Multiphysics & DeepLearning For Material Processing Simulations

TRANSVALOR

Leading Edge Solutions
For Virtual Manufacturing

FORGE® / Multiphysics

By Dr. José Alves

Speaker

Dr. José R. Alves Z.

2011 - Mechanical Engineer
Simon Bolivar University, Venezuela
Control Theory specialization at
Nagaoka University of Technology, Japan

2012 - Computational Mechanics specialization
Full field FE modeling of glass fiber reinforced PP
CEMEF, MINES ParisTech – PSL University, France

2016 - Ph.D on Simulation of Magnetic Pulse Forming
CEMEF, MINES ParisTech – PSL University, France

Head of Team and Scientific Developer at Transvalor S.A.
Multiphysics, Deep Learning, electromagnetism, damage-to-fracture modeling, Parallel computing, numerical algorithm optimization

Agenda

I. Transvalor S.A.

II. Multiphysics for bulk metal forming

III. Towards Deep Learning integration

Our DNA

Highly rooted in research

Research lab – 120 scientists

Driven by innovation

Transition from research projects to industrial software for the industries we serve

Designed for results

Industry relevance

Simulation intelligence

Our journey

1984
FORGE®

1988
Z-set

2005
COLDFORM®

2012
THERCAST®

2017
DIGIMU®

2019
SIMHEAT®

2021
TRANSWELD®

2024
THERCAST® NxT 3.0

2025
FORGE® NxT 4.1

TRANSVALOR

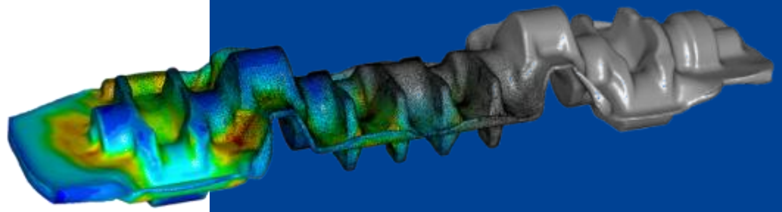
TRANSVALOR

+500 customers around the world

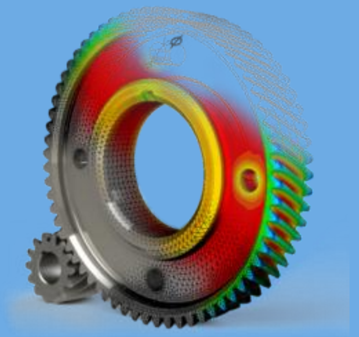
Close partnership with research laboratory

Transvalor’s software solutions

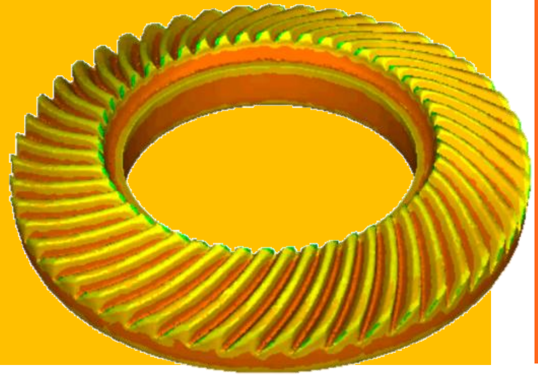
FORGE®
The reference in simulation for hot-warm-cold metal working



COLDFORM®
Dedicated simulation software for cold forming

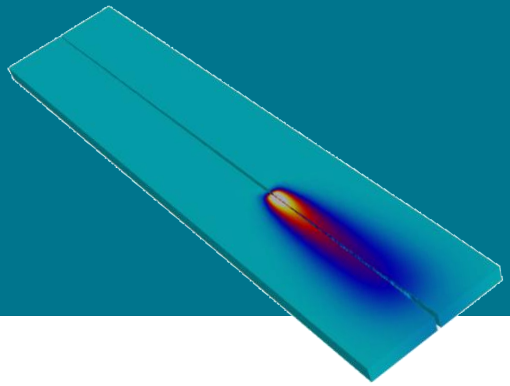


SIMHEAT®
Simulation solution for metal heat treatment processes

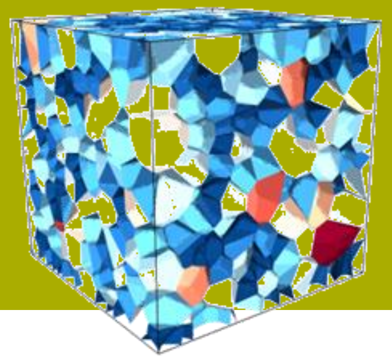


THERCAST®
Simulation software for metal casting processes

TRANSWELD®
Simulation software for welding processes

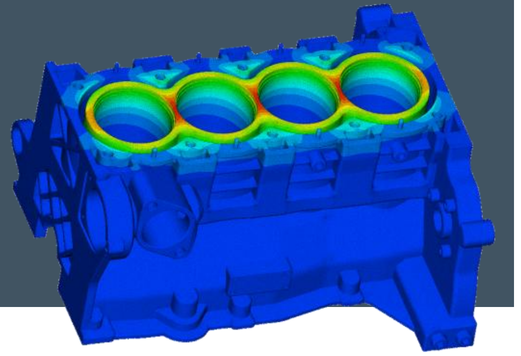


DIGIMU®
Solution for the prediction of microstructural evolutions



REM3D®
Simulation software for PU foams chemical foaming

Z-set
Non-linear material & structural analysis suite



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Agenda

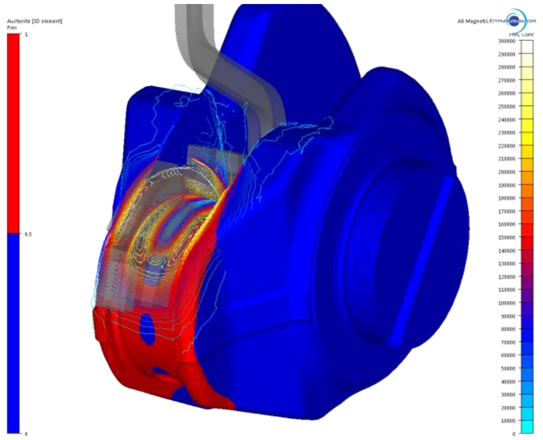
I. Transvalor S.A.

II. Multiphysics for bulk metal forming

III. Towards Deep Learning integration

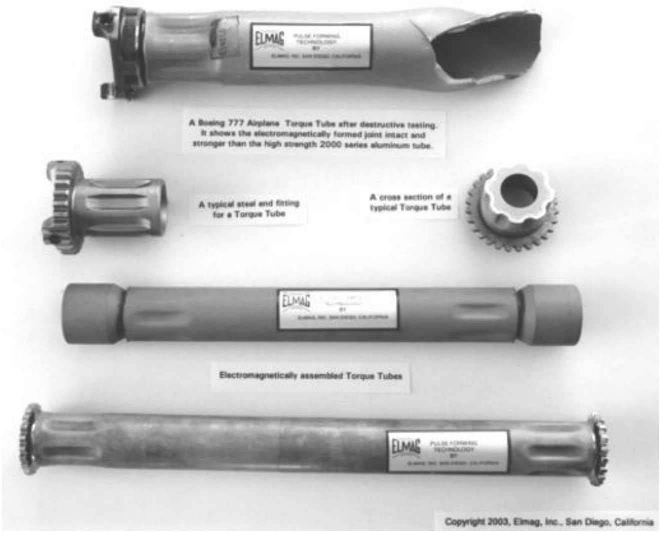
Electromagnetics Assisted Applications

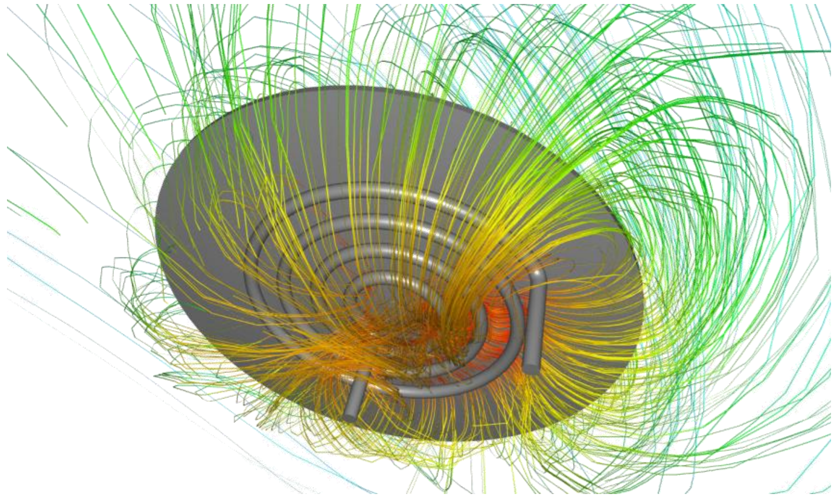
Induction Heating



… Control local surface hardness …

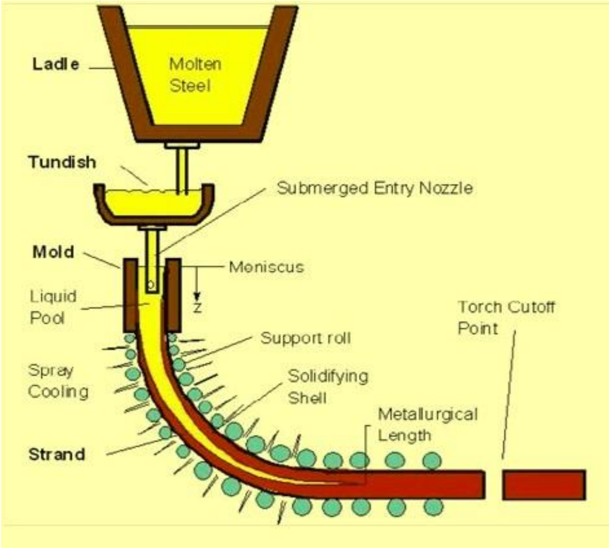
Magnetic Pulse Forming

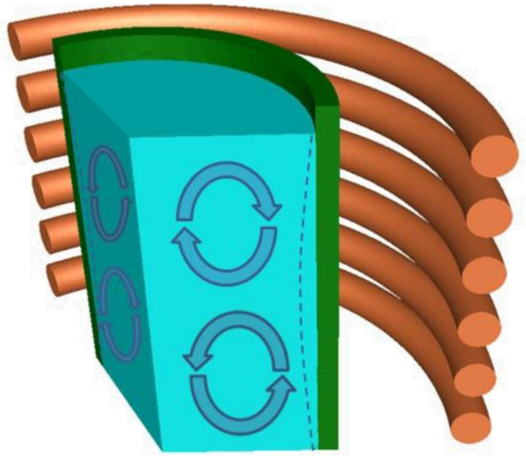




… Increase formability and eliminate elastic springback …

ElectroMagnetic Stirring





… Control solidification and segregation …

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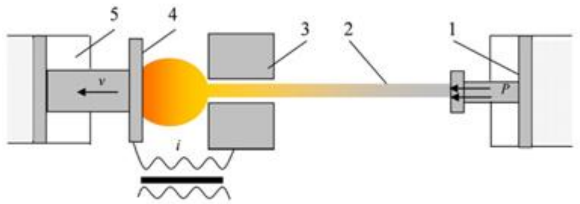
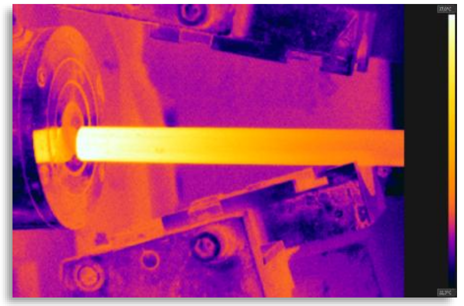
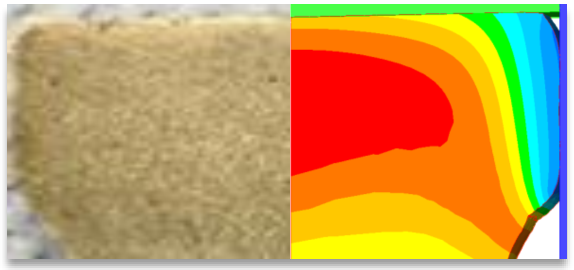
Electromagnetics Assisted Applications

Electric Upsetting



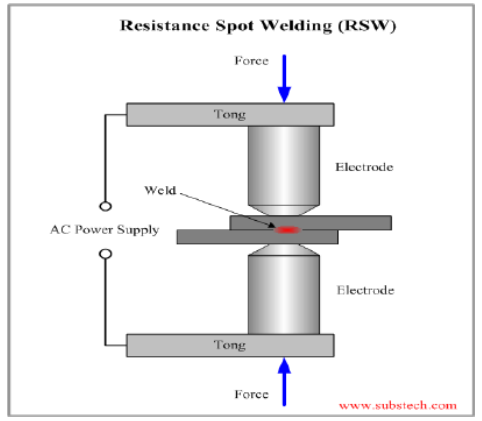
1-upsetting cylinder, 2-workpiece,
3-clamping electrode, 4-anvil, 5-anvil cylinder





… fast preforming …

Spot Welding



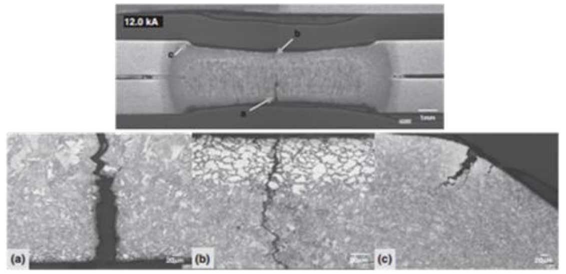
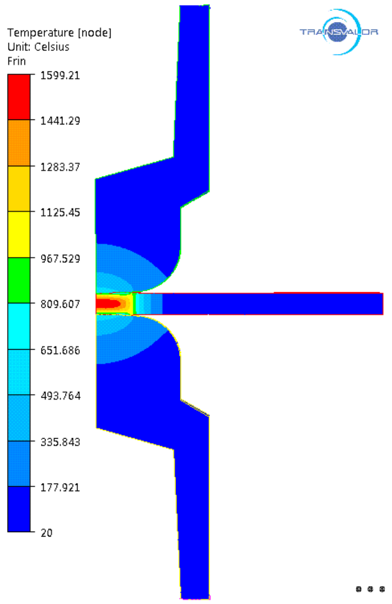


Fig. 6 Microstructure of the surface crack at a high welding current (12.0 kA).



… fast welding for assemblies …

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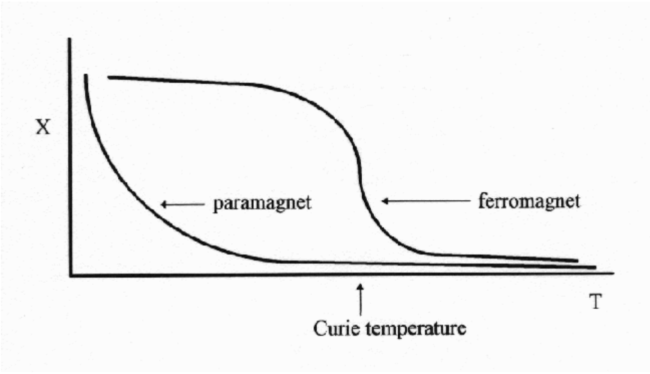
Fundamentals: Physics

Induction Driven Processes



Material properties modification

Heat Transfer

Energy Balance

$\rho C_p D_t T = \nabla \cdot (k \nabla T) + \dot{Q} + \underline{\underline{\sigma}} : \underline{\underline{\dot{\varepsilon}}}$

Joule Heating

$\dot{Q} = \vec{J} \cdot \vec{E}$

Electromagnetism

Maxwell

$\nabla \times \vec{E} = -\partial_t \vec{B} \,; \nabla \times \vec{H} = \partial_t \vec{D} + \vec{J}$

$\nabla \cdot \vec{B} = 0 \quad ; \nabla \cdot \vec{D} = \rho^e$

Deformation work

$\underline{\underline{\dot{\varepsilon}}}, \underline{\underline{\sigma}}$

$\vec{b} = \vec{J} \times \vec{B}$

Lorentz forces

Mechanics

Momentum

$\rho D_t \vec{v} = \nabla \cdot \underline{\underline{S}} - \nabla p + \rho \vec{b}$

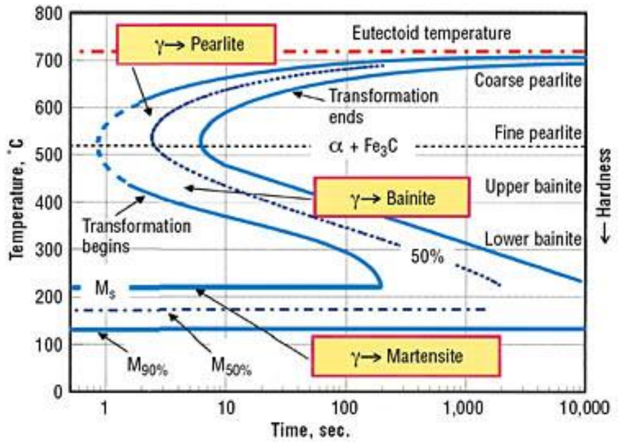
+ Mass Conservation

+ Constitutive Relations

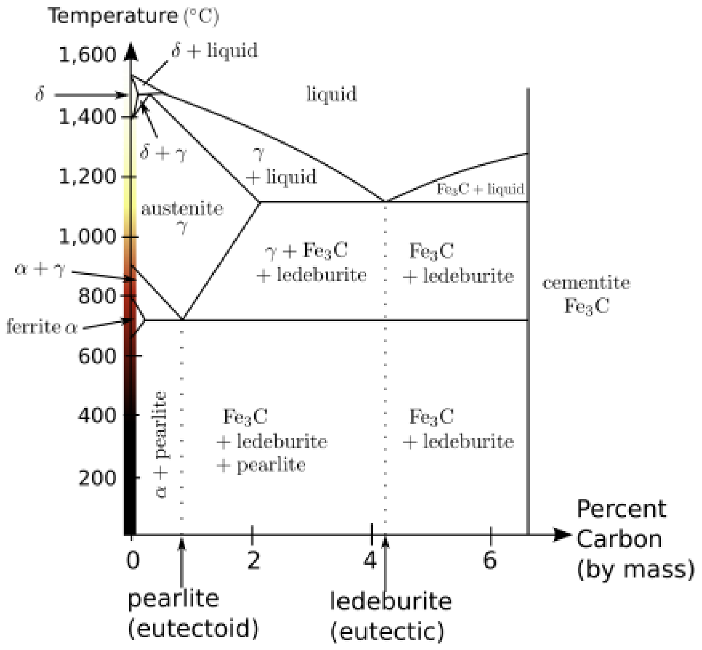
Displacements $\vec{x}, \vec{v}$

FORGE® Induction Electromagnetic Solver

FORGE® / THERCAST® Thermo-mechanical Solver



Material properties modification



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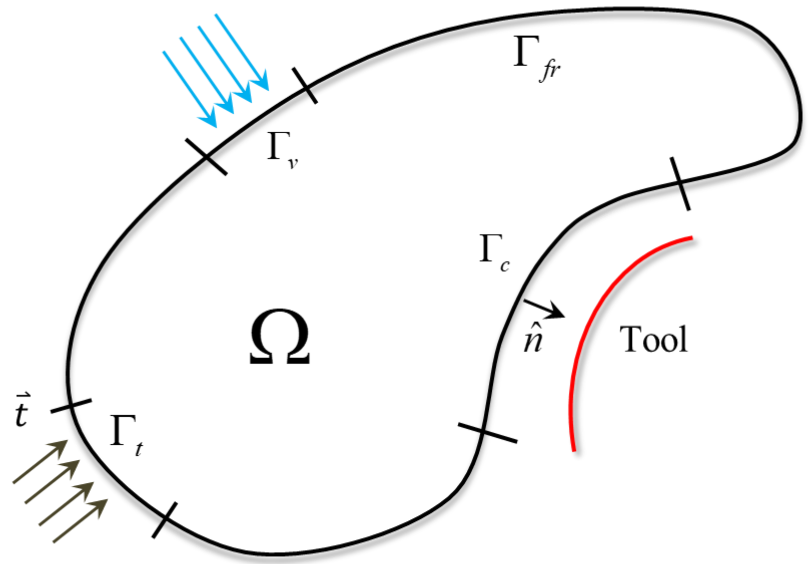
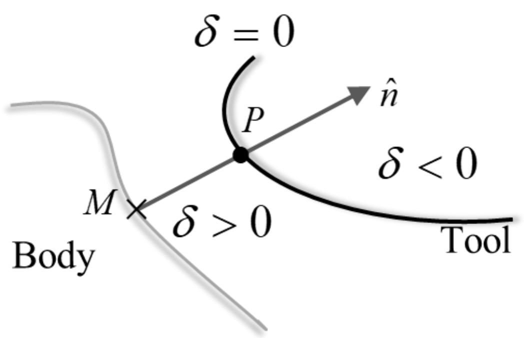
Fundamentals: Mechanics

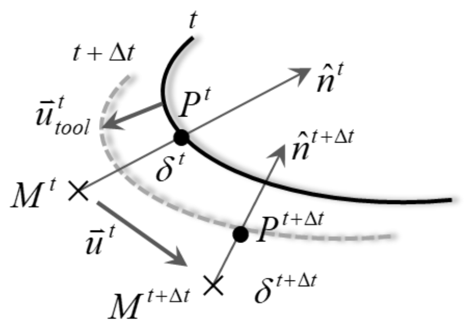
Fundamental Principles

Mass conservation for compressible media	$\nabla \vec{v} = -\frac{1}{\rho}\frac{d\rho}{dt}$
Conservation of linear momentum	$\nabla \cdot \underline{\underline{\sigma}} + \vec{b} = \rho \frac{D\vec{v}}{Dt}$
Conservation of angular momentum	$\underline{\underline{\sigma}} = \underline{\underline{\sigma}}^T$

