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Learning and prediction of geometrical dimensions in wire and arc additive manufacturing

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Faculty of Engineering Technology, University of Twente

This research is part of AiM2XL program:

Project1 – Microstructure and process based topology optimization for direct metal deposition

Daily Supervisor, Dr. Ir. Tom Vaneker, University of Twente

Project Leader, Dr. ir. Matthijs Langelaar, Delft University of Technology

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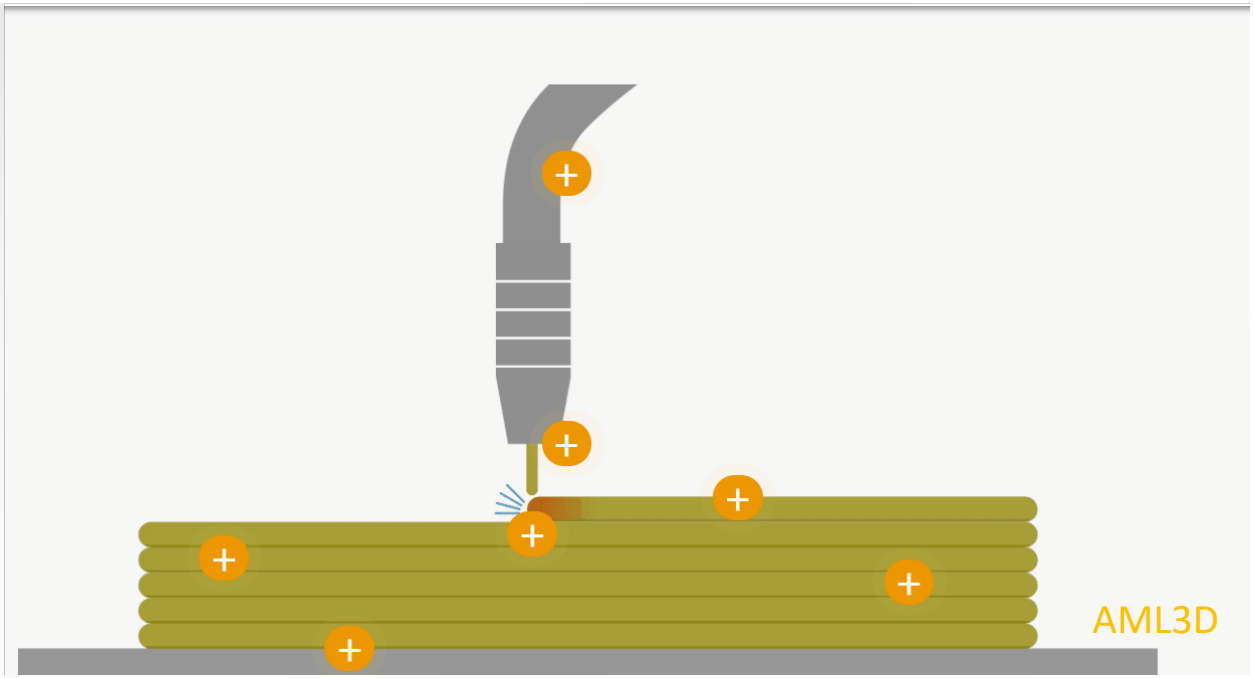
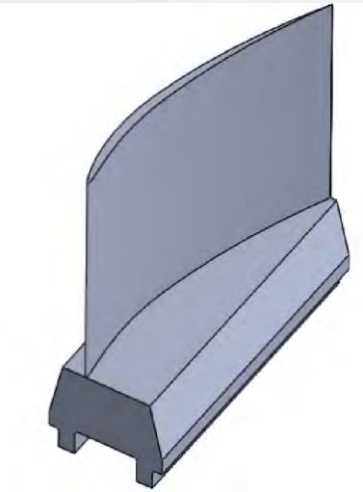
Industry Needs – A bit of motivation



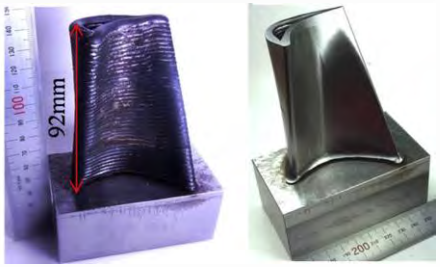
- WAAM is one-of-a-kind manufacturing
- Huge varieties and shape complexity
- Heterogeneous fabrication conditions with variations
- Disparate data generated under different process conditions

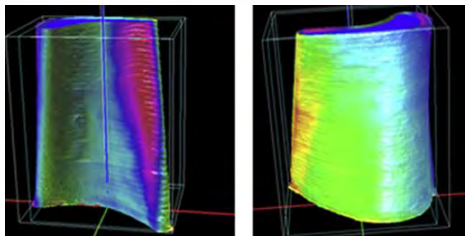
Industry Needs – A bit of motivation



34% energy saving

Campatelli et al. (2020); DOI: 10.1007/s40684-019-00071-y





Material removed could be reduced to 25%

Nagamatsu et. al. (2020); DOI: 10.1016/j.addma.2019.100896

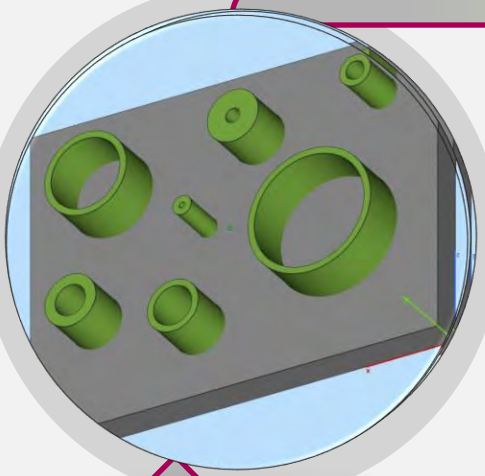
The overall used approach in the Aim2XL program

