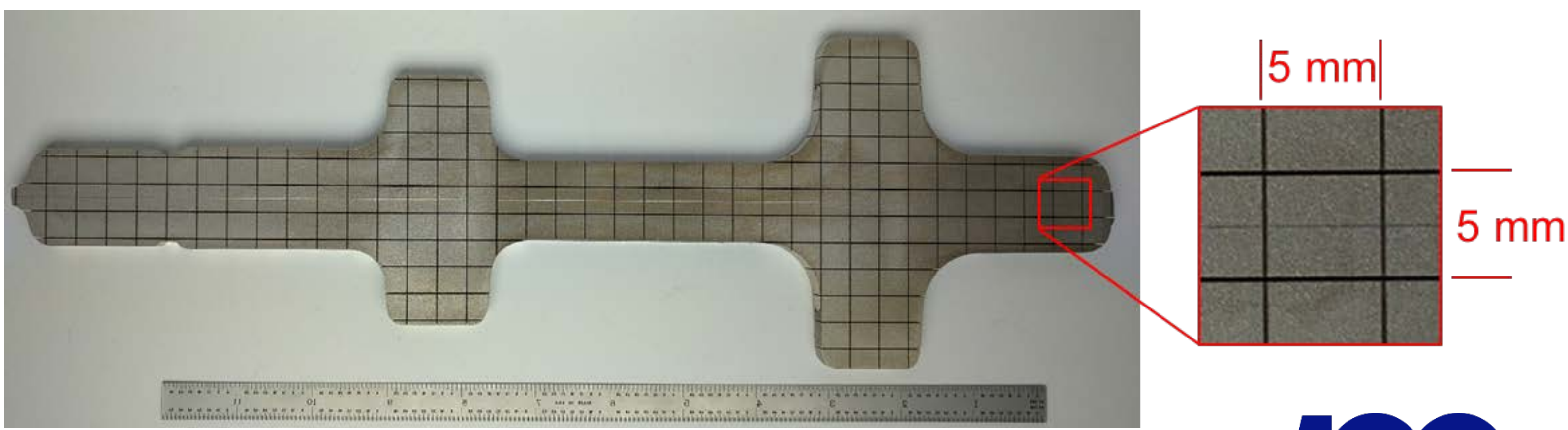


Experimental Setup: Diffraction d_0 Specimens

EDXRD



ND



EDXRD Data Reduction

Generalized Hooke's Law

$$\sigma_x = 2G\varepsilon_x + \lambda e$$

$$\sigma_y = 2G\varepsilon_y + \lambda e$$

$$\sigma_z = 2G\varepsilon_z + \lambda e$$

$$e = \varepsilon_x + \varepsilon_y + \varepsilon_z$$

Lamé Constants

$$\mathrm{G} = \frac{E}{2(1+\nu)}$$

$$\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)}$$

Step 1: Plane Stress Assumption

$$\sigma_y = 2G\varepsilon_y + \lambda e = 0$$

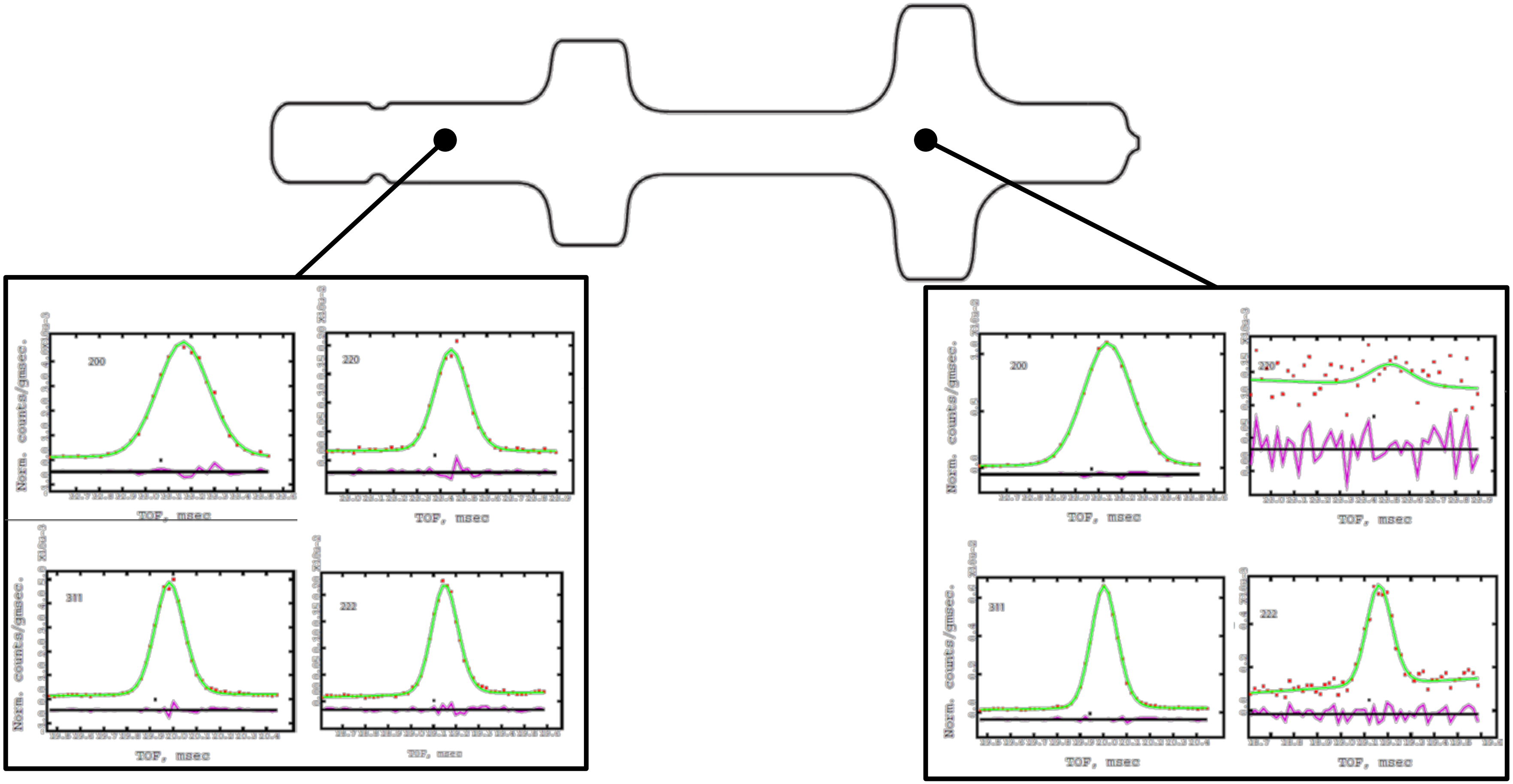
Step 2: Calculate Missing Strain Component

$$2G\varepsilon_y + \lambda\varepsilon_x + \lambda\varepsilon_y + \lambda\varepsilon_z = 0$$

$$\varepsilon_y = -\frac{\lambda(\varepsilon_x + \varepsilon_z)}{2G + \lambda}$$

Step 3: Calculate Remaining Normal Stress Components

ND Data Reduction: Inconsistent Peaks



Spatial inconsistency of {*200*}, {*220*}, {*311*}, & {*222*} peaks requires averaging of multiple peaks for strain calculation.

Uncertainty Calculation

- **Standard error propagation with two sources**
  - **Instrument error**
  - **Misfit peak fitting error**

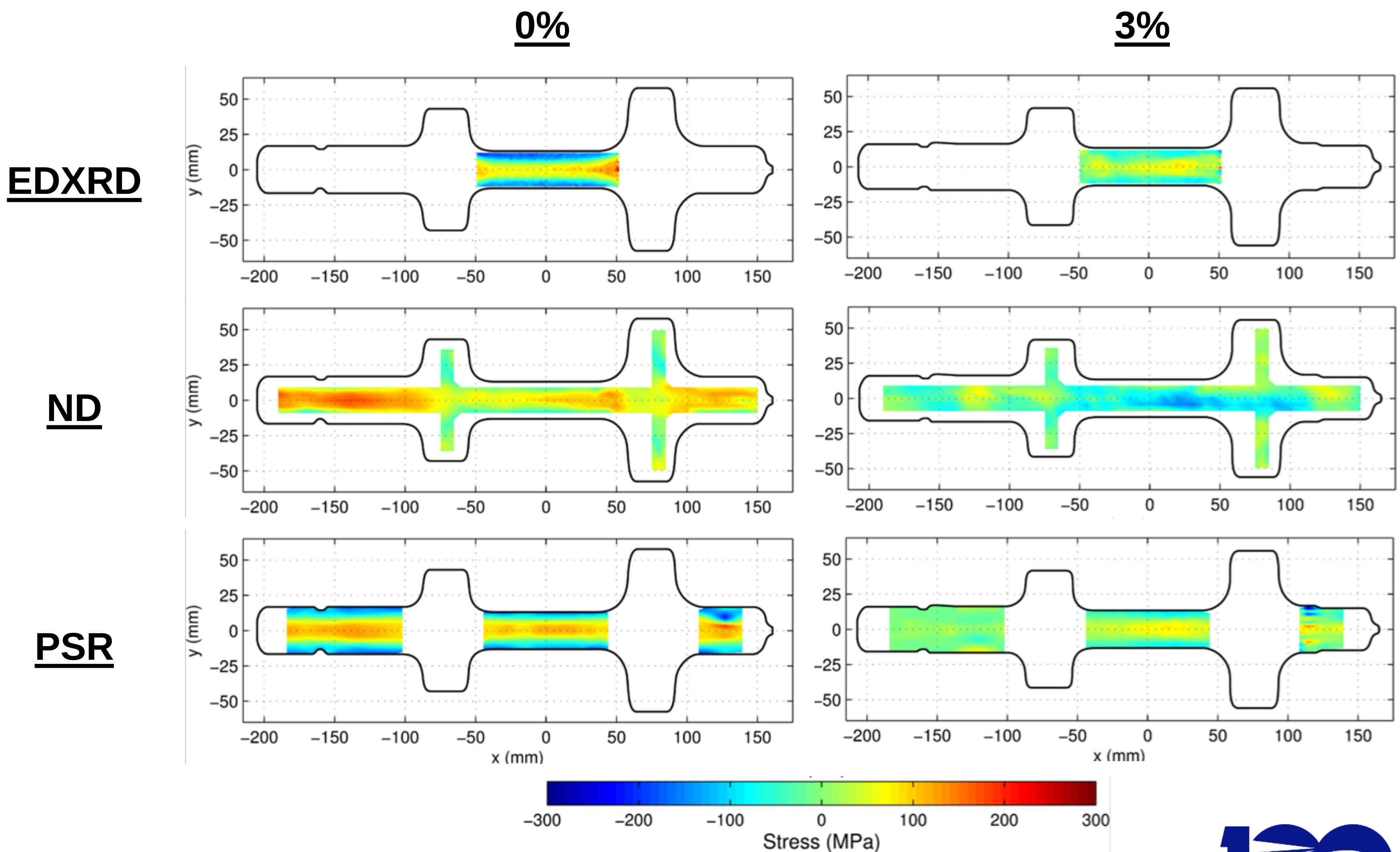
$$U\sigma_{i,\{hkl\}}^{2} = \left(\frac{E_{\{hkl\}}}{1-\nu^{2}}\right)^{2}\left(U\varepsilon_{i,\{hkl\}}^{2} + \nu^{2}U\varepsilon_{j,\{hkl\}}^{2}\right)$$

