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Towards Faster 3D Simulations of CFRTP Induction Welding

Leibniz-Institut für Verbundwerkstoffe

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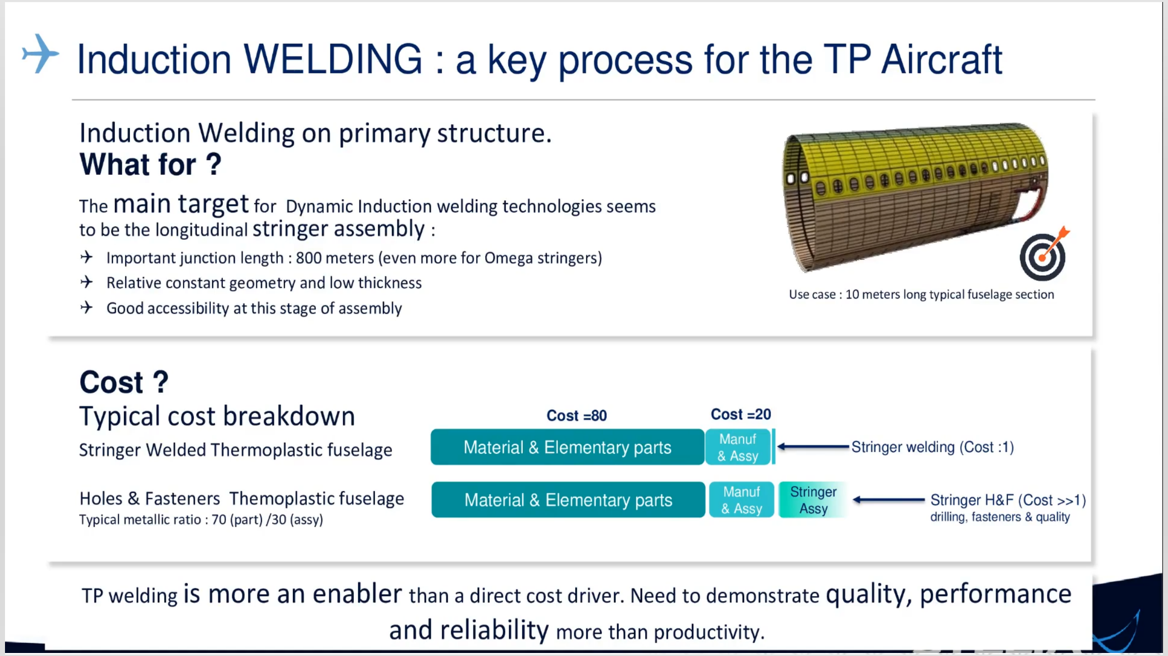
Motivation

Mass production of “thermoplastic composite” aircraft structures (fuselage, wing assemblies (stiffeners to skin, access panels…)

- Development of the ability to join **thermoplastic carbon/glass fiber composite parts** to themselves and existing/future metal alloys
  - For **composite/composite** we need conductive fibers (carbon) or matrix additives (conductive particles/fillers)
  - For **metal/composite** conductivity of the metal part can be utilized