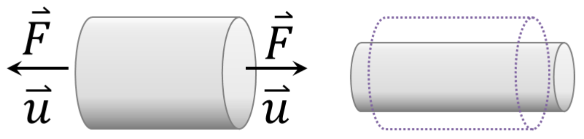


Contact



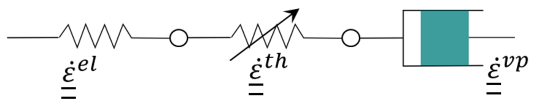


Constitutive Empirical relations



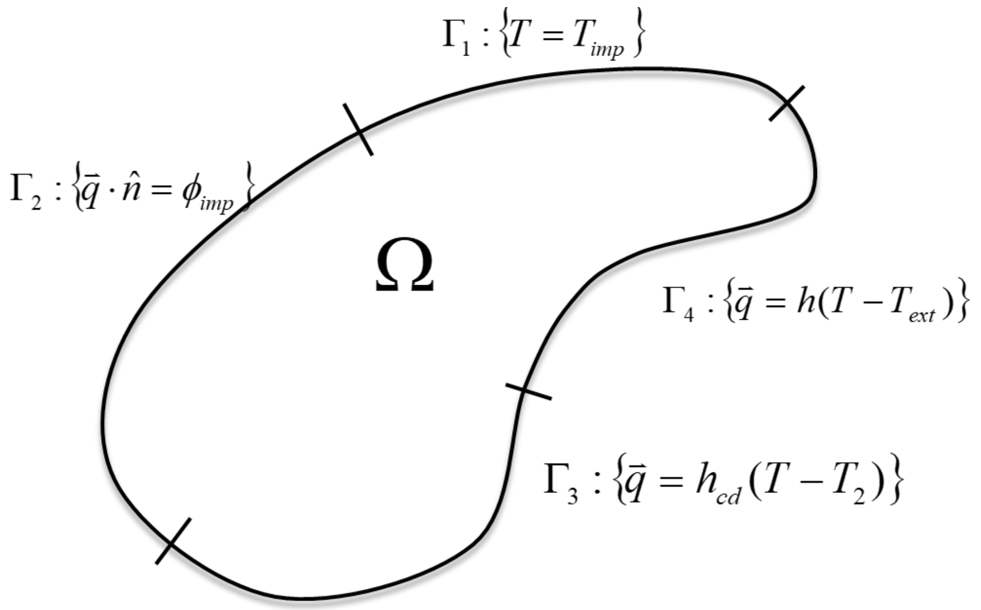
Hypothesis: Additive Strain

$\underline{\underline{\dot{\varepsilon}}} = \underline{\underline{\dot{\varepsilon}}}^{el} + \underline{\underline{\dot{\varepsilon}}}^{th} + \underline{\underline{\dot{\varepsilon}}}^{vp}$

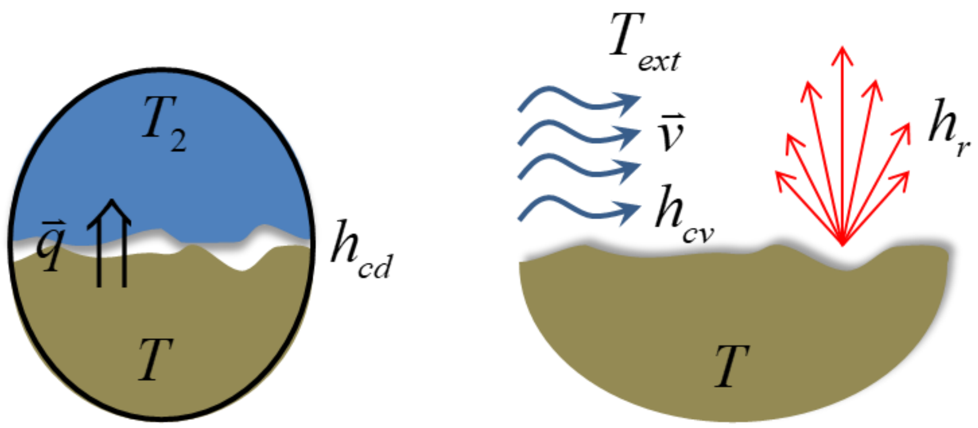


	Model	Contribution to mass conservation
Elasticity: Hooke's law	$\underline{\underline{\dot{\varepsilon}}}^{el} = \frac{1+\nu}{E}\underline{\underline{\dot{\sigma}}} - \frac{\nu}{E} tr\left(\underline{\underline{\dot{\sigma}}}\right)\underline{\underline{I}}$	$tr\left(\underline{\underline{\dot{\varepsilon}}}^{el}\right) = \frac{3(1-2\nu)}{E}\dot{p}$
Thermal expansion	$\underline{\underline{\dot{\varepsilon}}}^{th} = \alpha \dot{T} \underline{\underline{I}}$	$tr\left(\underline{\underline{\dot{\varepsilon}}}^{th}\right) = 3\alpha\dot{T}$
ViscoPlasticity:	$\underline{\underline{\dot{\varepsilon}}}^{vp} = \frac{3}{2}\frac{\dot{\bar{\varepsilon}}^{vp}}{\bar{\sigma}}\underline{\underline{S}}$	$tr\left(\underline{\underline{\dot{\varepsilon}}}^{vp}\right) = 0$
Flow rule example: Johnson-Cook [Johnson et al. 1983]	$\bar{\sigma} = (A + B\bar{\varepsilon}^n)\left[1 + C ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right]$	

Fundamentals: Heat Transfer



Heat transfer



Fundamental Principles

Energy conservation $$\rho C_p D_t T = -\nabla \cdot \vec{q} + \dot{Q} + \underline{\underline{\sigma}} : \underline{\underline{\dot{\varepsilon}}}$$

Constitutive Empirical relations

Fourier heat conduction $$\vec{q} = -k\nabla T$$

Convection with media:

$$-k\nabla T \cdot \hat{n} = h_{cv}(T - T_{ext})$$

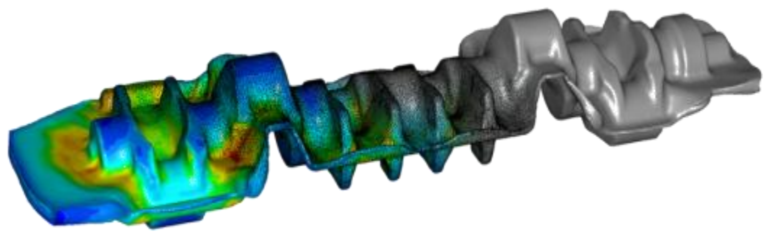
Radiation (simplified):

$$-k\nabla T \cdot \hat{n} = \epsilon_r \sigma_r (T^4 - T_{ext}^4)$$

Physical Couplings

Non-linearities in physical systems

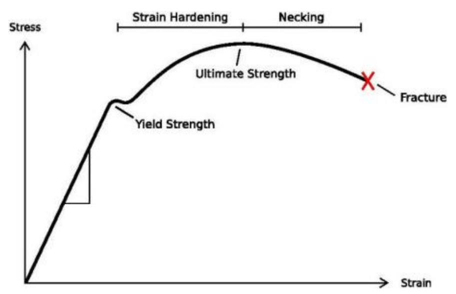
Shape non-linearities



Complex shapes
Mechanical Contact

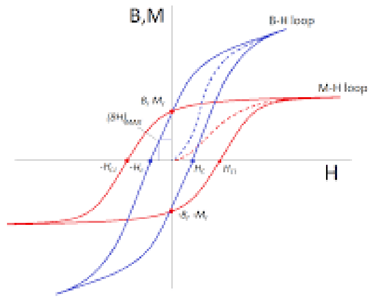
Material non-linearities

Material properties depend on State variable fields (e.g. Temperature, Magnetic field, Strain,…)



Elasto-plasticity

Magnetic hysteresis



Physical non-linearities

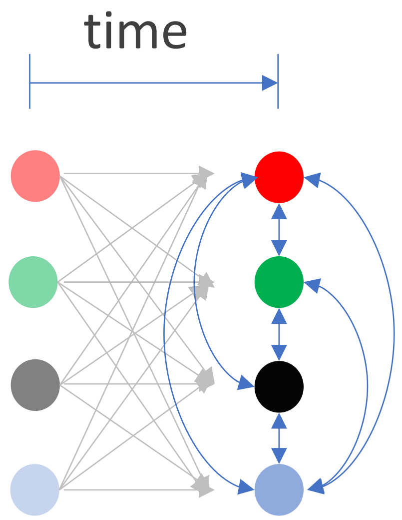
Physical principle has a non-linear dependency of the state variable OR different physics that need to be solved together

Ex: Green-Lagrange Strain tensor in finite strain theory

$$\vec{E} = \frac{1}{2}(\nabla\vec{u}^t + \nabla\vec{u} + \nabla\vec{u}^t \cdot \nabla\vec{u})$$

Couplings

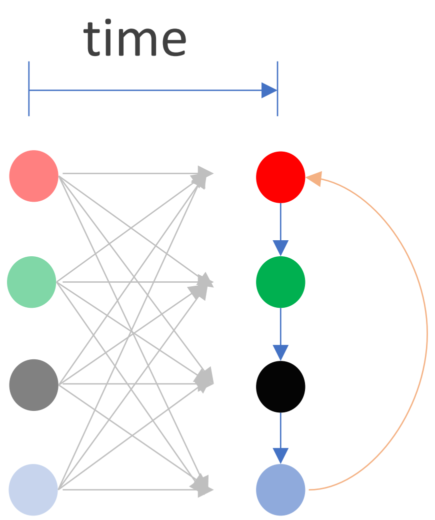
Strong



Solve all physical blocks together
… accurate but slow

Only done for small academic/semi-analytic problems

Sequential



Solve each physical block individualy and increment
… fast but less accurate

Most numerical softwares use this kind of approaches

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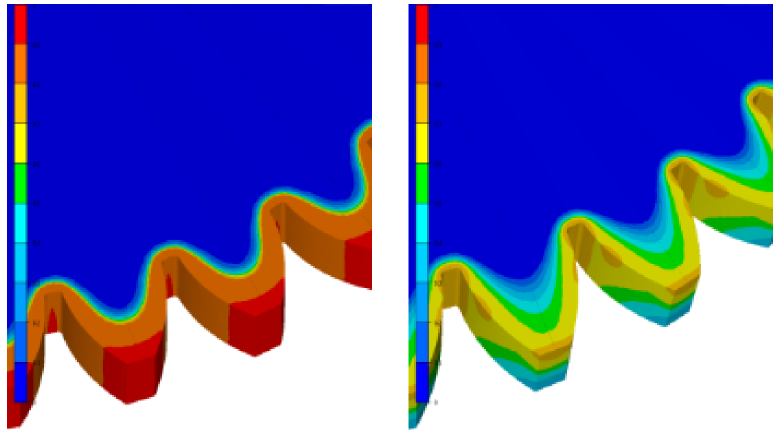
Application: Induction Heating

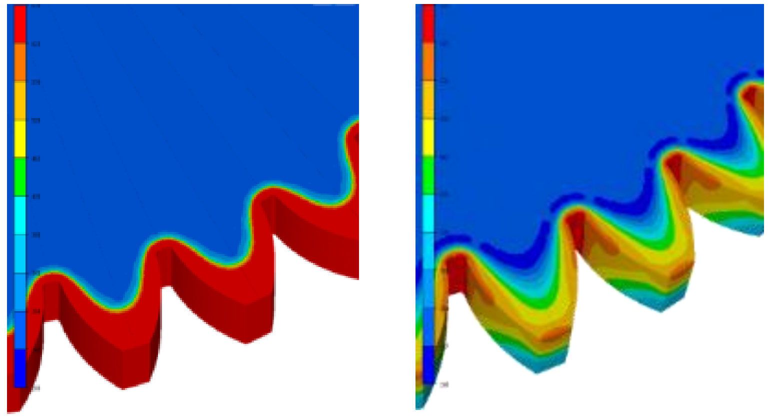
Heat Treaments by Induction Heating

Goals of HT simulations:

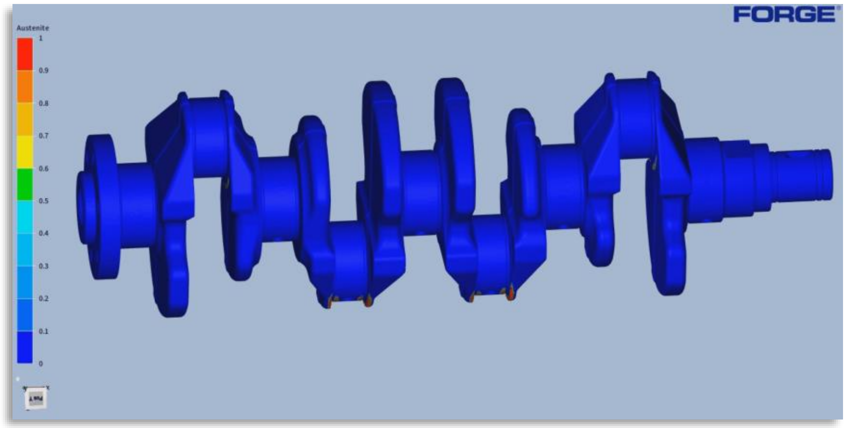
- Prediction of HAZ
- Prediction of phases and residual stresses after quenching
- Prediction of distortions
- Understanding of generator behavior and optimization of process parameters



Martensite (high or low frequency)



Hardness (high or low frequency)



Chained Heat Treatment Simulation

Study Case between:

NTN SNR

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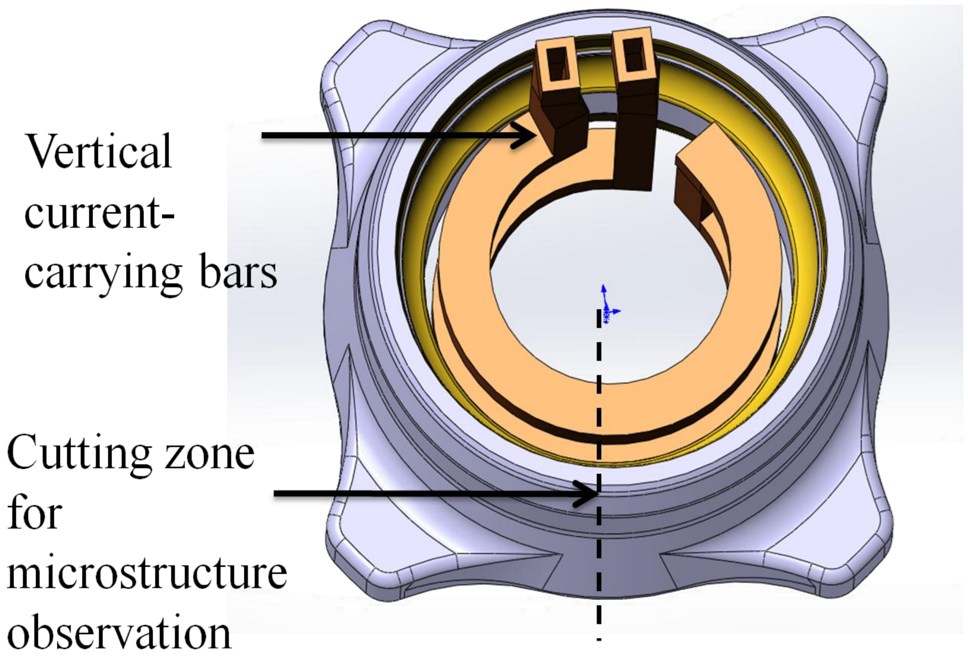
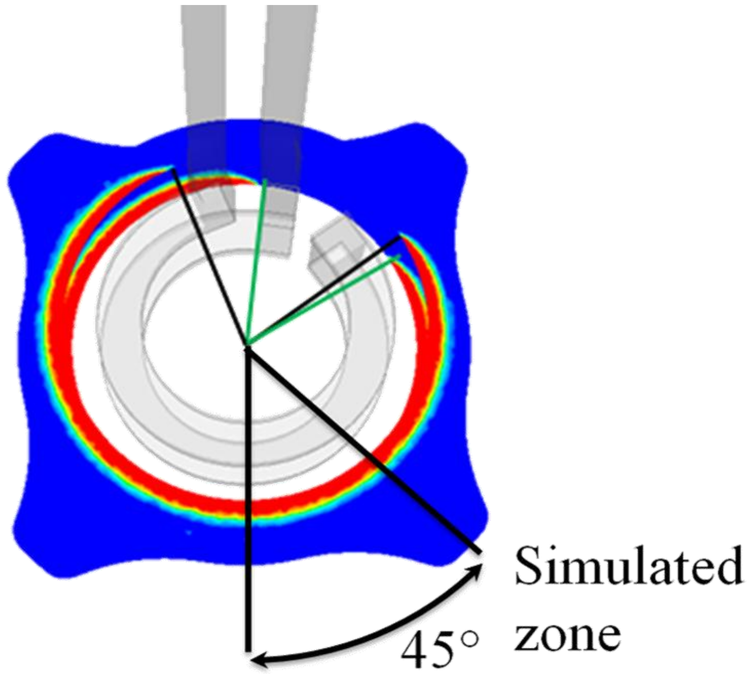
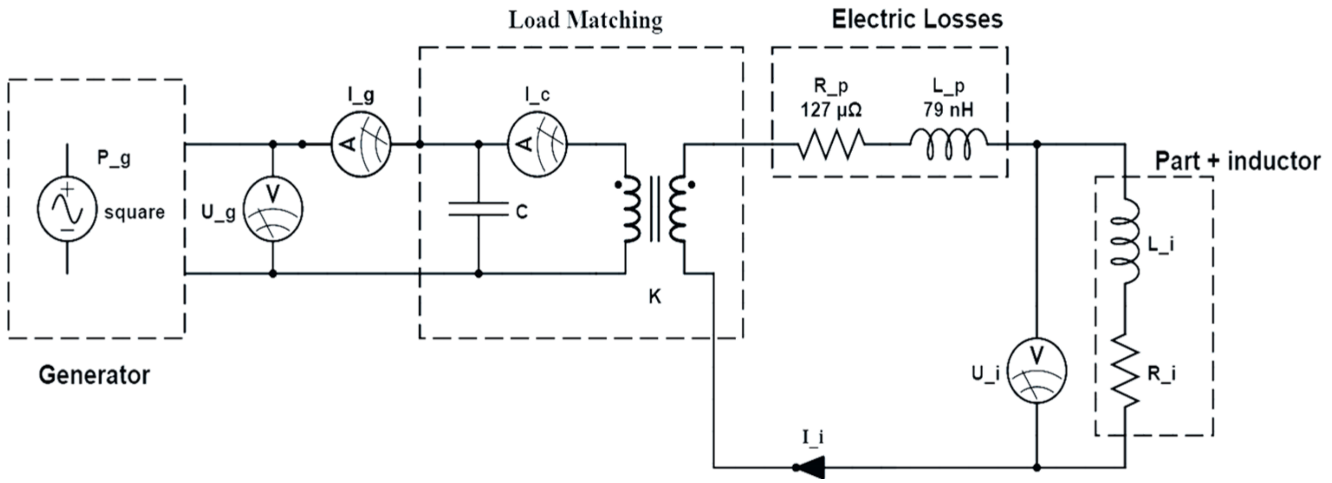
- EMAG-Thermochanical simulation piloted by a generator
- Followed by quenching simulation







[Lejay V., Barlier J., Fabro T. Settefrati A., “FEM Simulation of induction hardening: from the generator behavior to the quenched microstructure prediction. Comparison of experiments vs simulations.” 2016]