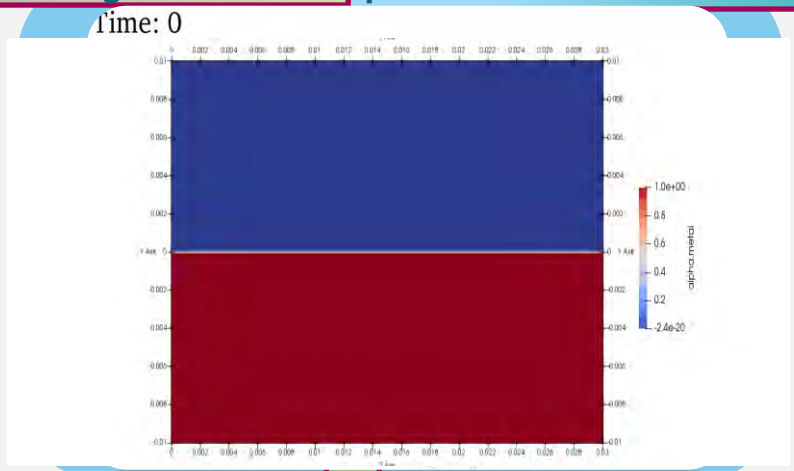
Design

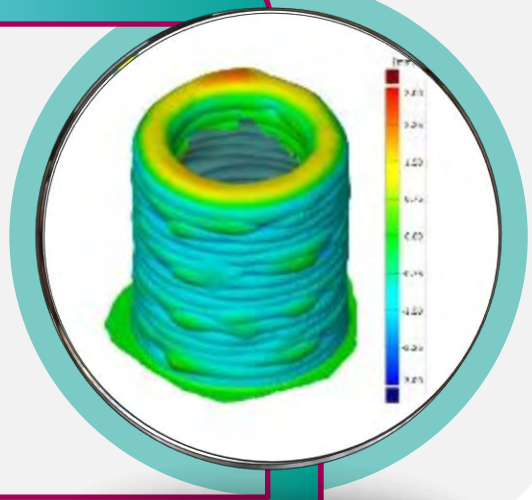
Process Simulation

Geometrical Performance

Integrated WAAM process controller







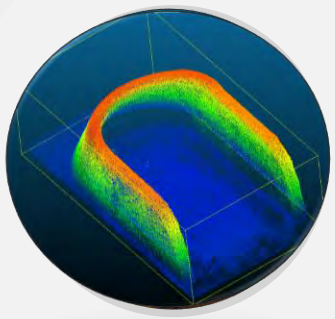
Continues improvement

Insight from performance

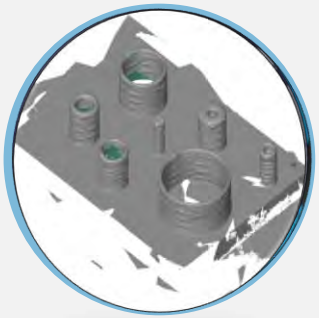
Outline – the focus of this talk

- Motivation: How to quickly learn deformation of WAAM produced parts for compensation plan based on limited benchmark test artefacts?
- Background
- Shape deviation control in WAAM
  - ✓ Assessing the deviation
  - ✓ Shape transformation for deviation modelling
  - ✓ Predictive deviation modelling using machine learning
- Summary and on-going research

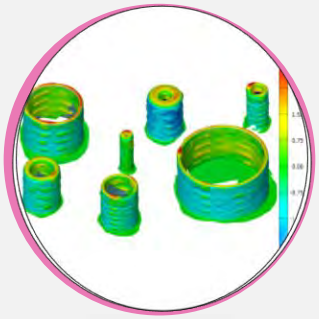
Shape deviation control in WAAM



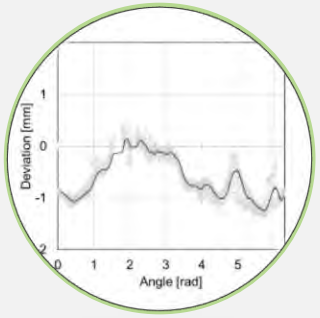
Point cloud



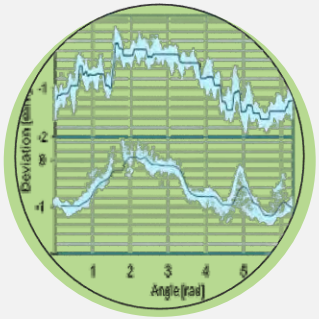
Gather layer boundary point



Obtain In-plane deviation data



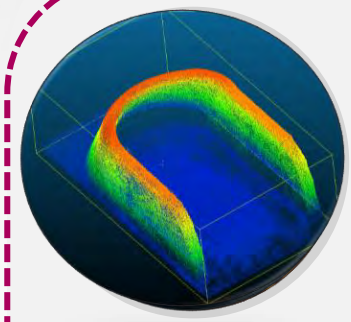
Shape transformation modelling



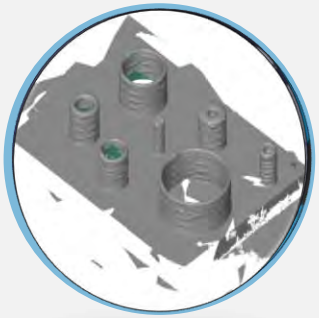
Predictive modelling using ML

- ✓ We develop a framework that enables automated deviation modelling from point cloud data collected across different processes and shapes in WAAM.