$$U\varepsilon_{i,\{hkl\}}^{2} = U\varepsilon_{i,\{hkl\},Misfit}^{2} + U\varepsilon_{i,\{hkl\},Instrument}^{2}$$

$$U\varepsilon_{i,\{hkl\},Misfit}^{2} = \left(\frac{ud_{i,\{hkl\}}}{d_{0,i,\{hkl\}}}\right)^{2} + \left(\frac{d_{i,\{311\}}Ud_{0,i,\{311\}}}{d_{0,i,\{311\}}^{2}}\right)^{2}$$

$$U\varepsilon_{i,\{hkl\},Instrument}^{2} = 20\mu\varepsilon$$

Measurement Results: σ_{xx}



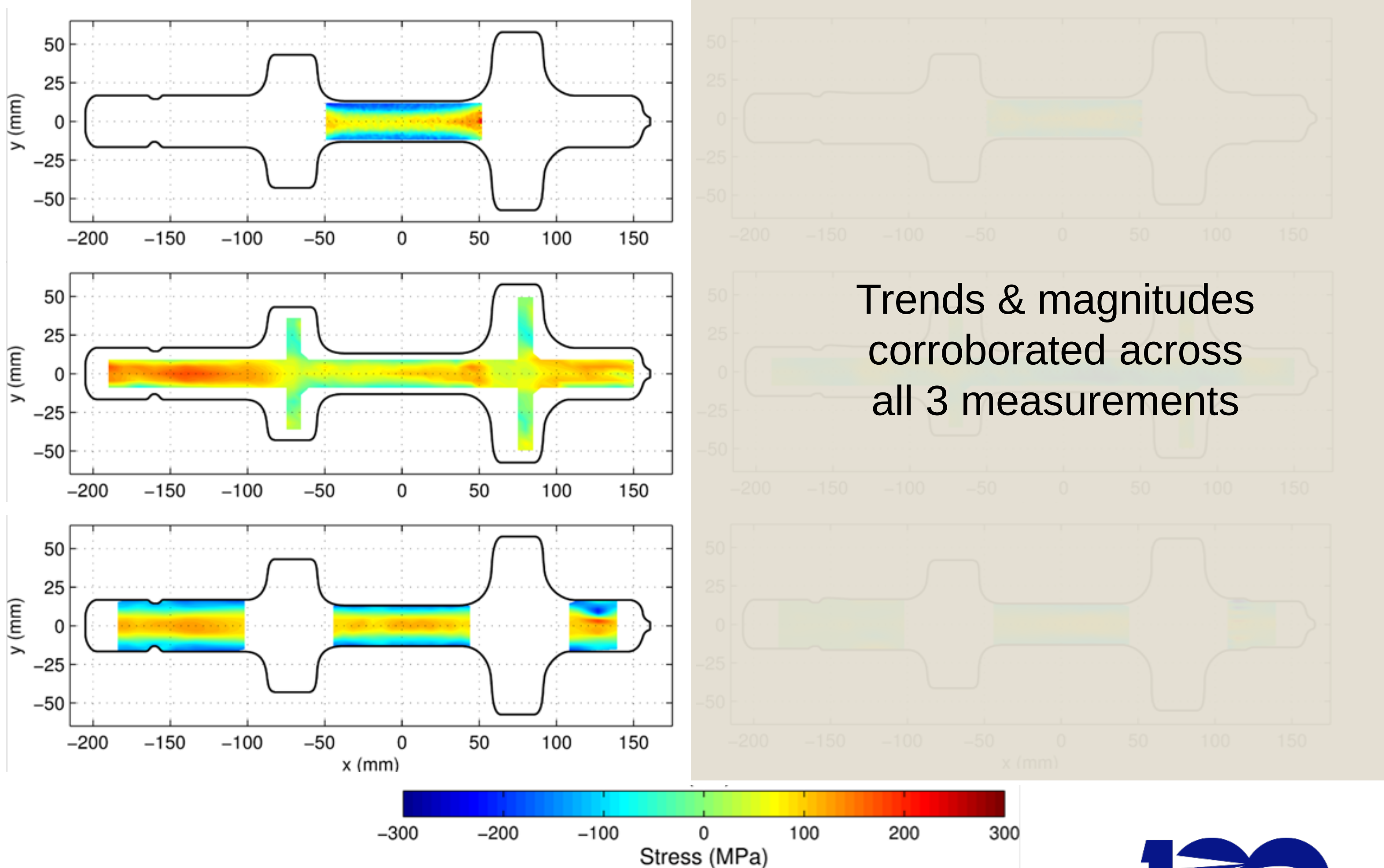
Measurement Results: σ_{xx}

0% | **3%**

EDXRD

ND

PSR



Trends & magnitudes corroborated across all 3 measurements

Measurement Results: σ_{xx}

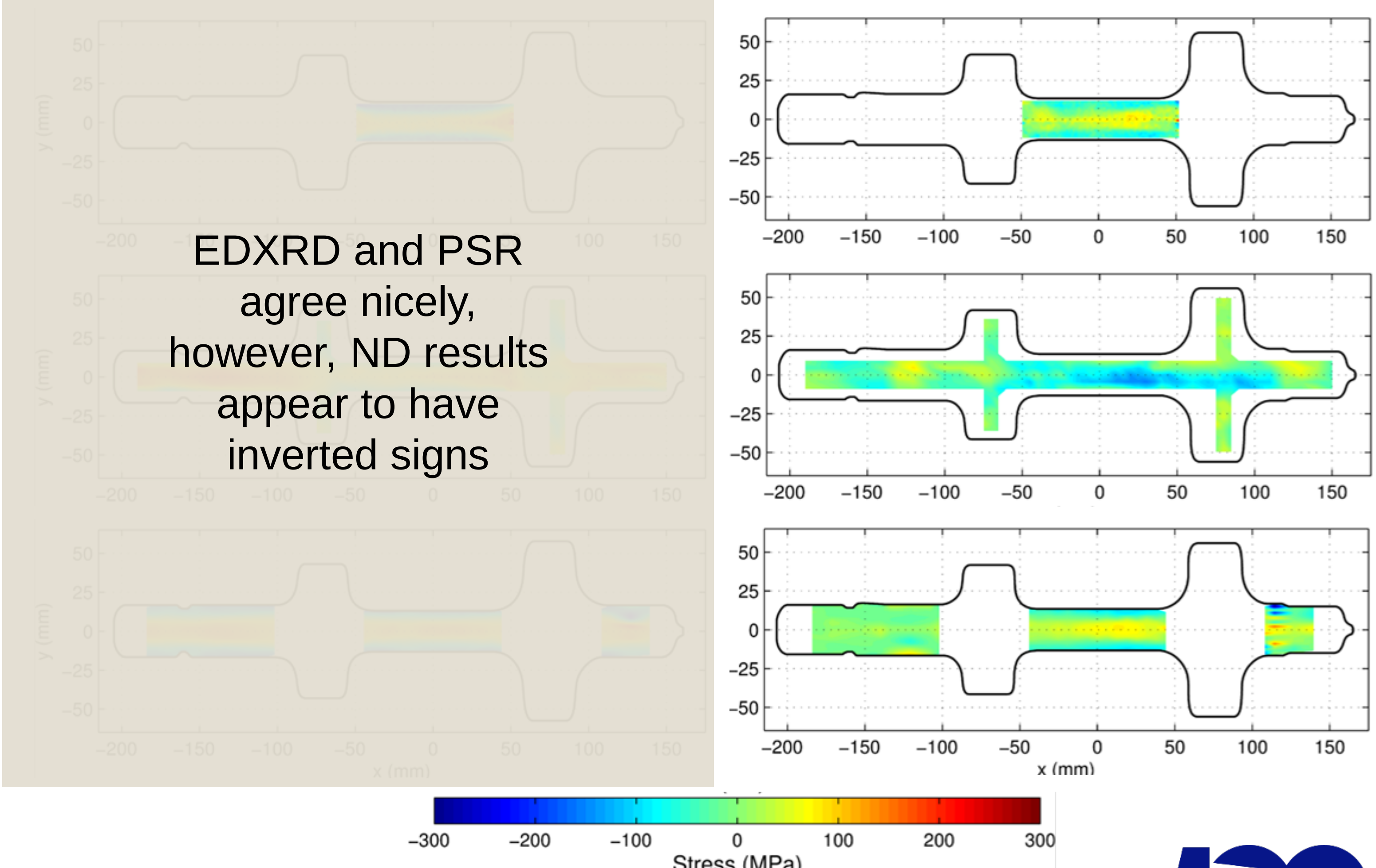
