A Computational Approach towards Proactive Scale Management for Steel Pipelines

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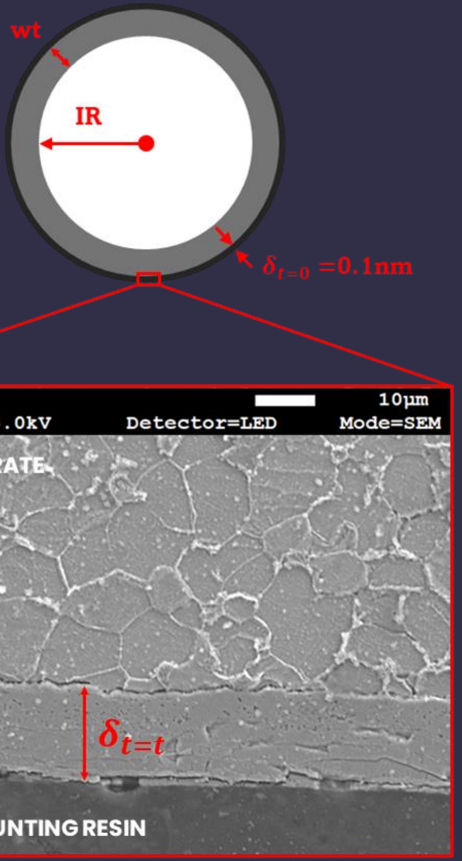
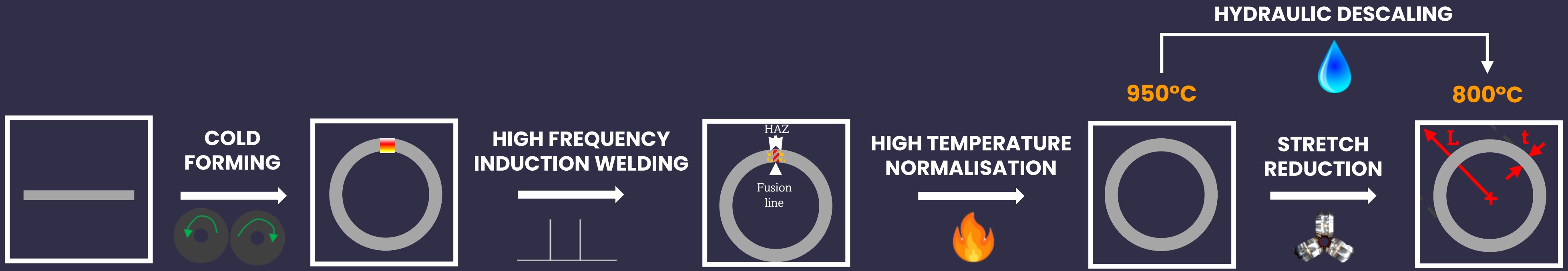
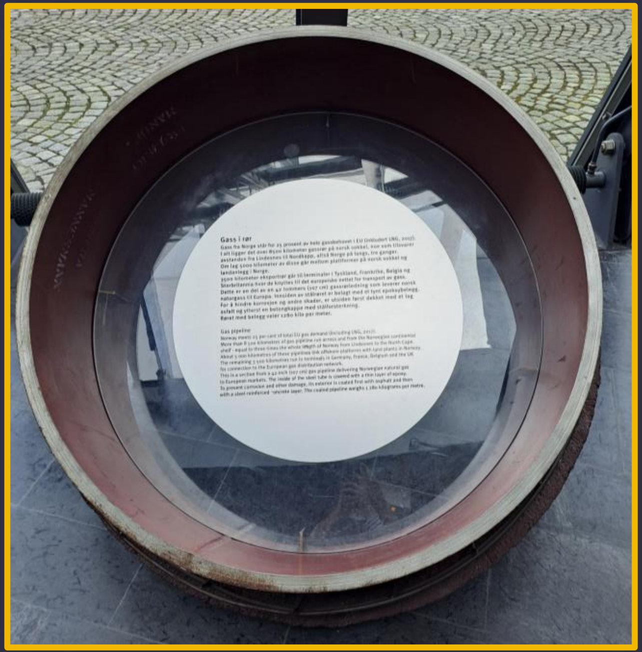
Tubes, TMP, and Thermochemistry



- **Oxide scale** growth on surface during high temperature processing
  - Yield loss – **1.5–3% total feedstock lost** due to scale
  - Surface **defects**
  - Premature **failure** (manufacture, installation and service)
  - Aesthetics – customer **product rejection**

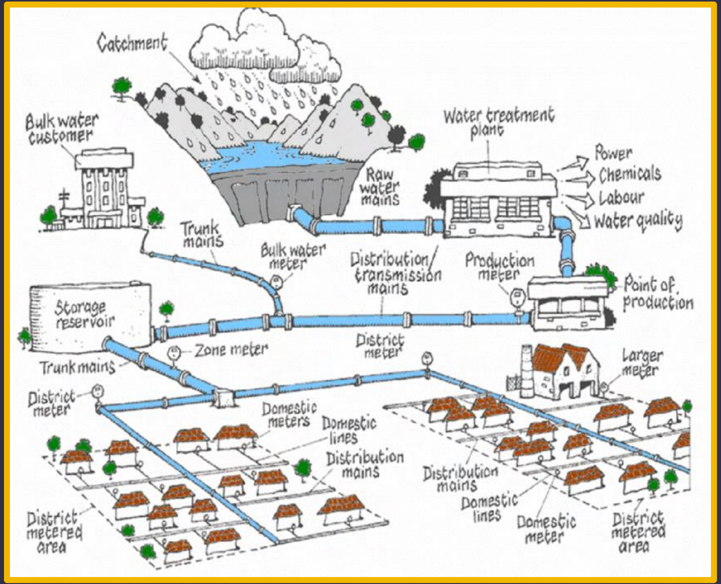


A shape of engineering significance...



(Norsk Oljemuseum, 2024)

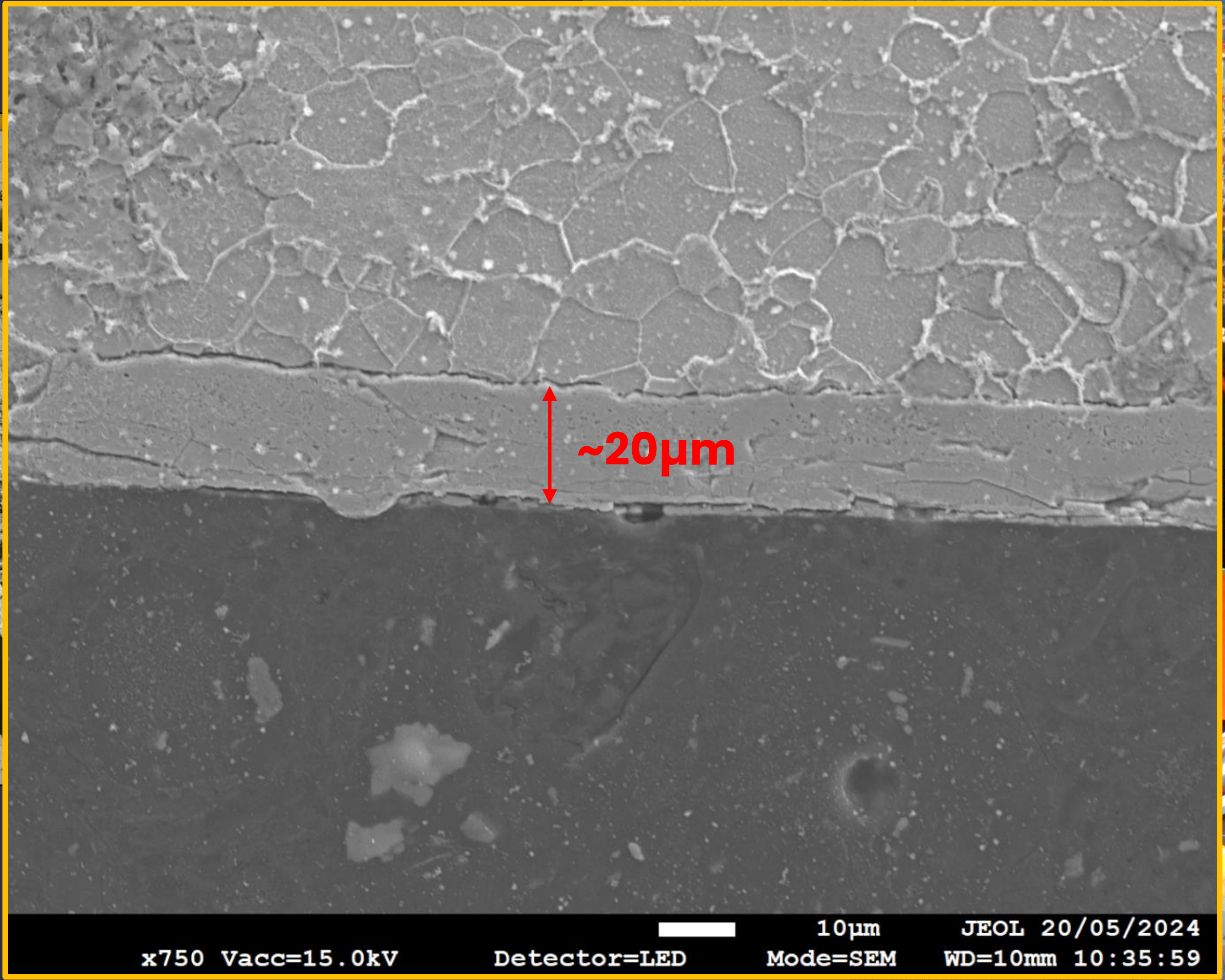
(BBC News, 2024)

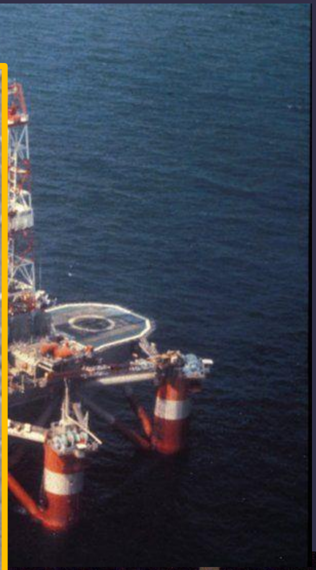


(E Romano, 2023)

Geometry matters…

(J Grant, 2019)