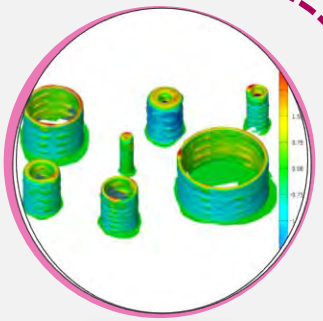
Shape deviation control in WAAM



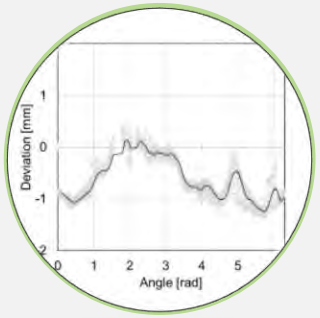
Point cloud



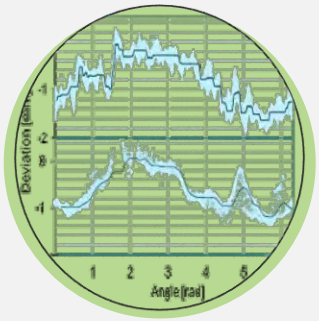
Gather layer boundary point



Obtain In-plane deviation data



Shape transformation modelling



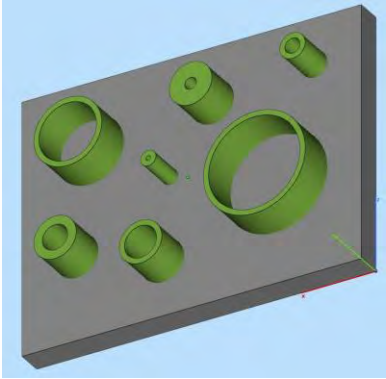
Predictive modelling using ML

Assessing the deviation

Assessing the deviation: Benchmark test artifact and processing parameters

✓ Processing parameters in the experiment

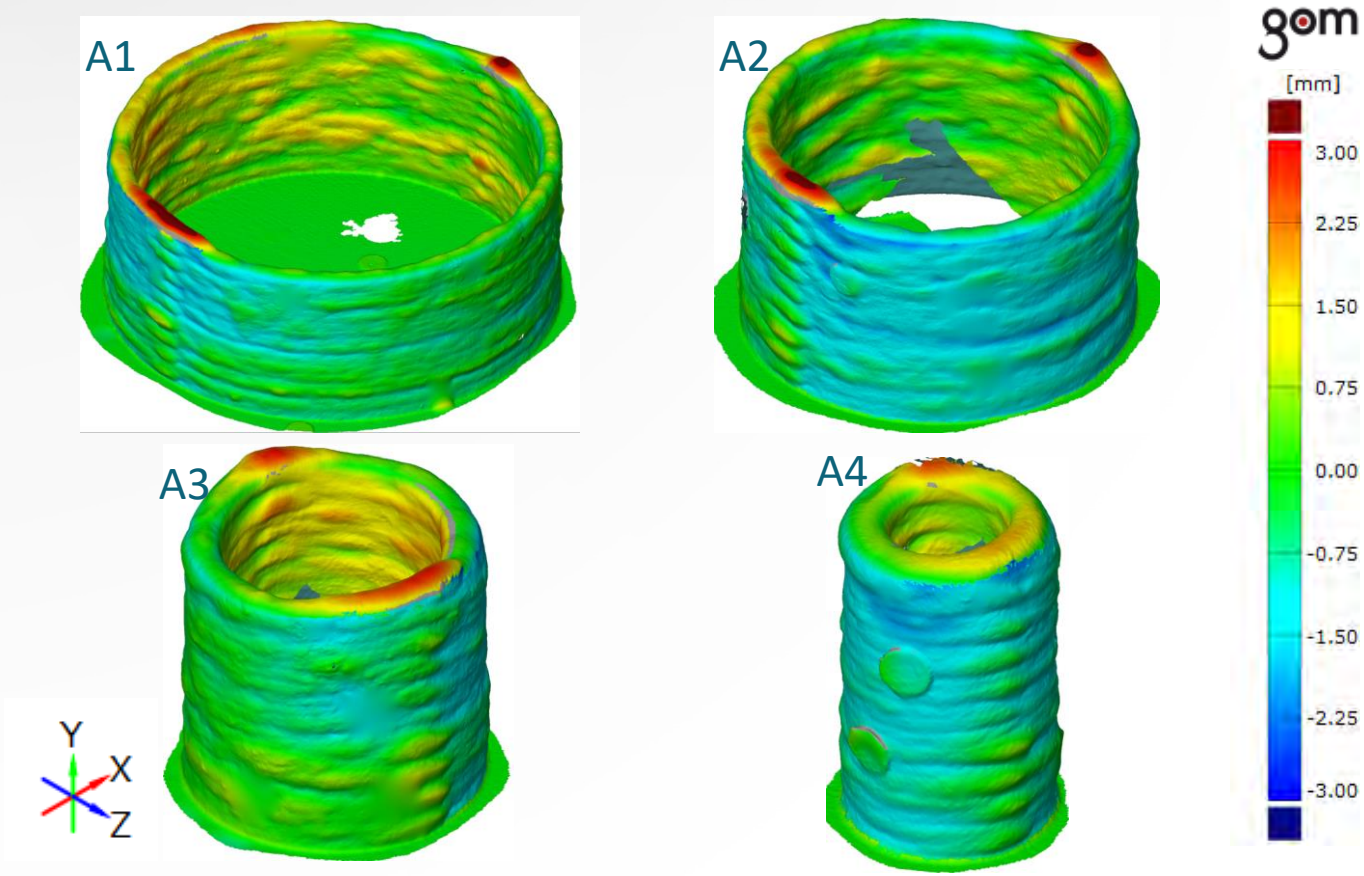
Specifications	A
Machine	Fronius TransPulsSynergic 3200 CMT R
Heat source	GMAW power source
Deposition strategy	Parallel overlapping
Voltage (V)	15.3
Current (A)	182.6
Travel speed (mm/min)	420
Wire feed speed (mm/min)	6000
Interlayer temperature (C)	50-90
Wire material	S690 (LNM MoNiVa)
Wire dimeter (mm)	Ø 1.2 mm
Number of layers	19



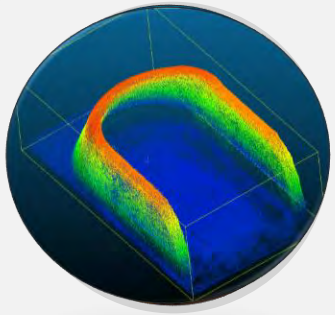
45 mm height
6 mm thickness: Ø20, 30, 50, 80, 20
10 mm thickness: Ø50
18 mm thickness: Ø50

Assessing the deviation: Qualitative analysis

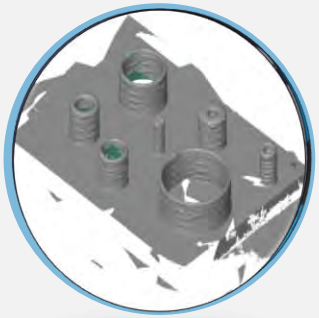
- ✓ Postprocess measurement data for inspecting part geometries



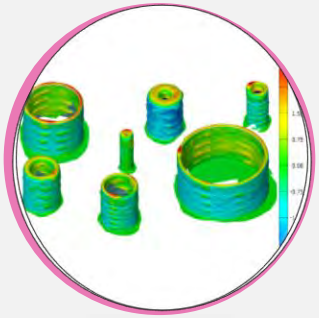
Shape deviation control in WAAM



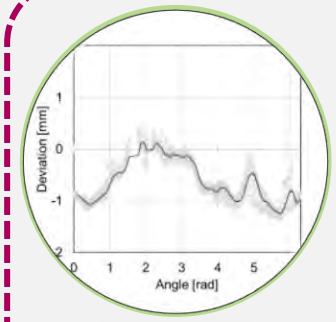
Point cloud



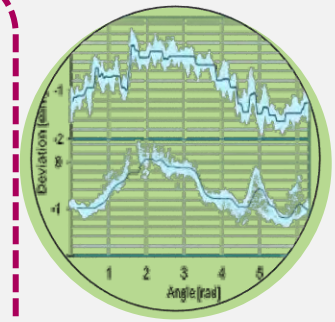
Gather layer boundary point



Obtain In-plane deviation data



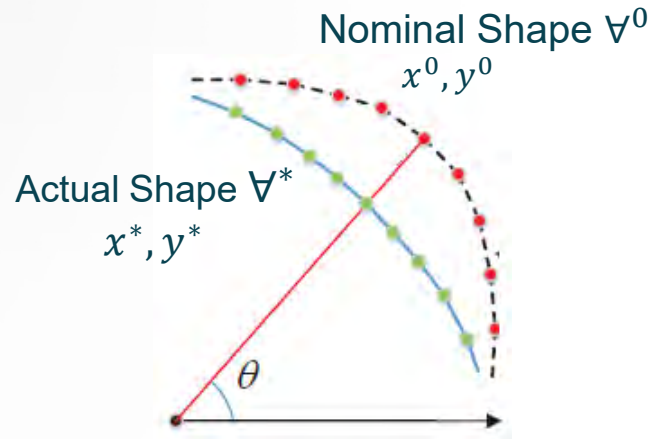
Shape transformation modelling

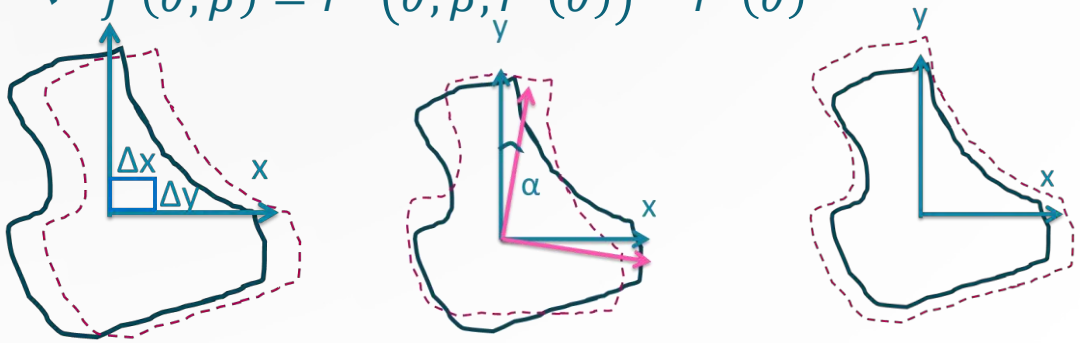


Predictive modelling using ML

Shape transformation for deviation modelling

- We transformed point cloud measurements
- Mathematical relationship
  - ✓ $\beta\left(\varphi_x, \varphi_y, \alpha, \Delta x, \Delta y\right)$
  - ✓ $(x^*, y^*, 1)^T = M^S M^R M^T (x^0, y^0, 1)^T$
  - ✓ $f\left(\theta; \beta\right) = r^*\left(\theta; \beta, r^0(\theta)\right) - r^0(\theta)$