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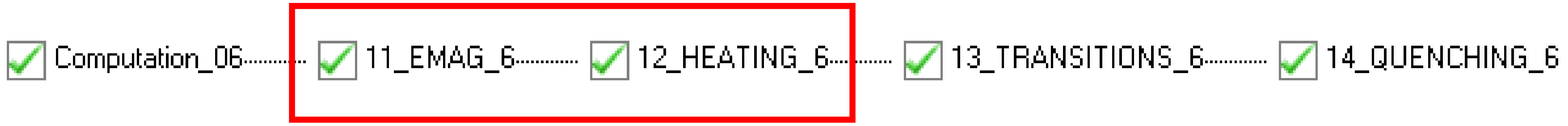
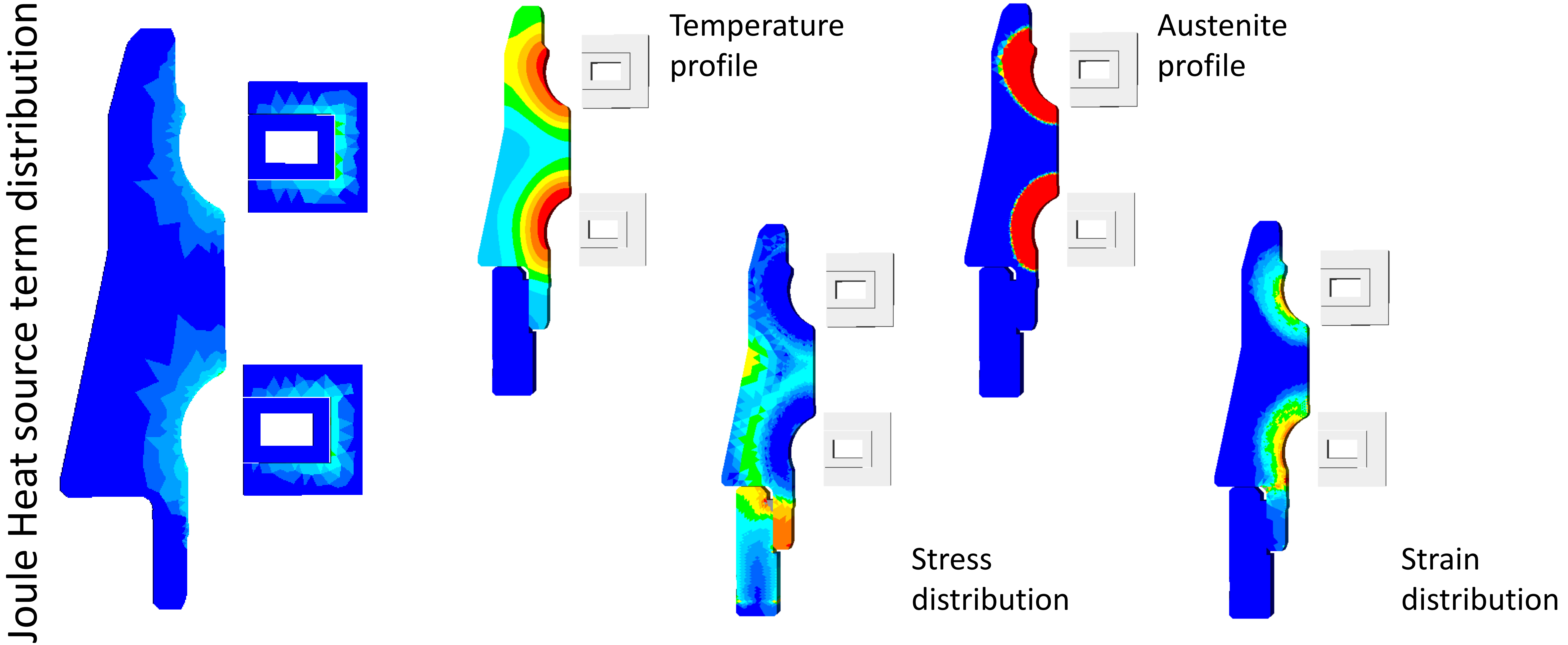
Chained Heat Treatment Simulation





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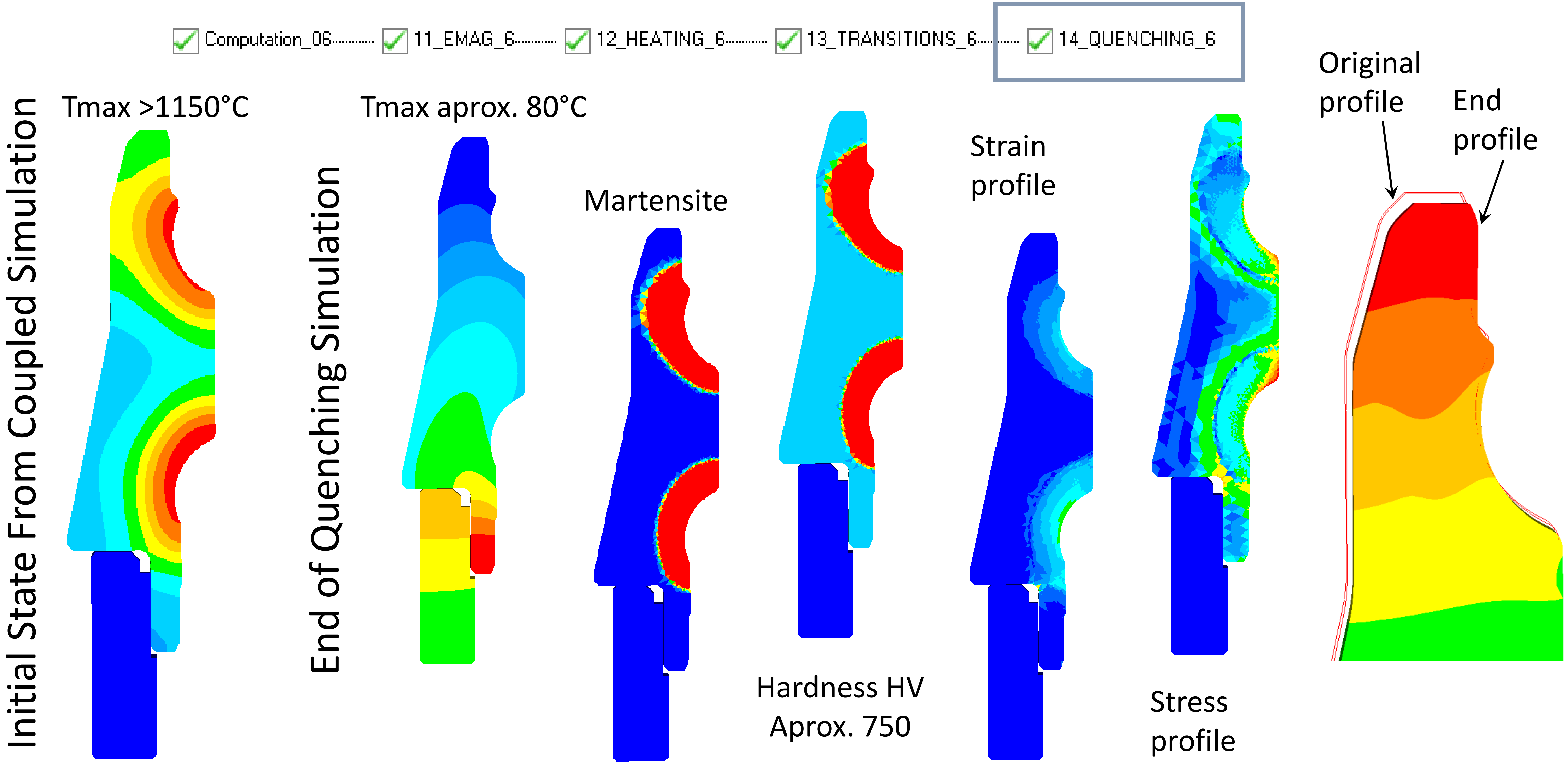
Chained Heat Treatment Simulation



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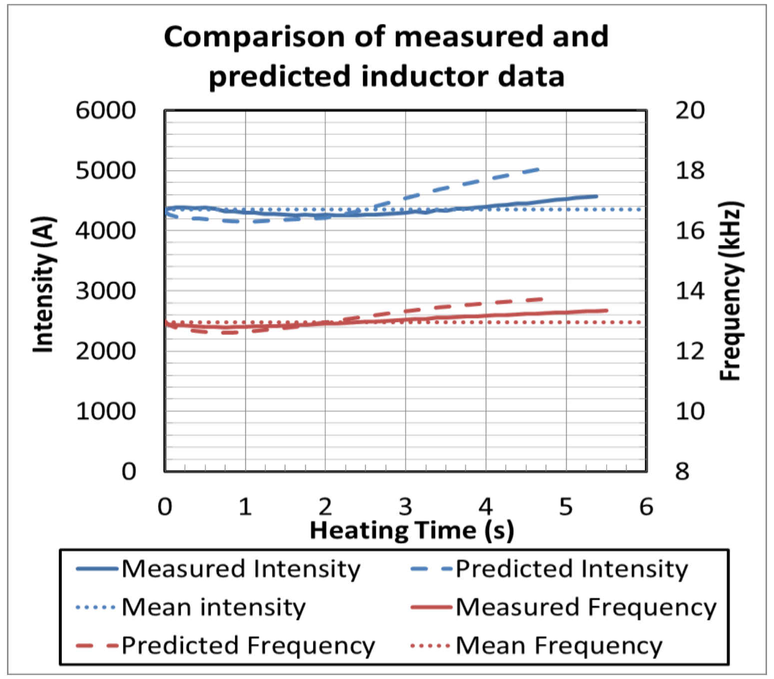
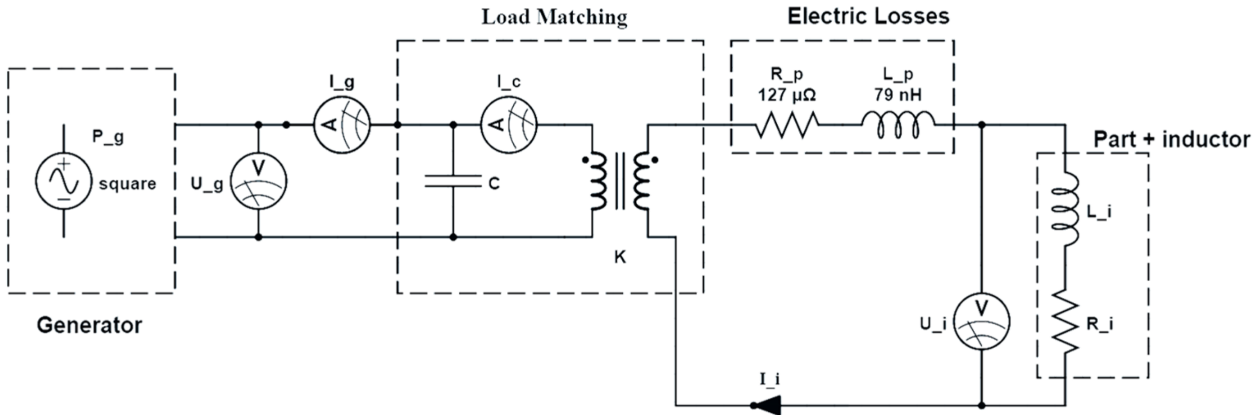
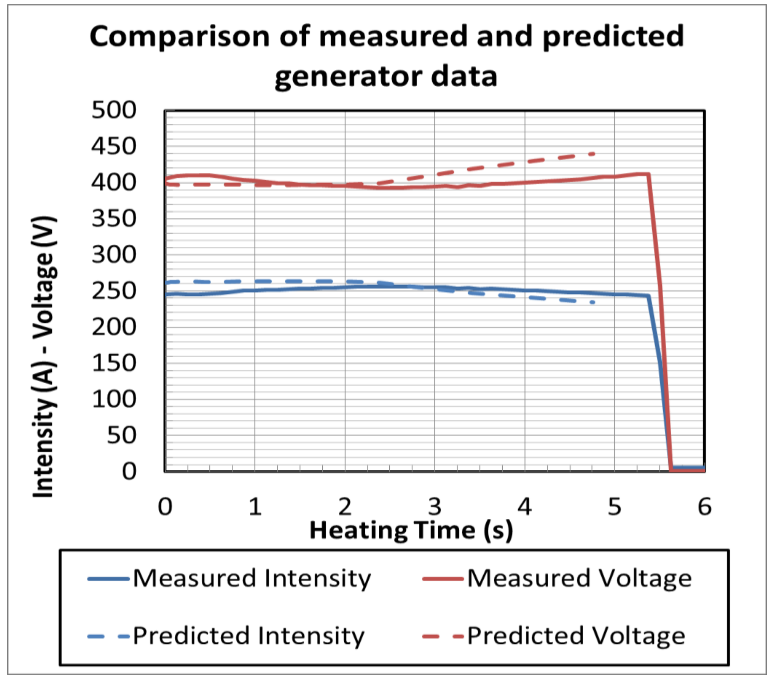
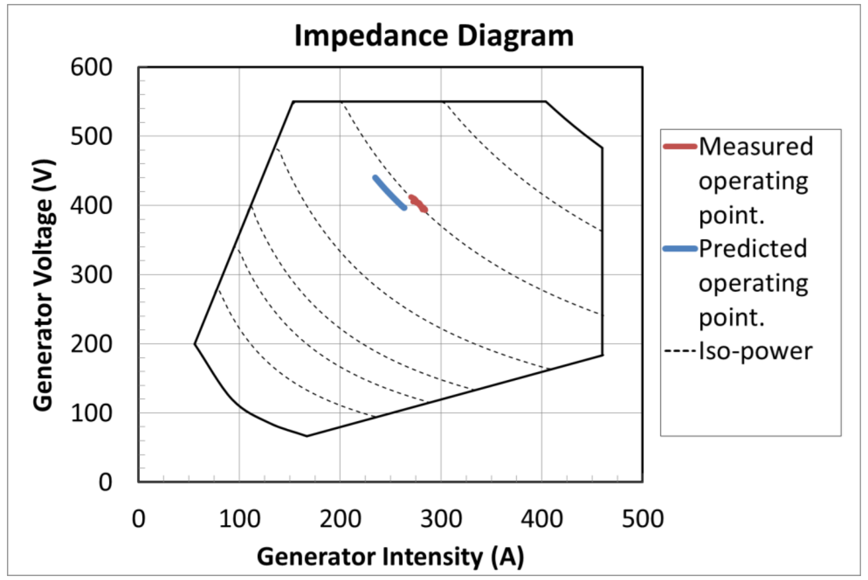
Chained Heat Treatment Simulation



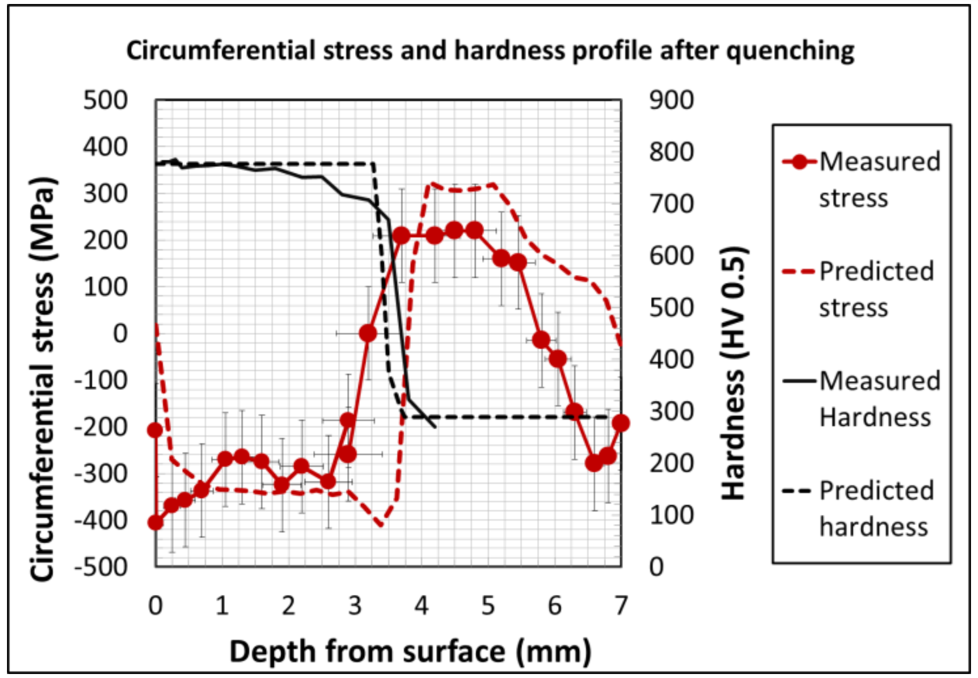
Prediction of Operation point

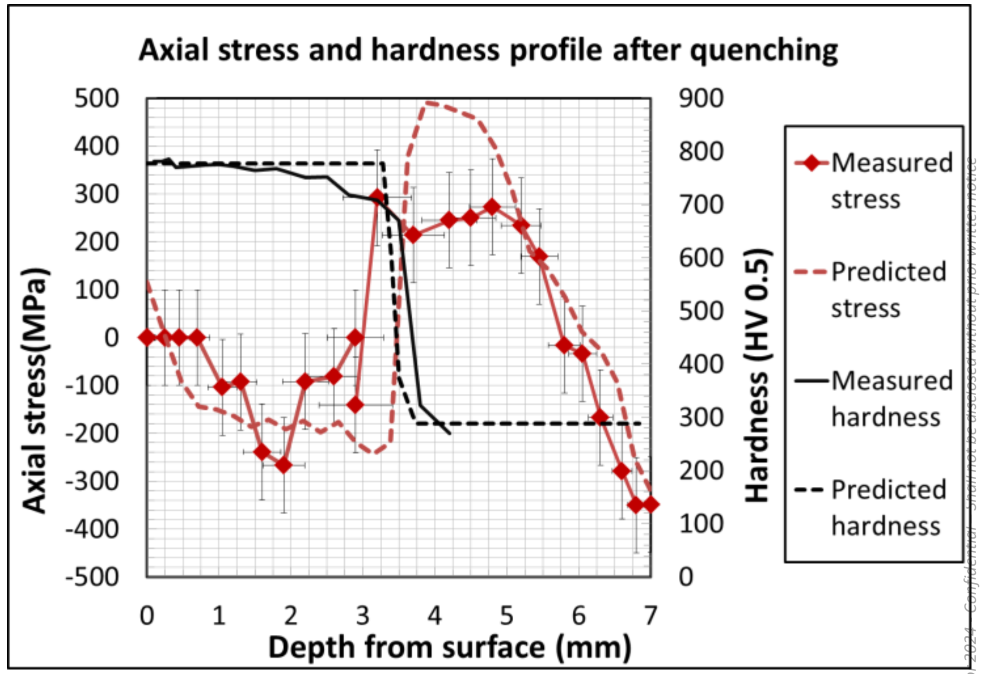






Bearing properties





[Lejay V., Barlier J., Fabro T. Settefrati A., “FEM Simulation of induction hardening: from the generator behavior to the quenched microstructure prediction. Comparison of experiments vs simulations.” 2016]

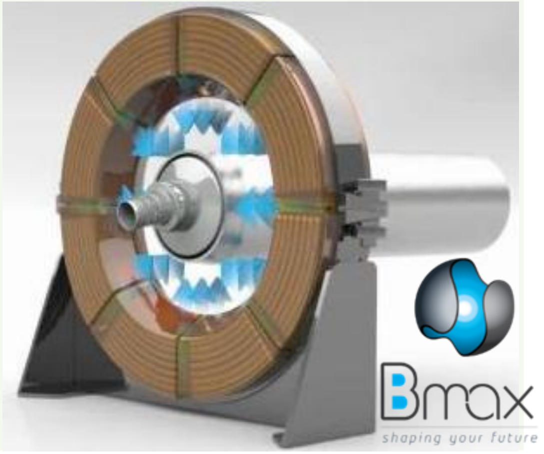
Application: Magnetic Pulse Forming

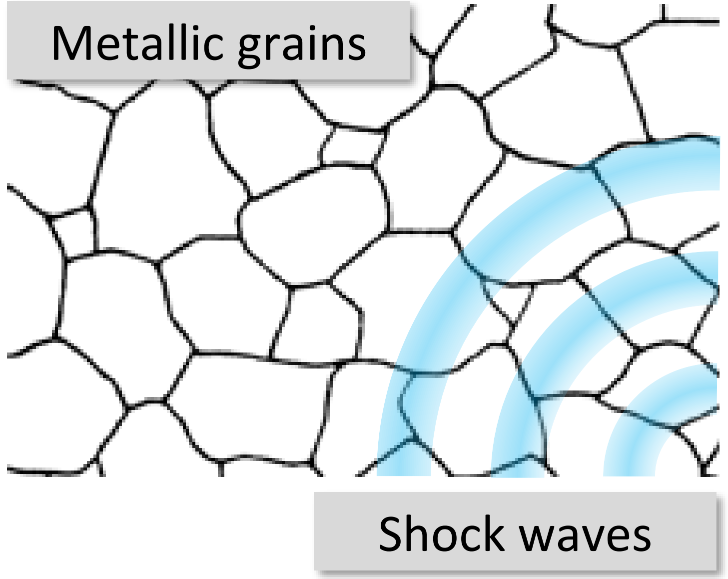
MAGNETIC PULSE FORMING

Process: Magnetic Pulse Forming

Mechanical joining and/or forming of metallic parts by electromagnetic induction

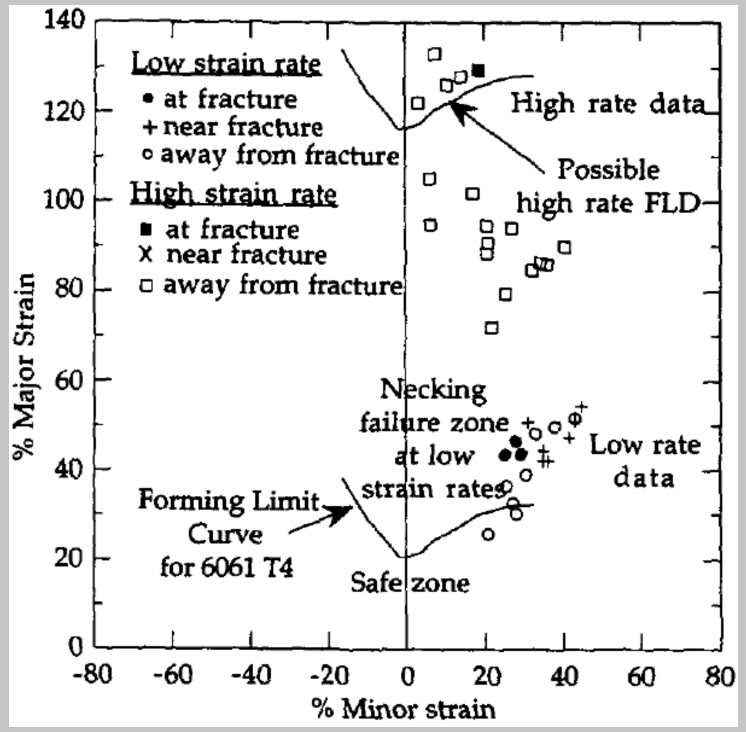
- Elimination of elastic spring back
- Improved mechanical joints by cold-welded surfaces
- Excellent electric surface conductivity between parts for electric applications
- Weld of dissimilar materials
- Preservation of surface quality due to lack of contact.