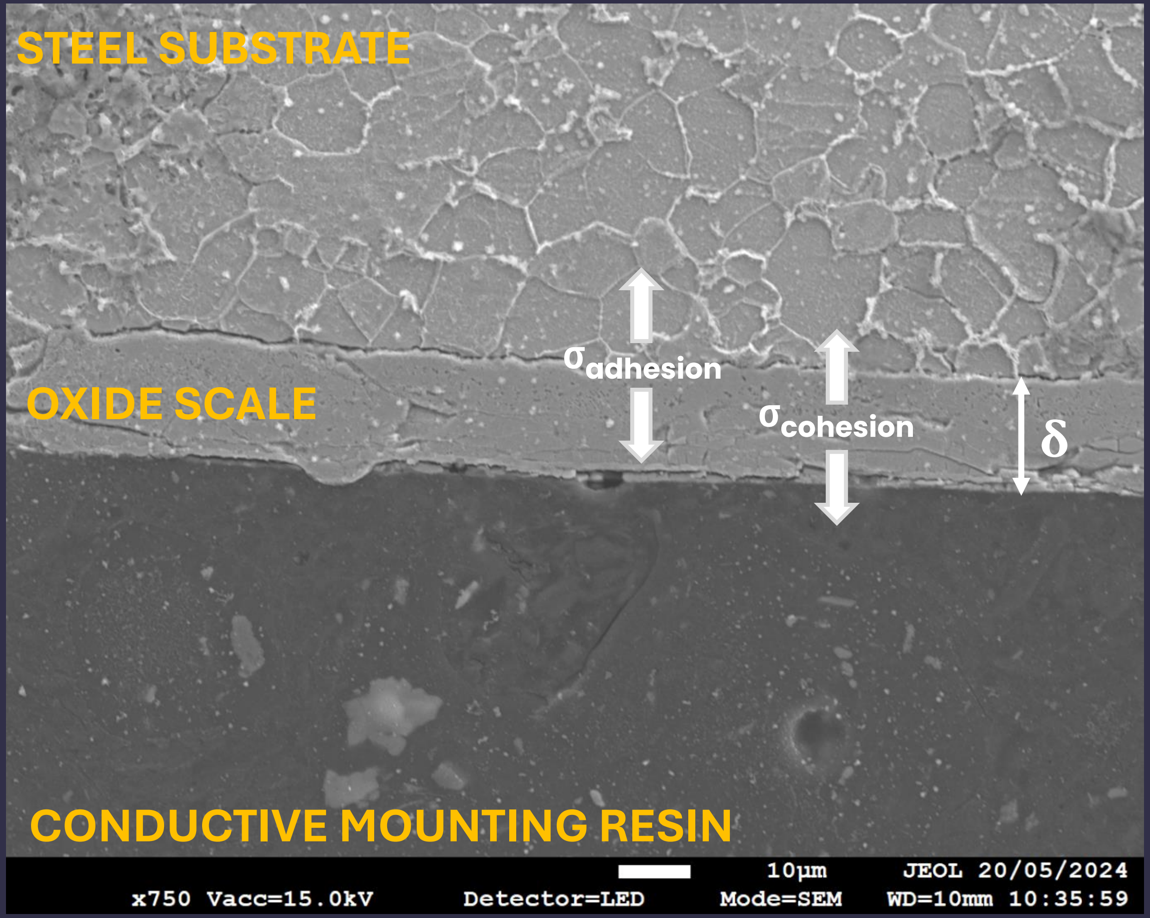




(Norsk Oljemuseum, 2024)

Project Background

$$\boldsymbol{Oxidation} = f\begin{pmatrix} Wall\ thickness, Chemistry, Thermal\ Cycle, \\ Furnace\ Environment, Heating\ Approach, Geometry \end{pmatrix}$$



- **Reduction of scale**
  - Reduced plant damage and contamination
- **Improved surface quality**
  - Consistent and predictable failure mode
- Key scale parameters
  - Thermodynamic – **thickness,** δ
  - Mechanical – adhesive/cohesive **strength,** $\sigma_{adhesion/cohesion}$

Project Background

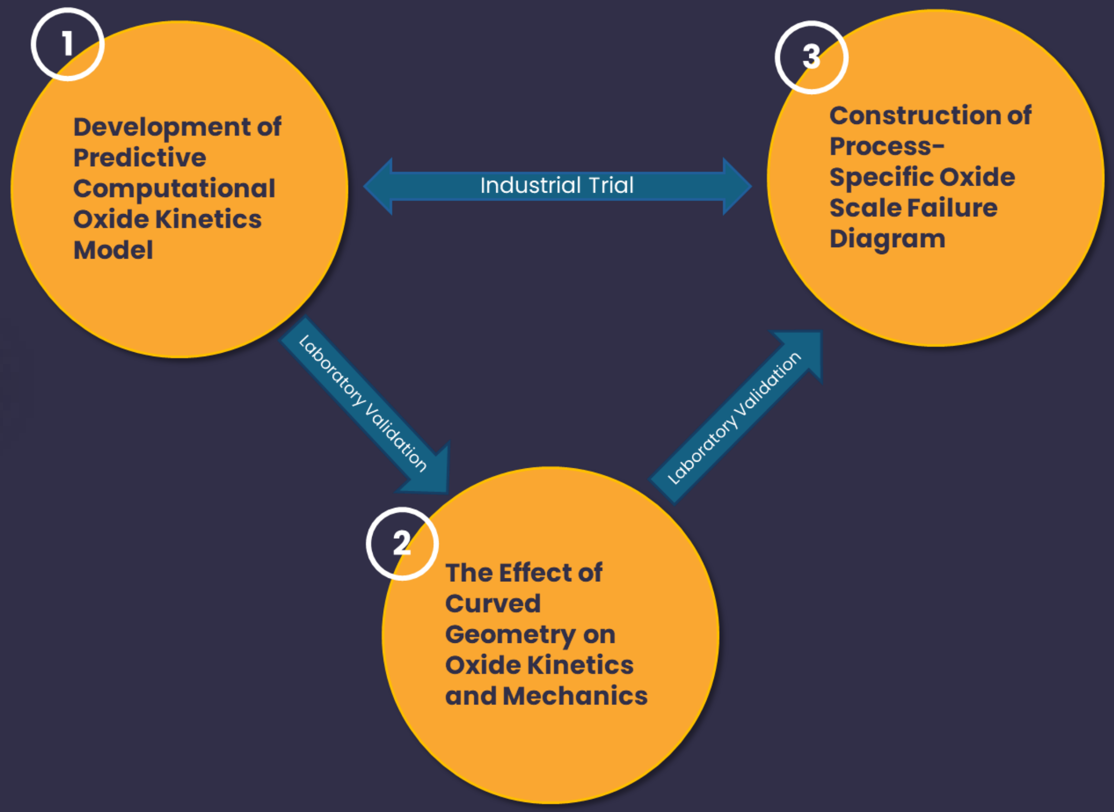
Proactive scale management

+

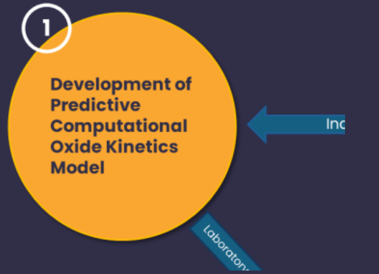
Computational thermodynamics

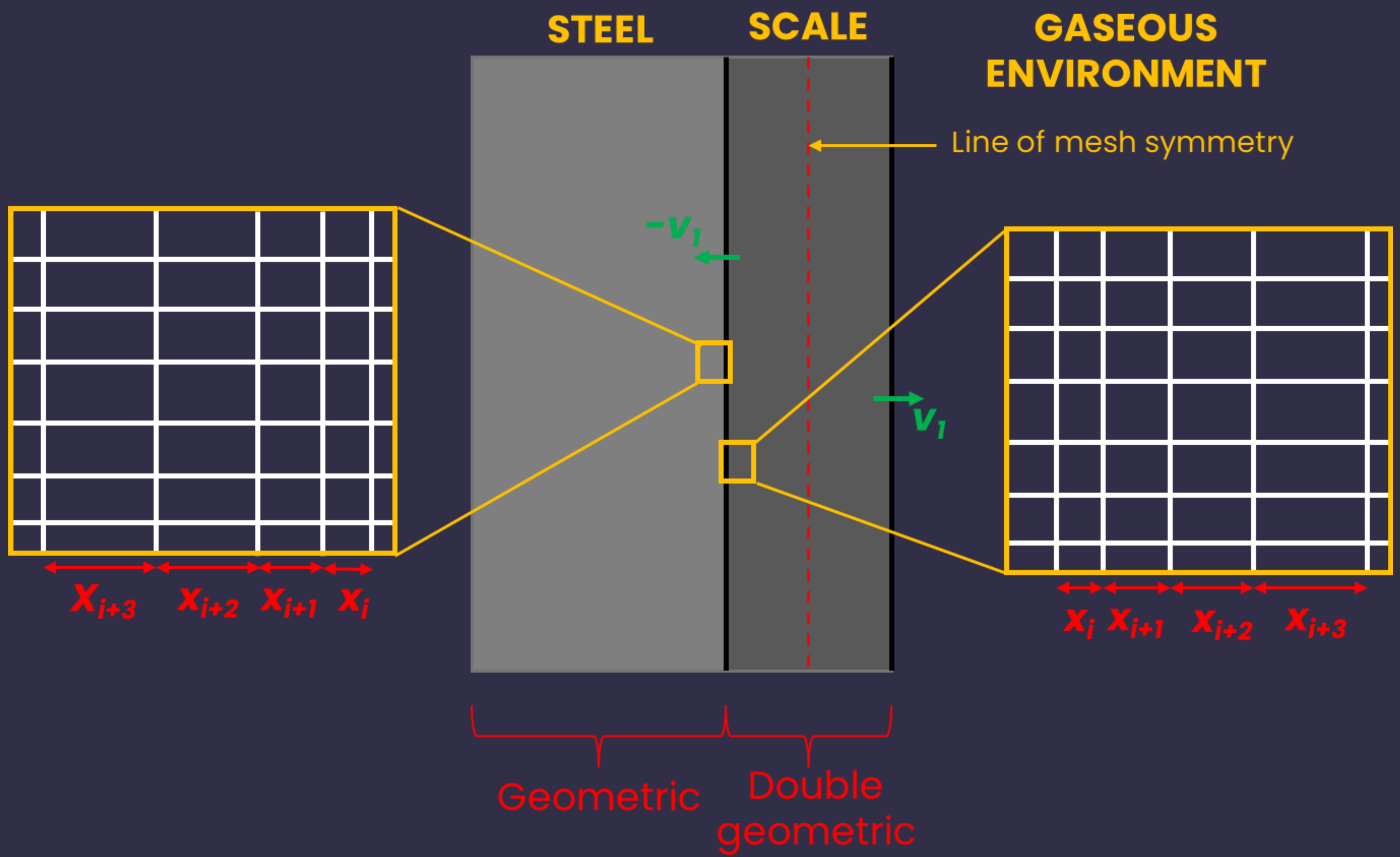
=

Increased manufacturing **agility**



Oxide Kinetics Computational Model





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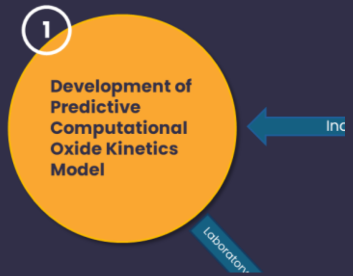


1 Sub-lattice modelling

2i Thermodynamic database development

2ii Kinetic database development

Visual Studio Code

DEFINING EQUATION

$$\frac{\partial c_k}{\partial t} = D\left(\frac{1}{r}\frac{\partial c_k}{\partial r} + \frac{\partial^2 c_k}{\partial r^2}\right)$$