Translation

$$M_S = \begin{bmatrix} s_x & 0 & 0 \\ 0 & s_y & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

Rotation

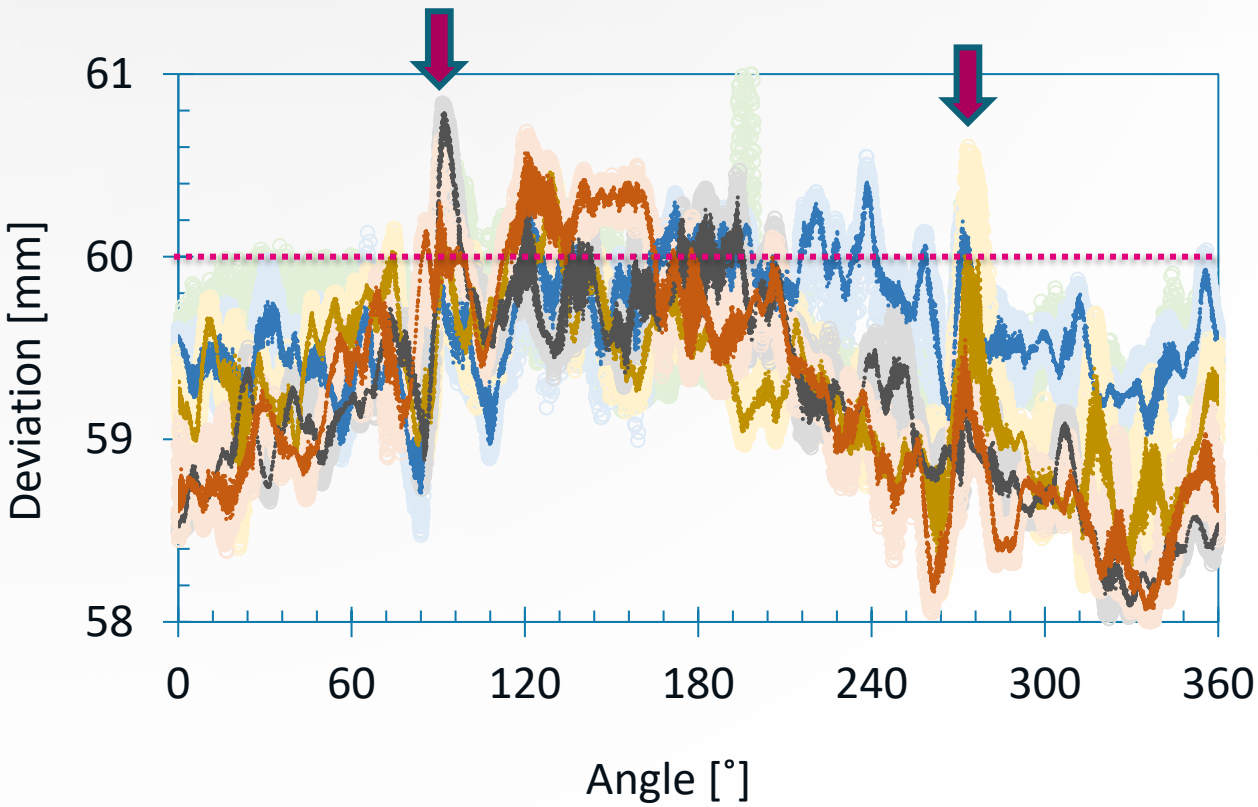
$$M_R = \begin{bmatrix} 1 & 0 & \Delta x \\ 0 & 1 & \Delta y \\ 0 & 0 & 1 \end{bmatrix}$$

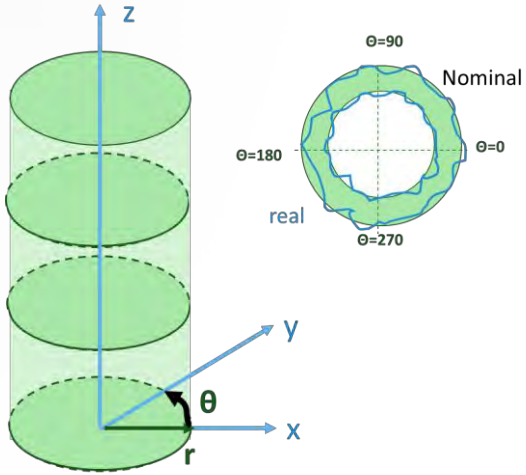
Scaling

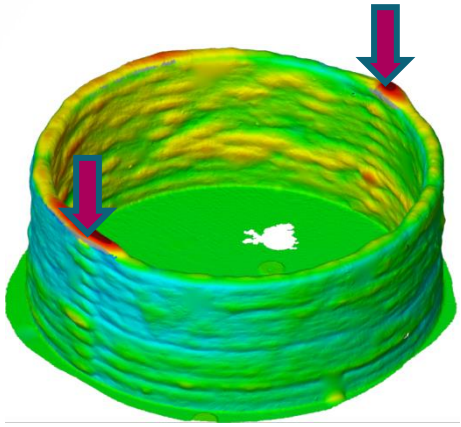
$$M_T = \begin{bmatrix} \cos(\varphi) & -\sin(\varphi) & 0 \\ \sin(\varphi) & \cos(\varphi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Shape transformation for deviation modelling

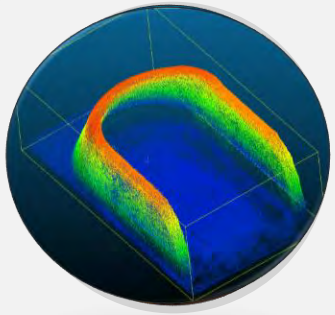
- ✓ Deviation profiles of cylinder A1 with a nominal radius of 60 mm at different layers