Mechanism: Kinematic softening (shock)

Inertial waves help release and redistribute stresses improving formability



FLD for 6061T4 aluminum(…)
[Balanethiram, V. and Daehn G.S., 'Hyperplasticity: increased forming limits at high workpiece velocity', 1994]

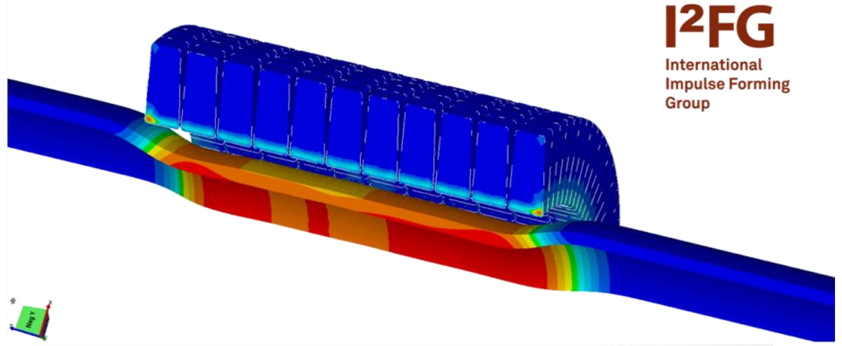
MAGNETIC PULSE FORMING

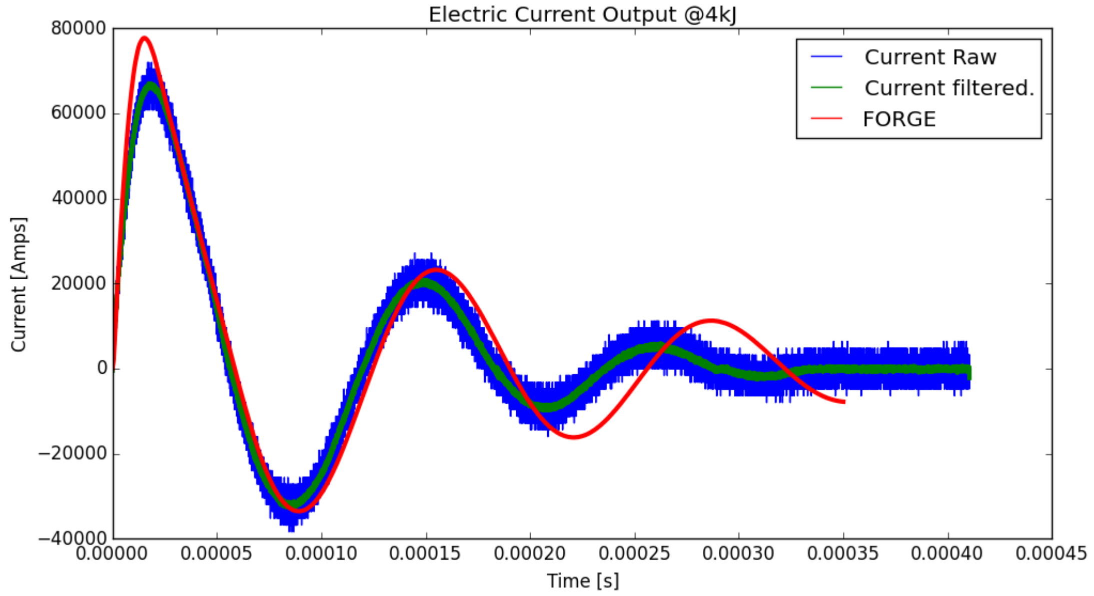
Benchmark (Work in Progress)

Study Case provided by:

IUL

I²FG
International Impulse Forming Group





[Bay F., Alves J., “A computational model for magnetic pulse forming processes – Application to a test case and sensitivity to dynamic material behaviour.” 2018]

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Application: Electromagnetic Stirring

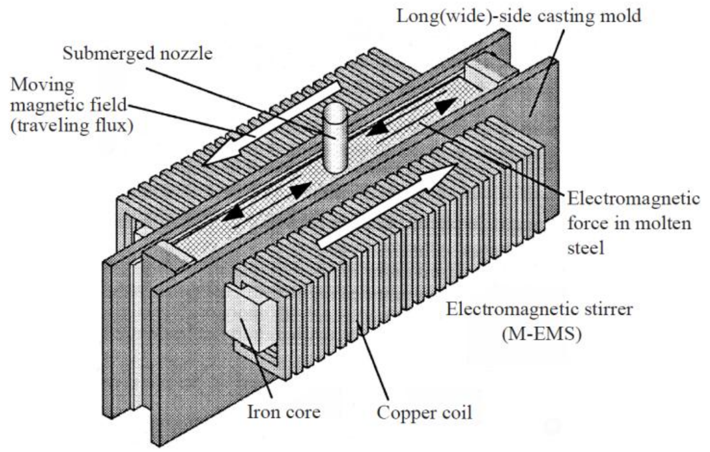
Electromagnetic Stirring

Process: Electromagnetic Stirring

Stirring of casted metal during continuous casting process

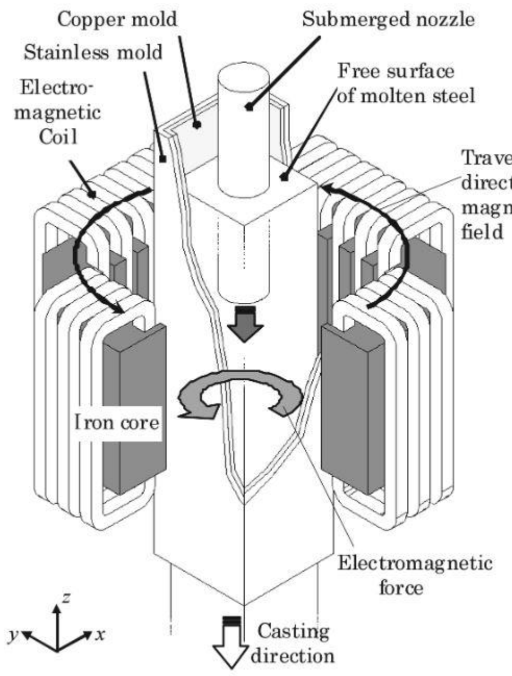
- Surface quality improvement
- Shell thickness uniformisation
- Gain in casting velocity
- Central porosity reduction
- Central segregation reduction
- Enlargement of the central equiaxed microstructure

Linear Stirrer



K. YOKOTA and K. FUJISAKI, NIPPON STEEL TECHNICAL REPORT No. 89 JANUARY 2004

Rotational Stirrer



S. Satou and K. Fujisaki, Electrical Engineering in Japan, 177(3):62–68, 2011.

Mechanism: Lorentz Forces

Variable magnetic field

- Eddy current creation

$$\vec{j} = -\frac{\nabla\times\vec{B}}{\mu}$$

- Lorentz forces driving the flow

$$\vec{f_L} = \vec{j}\times\vec{B}$$

- Volume force in Navier-Stokes equations

$$\rho\frac{D\vec{v}}{Dt} = \nabla\cdot s - \nabla p + \rho\vec{f}$$

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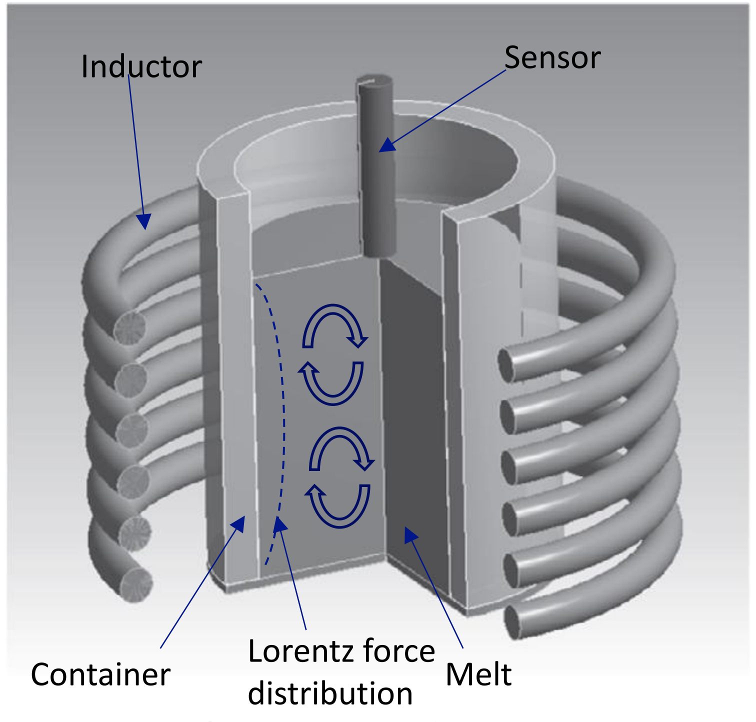
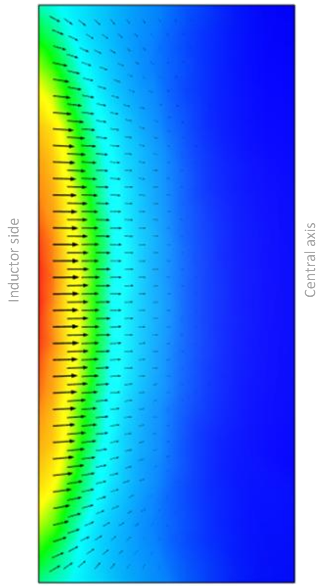
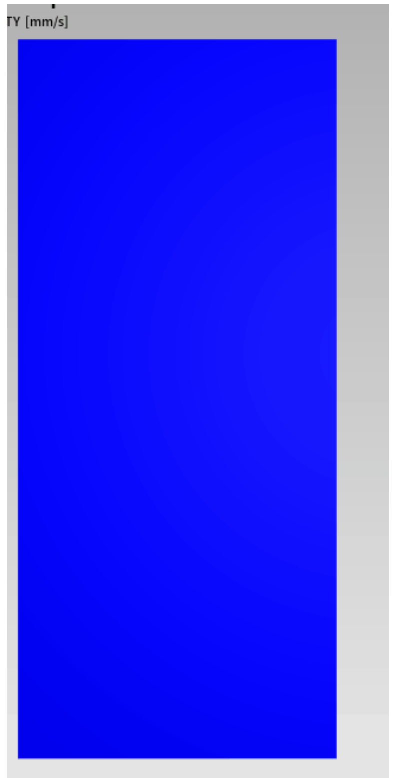
Electromagnetic Stirring

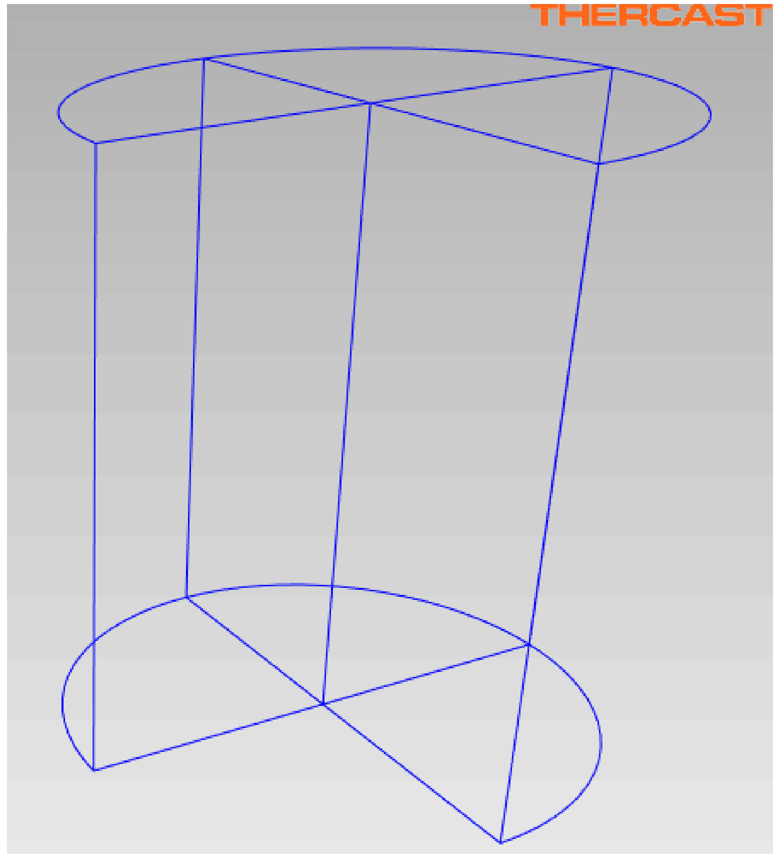
- MUSAEVA *et al.*, **Experimental investigation of low-frequency pulsed Lorentz force influence on the motion of Galinstan melt**, St. Petersburg Polytechnical University Journal: Physics and Mathematics 2 (2016) 193–200



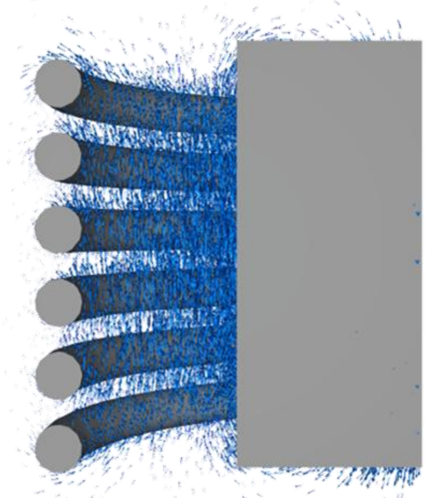
Resulting Lorentz force field averaged on a period



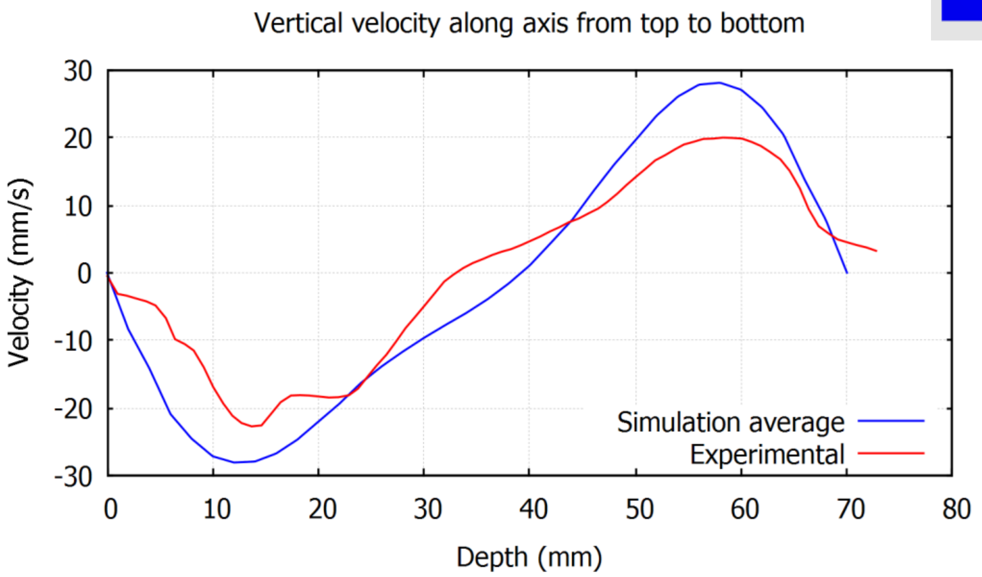




Streamlines in the melt, colored by vertical velocity magnitude



Electromagnetic field



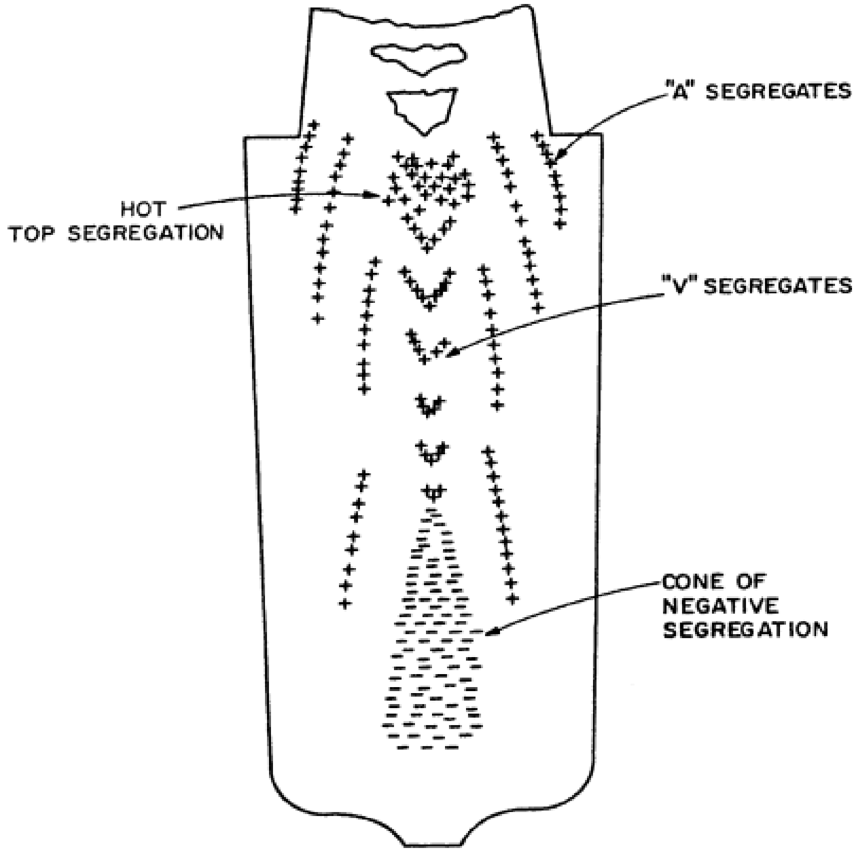
Electromagnetic Stirring

- Macrosegregation in as-cast products

- Varying composition of the solidified volume due to solute redistribution during solidification (microsegregation)

- Observed for centuries
- Extensive studies since the 20th century (more or less)
- Objective: increase the yield of production by minimizing the segregation

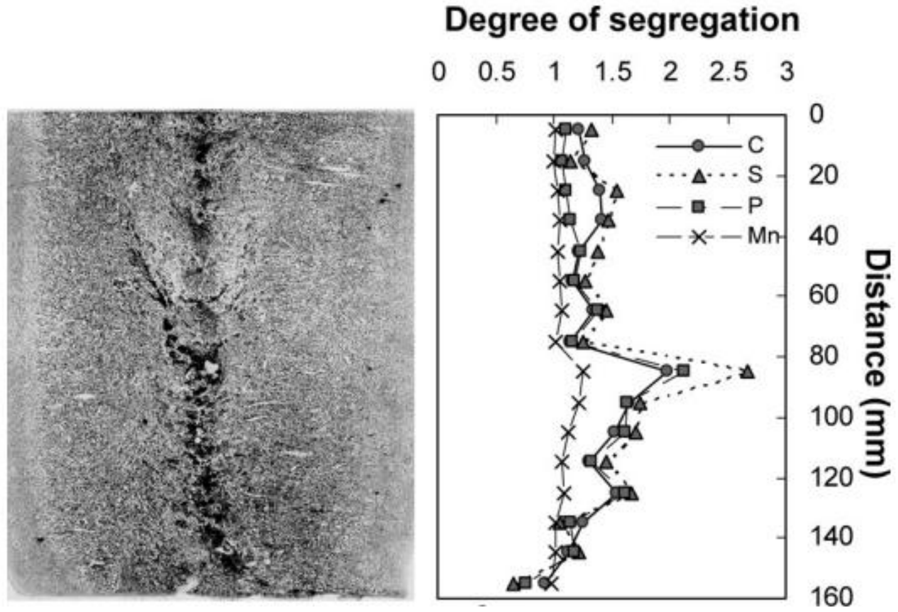
Ingot casting



[Flemings, *ISIJ International, vol. 40*, 2000]

Centerline segregation in high carbon steel (continuous casting)