0%

3%

EDXRD

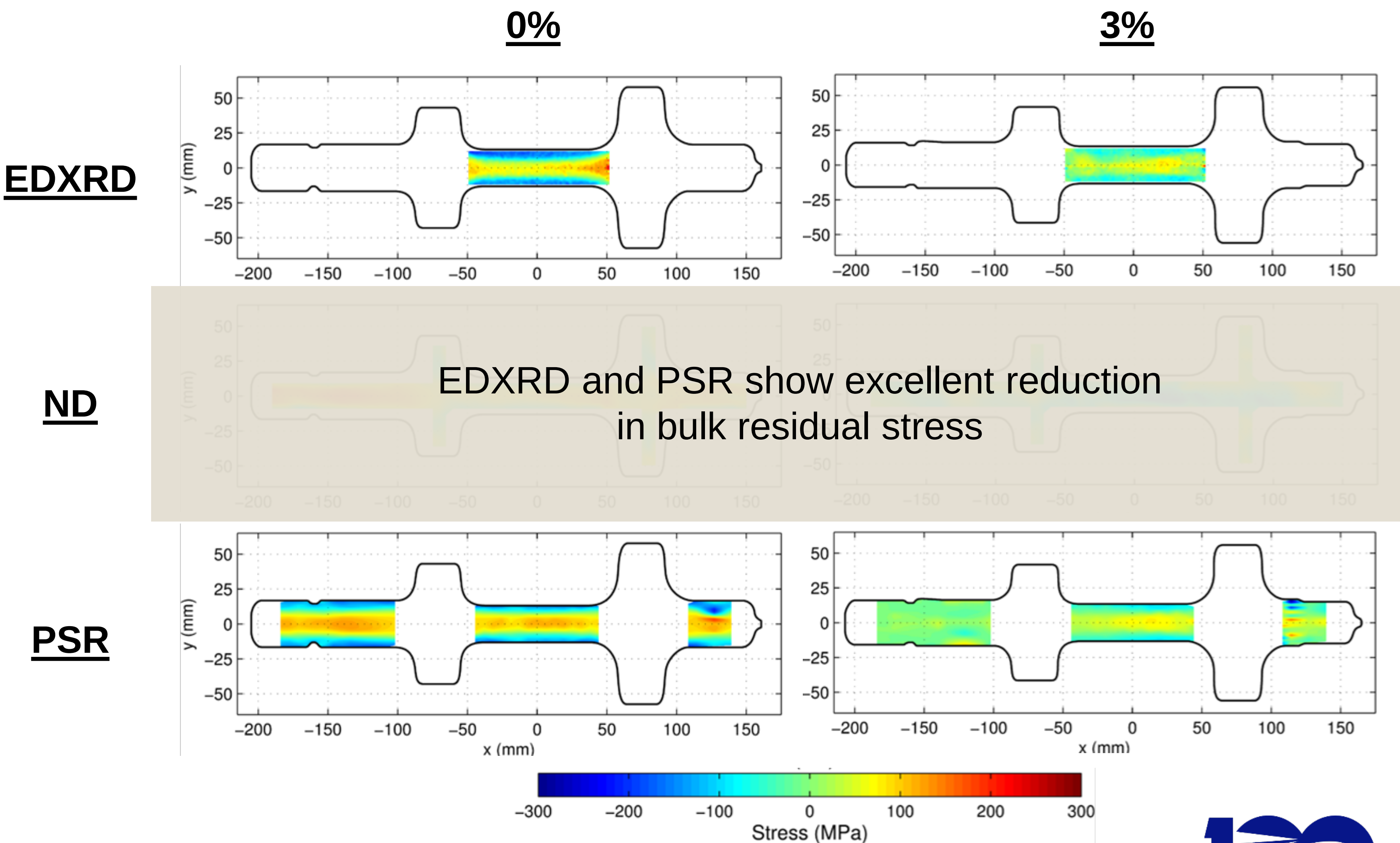
ND

PSR



EDXRD and PSR agree nicely, however, ND results appear to have inverted signs

Measurement Results: σ_{xx}



EDXRD and PSR show excellent reduction in bulk residual stress

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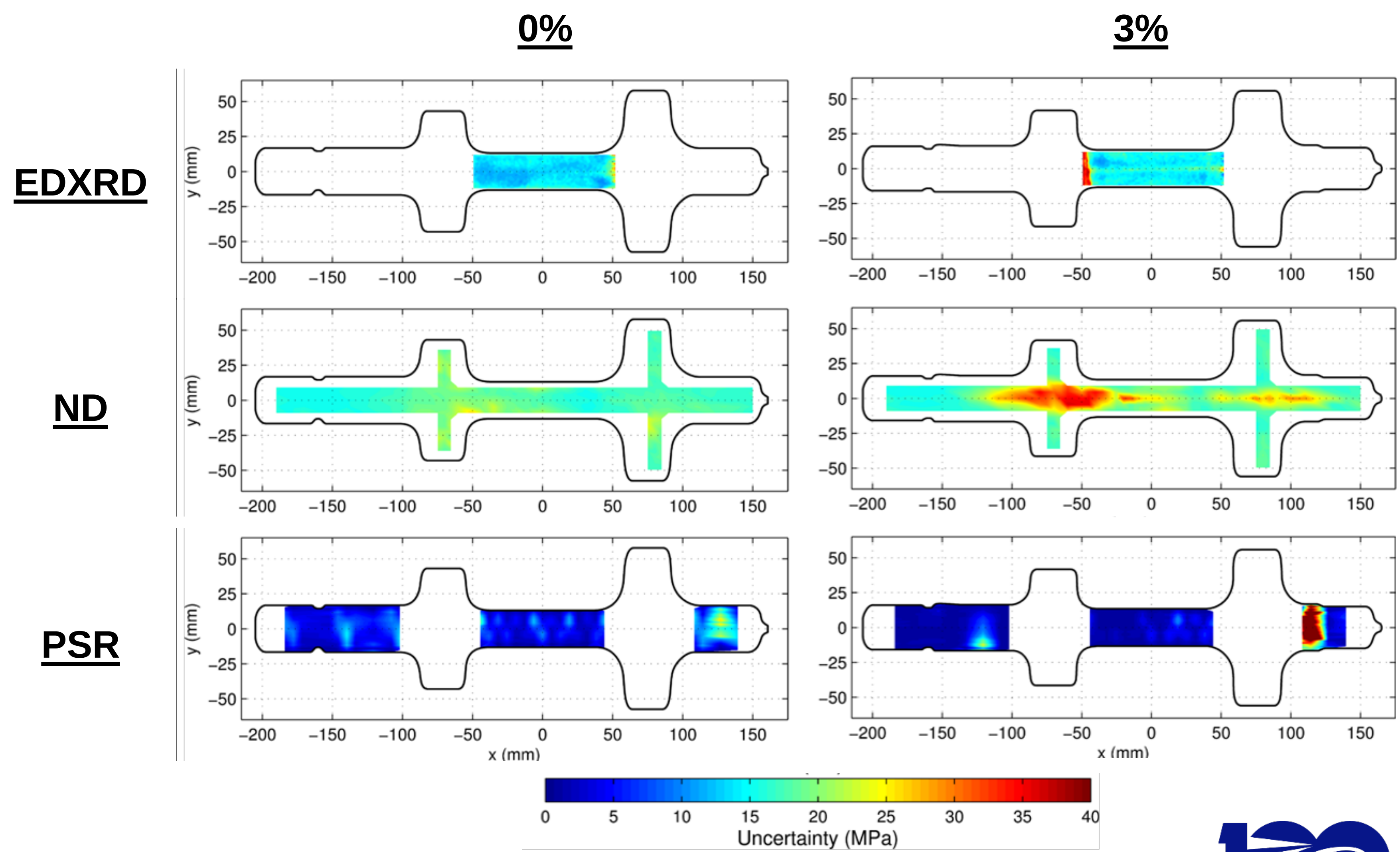
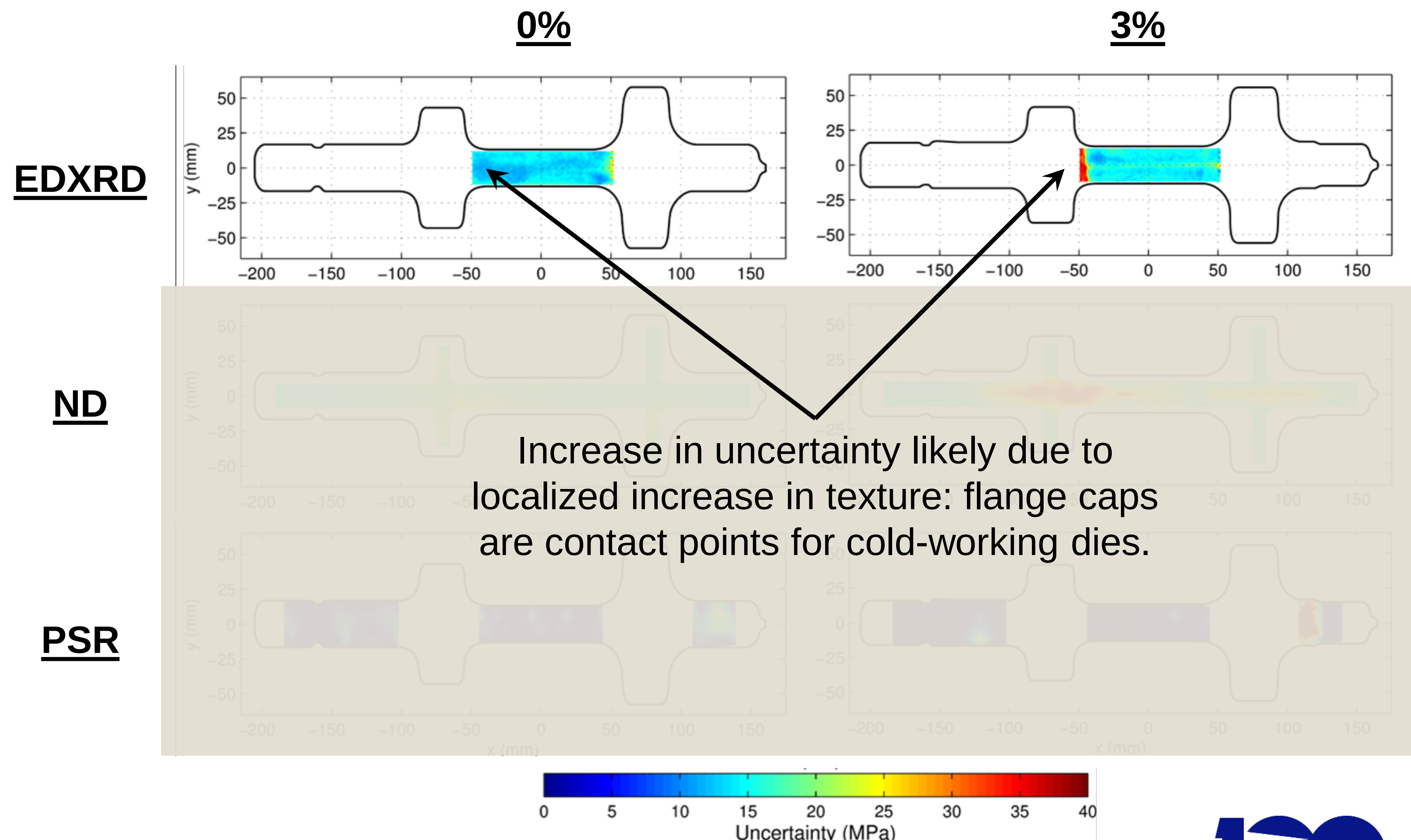
Measurement Results: $U\sigma_{xx}$



Measurement Results: $U\sigma_{xx}$



Increase in uncertainty likely due to localized increase in texture: flange caps are contact points for cold-working dies.