Second Order Non-linear Partial Differential Equation

4 Crank-Nicolson Scheme

Thermo-Calc Software

INTERVENING VARIABLE

$$J_k = f(r)$$

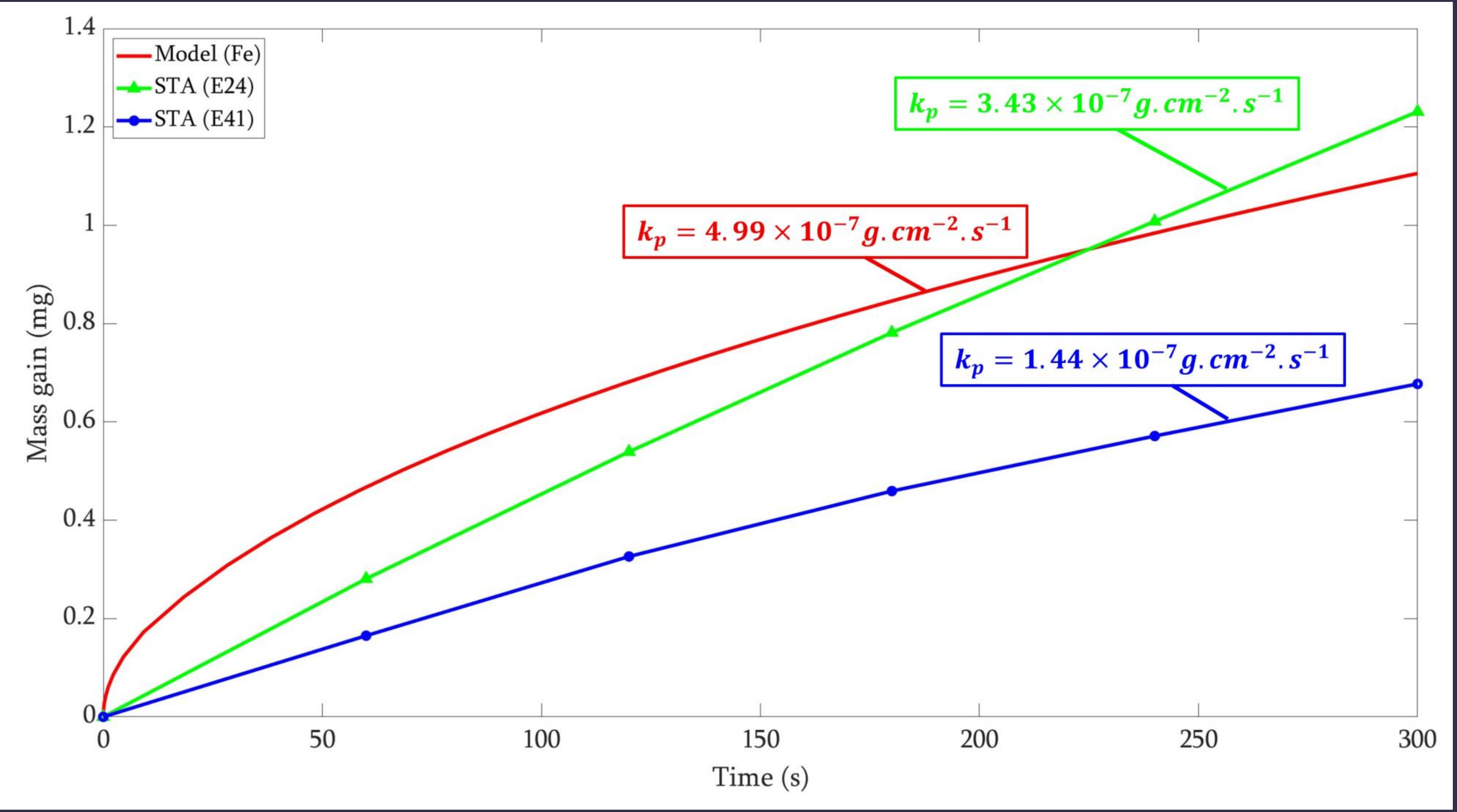
MOVING PHASE BOUNDARY SOLUTION

$$\Delta\delta_{t_{step}} = V_m^{\alpha}\frac{J_k^{\alpha} - J_k^{\gamma}}{x_k^{\alpha} - x_k^{\gamma}}t_{step}$$

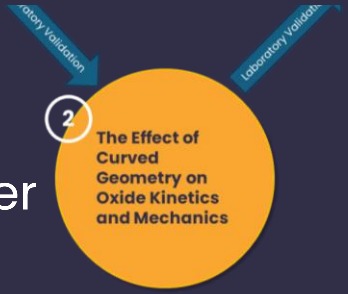
Isobarothermal system with fixed interfacial compositions

3 Computational Domain (Mesh, ICs, BCs)

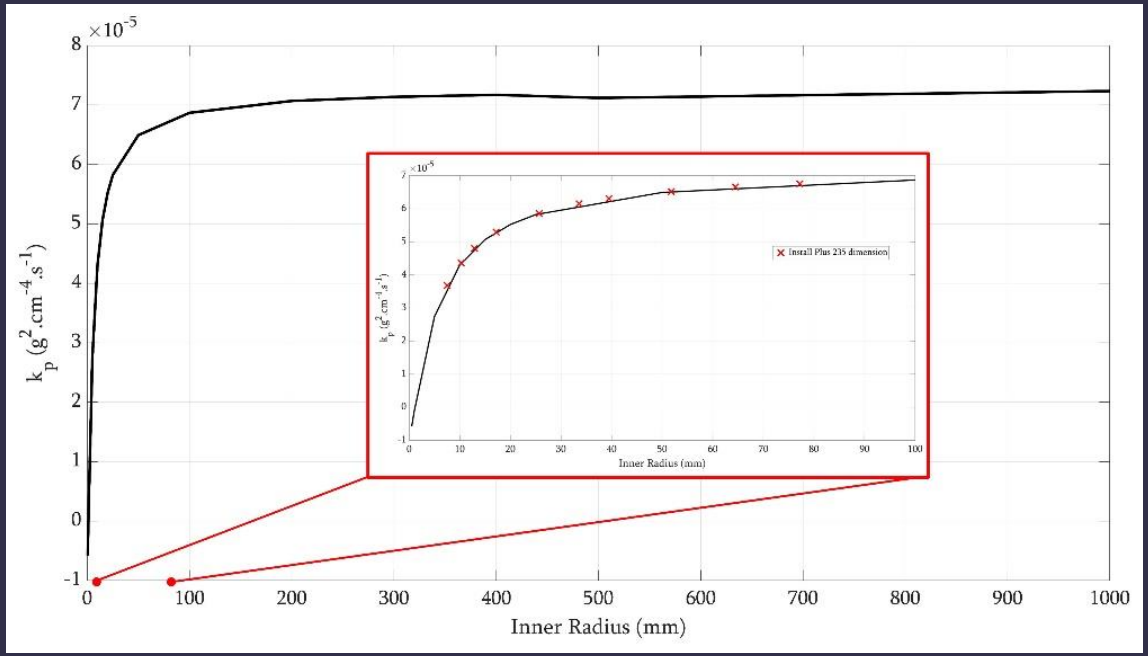
Oxide Kinetics Computational Model

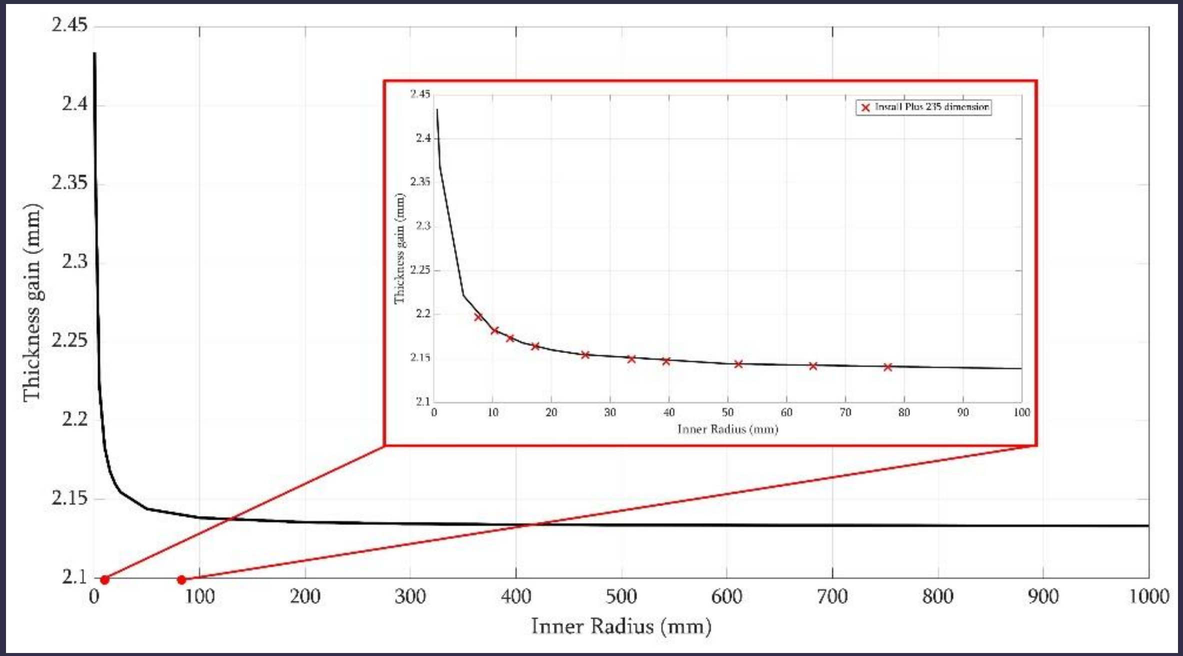


Curved Geometry Effects: Kinetics



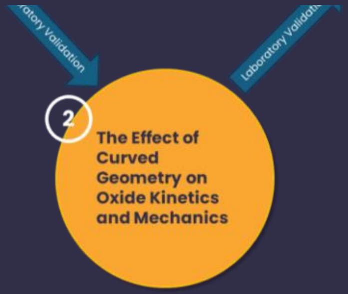
- For tubes with an inner **radius larger than 200mm**, inner diametric changes no longer influential.
  - **Approaching flat plate solution**
- Tata Tubes Install® Plus tube radii range from to 5.3mm to 80.6mm
  - Critical radius is **industrially relevant**



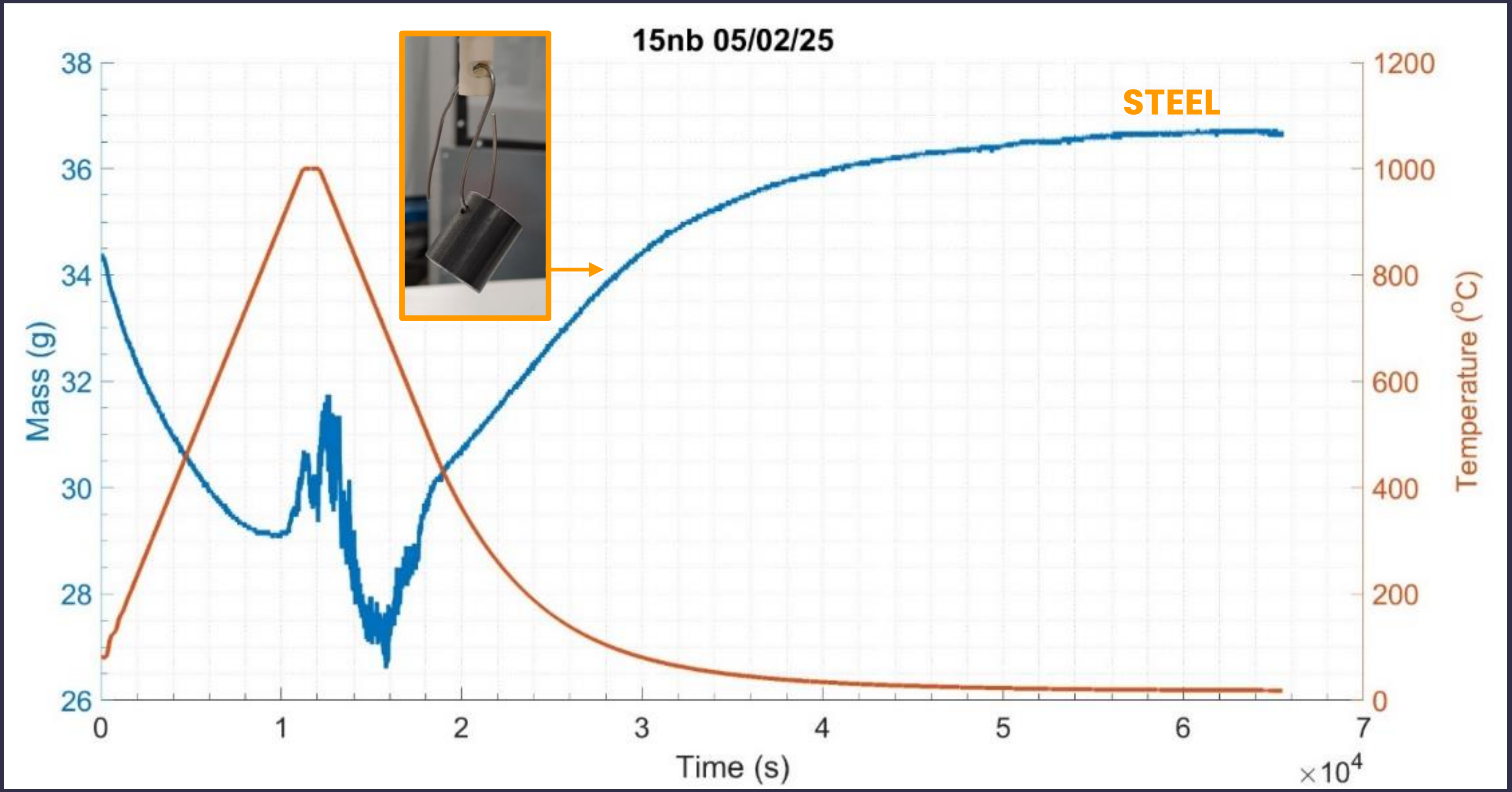


Kendall, M.; Coleman, M.; Cockings, H.; Sackett, E.; Owen, C.; Auinger, M. Computational Thermochemistry for Modelling Oxidation During the Conveyance Tube Manufacturing Process. *Metals* **2024**, *14*, 1402. https://doi.org/10.3390/met14121402