Sulphur prints and measured concentrations

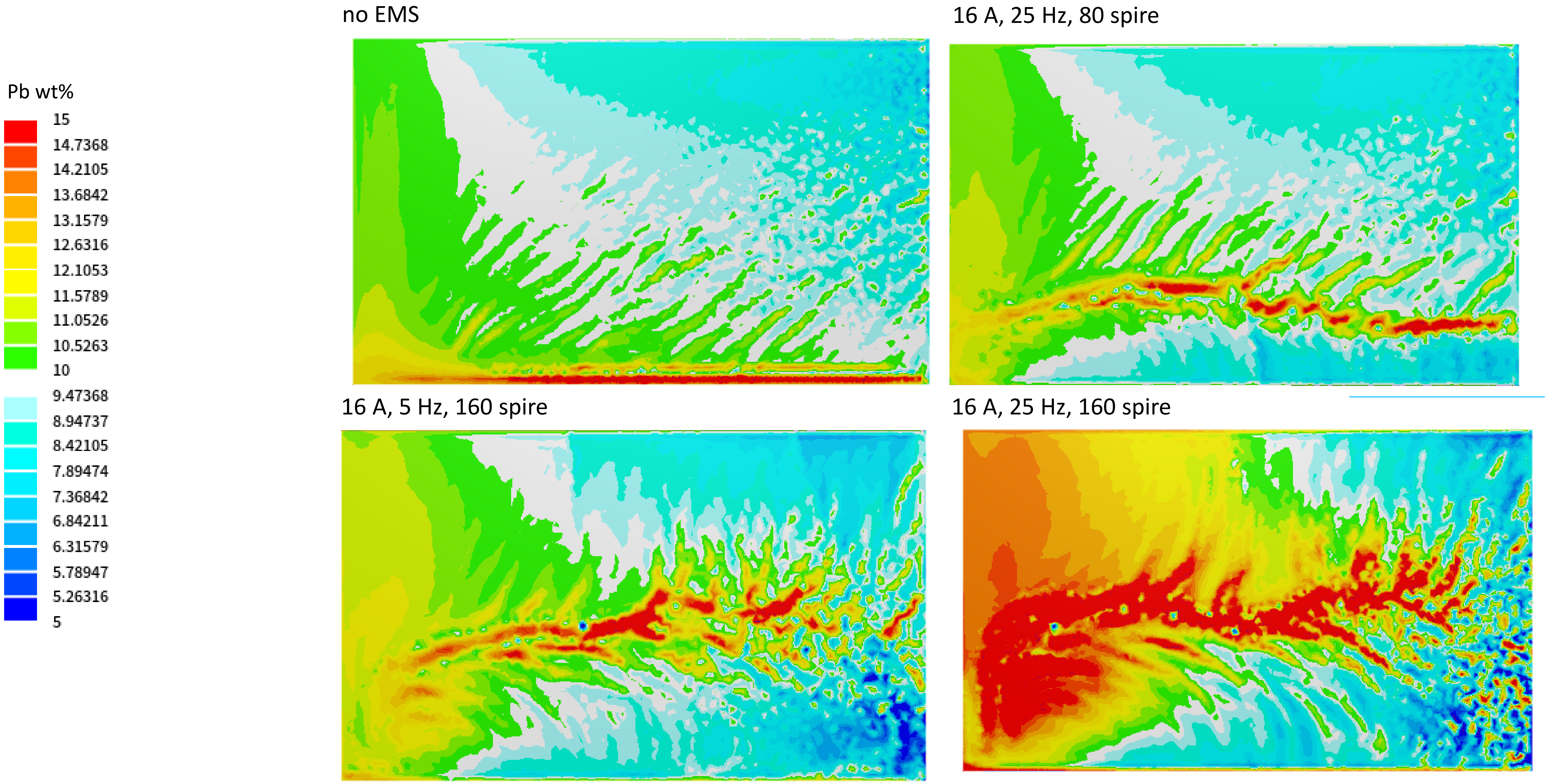


[Choudhary and Ganguly, *ISIJ International*, vol. 47, 2007]

- Macrosegregation can affect the mechanical properties of the finished product, or the different transformations applied to the as-cast product

Electromagnetic Stirring

Lead concentration pattern at 5000s with binary model over half-cutting plane of axis y



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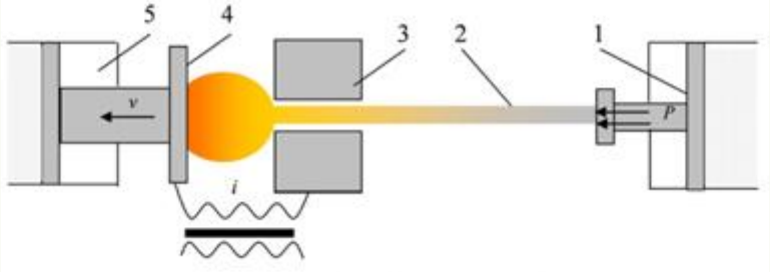
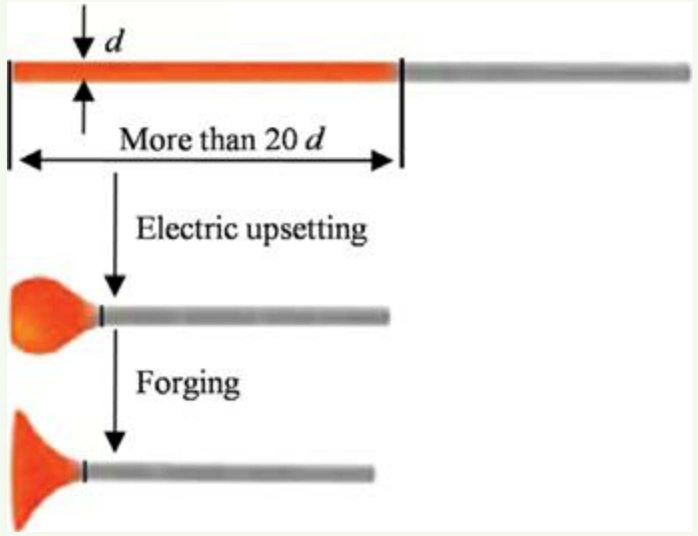
Application: Electric Upsetting

ELECTRICALLY ASSISTED FORMING

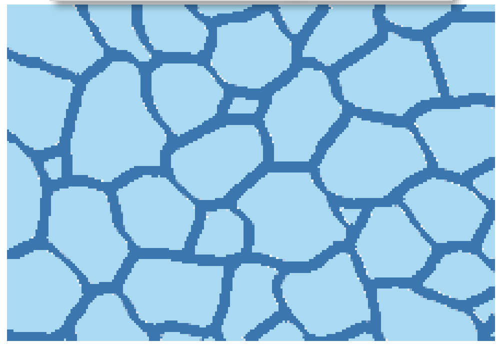
Process: Electric Upsetting





[Guozheng Q. et al, 'Influence of Electric Upsetting Process Variables on Temperature Field Evolution by Multi-Field Coupling Finite Element Analysis', 2015]

Metallic grains



$$T_{Grain\ boundaries} > T_{bulk}$$

Temperature is increased between the recrystallization point and the melting temperature

- Reduction of yield strength
- Increased ductility

Mechanism: Electrical Thermal Softening

Electric current increases grain boundary temperature above bulk temperature→ The material can achieve larger deformations before failure

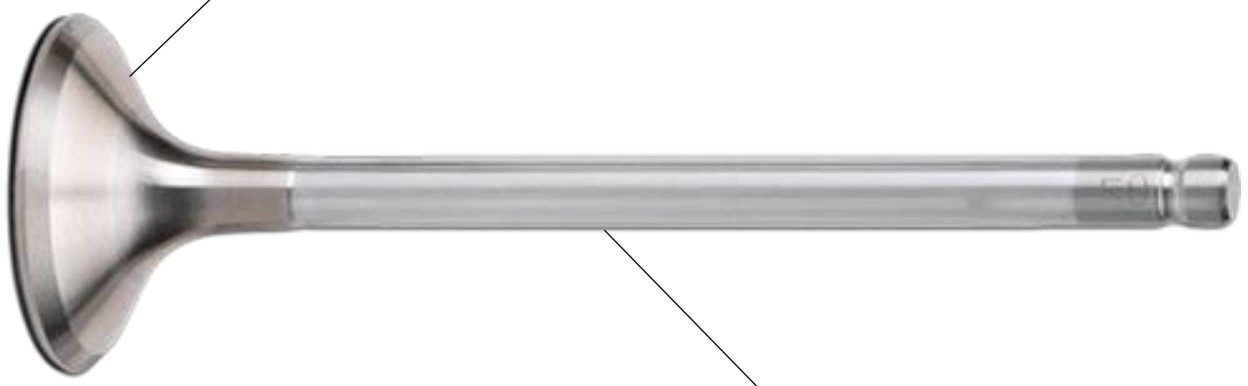
EAF formability improvement (Ti-G5).
[Salandro, W., 'Thermo-mechanical modeling of the electrically-assisted manufacturing (EAM) Technique During Open Die Forging', 2012]

Electrical upsetting

ENGINE VALVES MANUFACTURING

VALVE HEAD

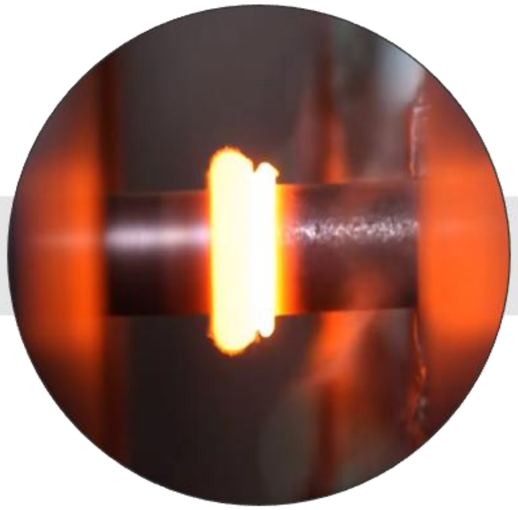
- 21-4N austenitic stainless steel
- 21% chromium and 4% nickel
- Excellent performance characteristics at elevated temperatures
- High resistance to heat and corrosion



VALVE STEM

- EN52 martensitic steel
- High tensile strength and abrasive wear resistance property

FRICTION WELDING



MACHINING
COOLING

ELECTRICAL UPSETTING

COOLING

FORGING

HEAT TREATMENT
MACHINING
FINISHING
…

TRANSVALOR

Electrical upsetting

IFUTEC®

LUW Forming Technology and Machine Tools Laboratory
HOCHSCHULE OSNABRÜCK
UNIVERSITY OF APPLIED SCIENCES

TECHNISCHE UNIVERSITÄT CHEMNITZ

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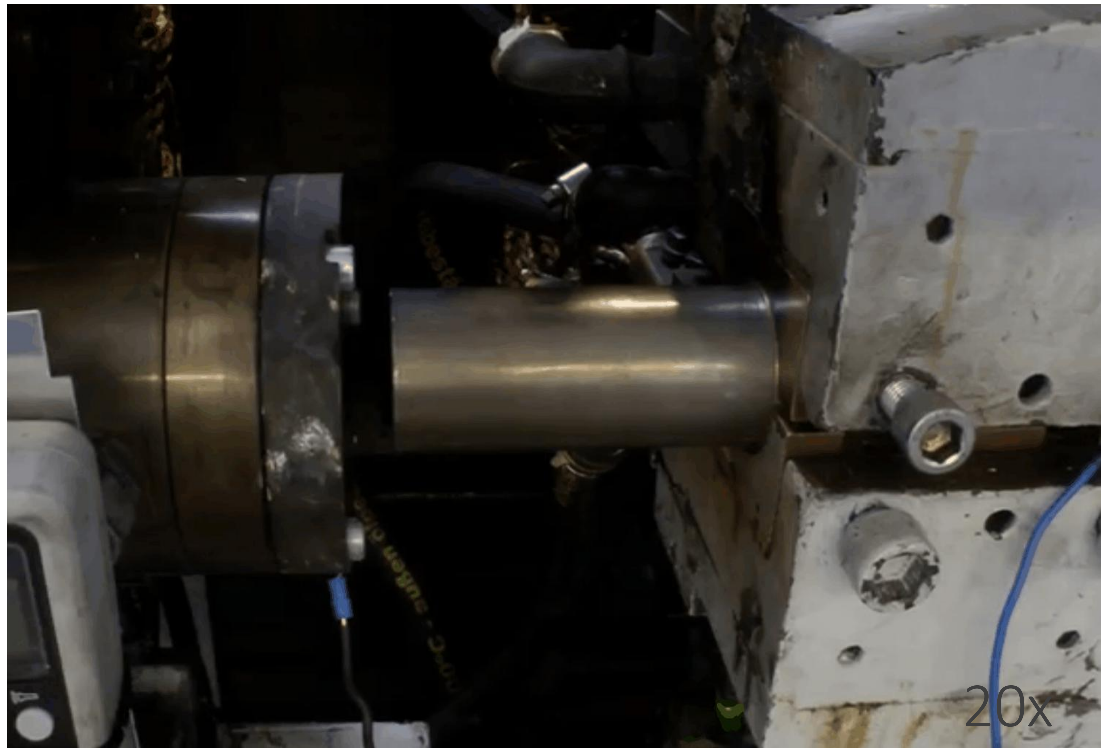
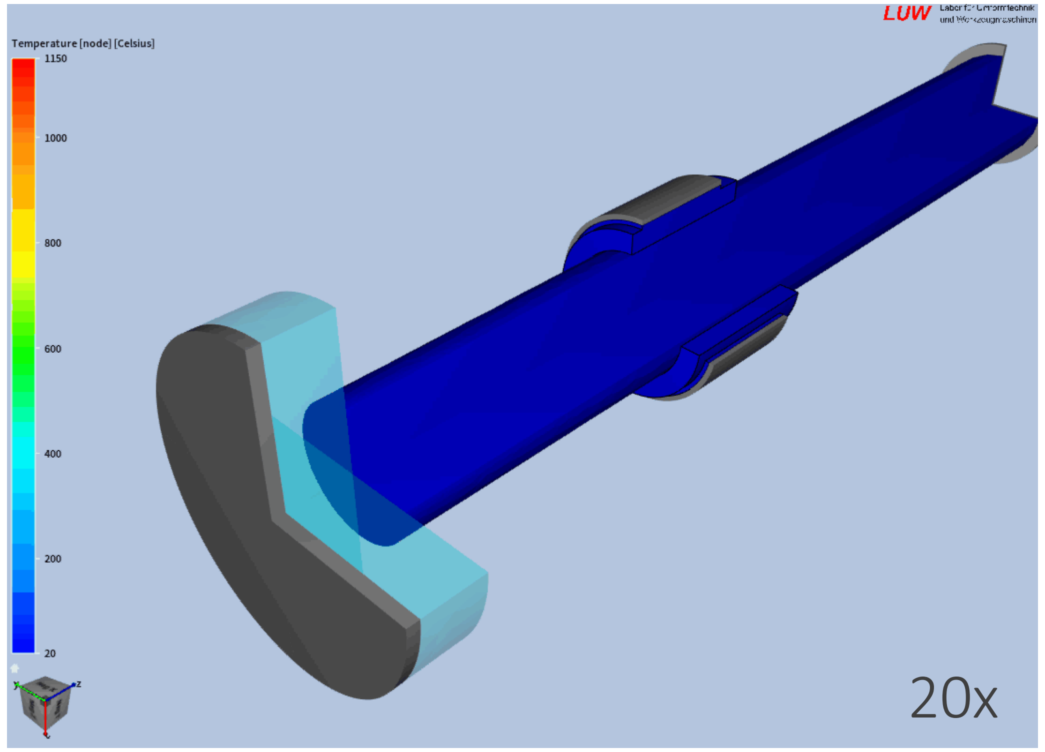
MATERIAL FORMING SIMULATION





Bundesministerium für Wirtschaft und Energie

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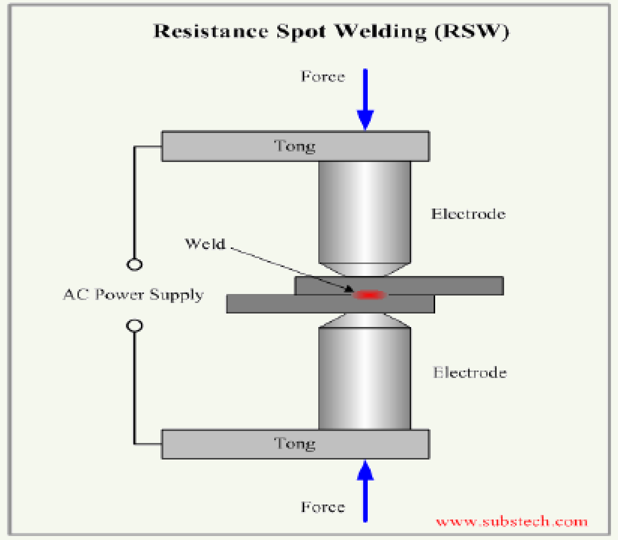
Application: Resistance Spot Welding

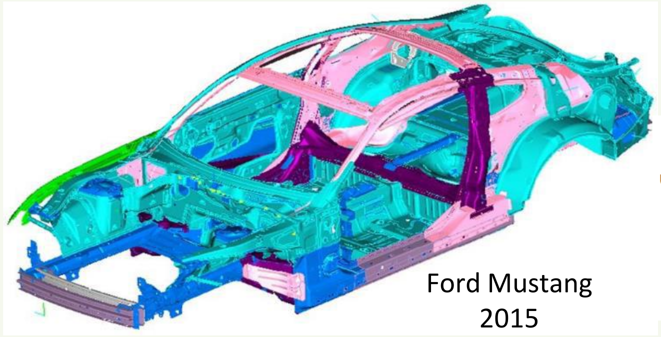
Resistance Spot Welding

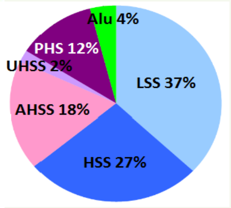
Process: Spot Welding



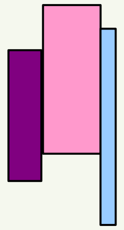
Joining by melting without additional material

Heavily used for assembly of body in white in the automotive industry





Structure / Structure / Cover



Mechanism: Controlled Melting and Cooling

Weld nugget size and penetration in the assembly drives the quality

Heat releated loss of mechanical properties are a major consern for controlability

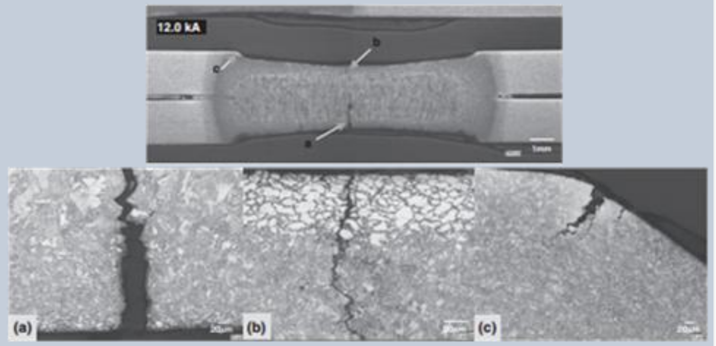


Fig. 6 Microstructure of the surface crack at a high welding current (12.0 kA)

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ELECTRICALLY ASSISTED JOINING

SPOT WELDING

(a)

Evaluation of Surface Crack in Resistance Spot Welds of Zn-Coated Steel

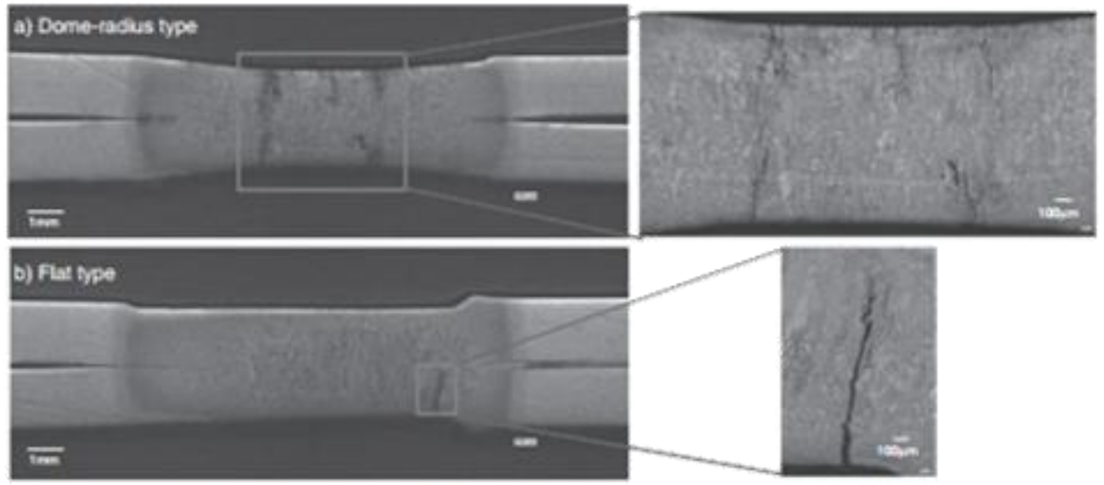

Fig. 5 Macrostructure of the surface cracks in the different electrode shape.

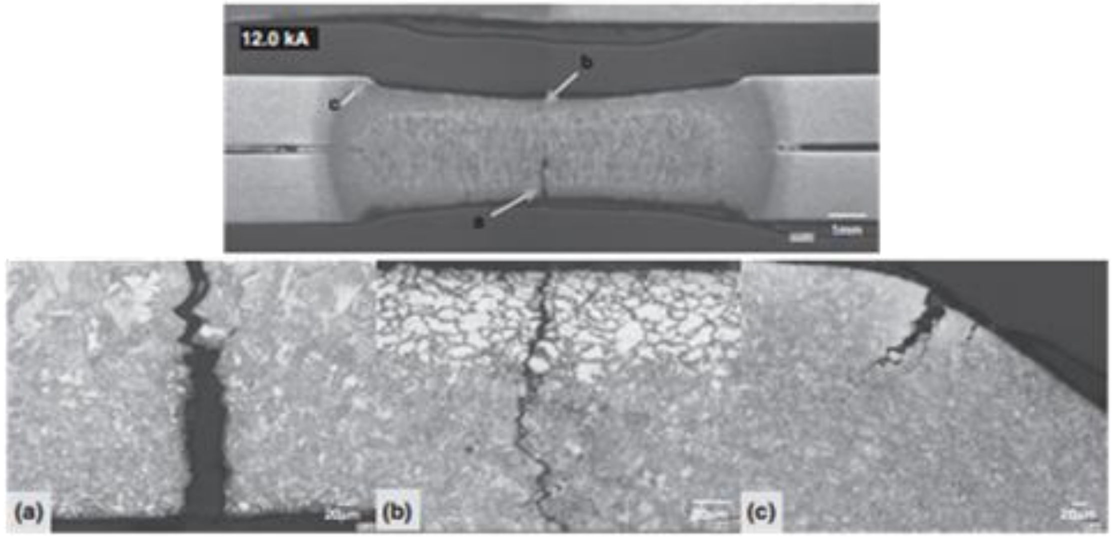

Fig. 6 Microstructure of the surface crack at a high welding current (12.0 kA).