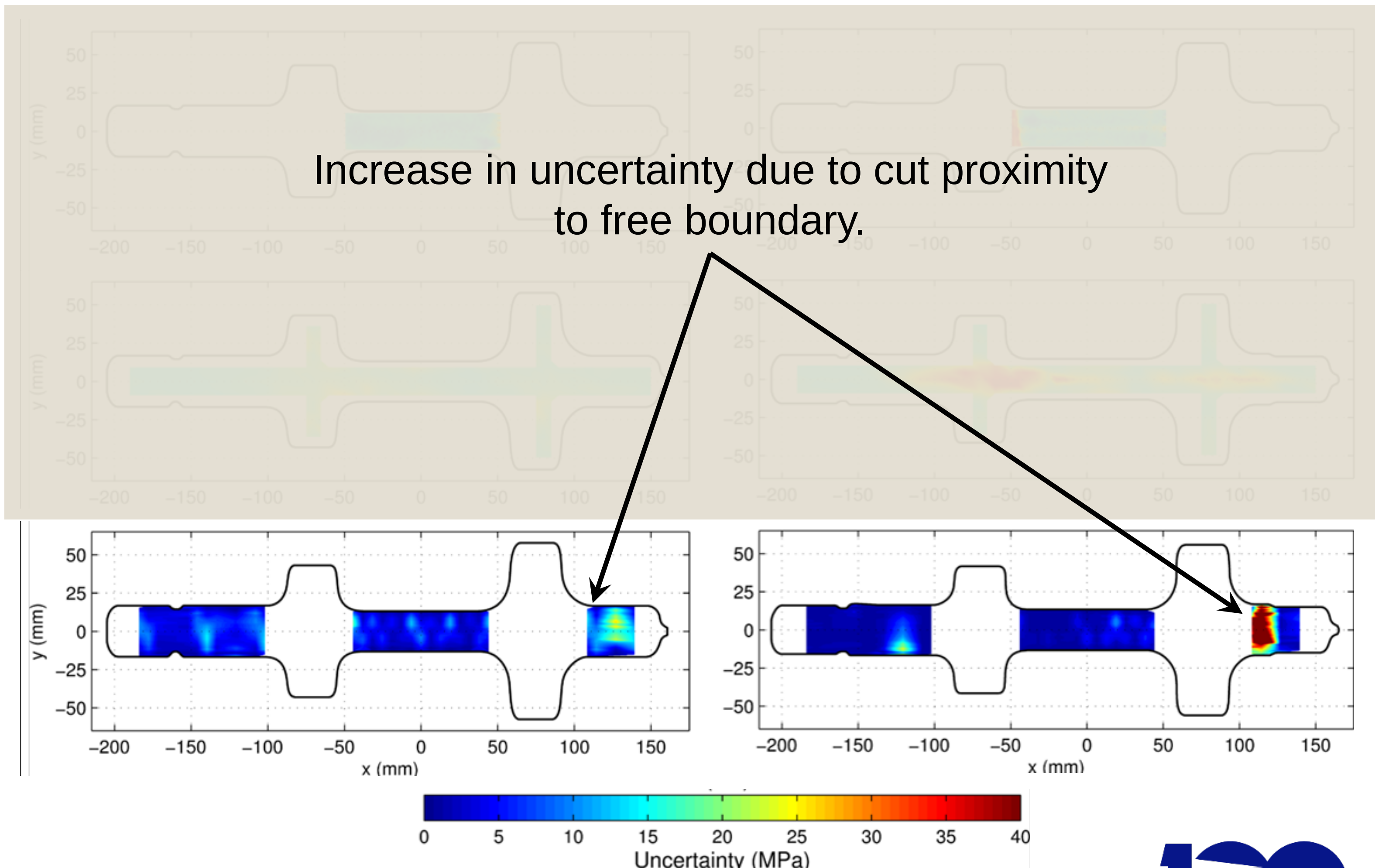
Measurement Results: $U\sigma_{xx}$

0% | **3%**

EDXRD

ND

PSR

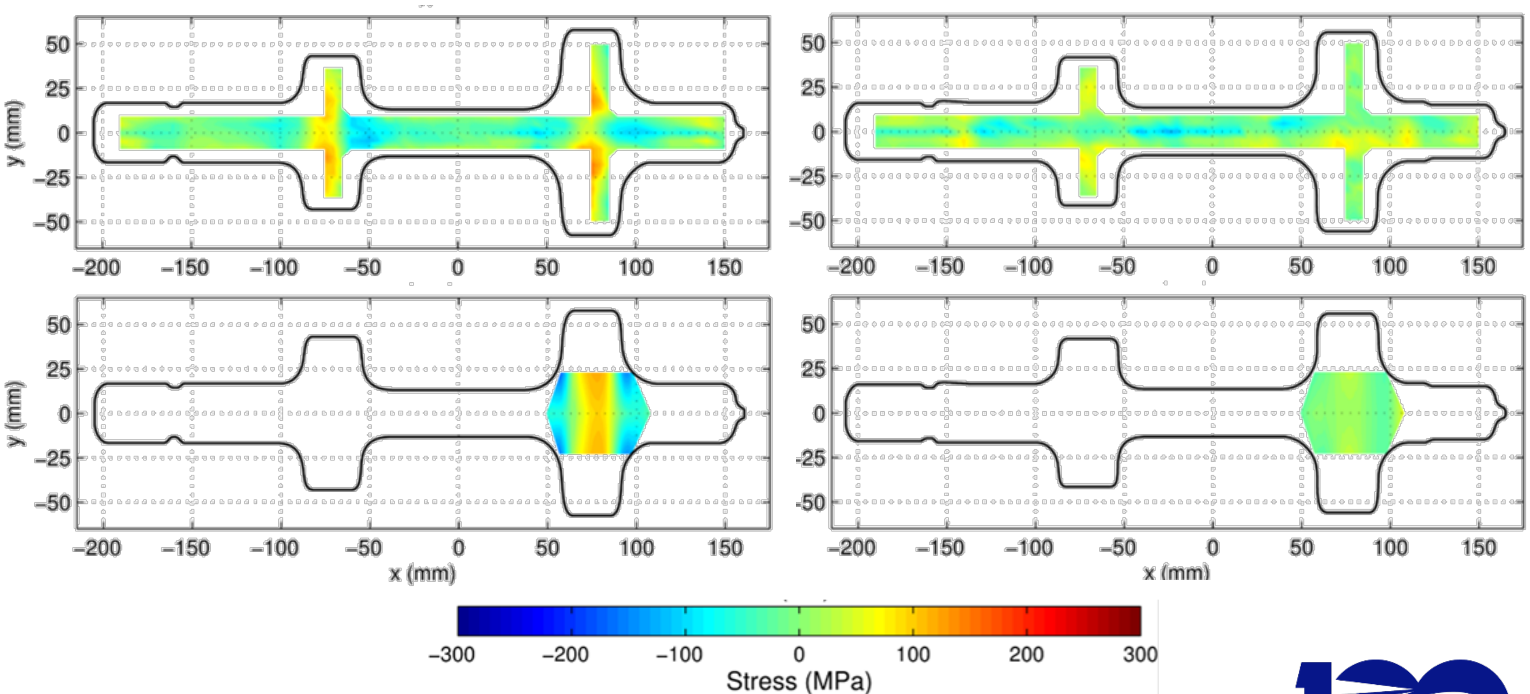


Measurement Results: σ_{yy}

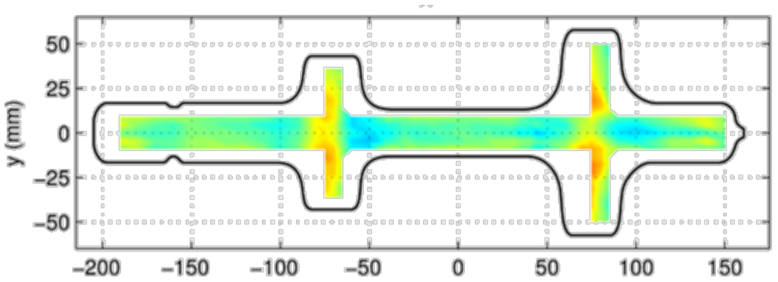
	0%	**3%**
EDXRD	**Not Measured**	**Not Measured**

ND

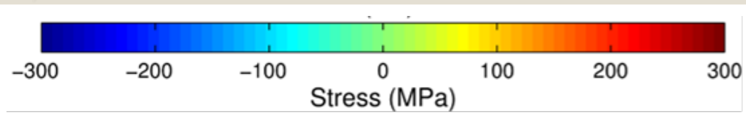
PSR



Measurement Results: σ_{yy}

	0%	3%
EDXRD	Not Measured	Not Measured
ND		
PSR		

0% ND data shows relatively small magnitude residual stresses: plane-stress assumption made in EDXRD data reduction mostly accurate.