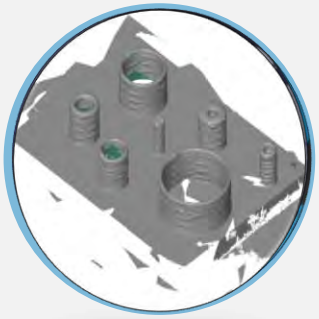




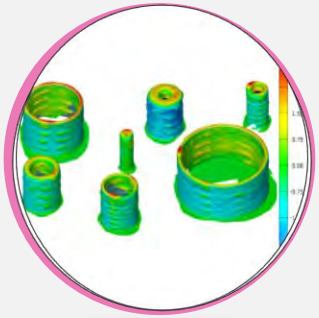
Shape deviation control in WAAM



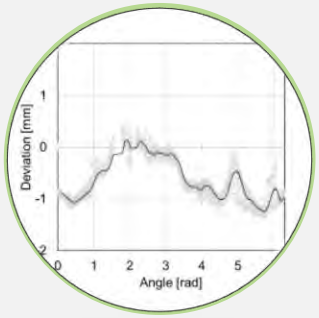
Point cloud



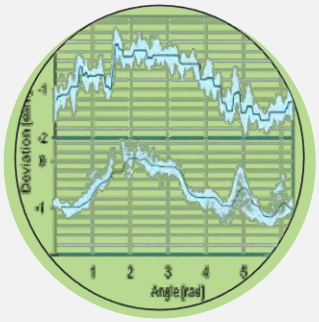
Gather layer boundary point



Obtain In-plane deviation data



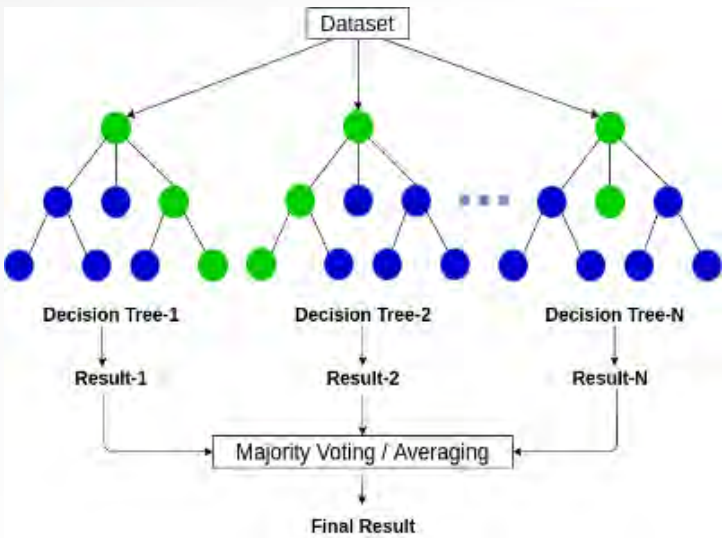
Shape transformation modelling



Predictive modelling using ML

Predictive deviation modelling using machine learning

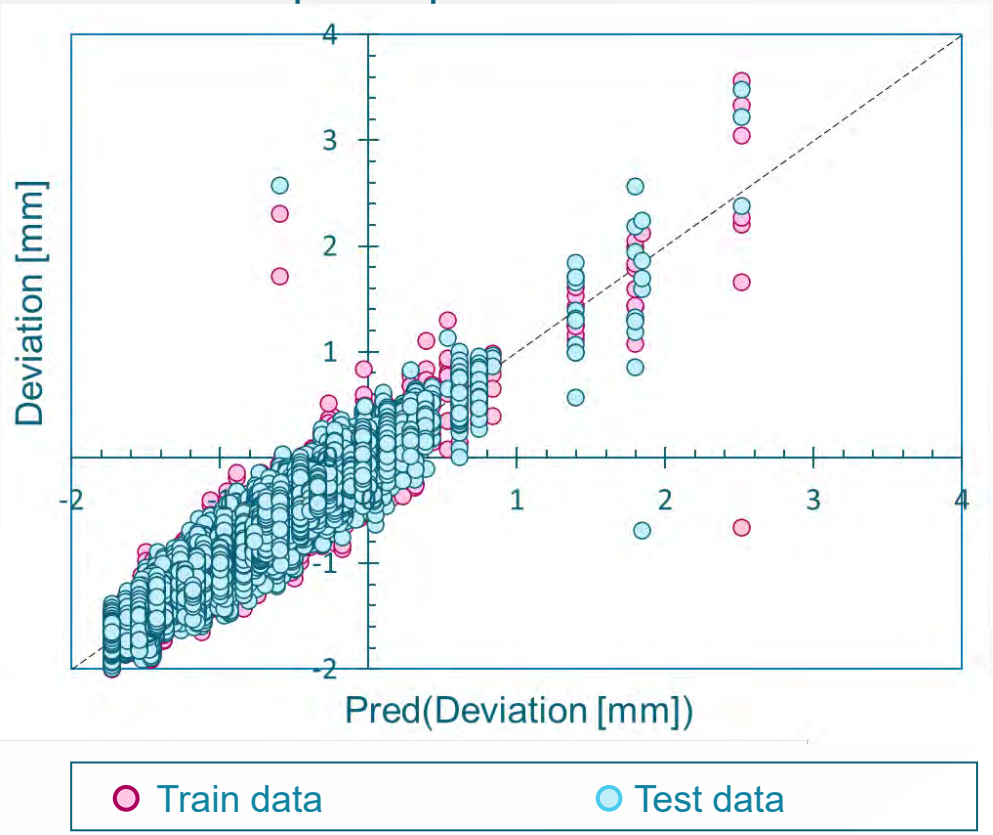
- We utilized Random Forest method
  - ✓ Input cell: r_n, θ, z
  - ✓ Output cell: deviation



- We used various metrics to evaluate the models' performance
  - ✓ Mean Absolute Error: $MAE = \frac{\sum_{i=1}^{n} |y_i - y_t|}{n}$
  - ✓ Mean Absolute Percentage Error: $MAPE = \frac{\sum_{i=1}^{n} \left| \frac{y_i - y_t}{y_i} \right|}{n} \times 100$

Predictive deviation modelling using machine learning

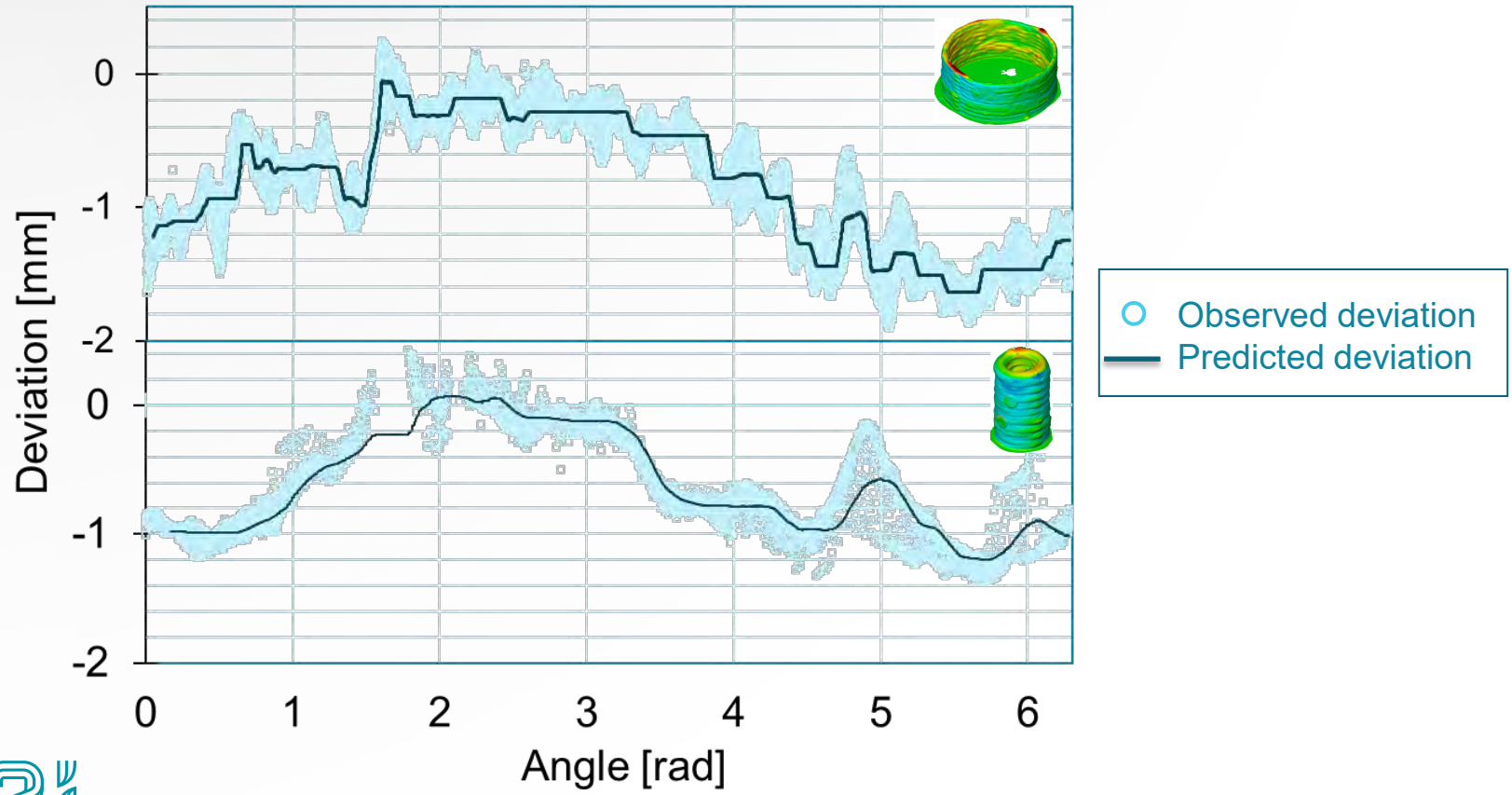
- ✓ We randomly selected 60% of the input data as training set
- ✓ We compared predicted values and observed values