(b)

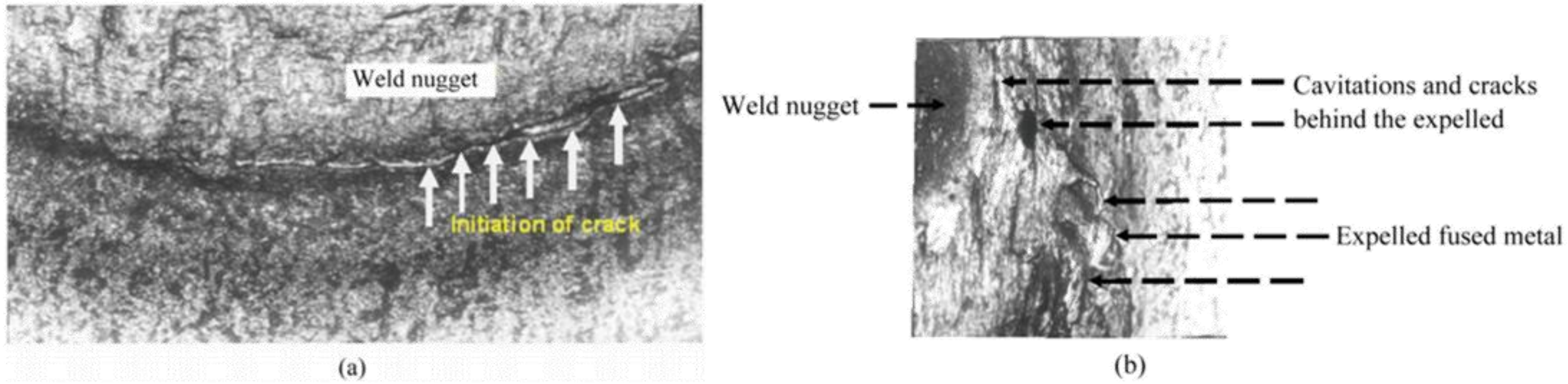

Figure 4. Fracture beside the weld bead; (a) crack initiation around the weld nugget; (b) the expelled weld metal.

Current problems in Spot-Welding:

•Evolution of the liquid zone (weld nugget) as fonction of the electric signal and the electrodes force: Control the fusion between plates.

•Apparition of cracks during cooling: understanding the problem and optimizing the process

Phase Transformation, migration of chemical species, nucleation and cracks propagation, etc...

(a) [Young K. et al, “Evaluation of Surface Crack in Resistance Spot Welds of Zn-Coated Steel” 2013]
(b) [Al-Mukhtar A. and Doos Q., “Cracking Phenomenon in Spot Welded Joints of Austenitic Stainless Steel” 2013]

ELECTRICALLY ASSISTED JOINING

SPOT WELDING

Study Case between:

Institut de Recherche Dupuy de Lôme

ArcelorMittal

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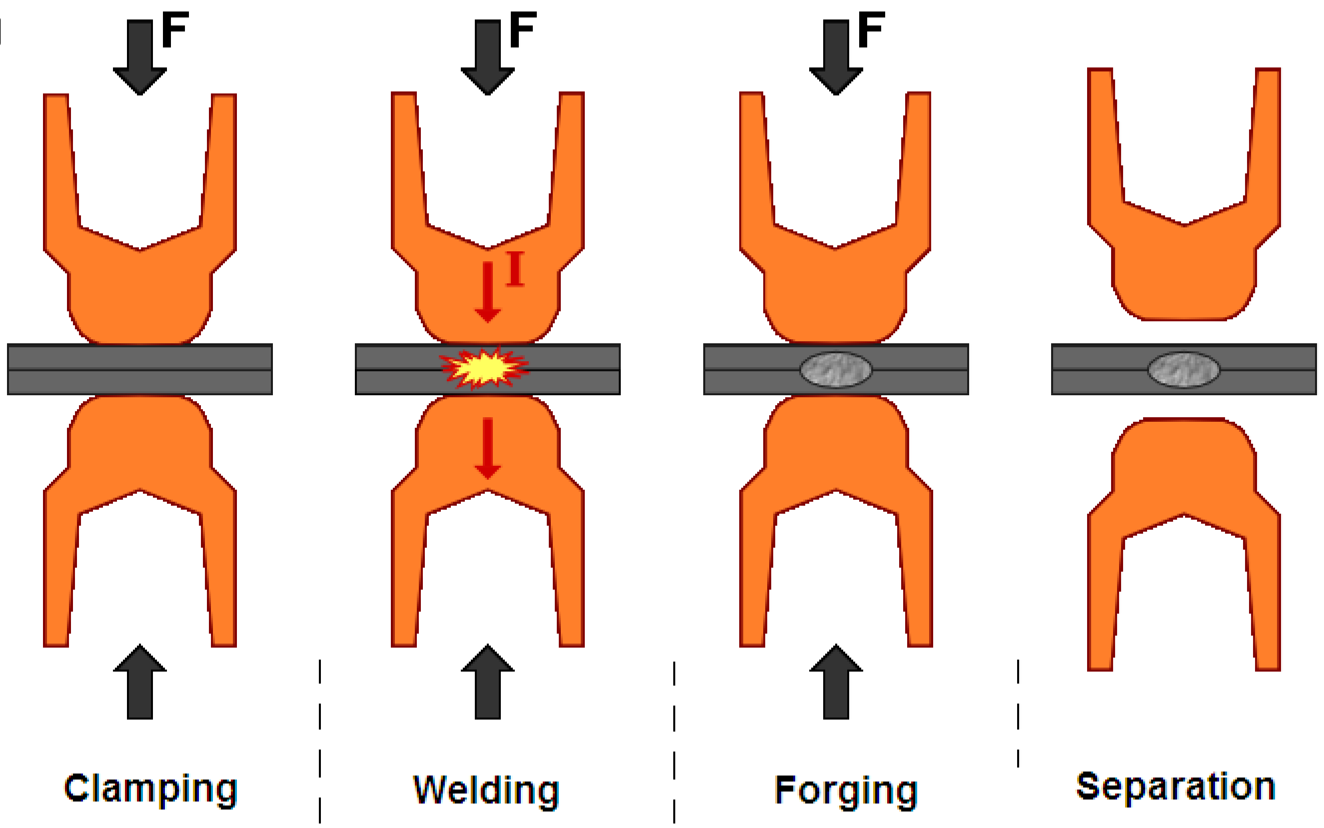
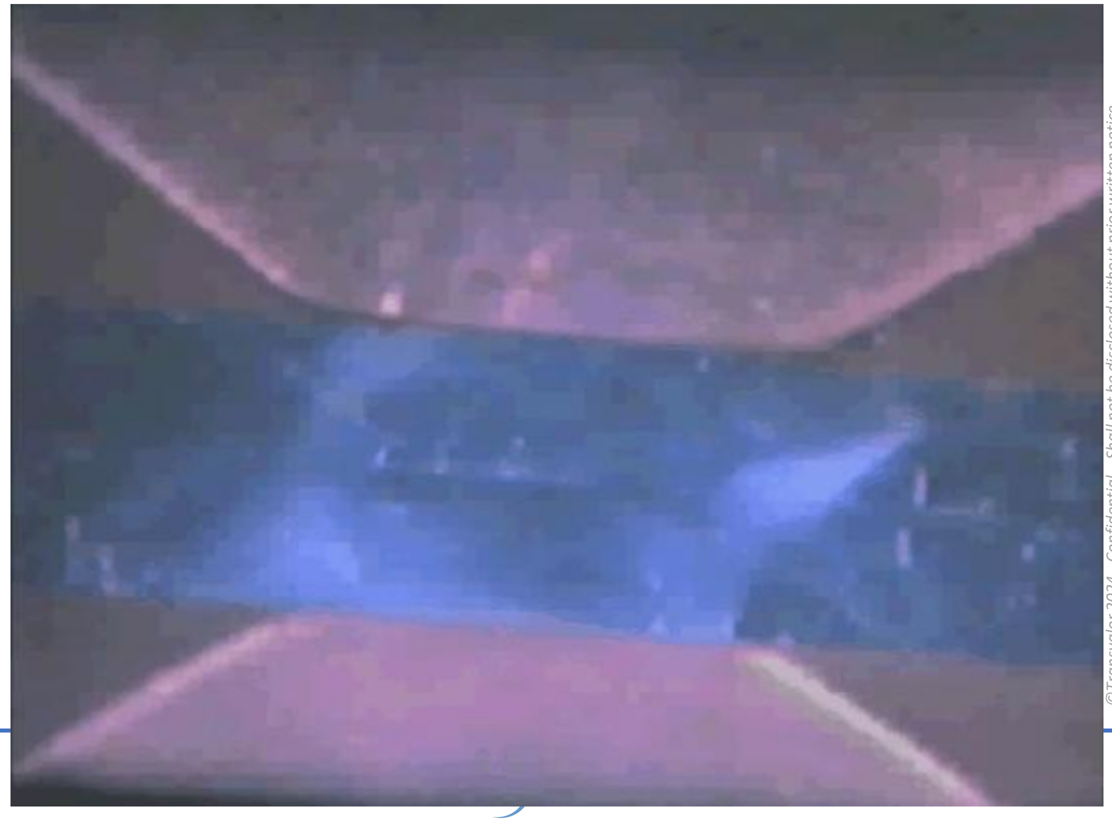
Simulations done with FORGE®2D

- **R**esistance **S**pot **W**elding (***R.S.W.***)
- Welding of thin carbon/alloy steel sheets (Automotive Industry)
- Force, welding current parameters
- Features
  - Dissimilar metals and thicknesses
  - High rate/automatic production
  - Small welded nugget
- Numerical Modelling
  - 2D axisymmetric model with electric solver
  - Multi-bodies deformable contact





[Queval J. et al, “Improvement of Weldability of Dissymmetric Assembly with very thin Sheet During Resistance Spot Welding” 2018]

ELECTRICALLY ASSISTED JOINING

SPOT WELDING

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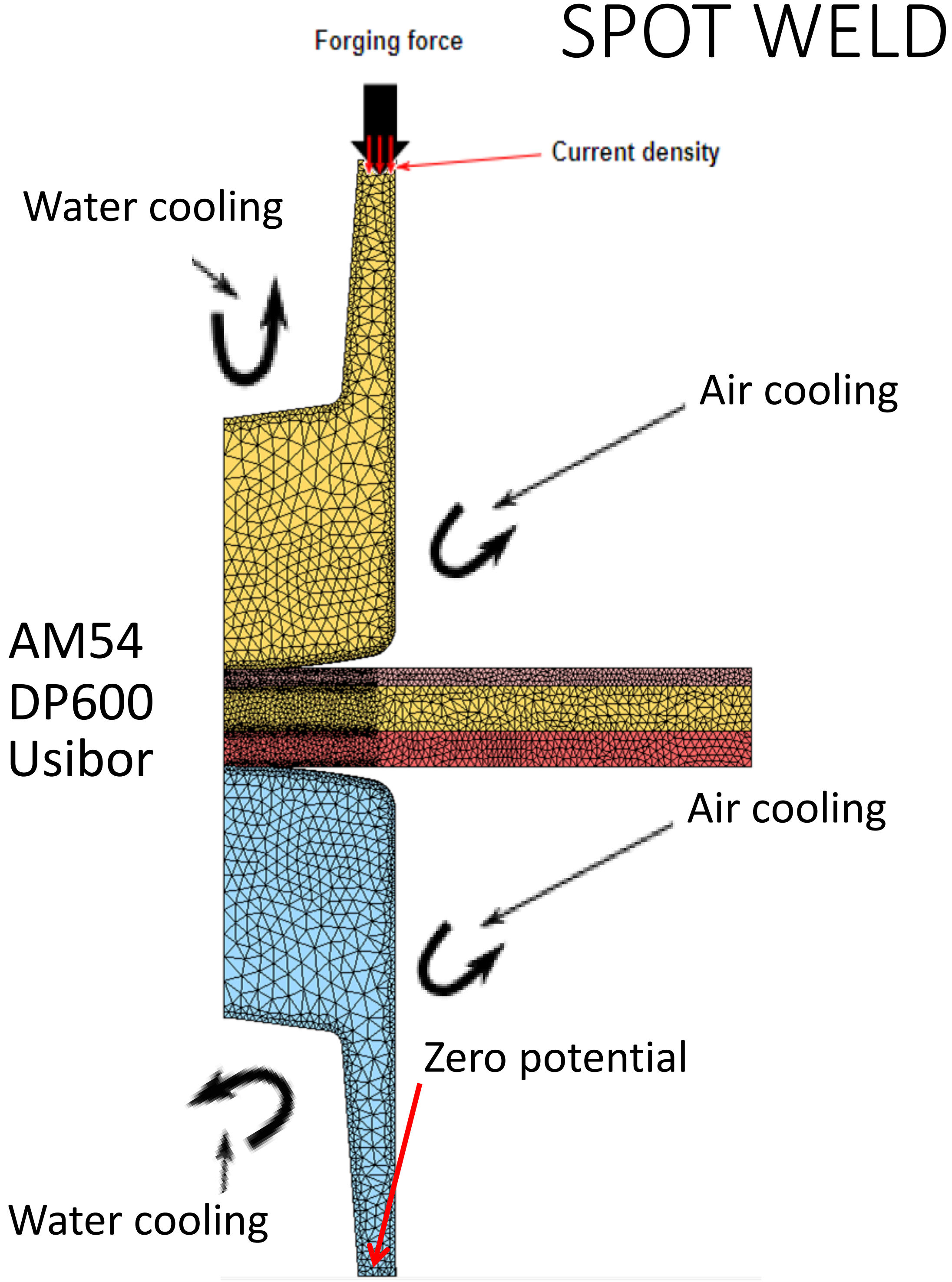
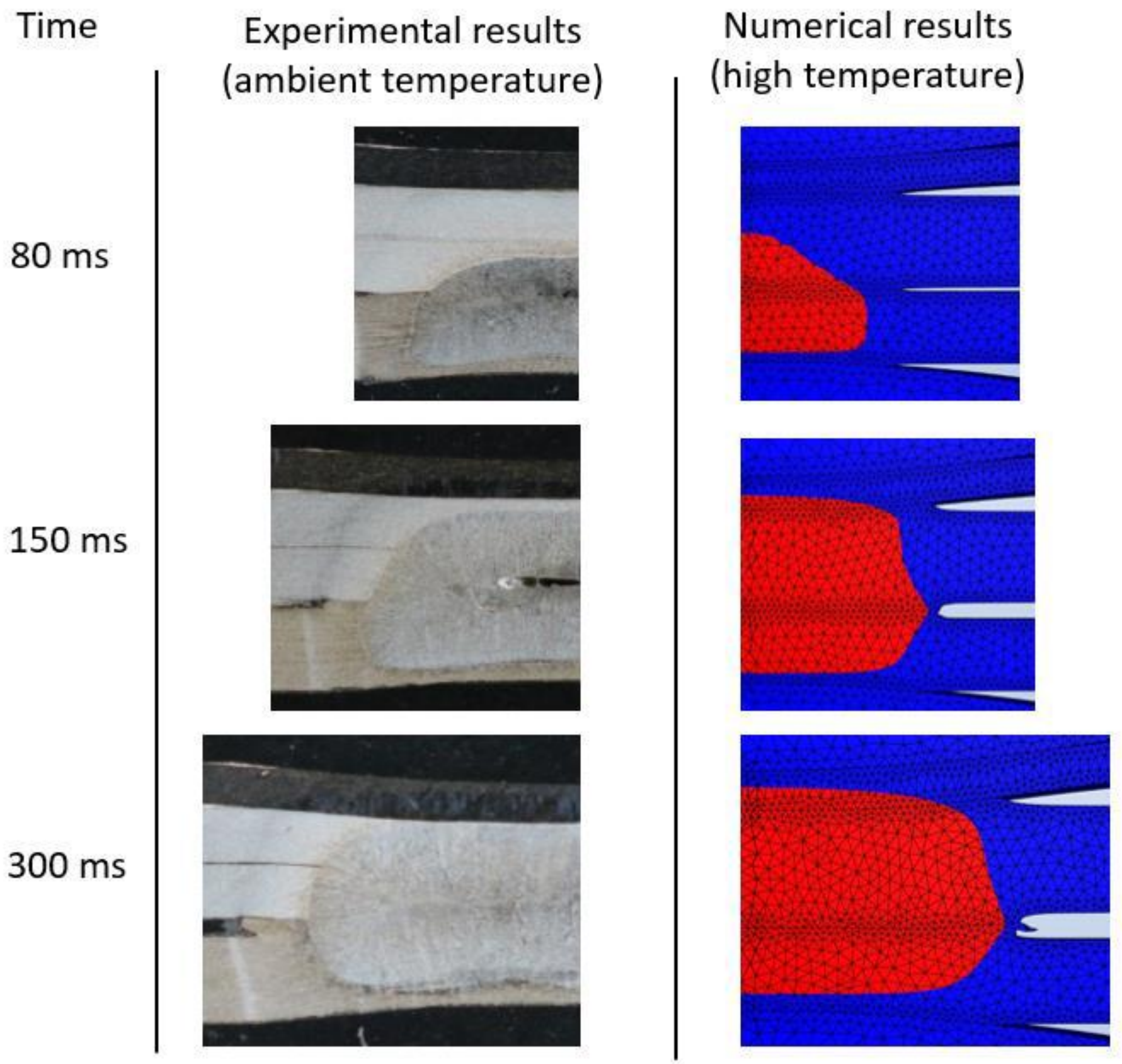




Comparison of the localization and the shape of the numerical molten pool (high temperature) and the experimental nugget (ambient temperature)

[Queval J. et al, "Improvement of Weldability of Dissymmetric Assembly with very thin Sheet During Resistance Spot Welding" 2018]

Agenda

I. Transvalor S.A.

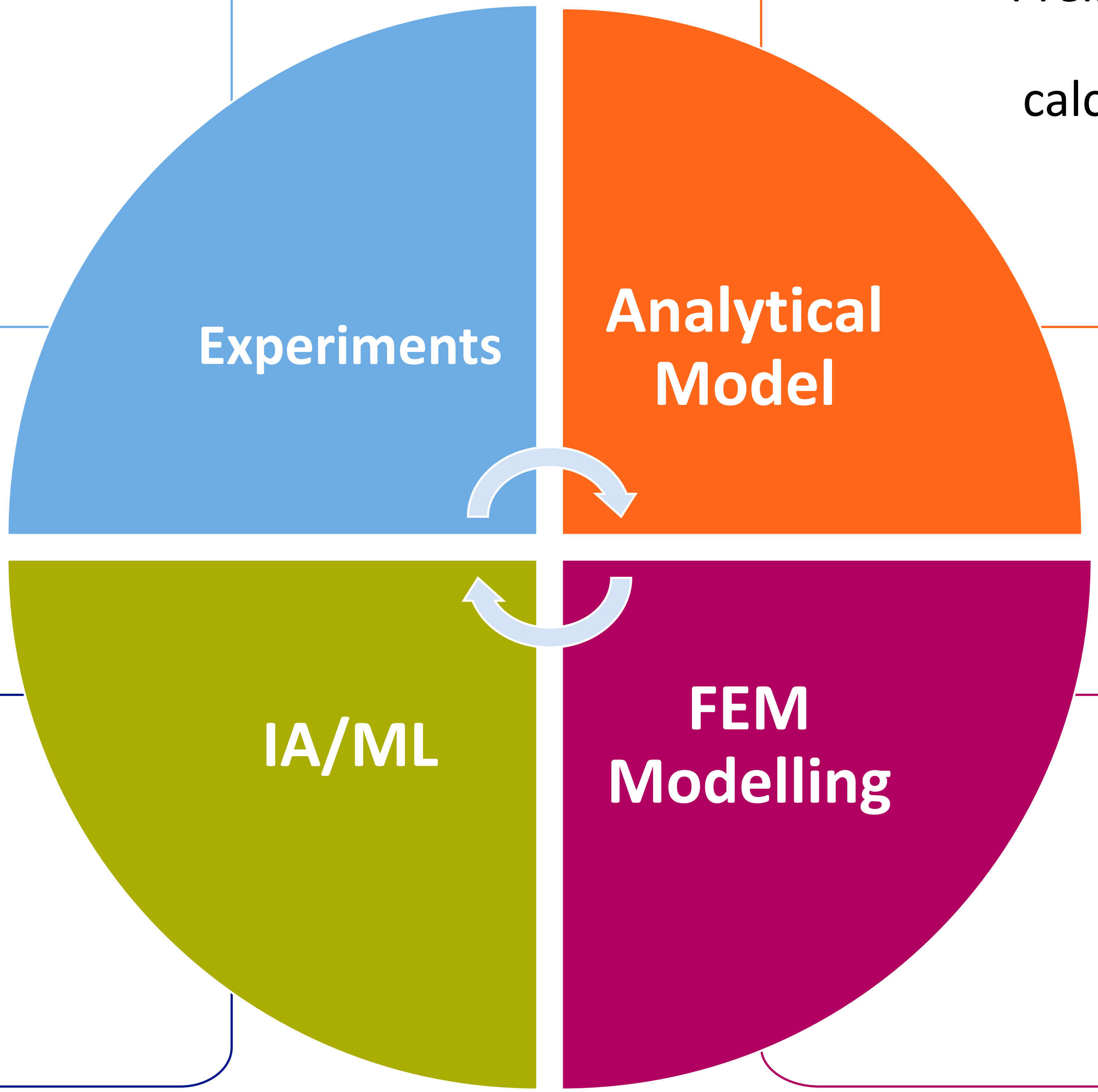
II. Multiphysics for bulk metal forming

III. Towards Deep Learning integration

Four Pillars of Engineering

- At the very beginning, engineers can only rely on experiments

- Preliminary basic approaches to model the physics and calculate simple phenomena