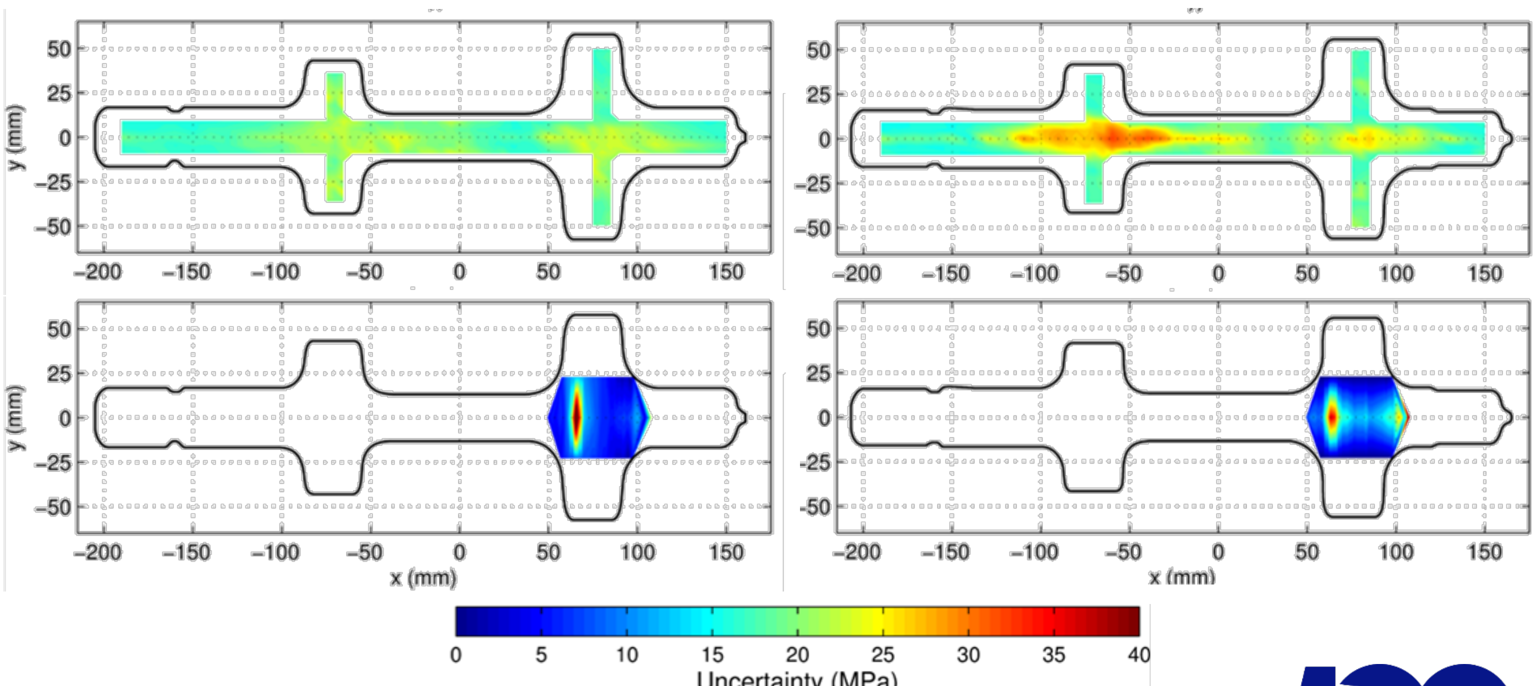


Measurement Results: $U\sigma_{yy}$

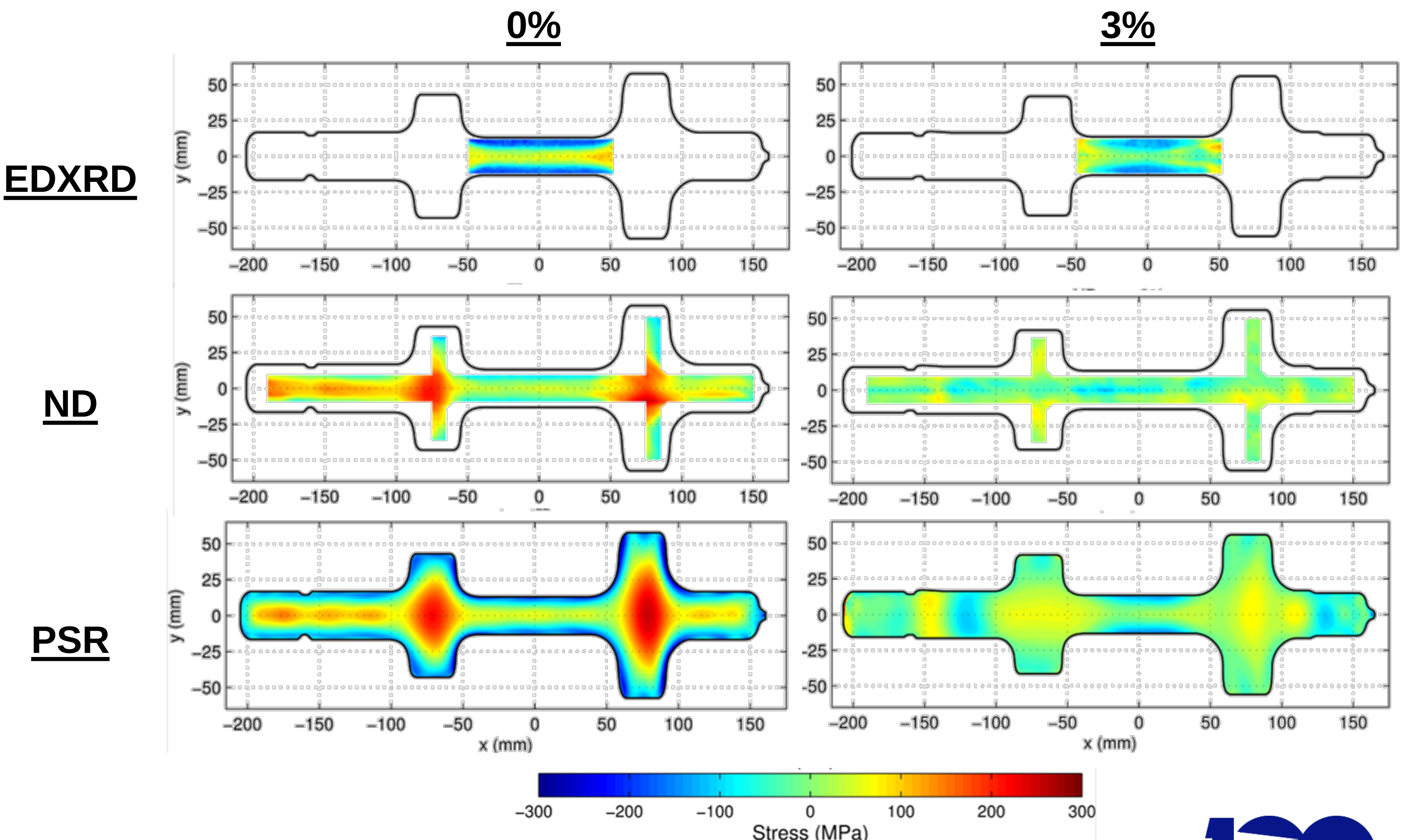
	0%	3%
EDXRD	Not Measured	Not Measured

ND

PSR



Measurement Results: σ_{zz}

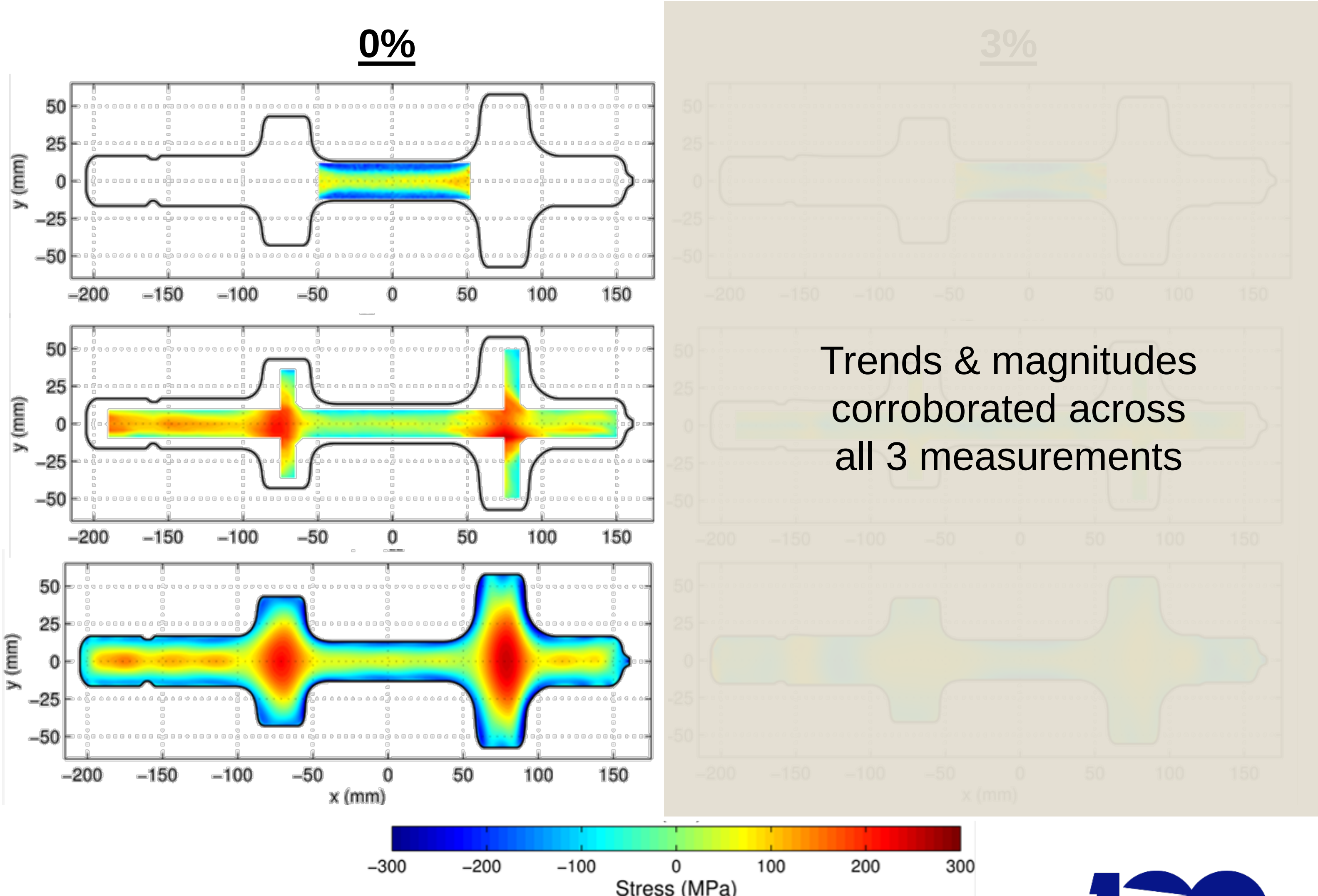


Measurement Results: σ_{zz}

EDXRD

ND

PSR