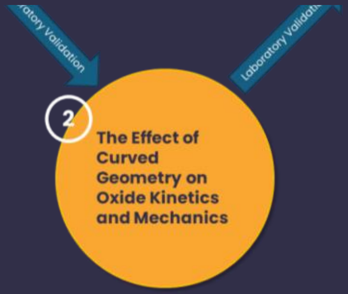
Curved Geometry Effects: Kinetics



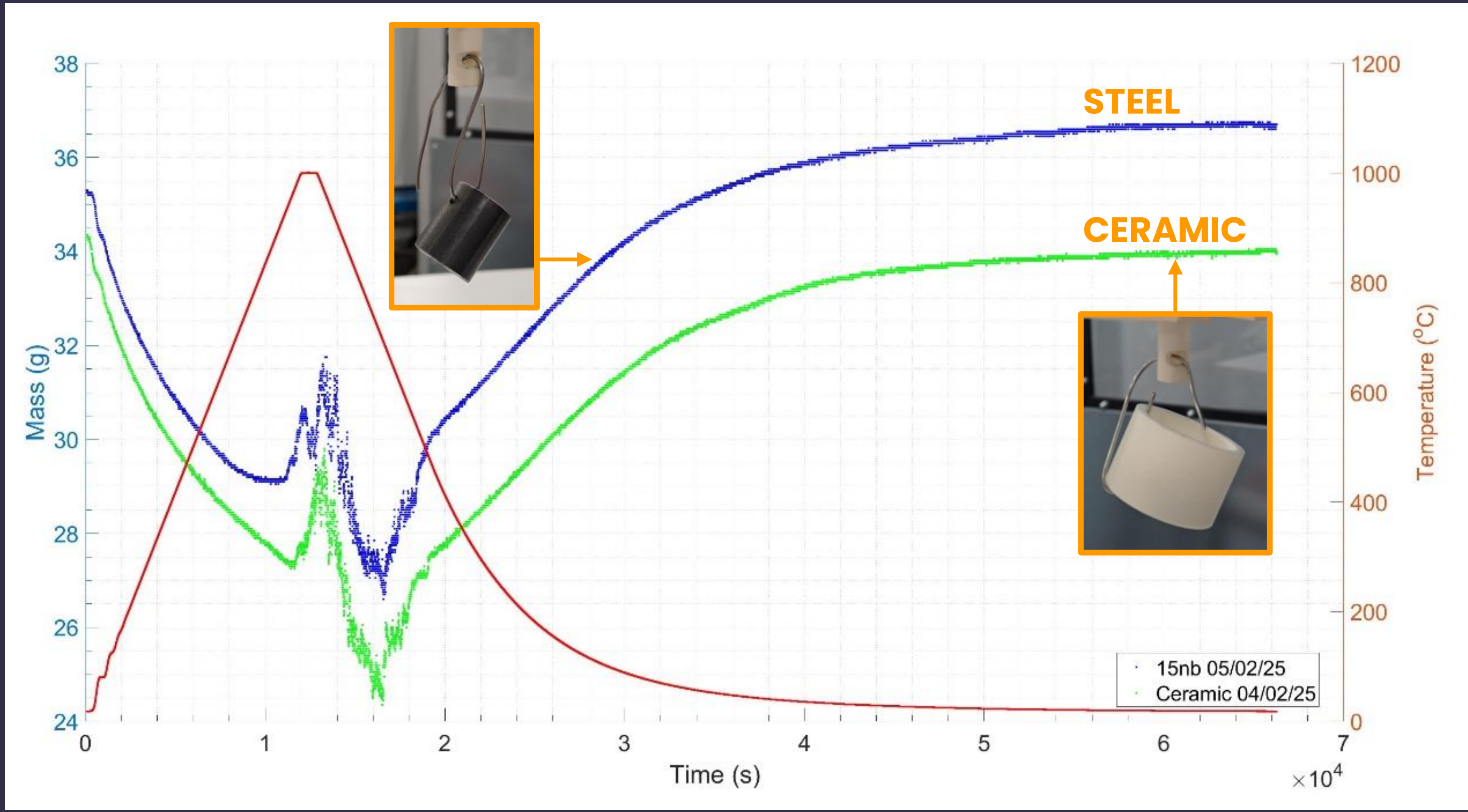
- Thermogravimetric Analysis – experimentally challenging
  - Unexpected **mass loss** and isothermal **noise**
  - **Forced vibration** induced by thermal currents
  - **Compressible flow boundary layer effects** within furnace tube and sample tube



Curved Geometry Effects: Kinetics

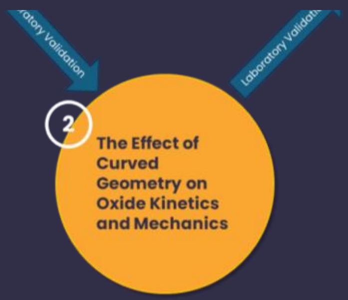


- Thermogravimetric Analysis – experimentally challenging
  - Unexpected **mass loss** and isothermal **noise**
  - **Forced vibration** induced by thermal currents
  - **Compressible flow boundary layer effects** within furnace tube and sample tube
  - **Refractory 'dummy' test**
  - Oxide mass gain = difference between curves



- **5% difference** between experiment and model prediction for same conditions

Curved Geometry Effects: Mechanics



Stress induced by **oxide**

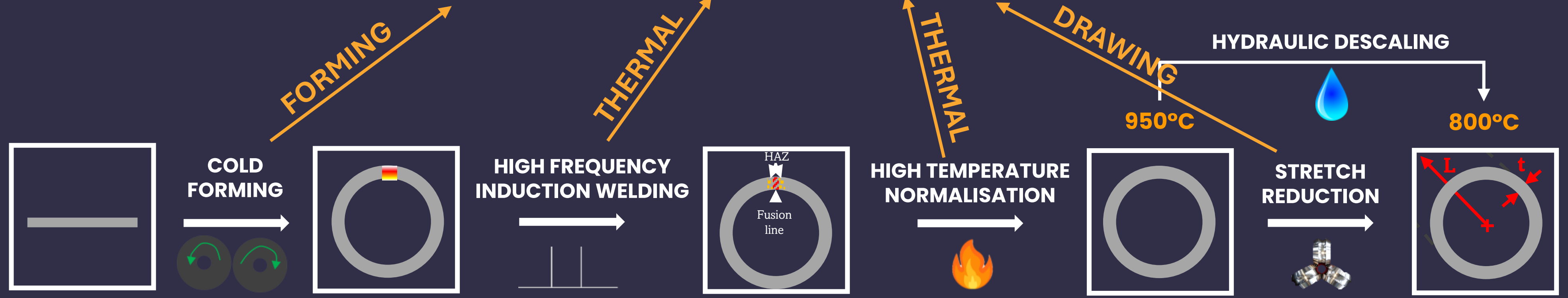
OXIDE

- Thermal mismatch
- Phase transformation
- Growth

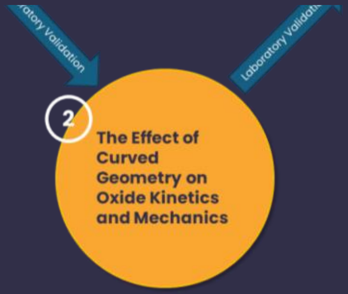
Multi-layer residual stress transfer from substrate to oxide

METAL

Residual stresses from the **manufacturing** process



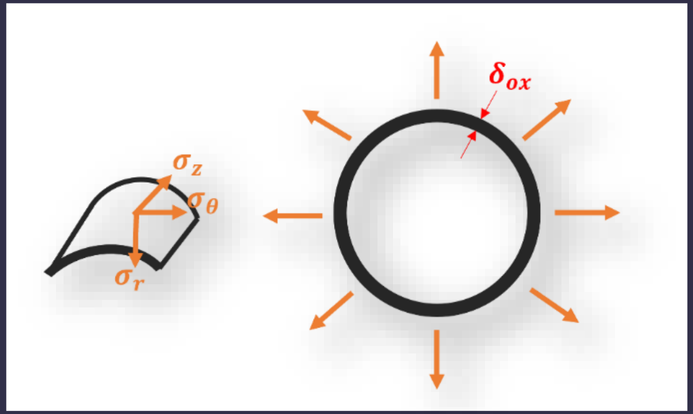
Curved Geometry Effects: Mechanics



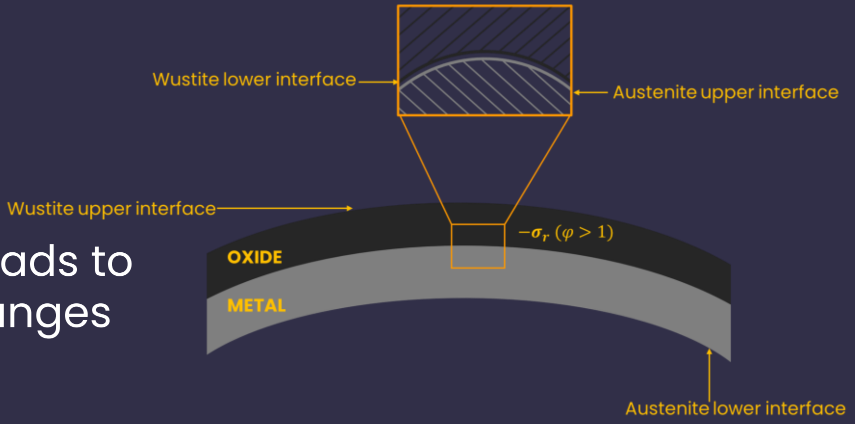
- **Mechanical** approach ('Equal biaxial stretching')
  - "Clamped" oxide (no material flow),
  - Surface area change,
  - Change in material thickness

$$\sigma_1 = A{\varepsilon_1}^n$$

$$where\ A = \frac{K\left(\sqrt{\frac{4}{3}\left(1+\beta+\beta^2\right)}\right)^n}{\sqrt{1-\alpha+\alpha^2}}$$

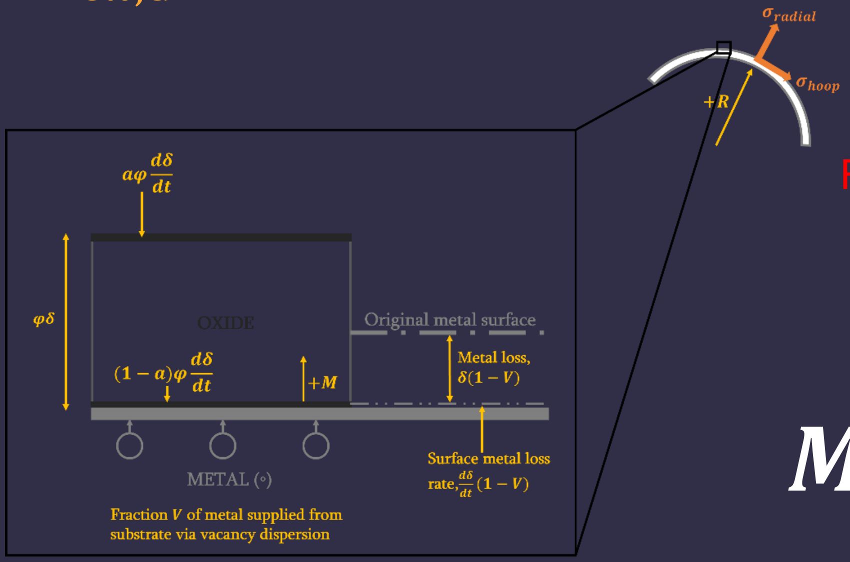


- **Oxidation-centric** approach
  - Metal-to-oxide transformation + phase/microstructural transformations
  - Specific to **curved surfaces**
    - New oxide at metal-scale interface and substrate retreat leads to **contact loss** – oxide no longer able to follow volumetric changes
  - Thermally, $\sigma_{ox,T}$, and dimensionally, $\sigma_{ox,G}$, induced