Prediction Errors			
	MAE	R^2	MAPE (%)
A1	0.015	99.76	8.19
A2	0.014	99.81	7.37
A3	0.011	99.89	5.78
A4	0.007	99.91	3.26

Predictive deviation modelling using machine learning

- ✓ The prediction results on two cylinder radii: A1 (60 mm) and A4 (15 mm)
- ✓ The main patterns in shape deviation are captured



Summary

- We develop a new framework to model the systematic deviations in WAAM with limited experimental runs.
  - ✓ The method combines a transformation perspective and a ML method.
  - ✓ Random forest predicts the shape deviation of WAAM process with a mean absolute percentage error of less than 8.2%.

- The deviation in a case study (cylindrical shapes) was presented – the methodology will be implemented in other geometrical features systematically.

Broader Impacts

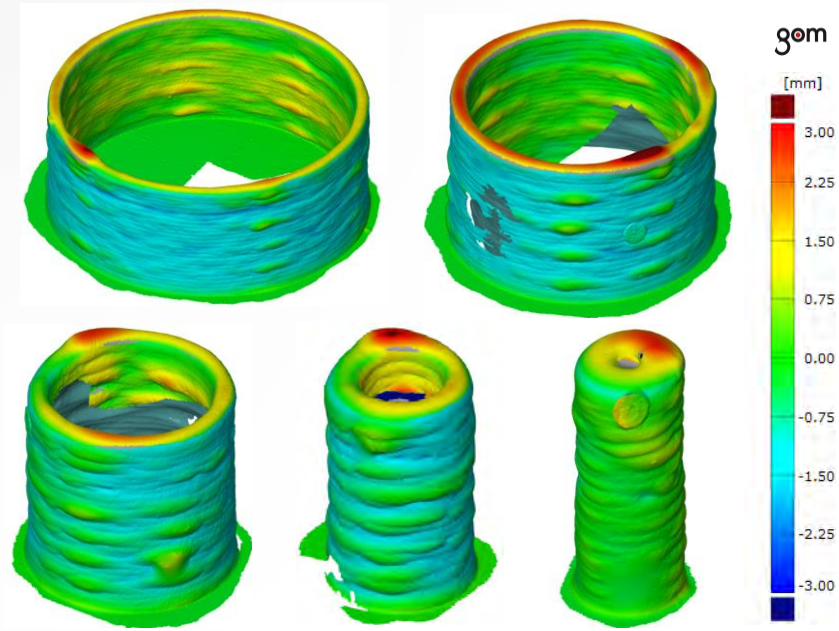
- Smarter control of WAAM with the potential of practical application for a large community of AM users.

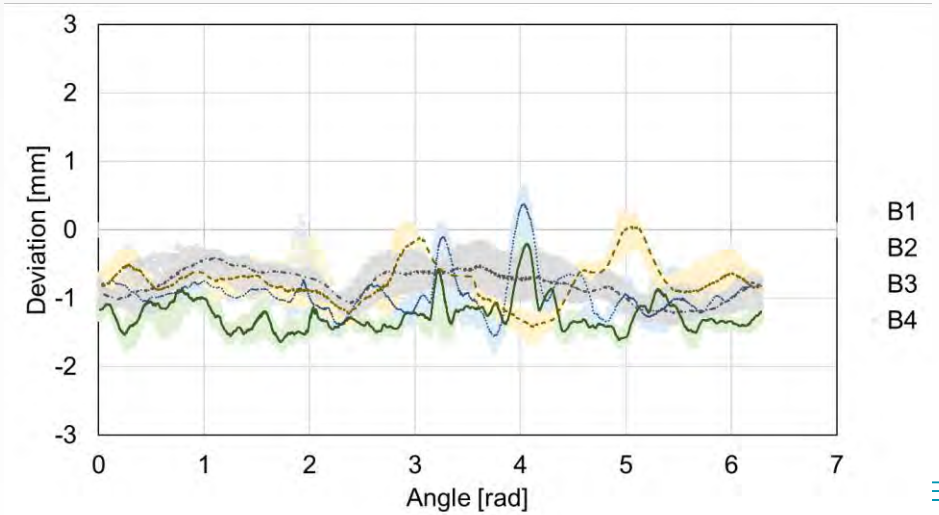
- This study will enable designers to evaluate the geometrical performance of WAAM products prior to manufacturing.

On-going research – Model Transfer

✓ Deviation modelling of cylinders under new processes

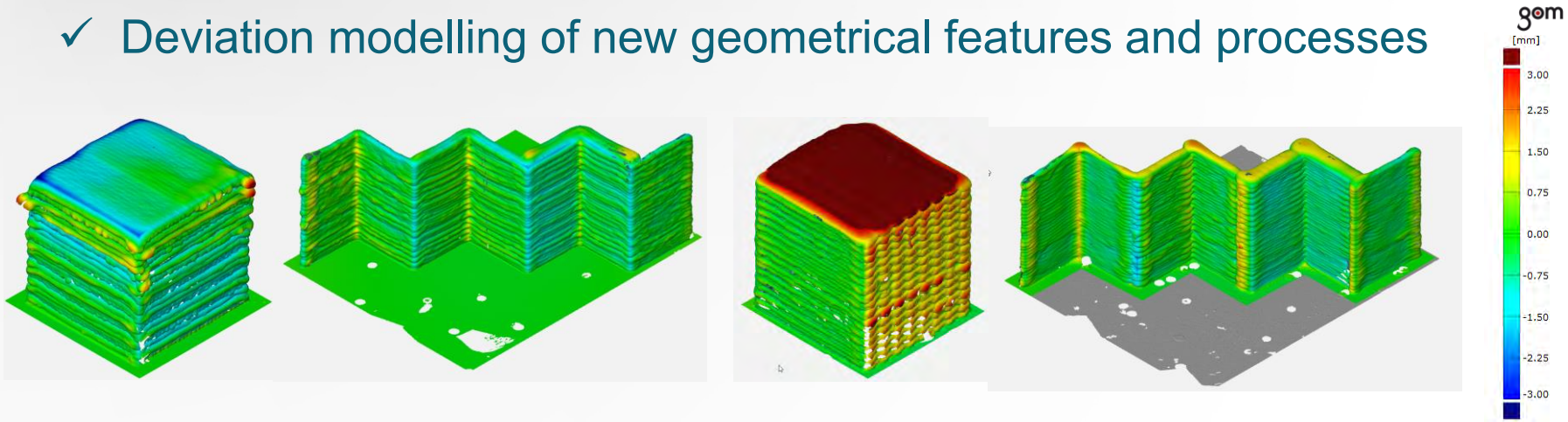
Specifications	B
Heat source	GMAW
Deposition strategy	Weaving strategy
Voltage (V)	14.1-15.8
Current (A)	105-142
Travel speed (mm/min)	170-1000
Wire material	SS 316L
Wire dimeter (mm)	Ø 1.2 mm
Number of layers	25