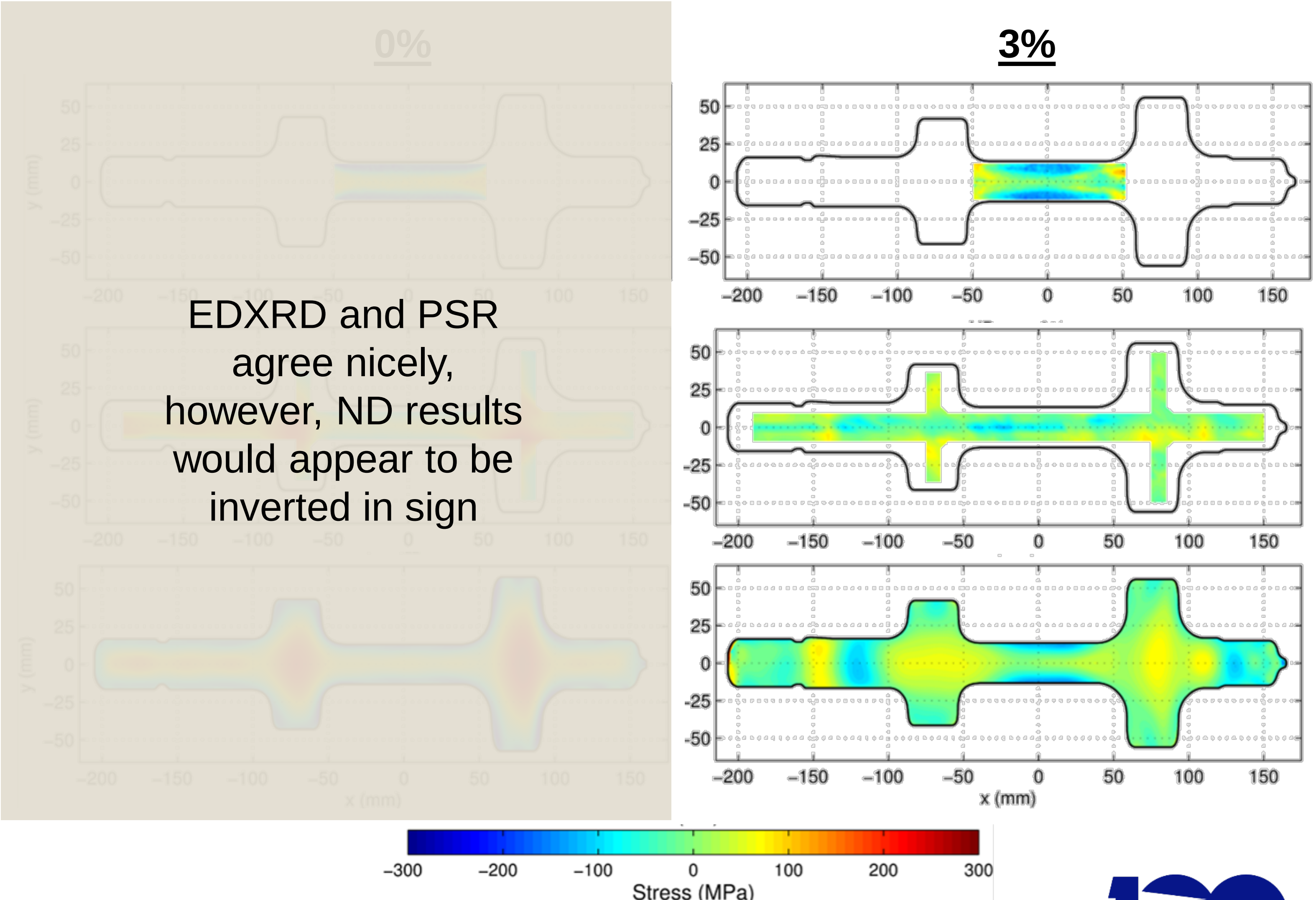
Trends & magnitudes corroborated across all 3 measurements

Measurement Results: σ_{zz}

EDXRD

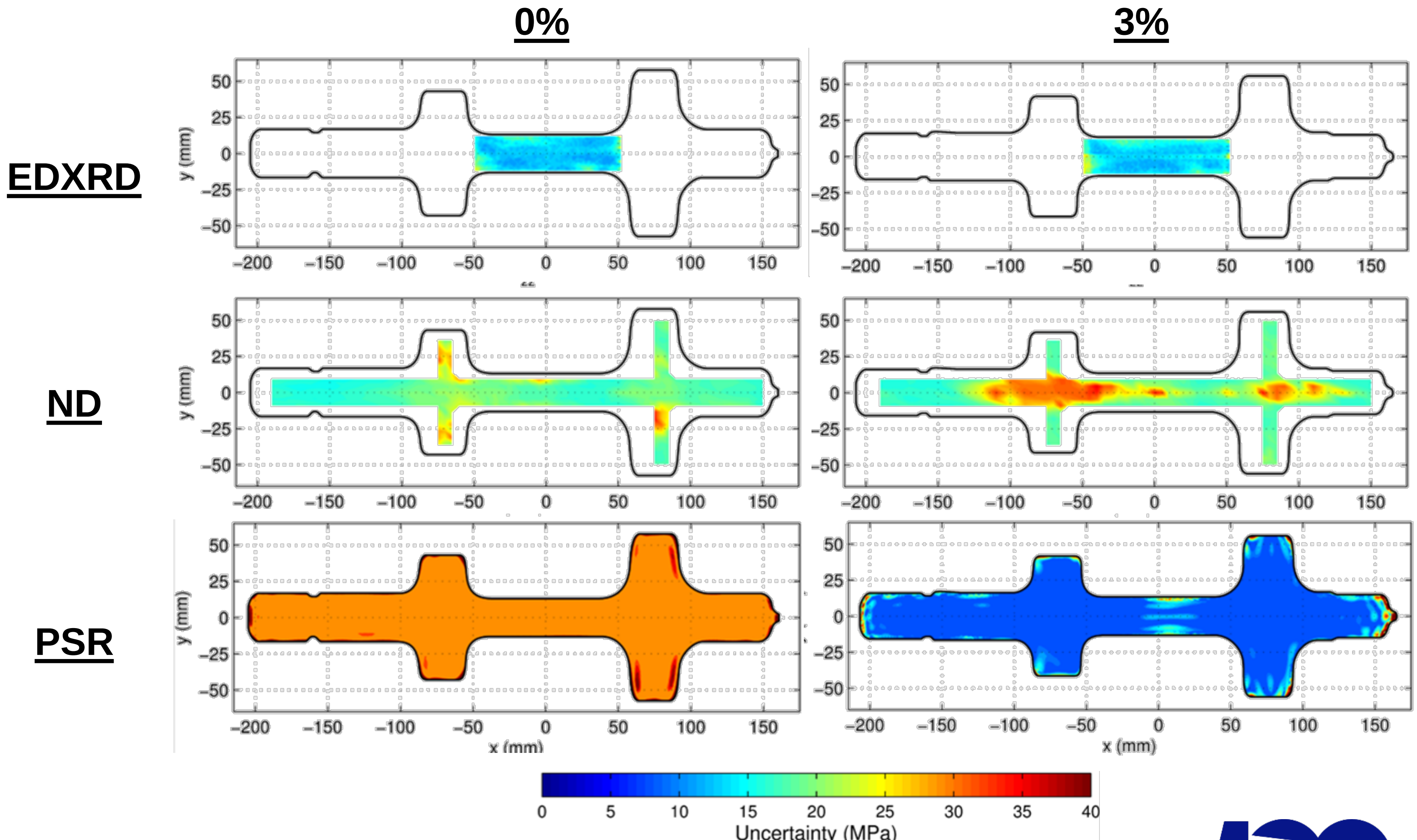
ND

PSR

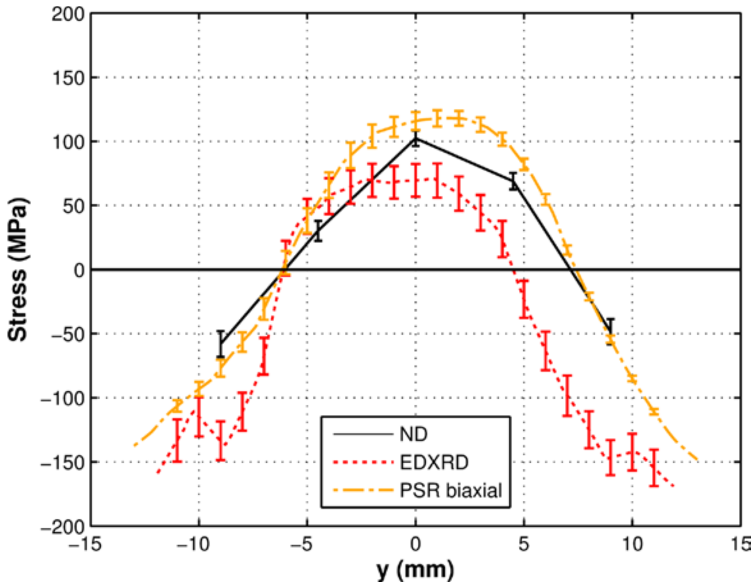


EDXRD and PSR agree nicely, however, ND results would appear to be inverted in sign