Curved Geometry Effects: Mechanics

$\sigma_{ox,G}$



$$\varphi = \frac{V_{oxide}}{V_{metal}} = \frac{W_{oxide}\rho_{metal}}{W_{metal}\rho_{oxide}}$$

From thermodynamic database

$$M = \varphi(1-\alpha) - (1-V)$$

Fraction of oxide formed due to oxidation at the scale outer surface (remainder at metal-scale interface)

Fraction of metal supplied from bulk due to vacancy injection mechanism (remaining fraction from metal surface immediately below oxide)

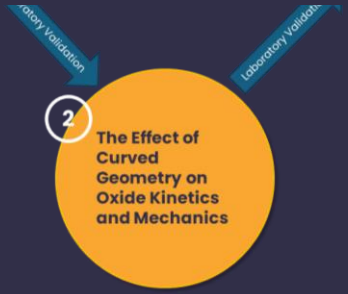
Predicted by model

$$\varepsilon_{ox}^{h} = -\frac{M}{R\varphi}d$$

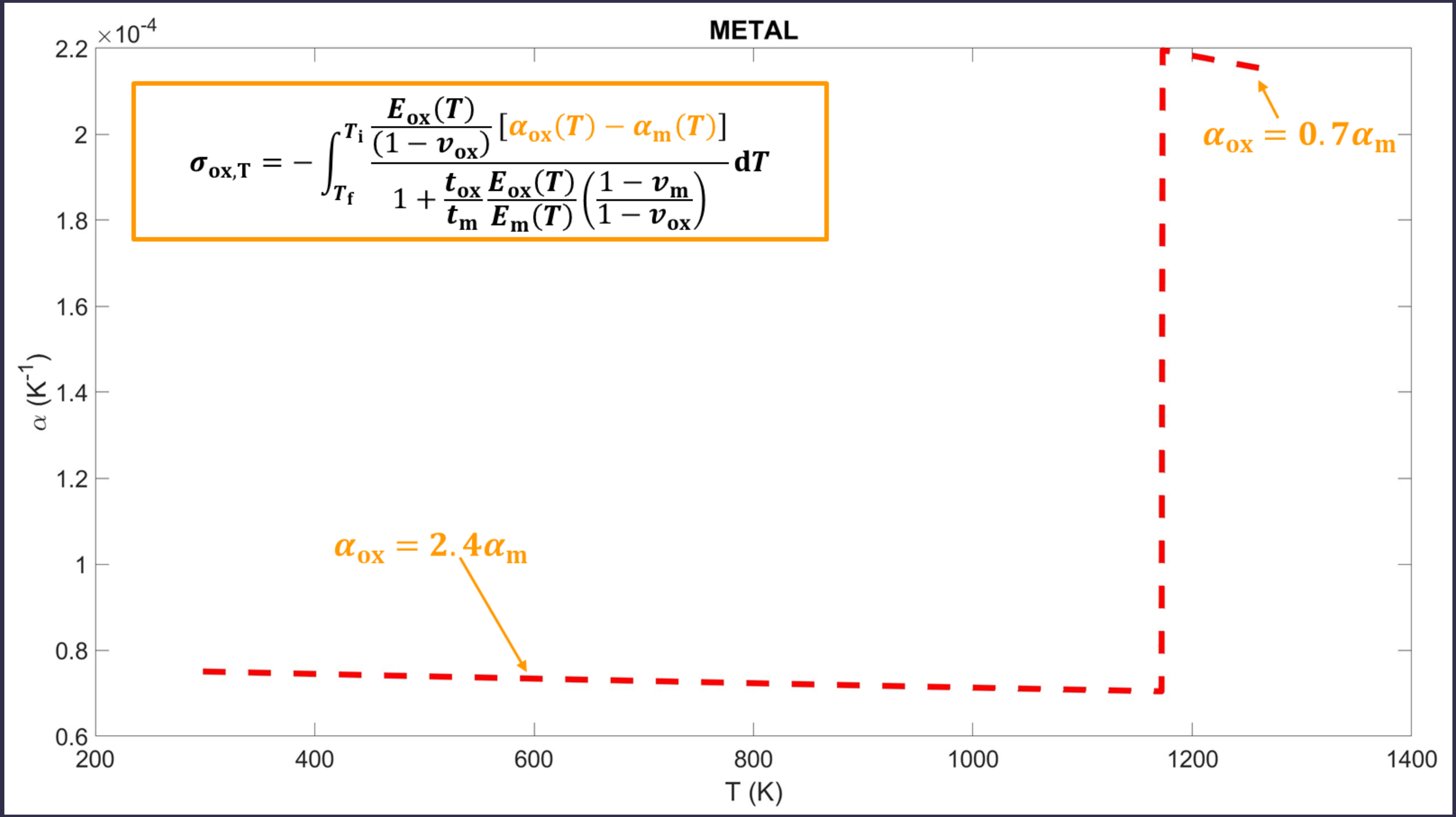
$$\varepsilon_{ox}^{r} \approx \frac{d}{R}\varepsilon_{ox}^{h}$$

Tube inner radius (already defined in model)

Curved Geometry Effects: Mechanics

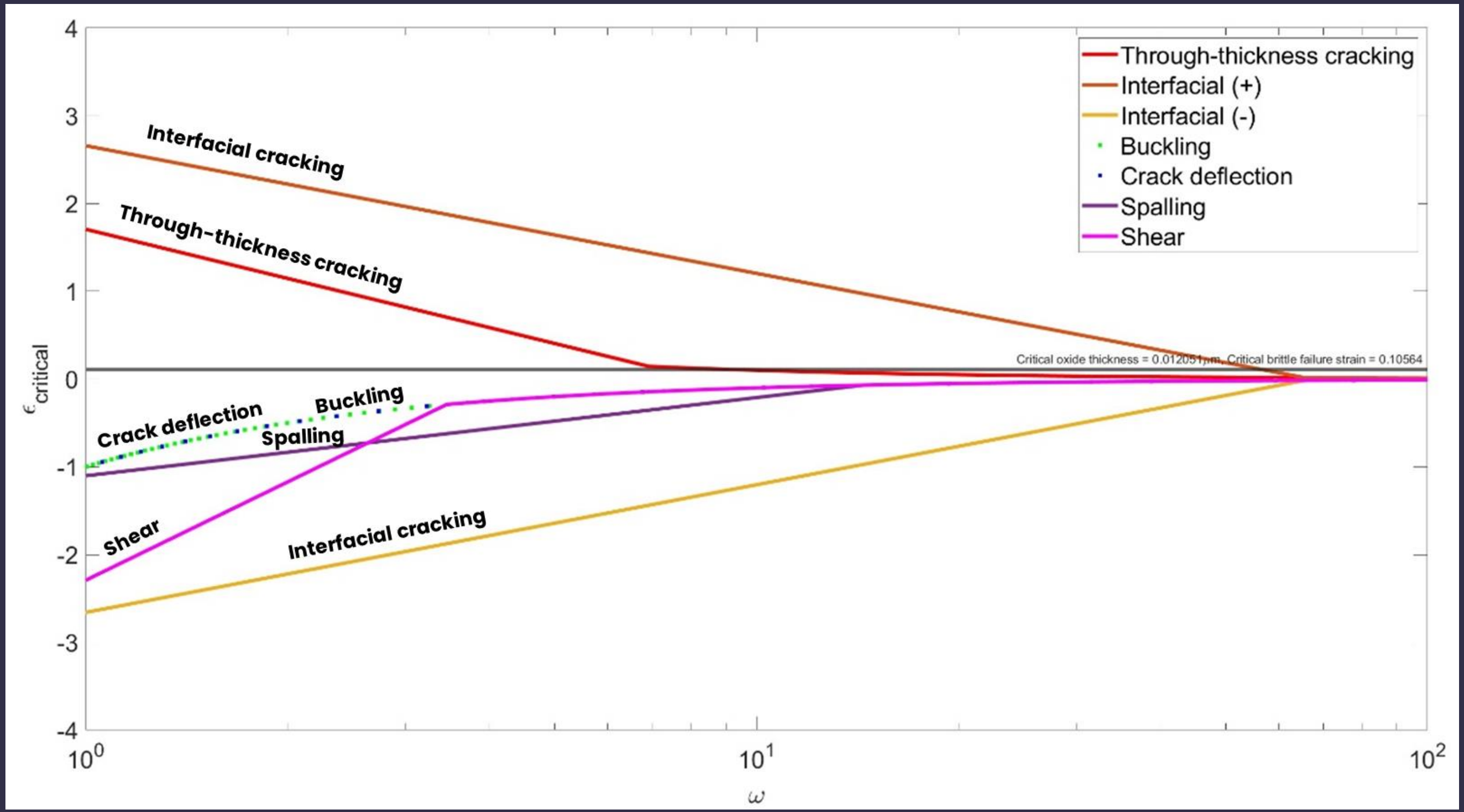


$\sigma_{ox,T}$



Advanced Oxide Scale Failure Diagram

- Fracture mechanics theory
- **Operational history parameter,** ω
  - Better representation than oxide thickness alone



Geometry parameter

Roughness amplitude and period

Fracture toughness (Mode I)

$$\omega = \omega(K_{IC}, c, f, E, \upsilon, r, \lambda, \delta_{ox})$$

Defect size

Advanced Oxide Scale Failure Diagram

Case Study: Transition to induction heating technology at Corby site

- **Faster**, more aggressive **heating**
- Improved **operational control**
- **Operational history changes** → total strain changes
  - Maximum permissible **residual hoop stress of 100MPa at 530Hz** current frequency (Drobenko et al, *International Journal of Engineering Science*, 2017) – numerical result
- $\boldsymbol{\varepsilon_{gas}}$ **=-0.0948,** $\boldsymbol{\varepsilon_{ind}}$ **= 0.0032**
  - Change from overall tensile to compressive strain if heating controlled