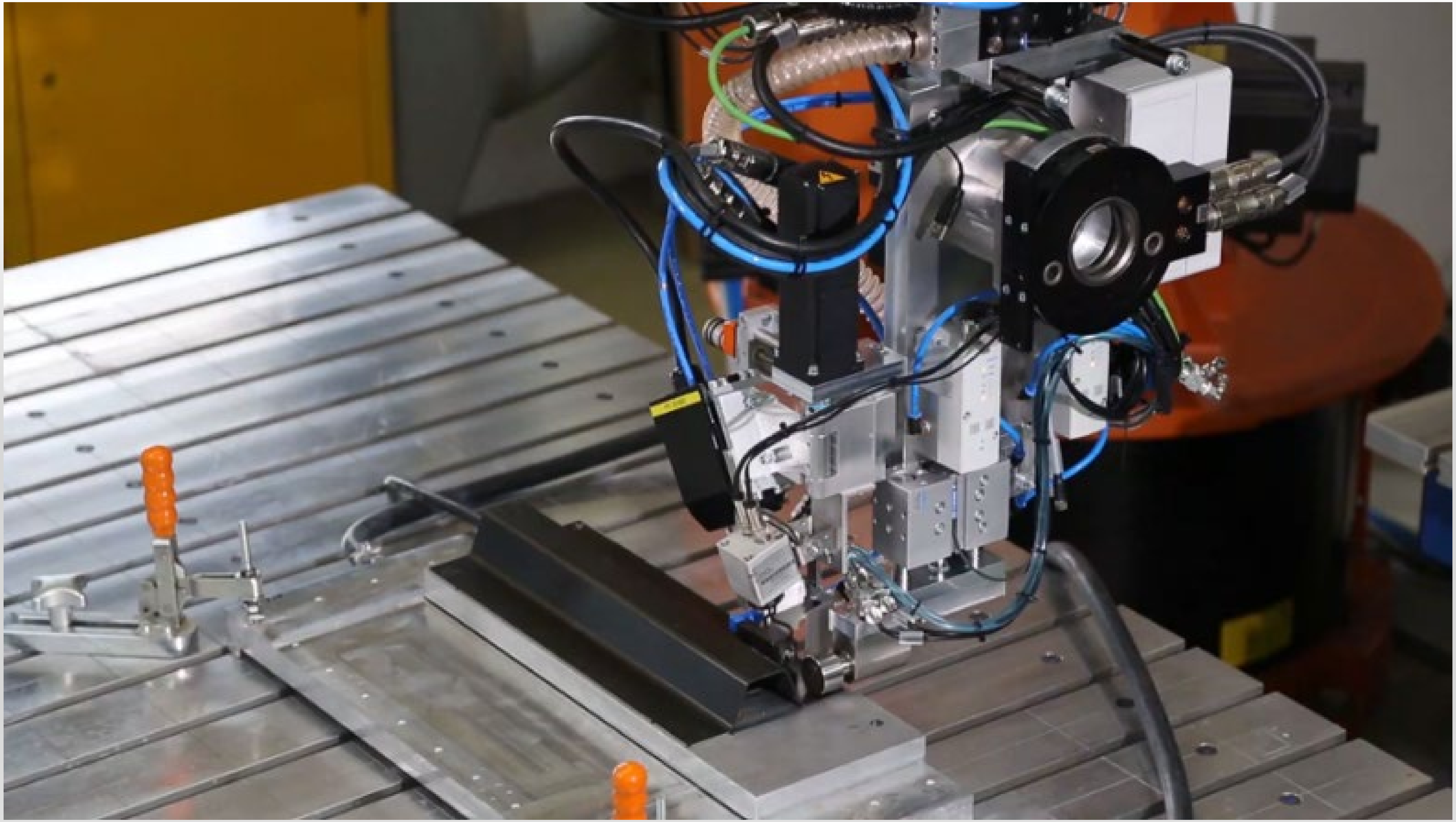
KVECOMPOSITESGROUP
Daher Aerospace S.A

GKN AEROSPACE



Images courtesy of Composites World Seminar „Induction Welding for Dustless Assembly of Aircraft Within a Decade“, 9. June 2021.
https://www.bigmarker.com/gardner-business-media-inc-w1/Induction-Welding-for-Dustless-Assembly-of-Aircraft-Within-a-Decade?bmid=83c652617c71