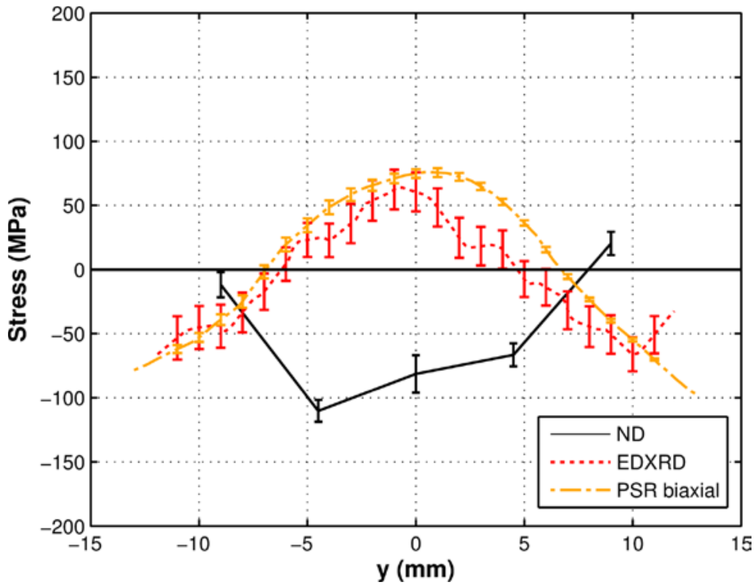
Measurement Results: $U\sigma_{zz}$



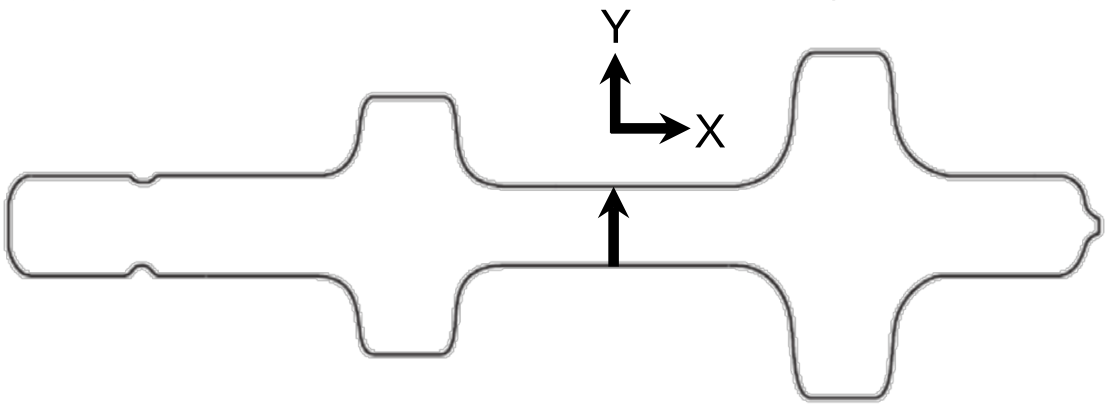
σ_{xx} Line Plots



0% Cold-work



3% Cold-work



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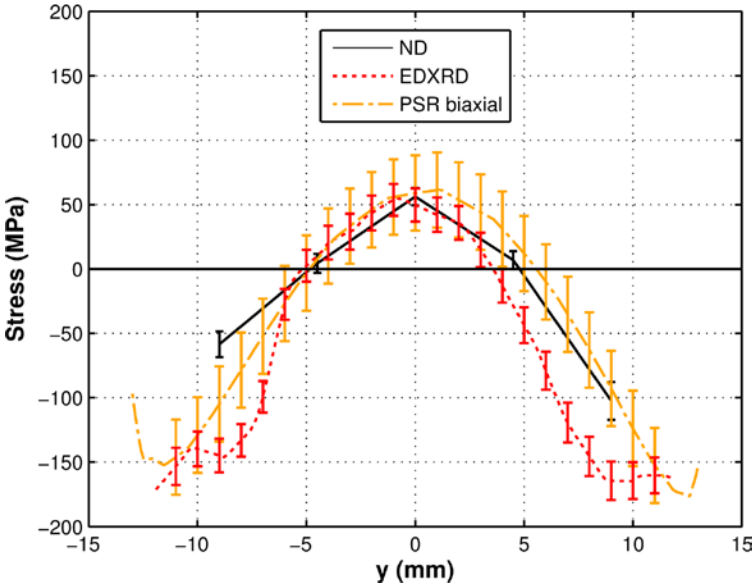
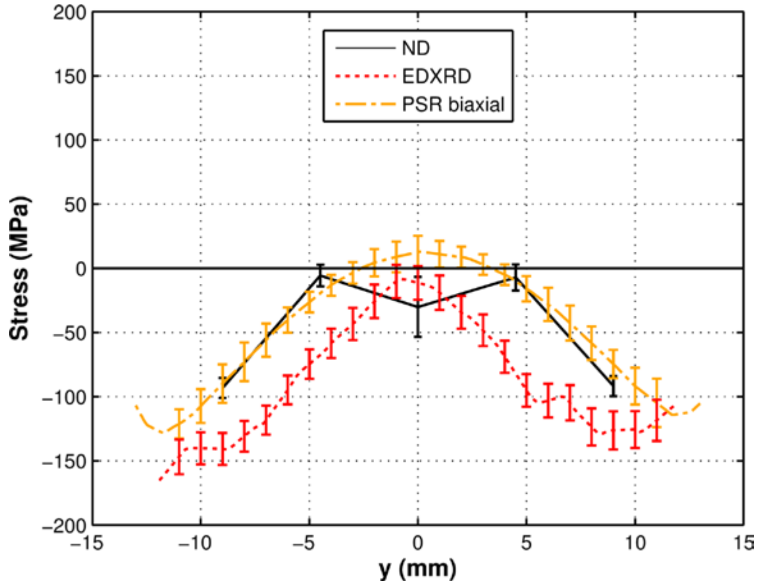
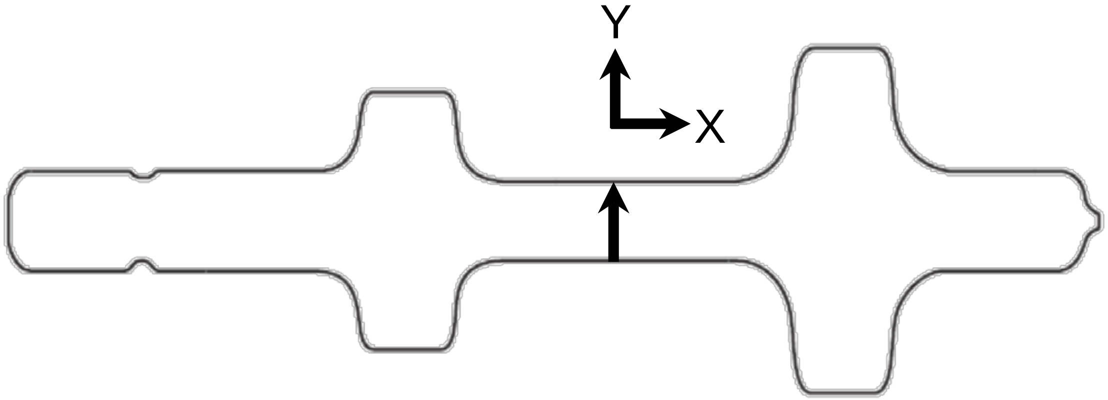
σ_{zz} Line Plots