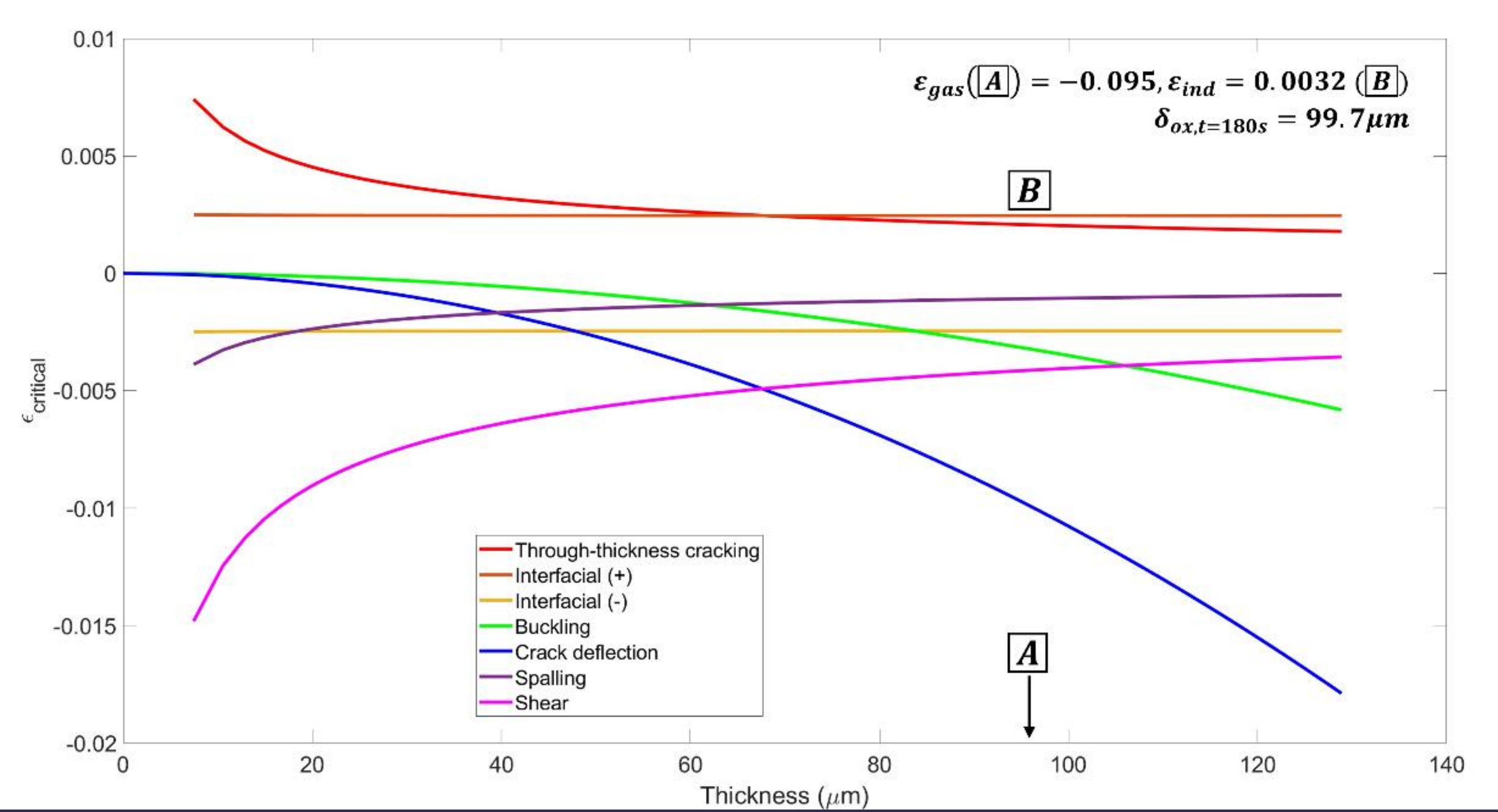
Hoop Stress Source		ε_{gas} (-)	ε_{ind} (-)	
Oxidation-induced	Thermal mismatch	**-0.0988**	**-0.0008**	Analytical results
	Growth stress (intrinsic)	0.0047	0.0047	
Manufacturing-induced	Forming	-0.0007	-0.0007	X-ray Diffraction result
	Drawing			

Advanced Oxide Scale Failure Diagram

Case Study: Transfer to induction heating technology at Corby site

- **Parabolic rate law** – 1s resolution data for normalisation soak period ($t \leq 5$mins)
  - Oxide thickness, δ, of 99.7μm after 3-minute normalisation at 1000°C

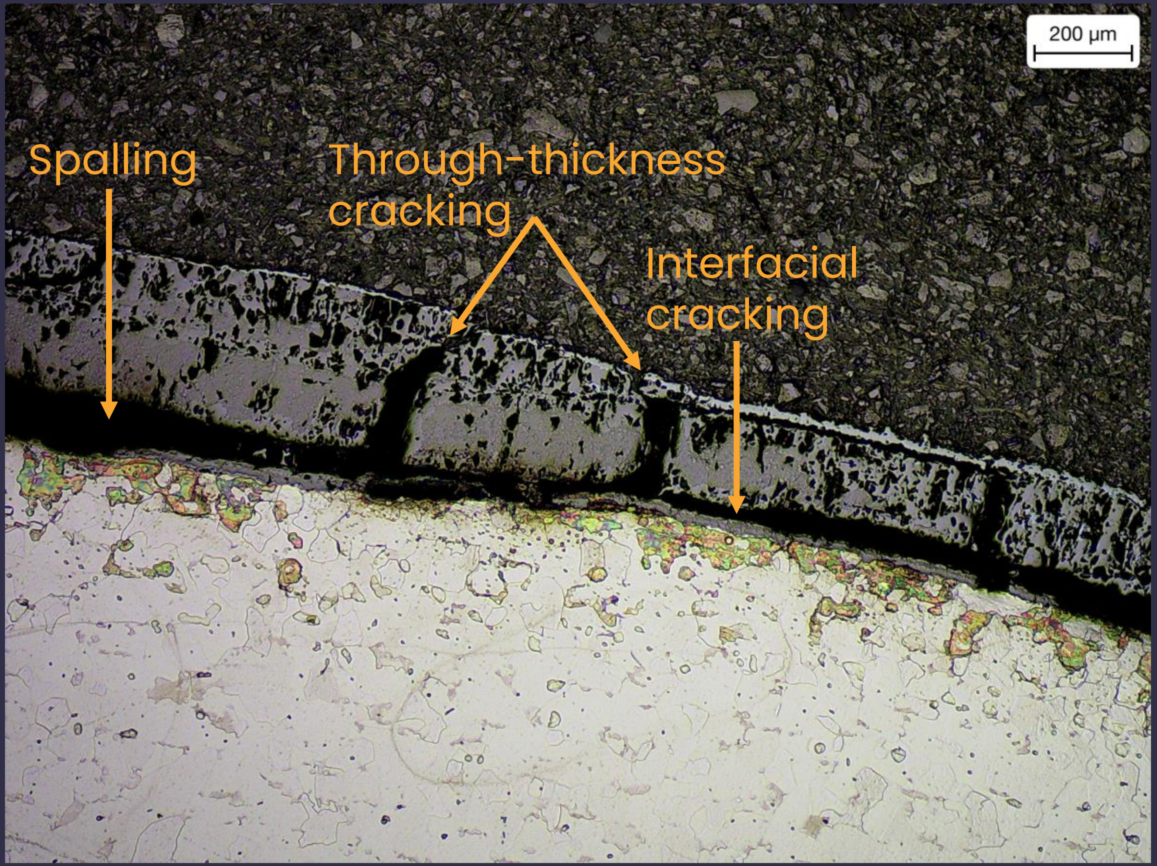
$$\delta^2 = k_p t$$



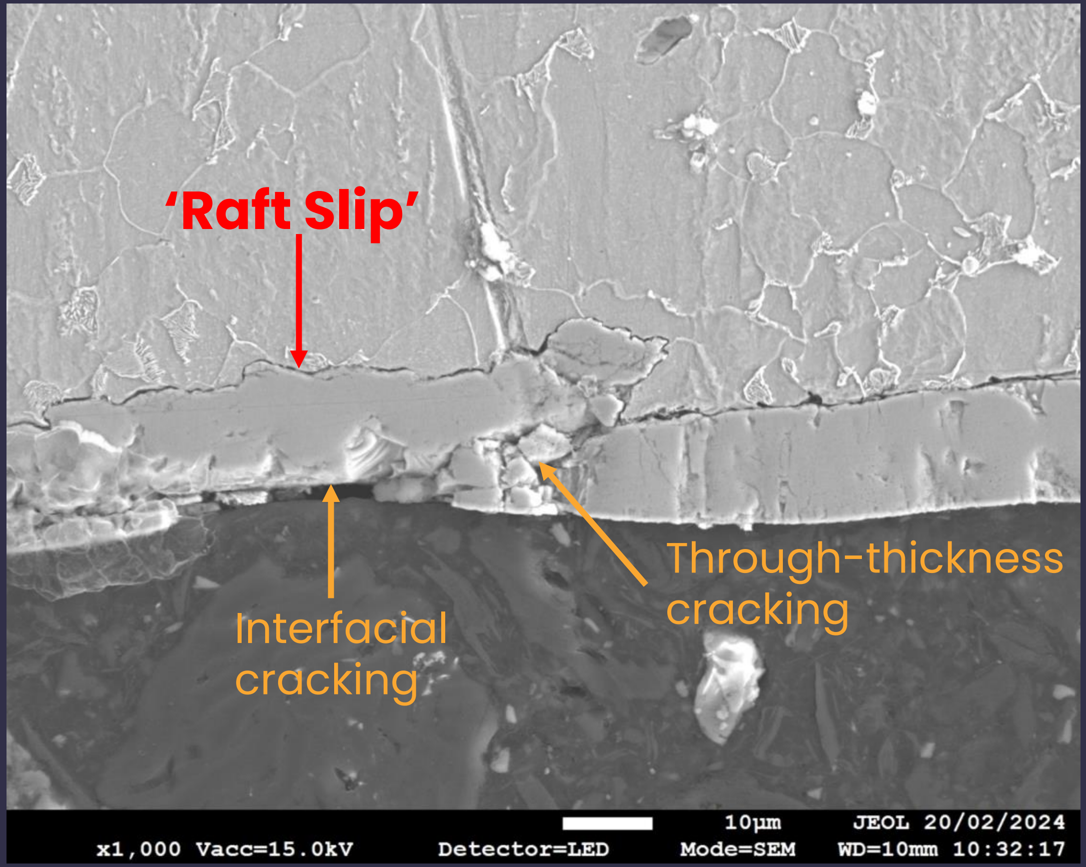
Advanced Oxide Scale Failure Diagram

Case Study: Transfer to induction heating technology for tube normalisation at Corby site

Gas furnace normalisation



Induction furnace normalisation

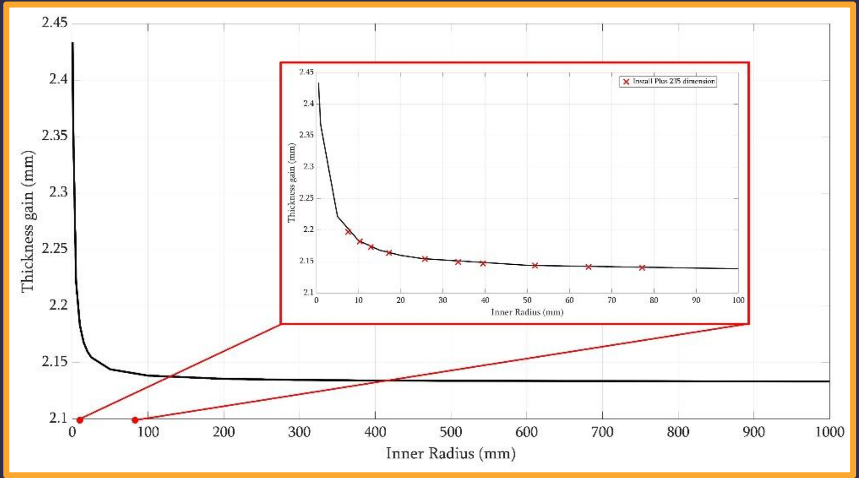


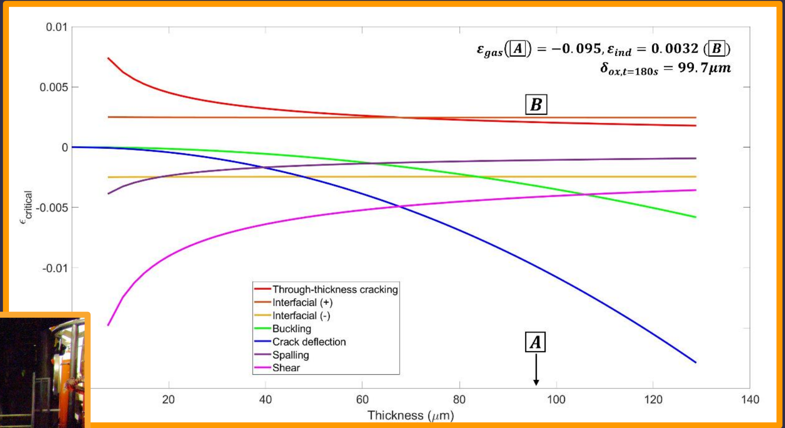
Conclusions

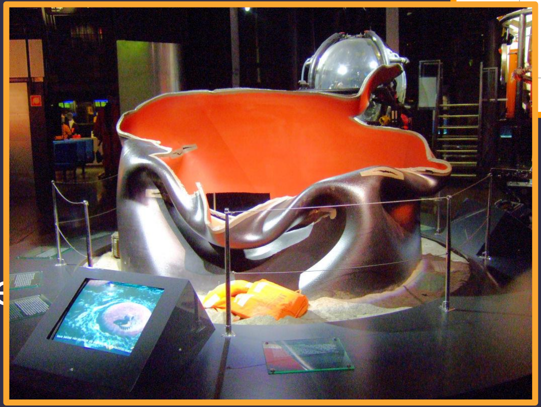
- **Experimental** (thermogravimetric) assessment of high-temperature oxidation on curved surfaces prone to **significant uncertainty**.
  - Difficult to recreate **complex industrial conditions**.
- **Computational**, geometry-specific modelling of oxidation offers better opportunity for multiple **parameter control** and **continuous** oxide thickness gain **data**.
- High-temperature oxidation of carbon steel on **curved geometry** should be **considered separately** from planar geometries for small radii (≤**200mm** internal) tubes.
- Oxide thickness data is integral to **analytical mechanical models** of oxide stress state and adhesion.
  - **Advanced Oxide Scale Failure Diagram** can be used to represent critical strains for different failure modes.
    - Example of use during assessment of Tata's transition from **gas-barrel to induction furnace** normalisation of conveyance tubes.