- Quick methods able to capture non-linear behaviors at least cost

- Today, we trust in FEM modelling to obtain High-Fidelity results

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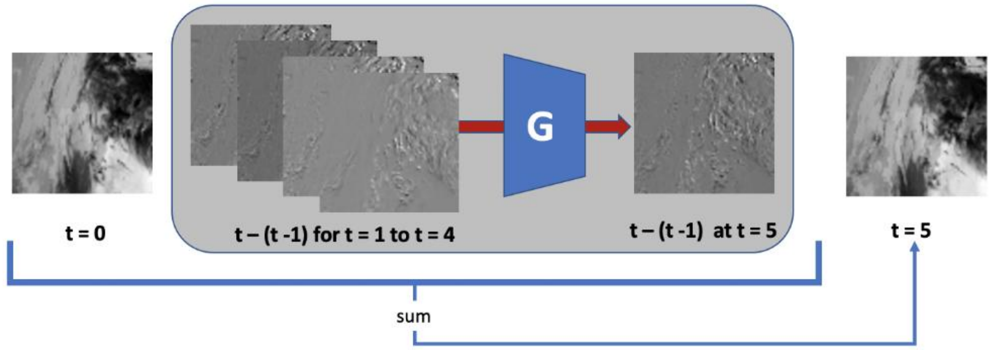
A vision for customed solutions

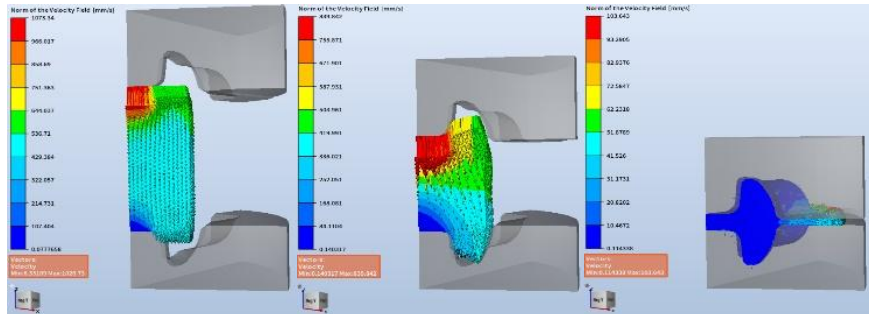
Forecasting

From a given initial state fast-forward to predict a future state

« will it rain tomorrow? »
« will my part fail? »



Fast-forward a numerical version of a physical process



Optimization

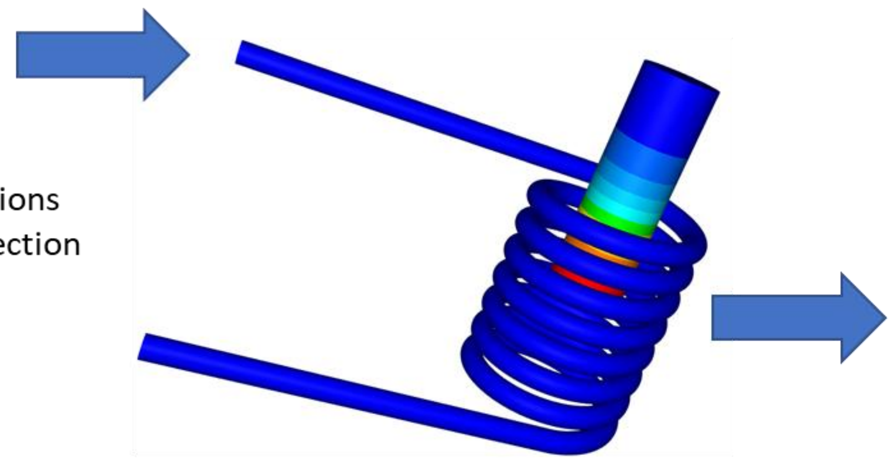
Reverse engineer to know which initial condition gives a final (desired?) state

« why is it raining today? »
« why is my part failing?»

Inverse problem

Inputs

- Current
- Frequency
- Initial conditions
- Material selection
- Geometry
- etc

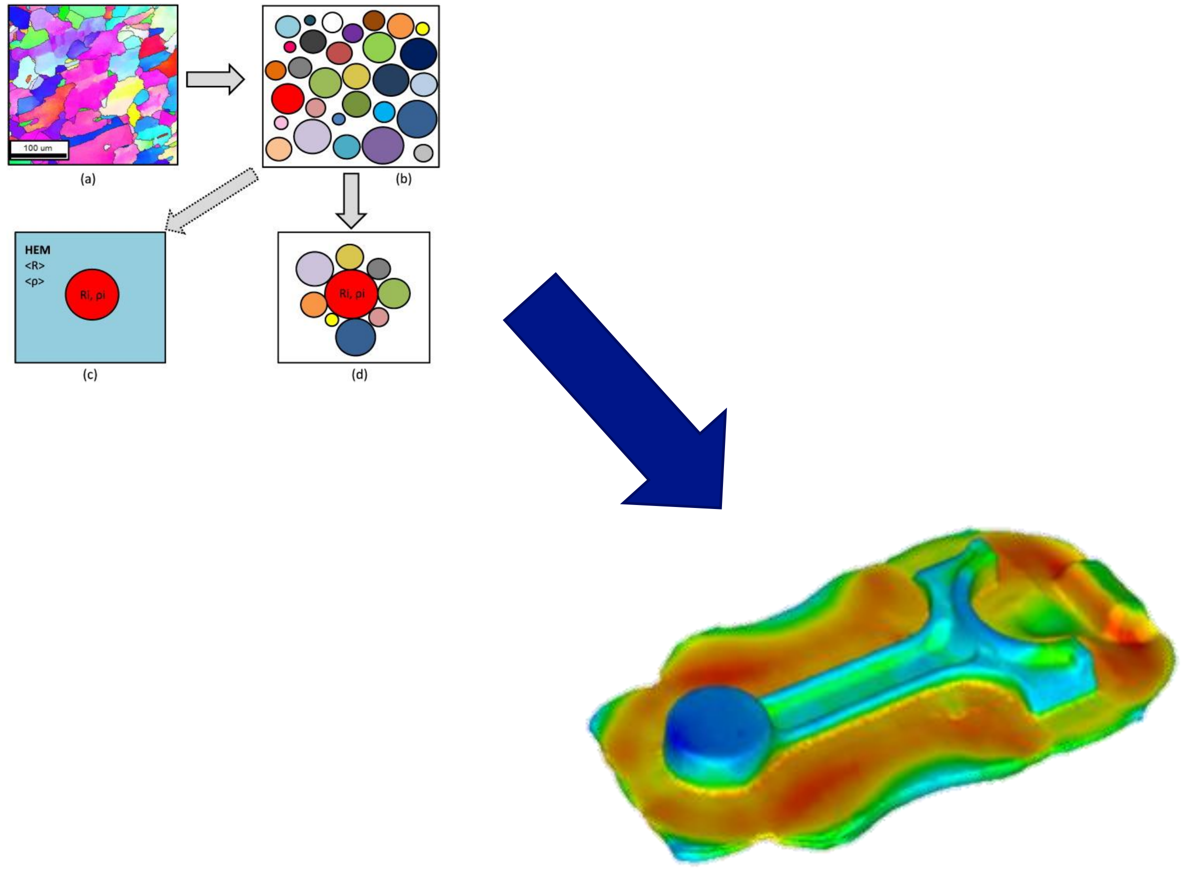


Outputs

- Temperature
- Metallurgy
- Distorsions
- Residual stresses
- Final in-use properties (hardness)
- etc

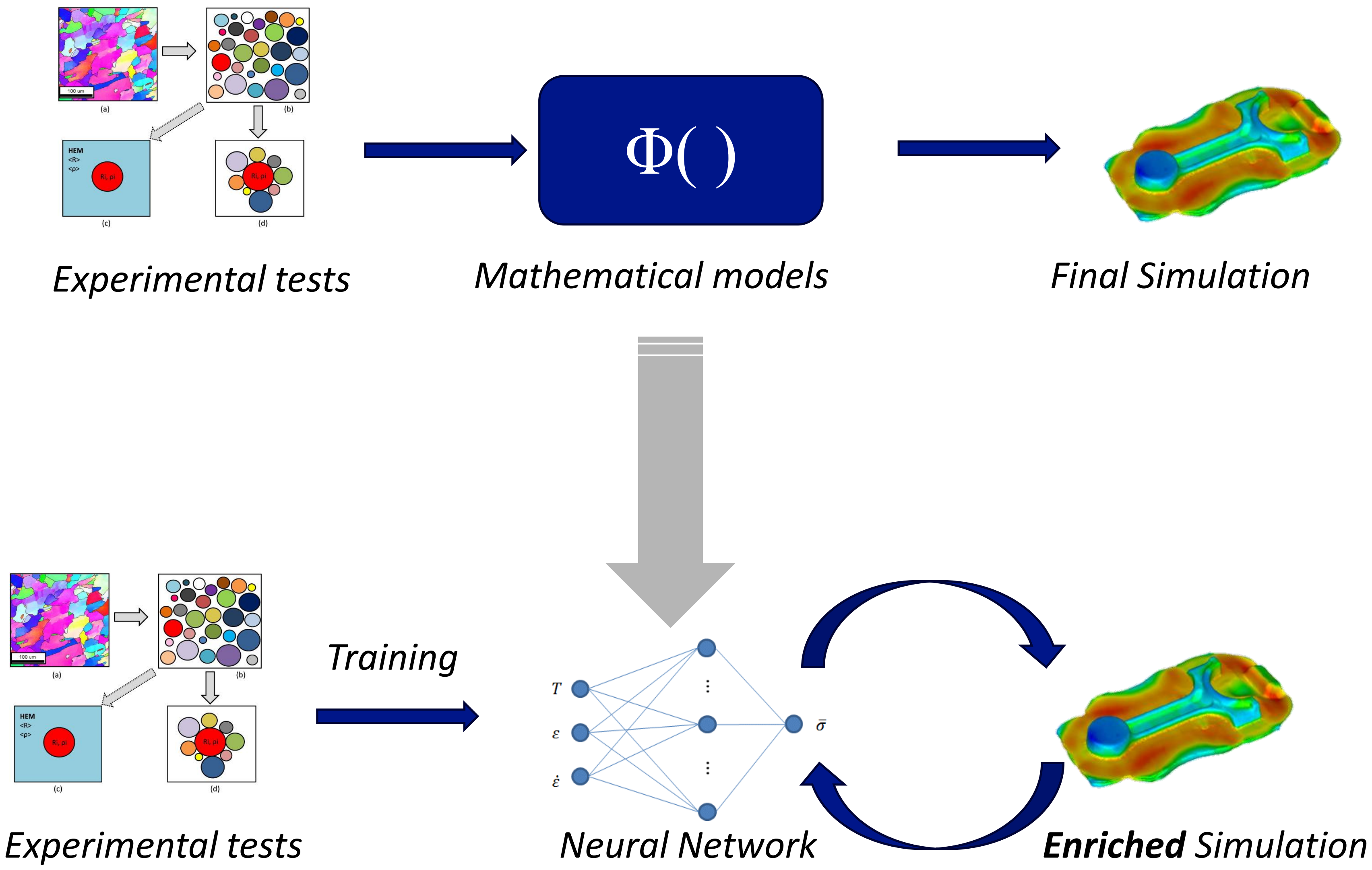
Direct problem

Towards a new approach for complex material modelling



… A different way of bridging the micro and the macro

A M.L. approach to assist process modeling:



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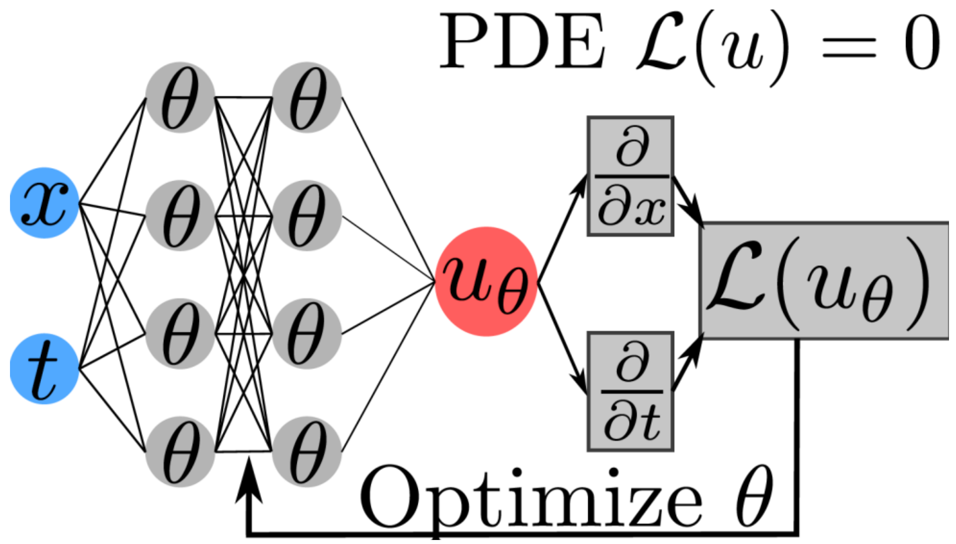
Physics Embedded Surrogacy

From Physics-Informed Neural Networks to Physics-Embedded Graph Architectures

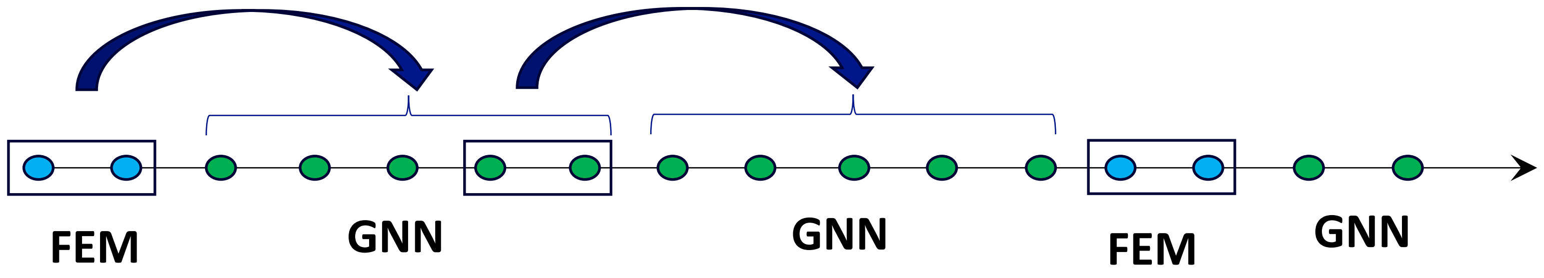


- NN are efficient for interpolation, but less for extrapolation => **need to include physical knowledge** to eliminate spurious solutions

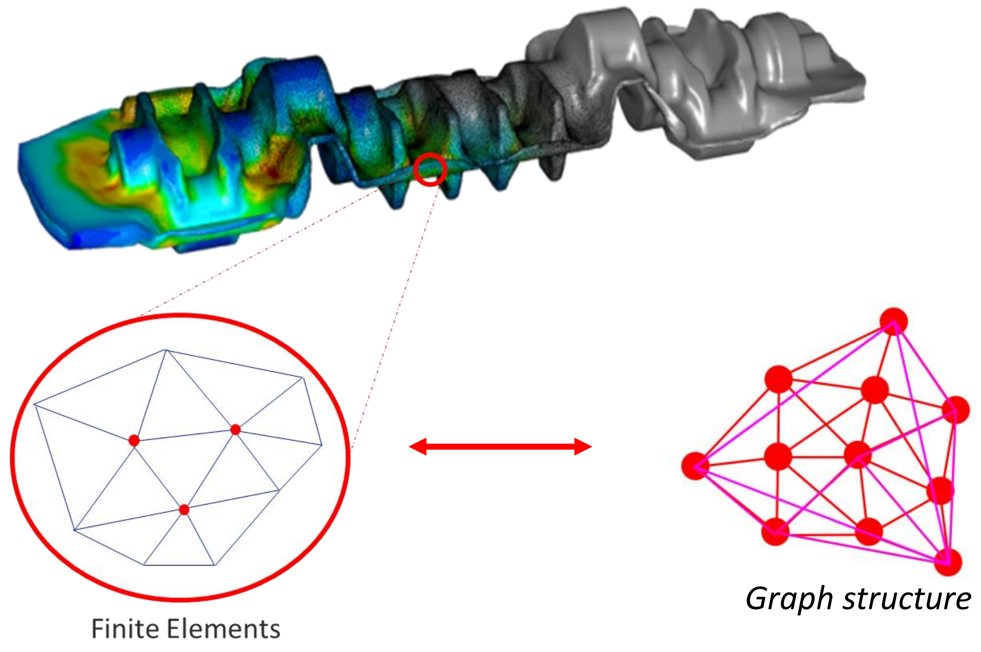
- Classical PINNs use physical knowledge **only** during training phase… and they have been designed for the analysis of **structured** data…

Hybrid GNN-FEM :

Towards accelerated simulations **combining** GNNs & FEM



- GNN covers the analysis of unstructured data (meshes)
- Training with Physical knowledge, and with numerical simulations
- Inclusion **inside** the FEM framework



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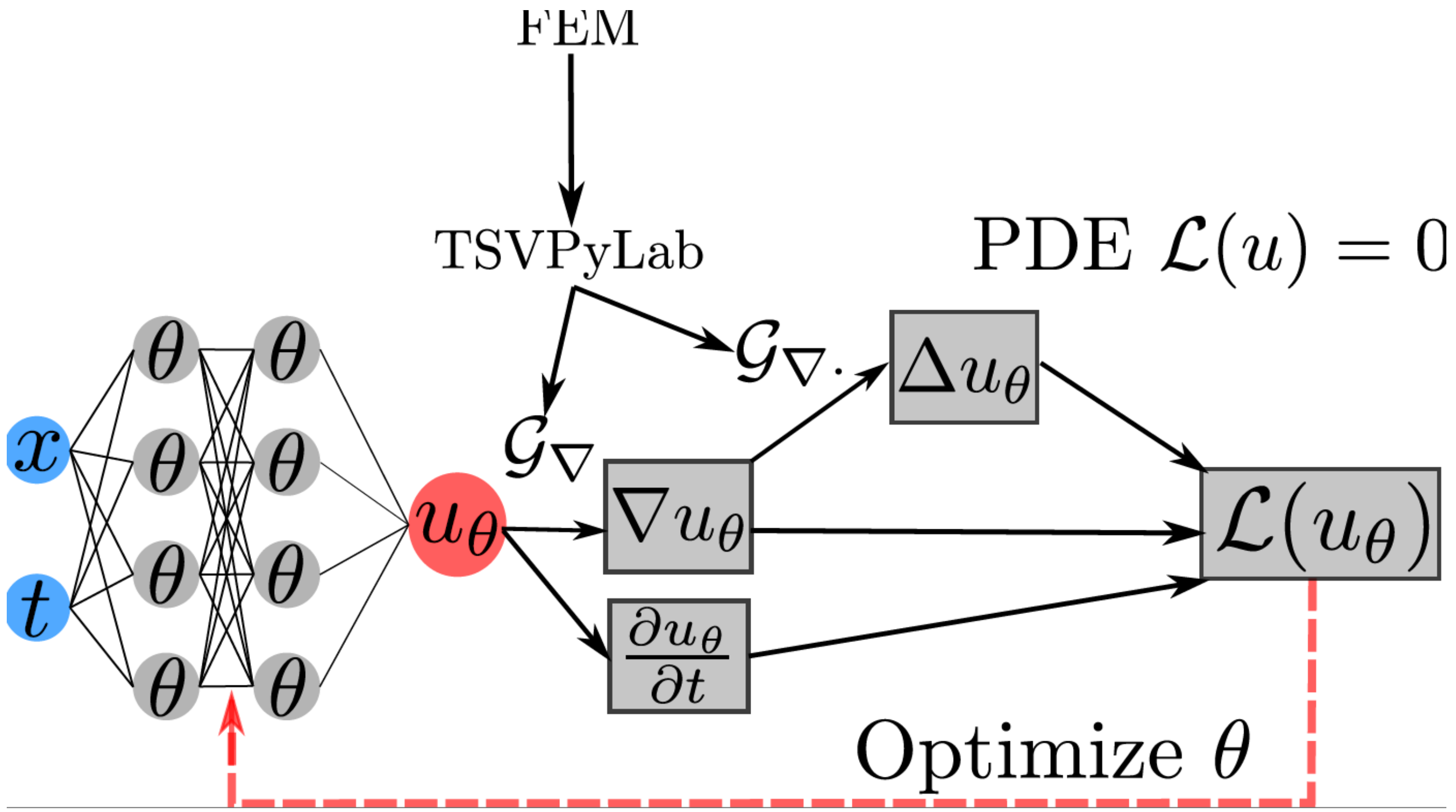
The Space-propagation problem
A Hybrid approach for complex geometries