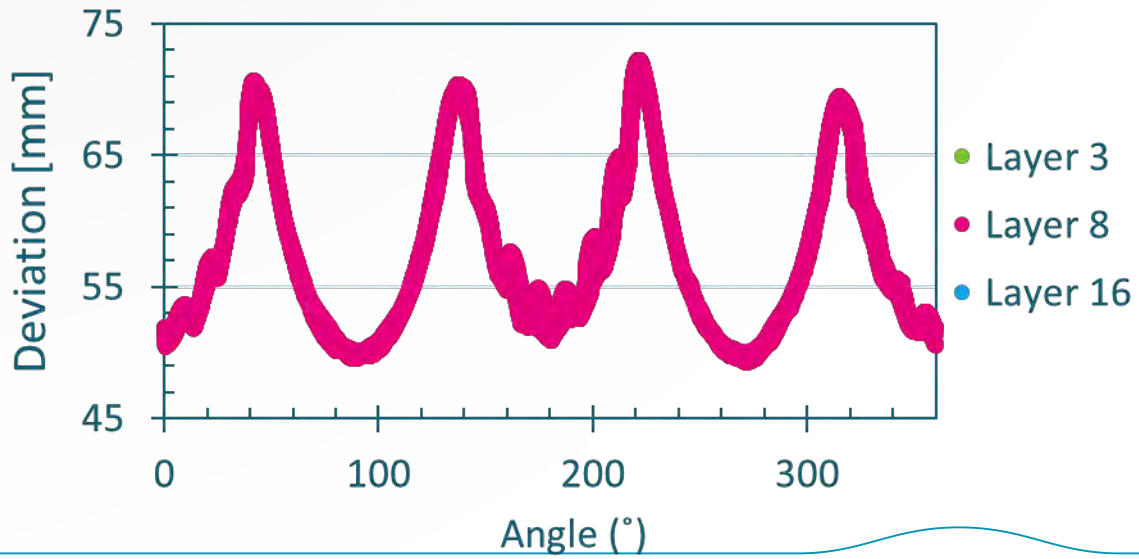




On-going research – Model Transfer

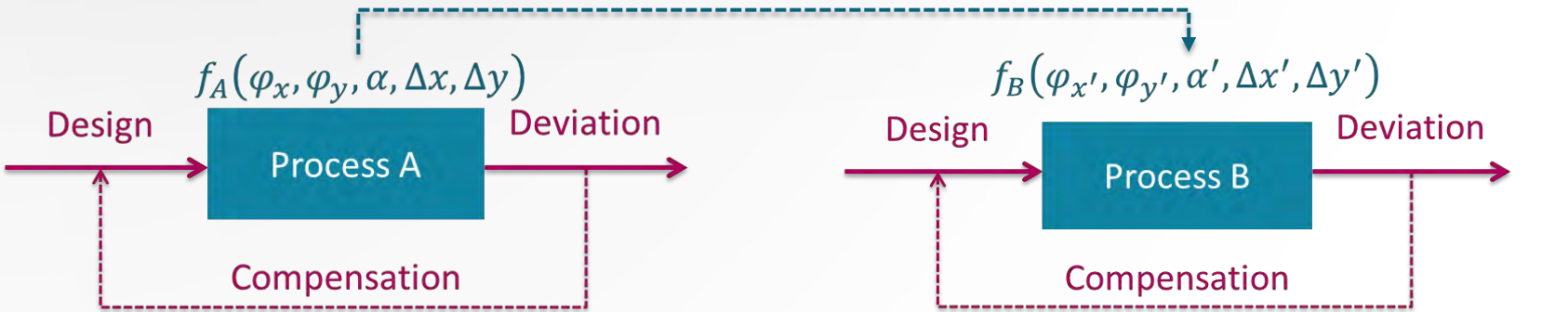
✓ Deviation modelling of new geometrical features and processes

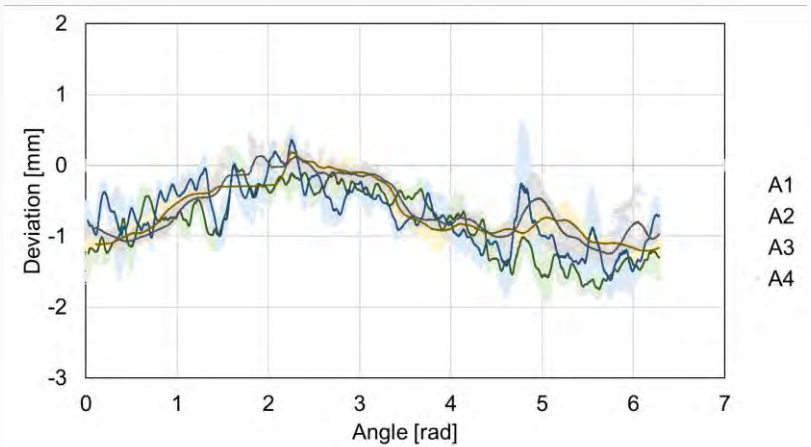


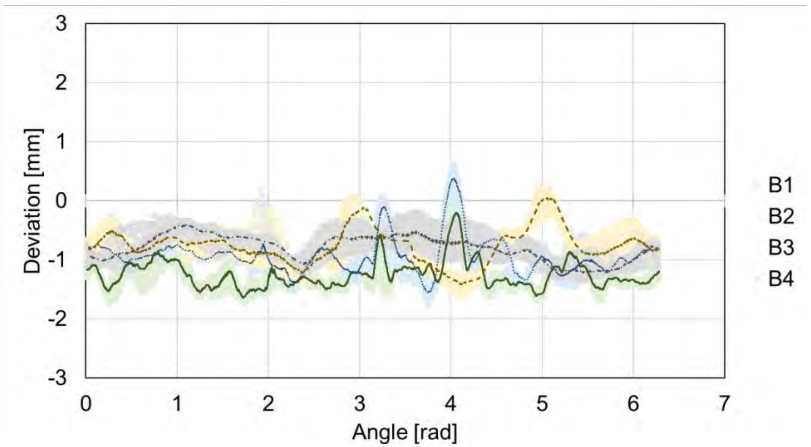


On-going research – Model Transfer

- How can we transfer the model across processes in WAAM characterized by different process conditions without repeating previous procedures?







Acknowledgement

- This research was carried out under project number P16-46/S17024x, which is part of AiM2XL program framework of the Partnership Program of M2i and NWO. The research was conducted in collaboration with industrial partners and supported by the RAMLAB.