Real-World Applications & Impact

- Impact at different levels
  - **Company**
    - More efficient use of feedstock
    - Extended plant life
    - Industry 4.0 techniques
  - **Scientific**
    - New applications for computational thermochemistry
  - **Community**
    - Better use of resources
    - Transition to sustainable manufacturing tech
    - Higher quality products with improved service







With thanks to

M2A COATED

TATA

UKRI
Engineering and Physical Sciences Research Council

Coleg Cymraeg Cenedlaethol

Advanced Oxide Scale Failure Diagram

Case Study: Transfer to induction heating technology for tube normalisation at Corby site

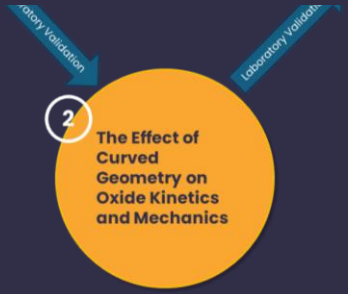
For δ_{ox} = 100μm (provided by model):

- ε_{gas} =-0.0032, ε_{ind} = 0.0032
    - Transition from overall compressive to overall tensile strain with heating control
- **Spalling eliminated** via heating control
    - **Compressive failure modes eliminated** by **tensile state** e.g. buckling, crack deflection
    - Many other options for parameter control

Failure Mode	Critical strain for 100 (-)	$\varepsilon_{gas} \geq \varepsilon_{crit}$?	$\varepsilon_{ind} \geq \varepsilon_{crit}$?
Buckling	-0.0035	×*	×
Crack deflection	-0.0107	×	×
Interfacial cracking	±0.0025	✓	✓
Shear	-0.0041	×	×
Spalling	-0.0011	✓	×
Through-thickness cracking	0.0020	✓	✓
Brittle*	±0.1056	×	×

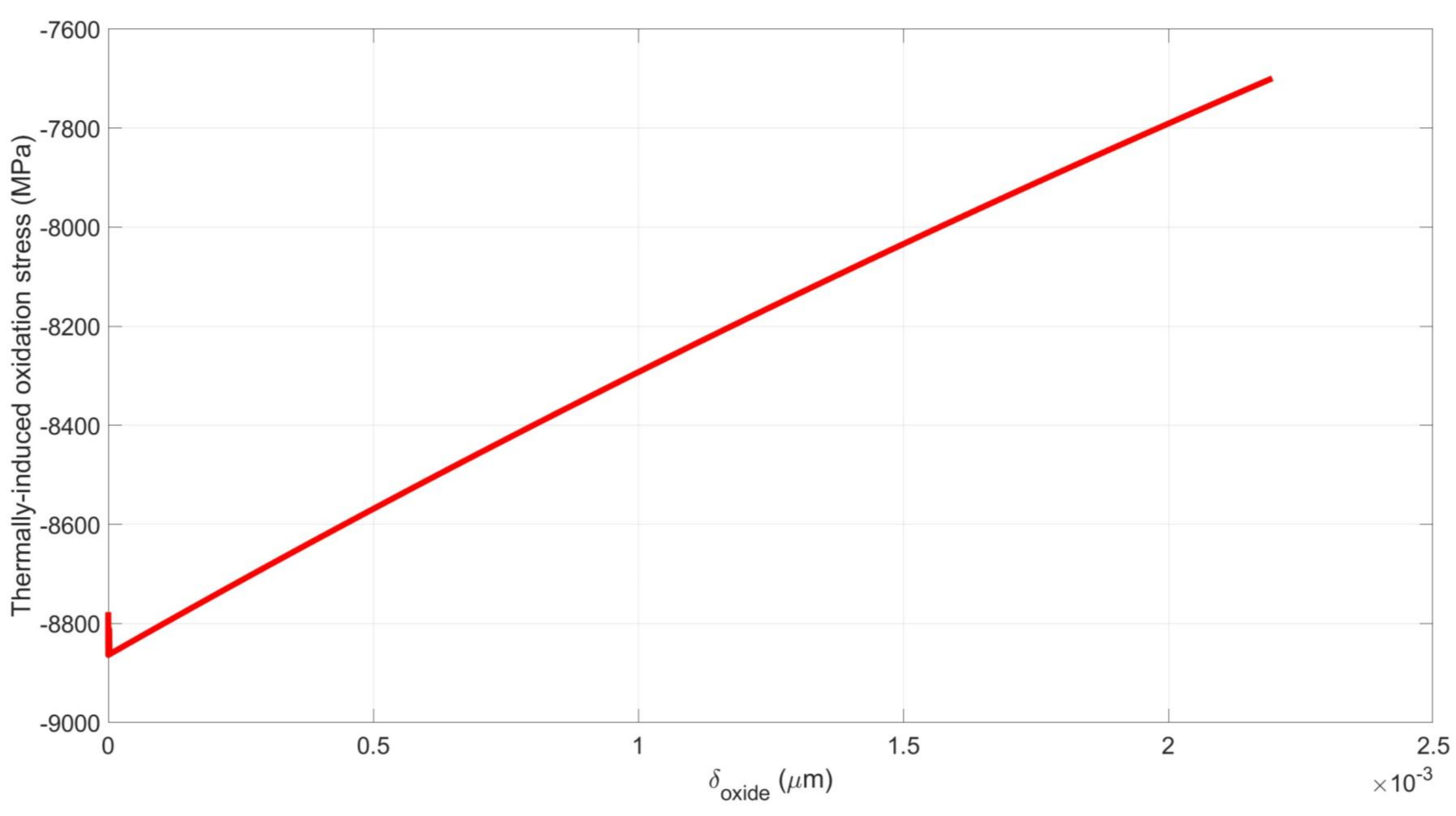
* borderline

Curved Geometry Effects: Mechanics



$\sigma_{ox,T}$

Composite Simpson's rule on stress differential function



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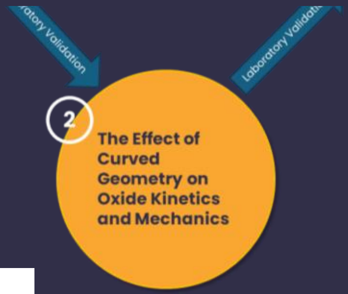
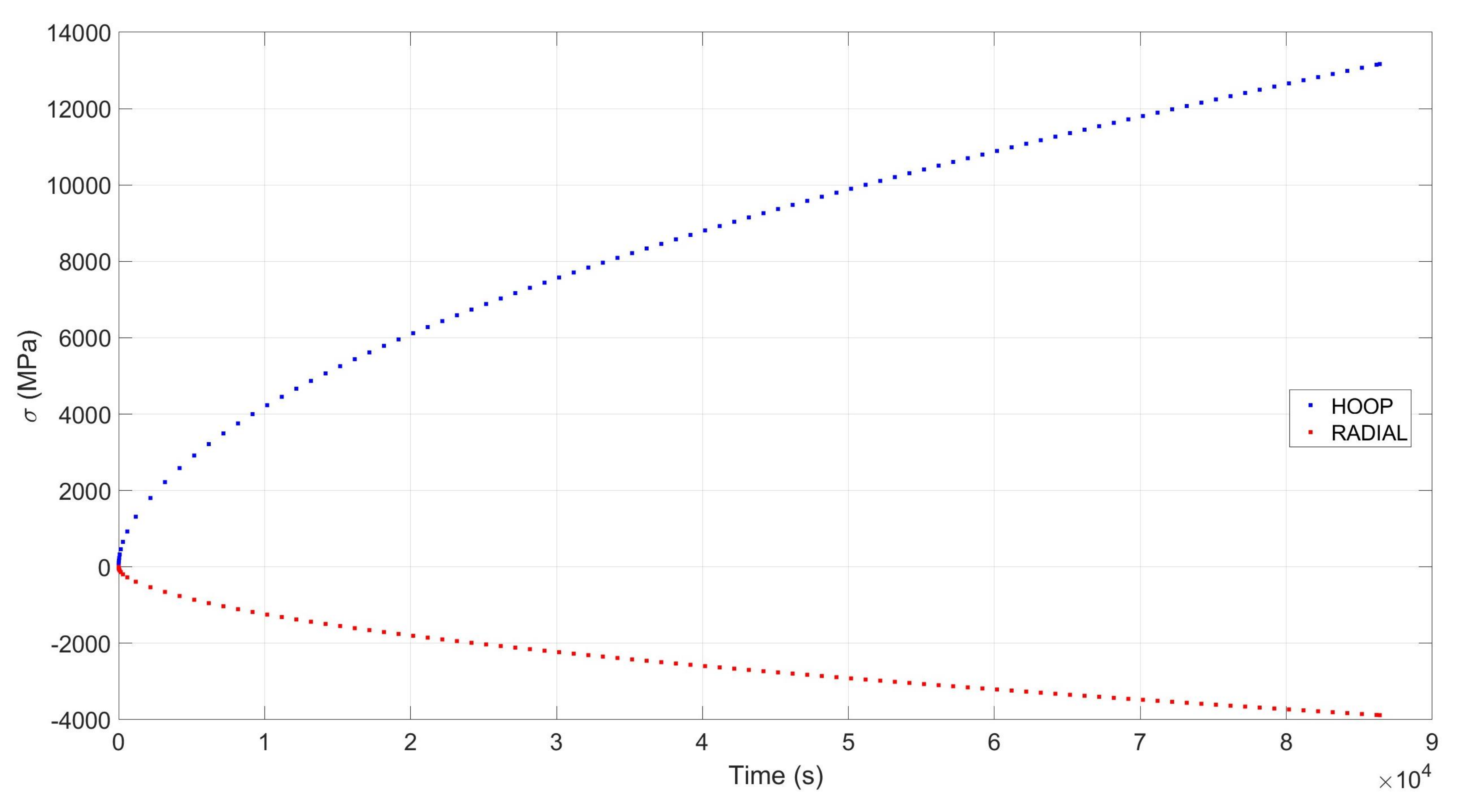
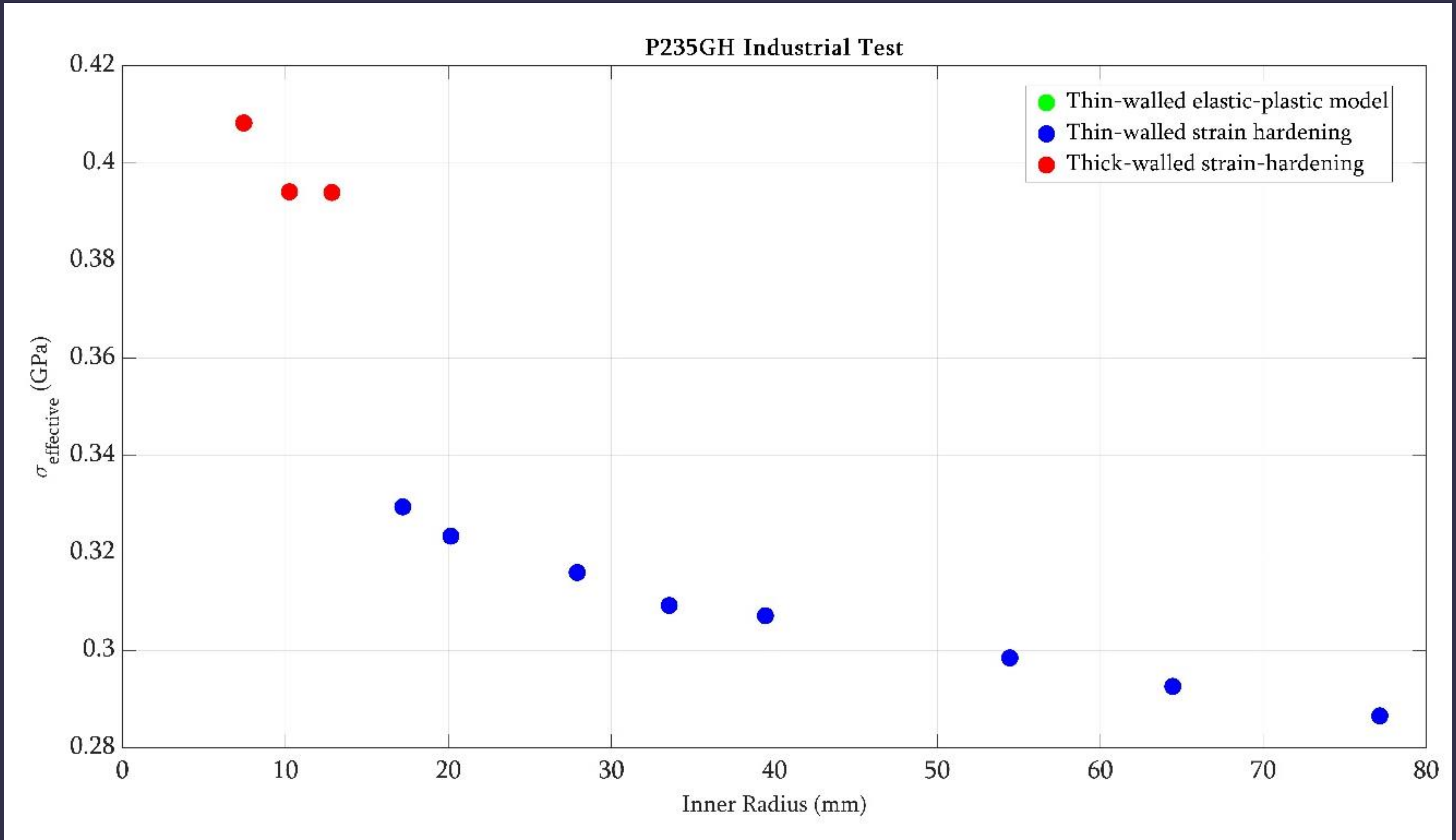