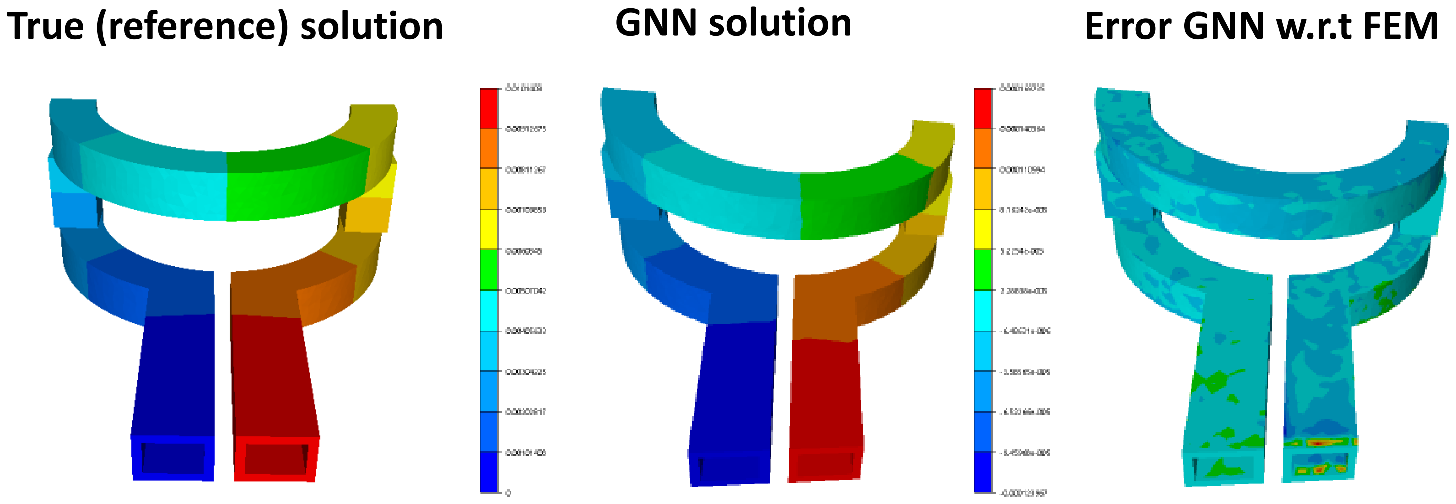
Combine both worlds

- **Finite Element geometrical knowledge and Deep Learning expressivity**

- Usecase: Electrostatic problem, GNN on a complex geometry, unreachable for plain NN or classical autodifferentiation

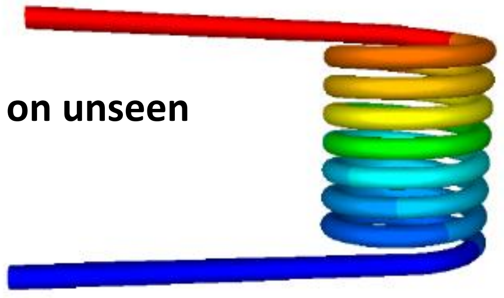
Workflow: Finite Element techniques used during training



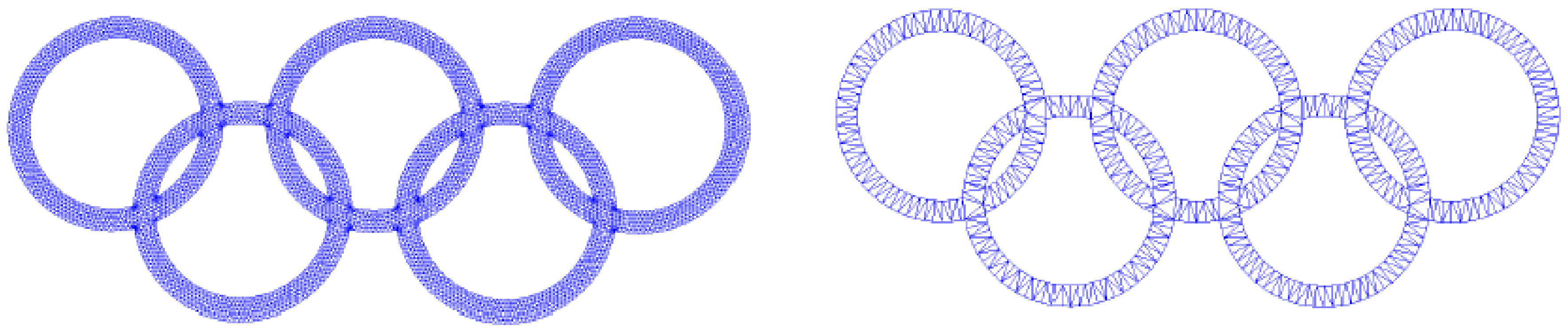


L1 error < 0.2%

Prediction on unseen geometry

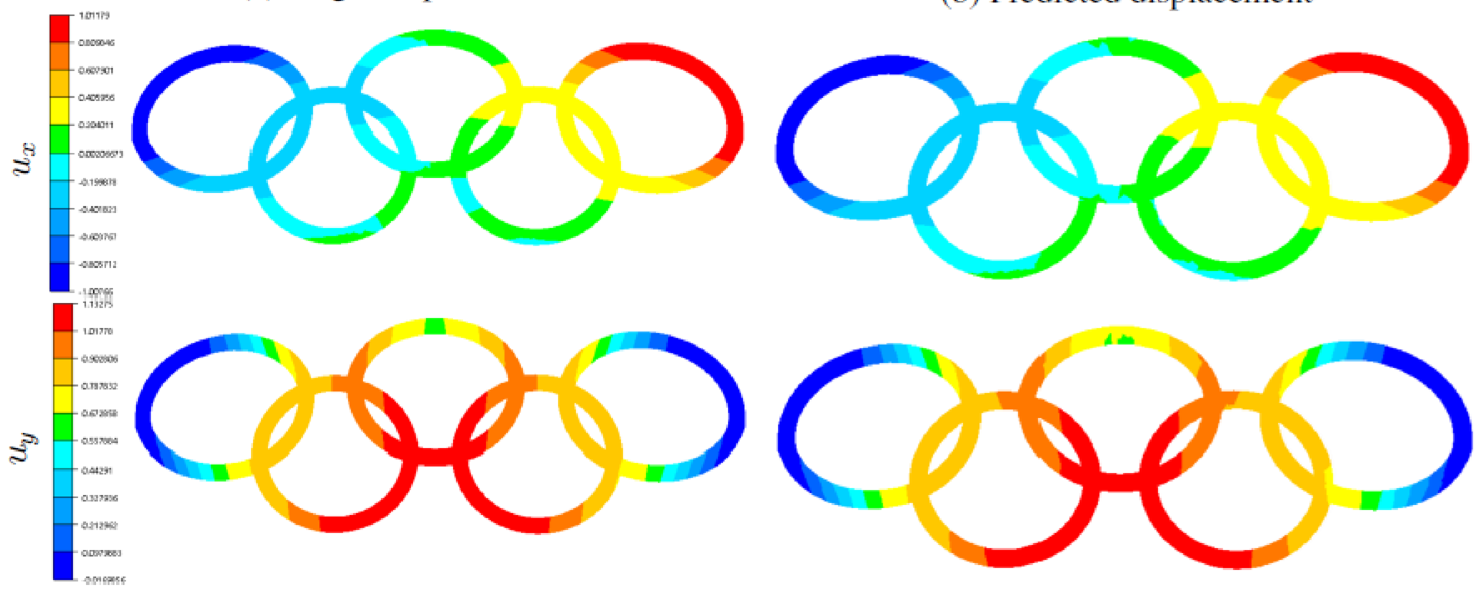


The Space-propagation problem
A Hybrid approach for complex geometries



(a) Fine mesh (b) Coarse mesh

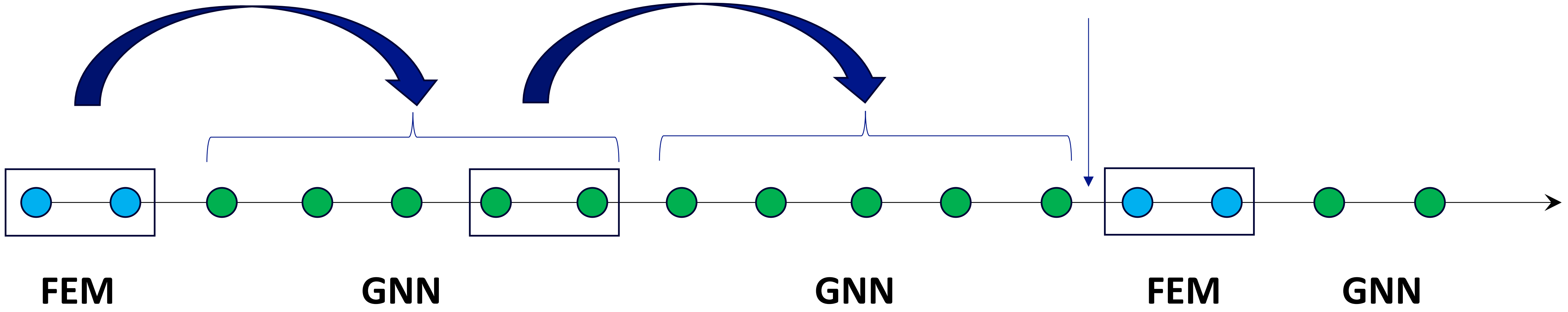
(a) Target displacement (b) Predicted displacement

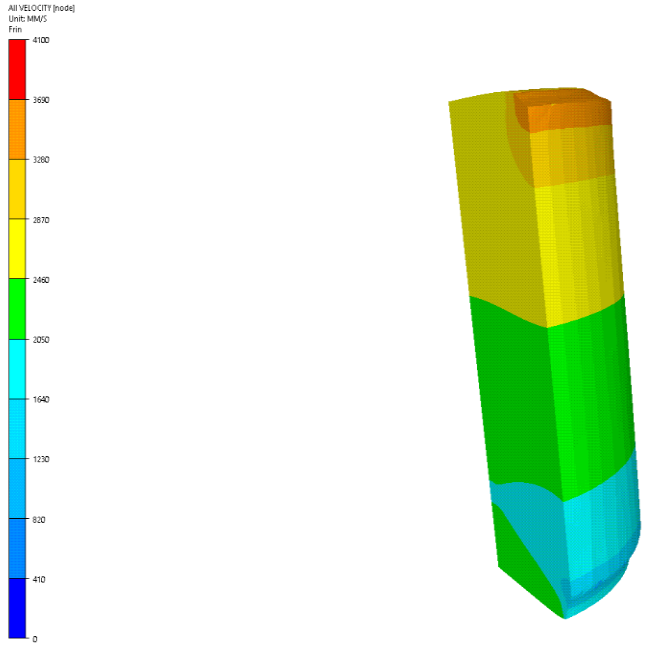


[Chenaud M., Magoules F. Alves J., Physics-Informed Graph-Mesh Networks for PDEs: A hybrid approach for complex problems, 2024]

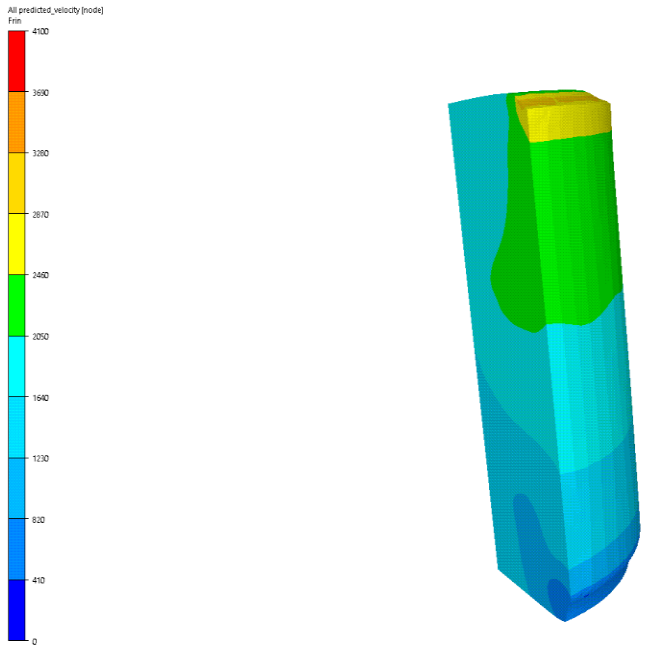
The Time-evolution problem

After roll-outs, error can accumulate.
Reduce error by switching back to FEM





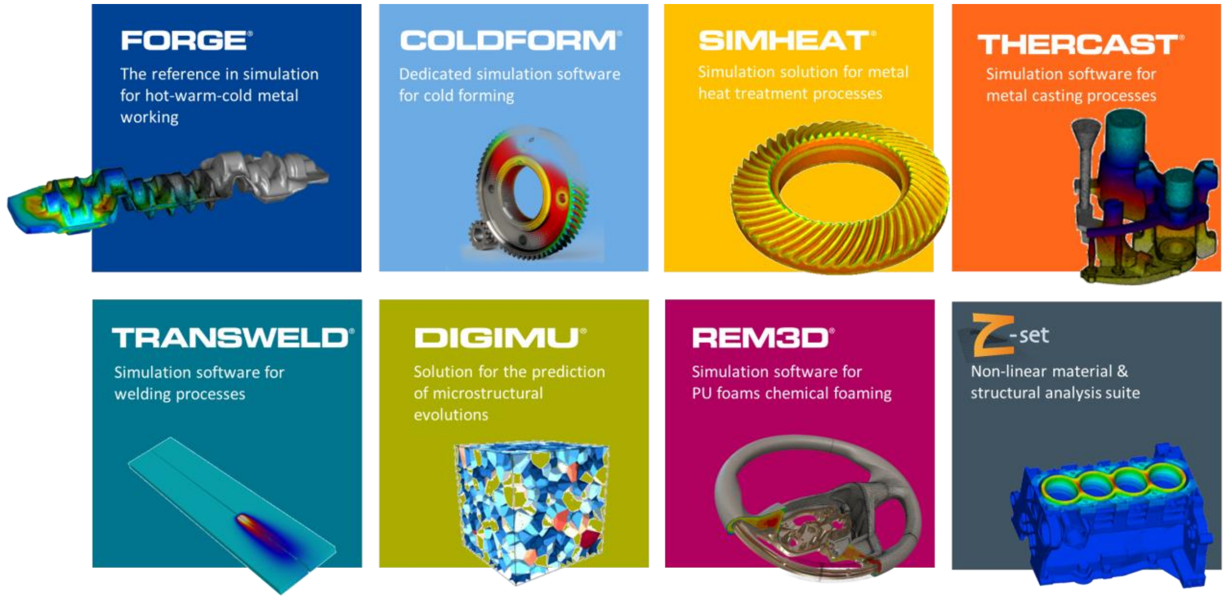
Velocity of displacement – Hammer forging case



Predicted velocity

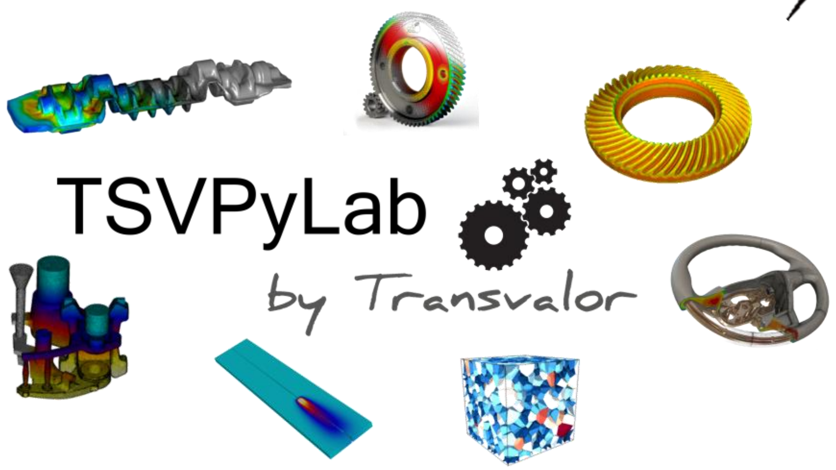
TSVPyLab

TSVPyLab – Interoperability



- ➢ Easily define complex initial or boundary conditions

- ➢ Quick visualization within python for prototyping
- ➢ Interoperability with all the scientific libraries in the python ecosystem



3D Visualization

PyVista

Scientific calculus

NumPy SciPy

DeepLearning

PyTorch PyG

- ➢ Generate large amount of high-fidelity data with Transvalor Software
- ➢ Manage Design-of-Experiements with ease using the Optimization module

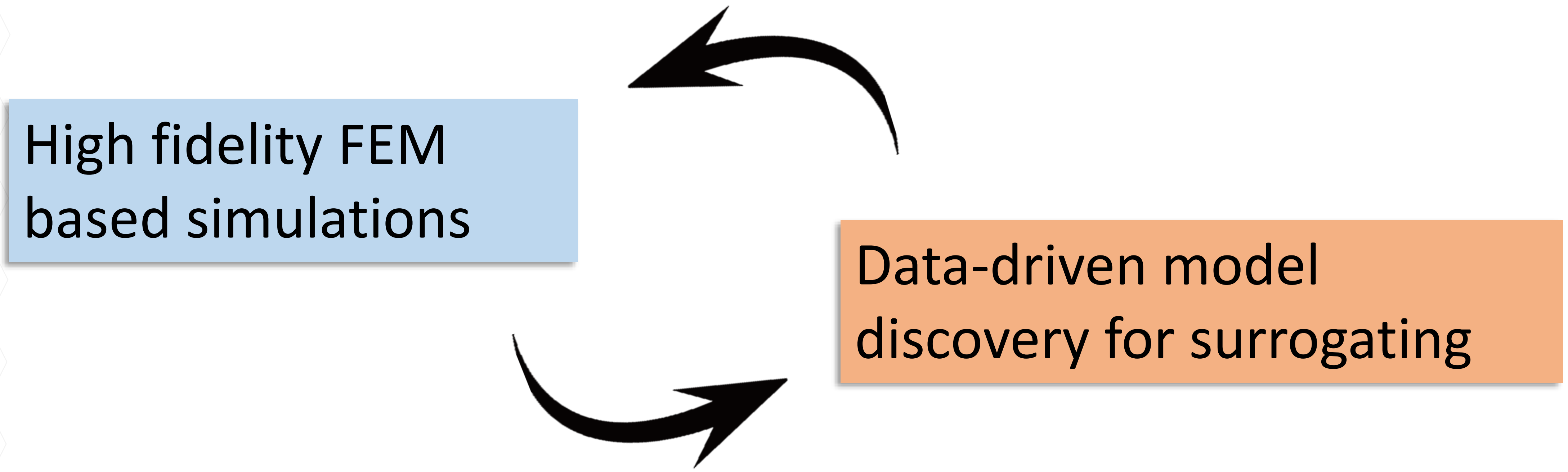
- ➢ Custom advanced pre-&-post processing for field and geometric manipulation

TRANSVALOR

Take away messages

Multi-physics & Multi-scale

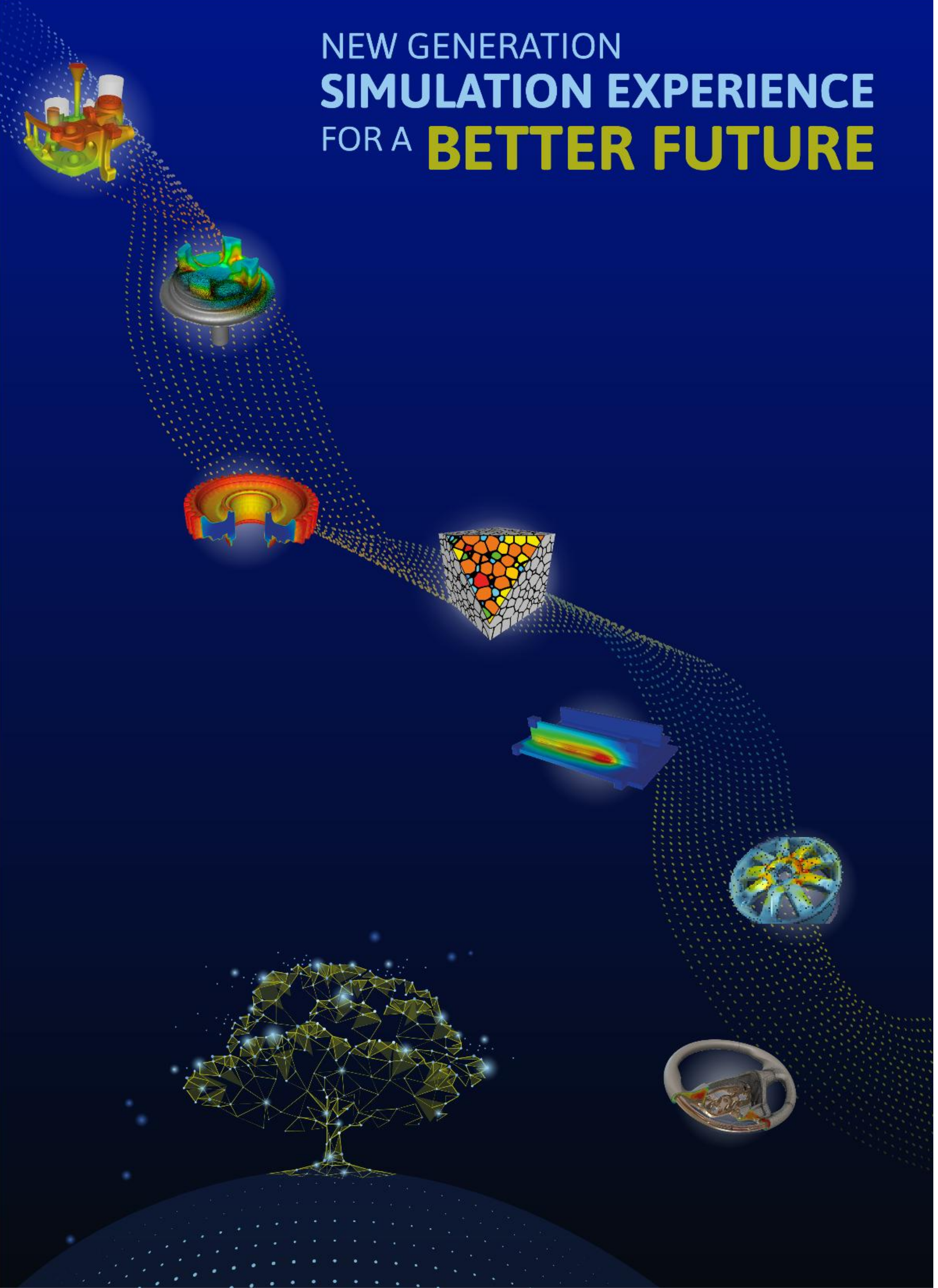
Data Interoperability



Bridge physical scales

Challenge performance

Building up towards digital twins



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Thank you

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