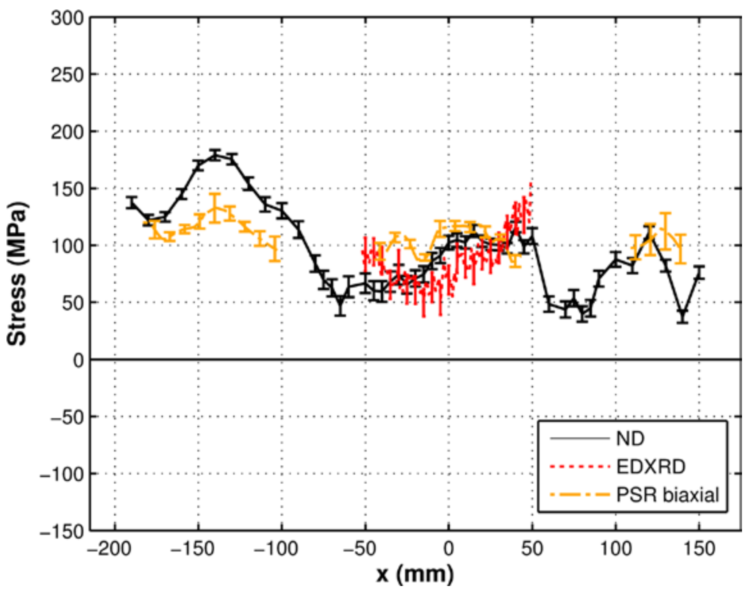
0% Cold-work



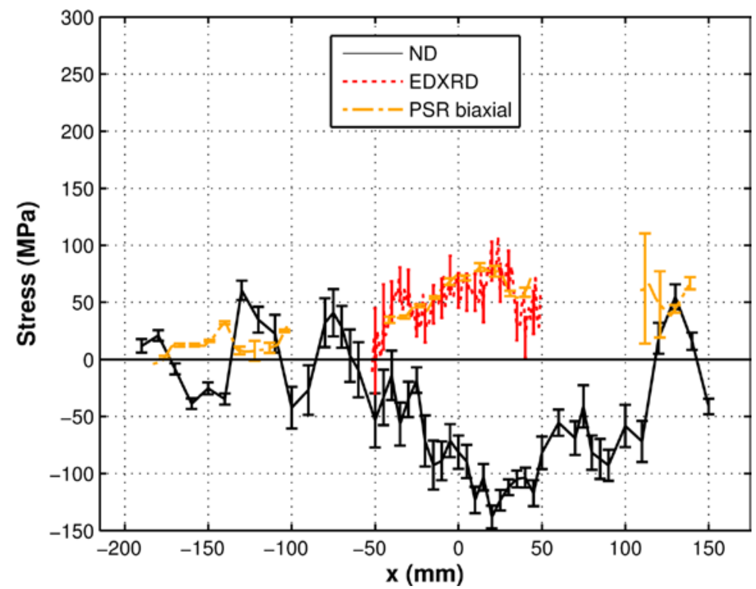
3% Cold-work



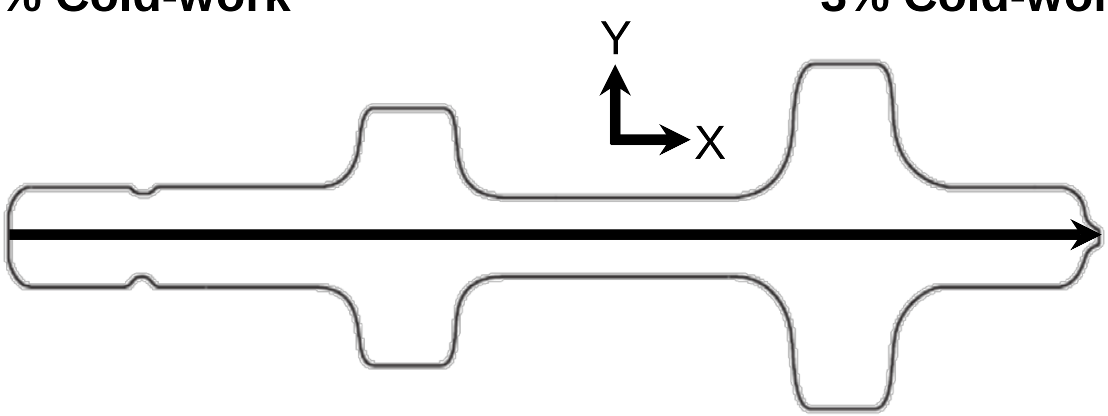
σ_{xx} Line Plots



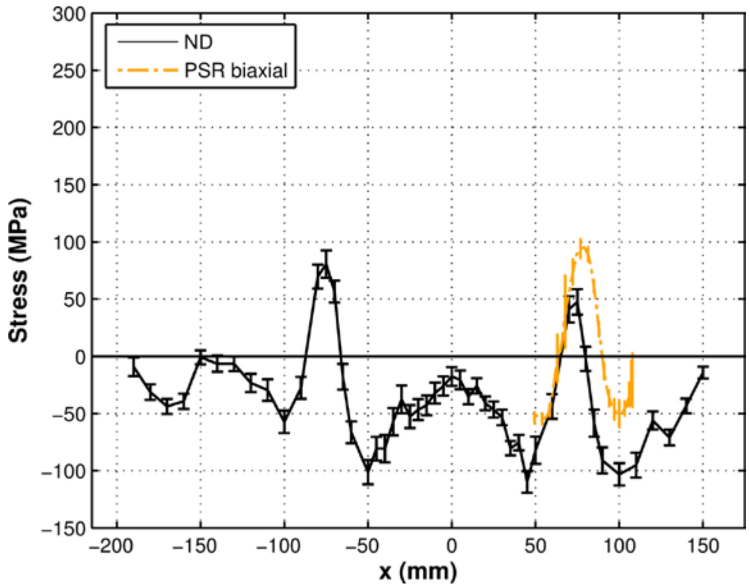
0% Cold-work



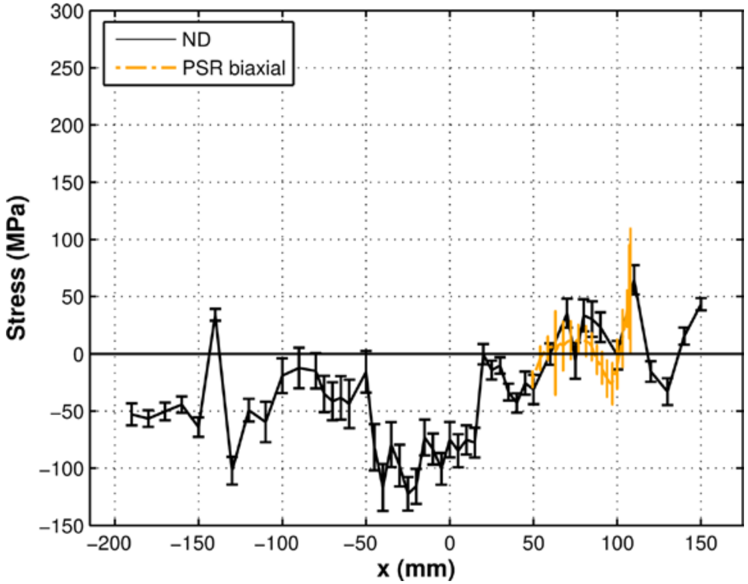
3% Cold-work



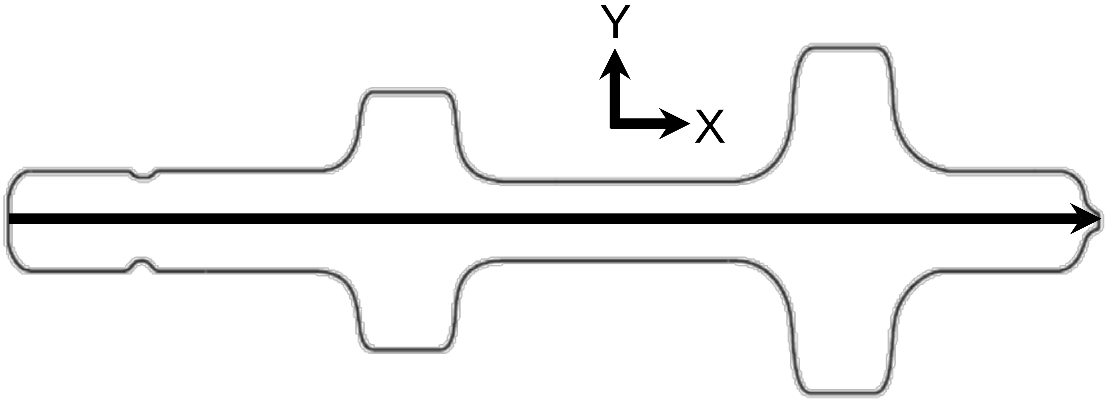
σ_{yy} Line Plots



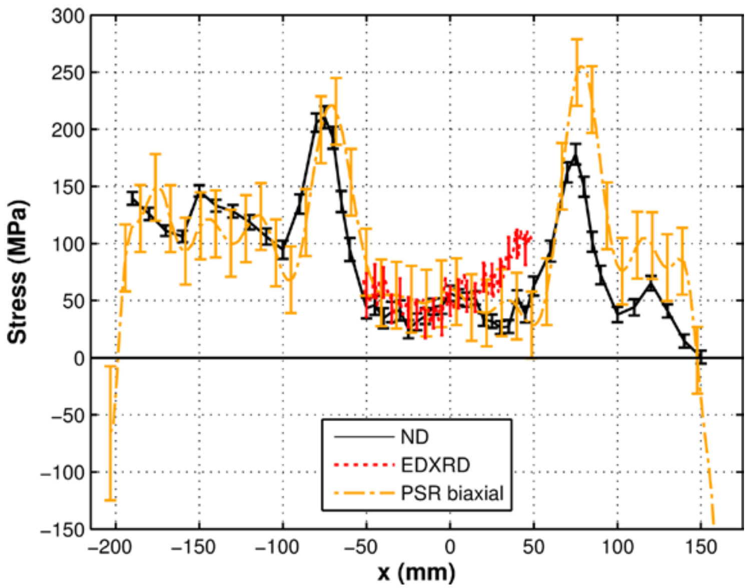
0% Cold-work



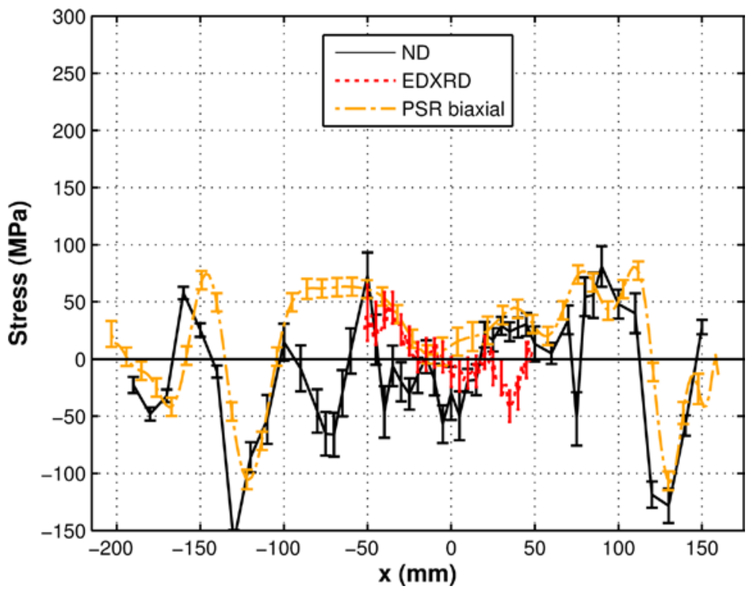
3% Cold-work



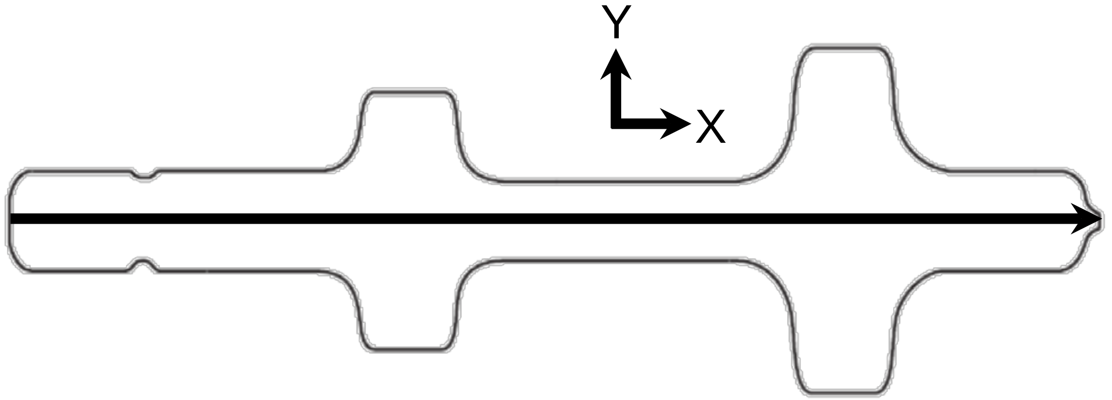
σ_{zz} Line Plots



0% Cold-work



3% Cold-work



Conclusions

- Cold working effectively reduces magnitude of bulk residual stresses due to forging process
- Questionable results from 3% cold work ND experiment
  - Currently investigating texture in 3% specimens
- All techniques are viable for 3-component tensor residual stress measurements
  - EDXRD limited by geometry and stress-state tri-axiality
  - PSR limited by magnitude of shear stress

Questions