$\sigma_{ox,G}$



Curved Geometry Effects: Mechanics

Manufacturing stress: Forming



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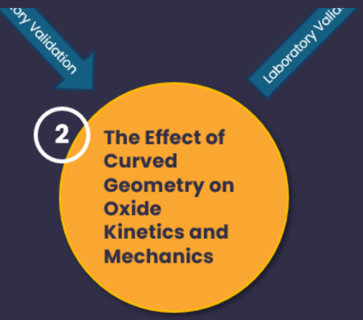

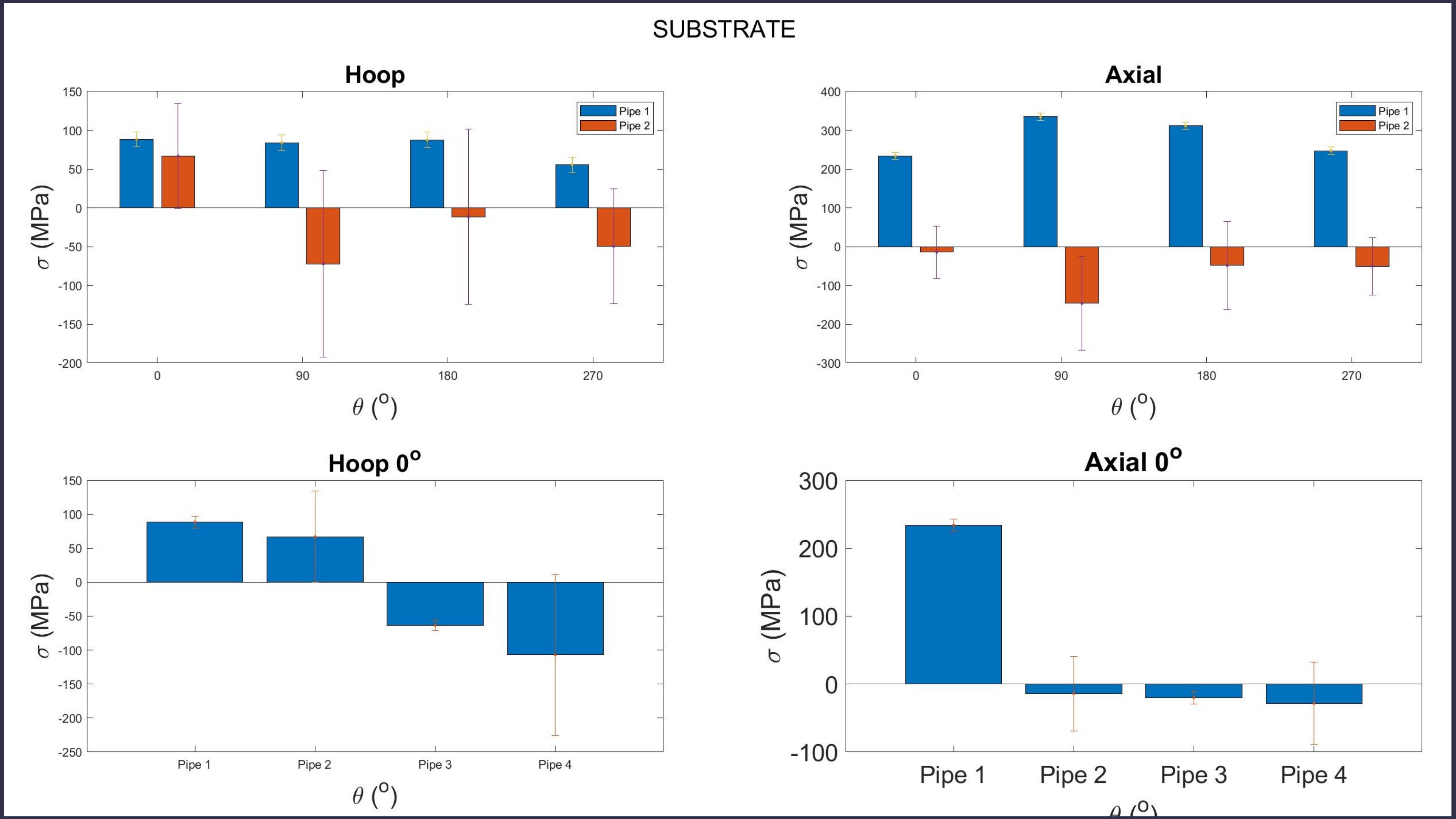

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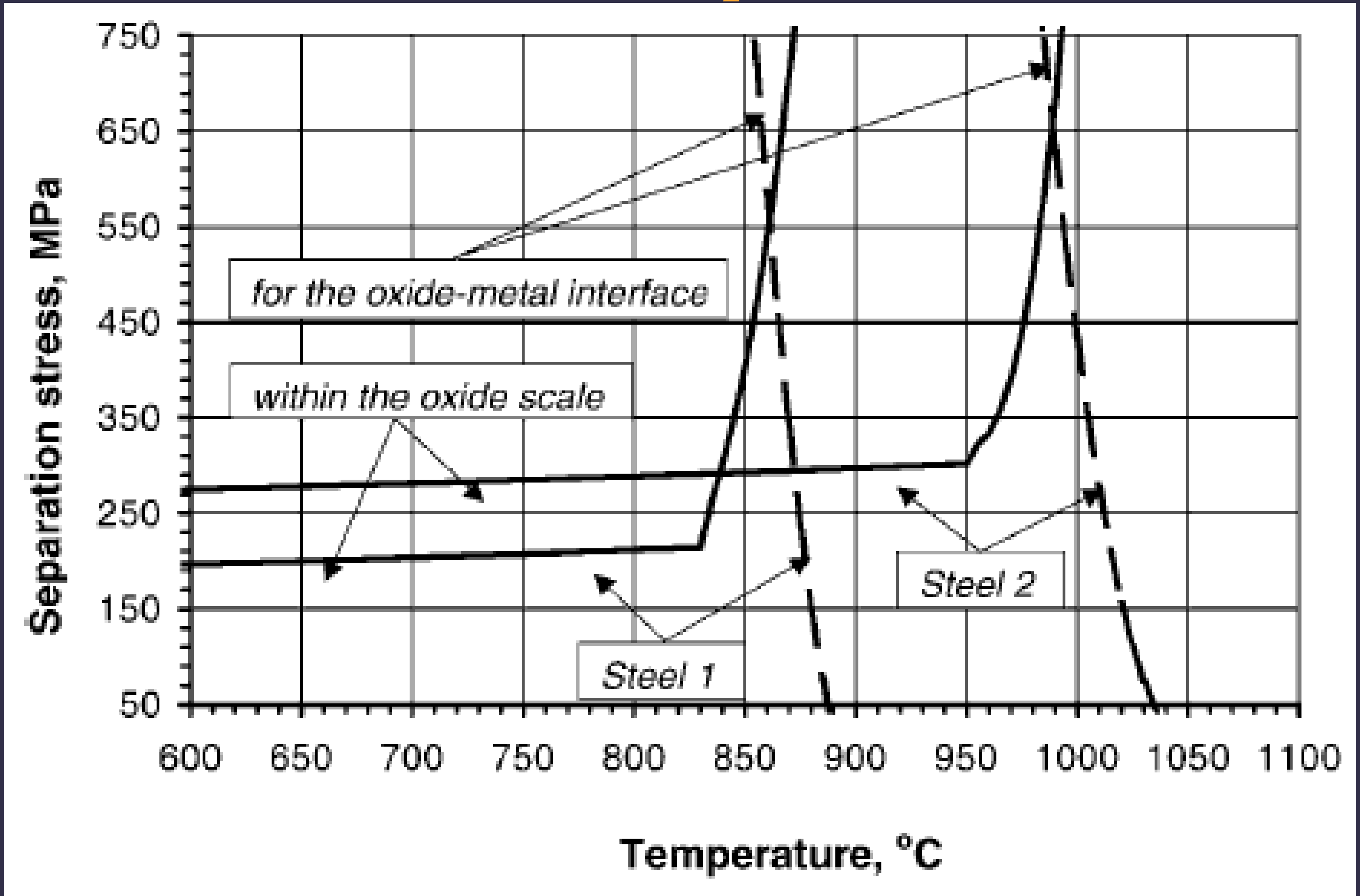

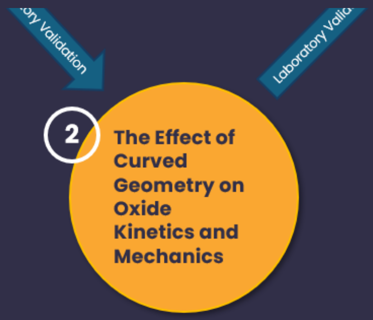

M. Krzyzanowski and J. H. Beynon, *Modelling and Simulation in Materials Science and Engineering, 2000.*