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  - ✓ ir. Aravind Babu

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- UTwente
  - ✓ Dr. ir. Tom Vaneker
  - ✓ Thomas Vincent

Thanks for your attention

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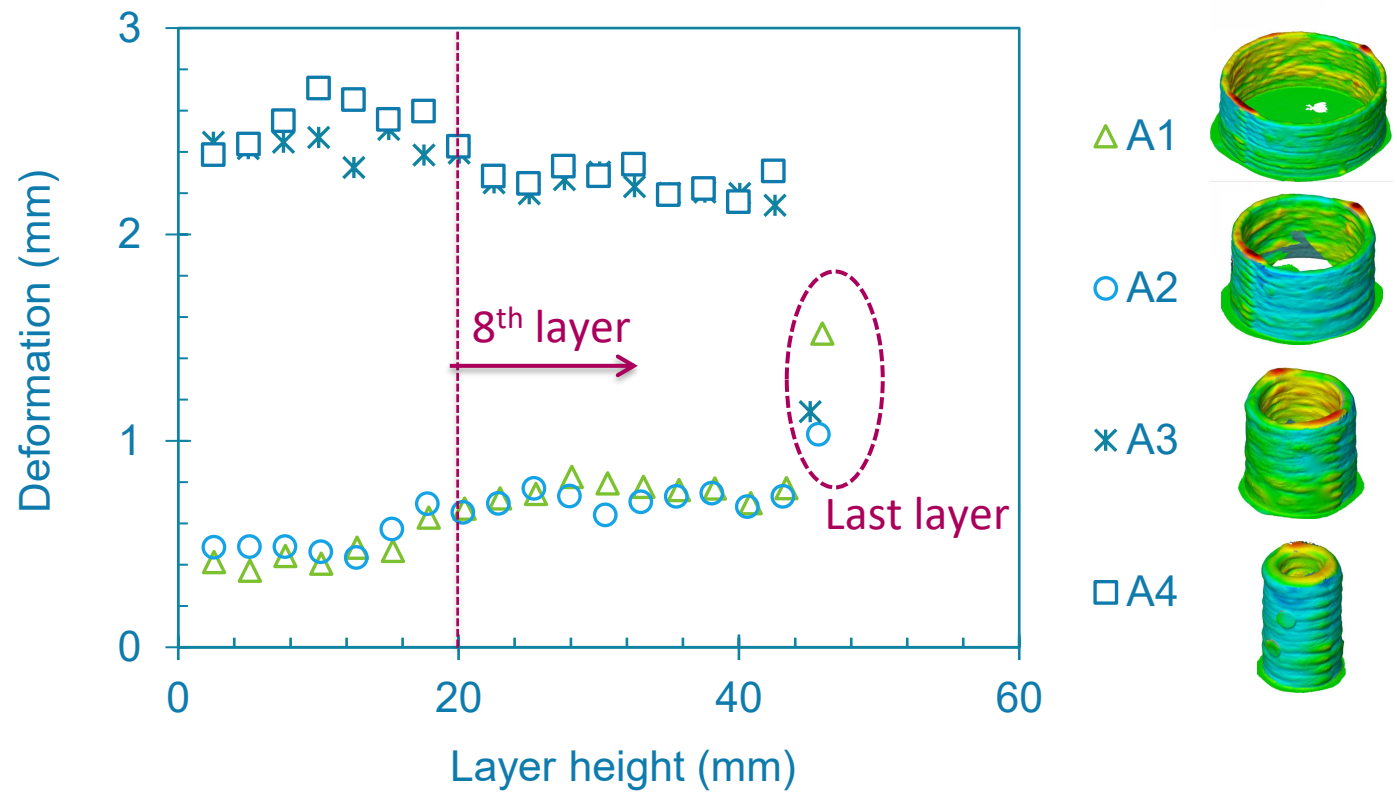
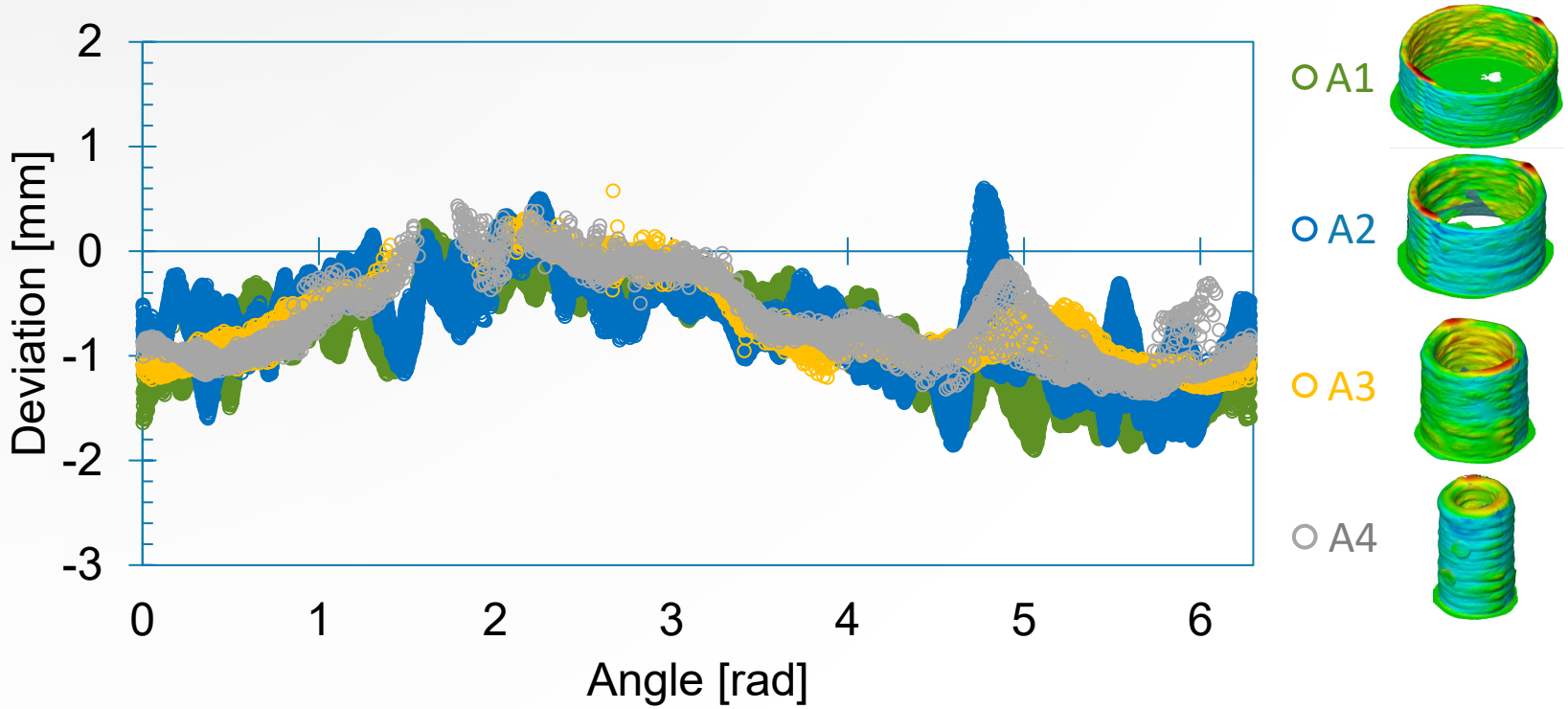
Assessing the deviation: Observation

- ✓ There are variations in the deformation profile along the wall height from the 1st to the 19th layer



Shape transformation for deviation modelling

- ✓ Deviation profiles of cylinders (A1, A2, A3, and A4) with nominal radius of 60, 40, 25, and 15 mm