Induction Welding at IVW



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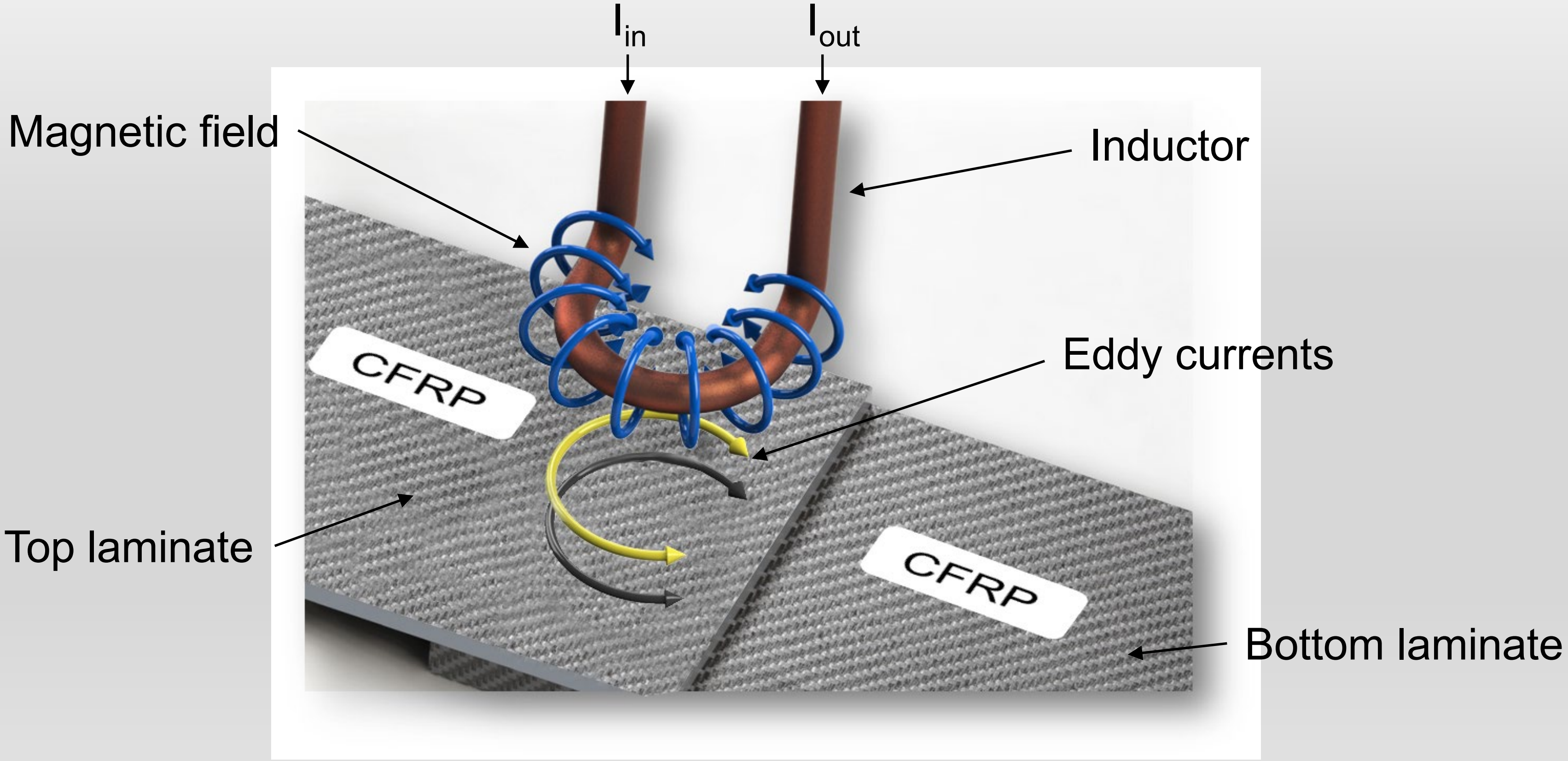
Induction Welding Simulation Basics

- Alternating magnetic field
- Induced eddy current in electrically conductive material
- Heating by Joule losses and hysteresis
- Pressure applied for consolidation and maintained during cooling



Material Properties and Process Inputs

Type of Physics	Material Property		Process Inputs	
Mechanical	Stiffness (Pa)	E_1, ν_1	Coupling Distance (m)	d_1
		E_2, ν_2	[3]Coil/Roller Velocity (m/s)	v
		E_3, ν_3	[3]Coil to Roller Distance (m)	d_2
			[3]Roller Normal Contact Force (N)	F_N
	Density (kg/m^3)	ρ	[3]Roller Contact Friction Coefficient	μ_{fric}
Thermal	Heat Capacity (J/(kg*K)	Cp	Free Surface Convection Coefficients (W/m²*K)	h_{top}
				h_{bottom}
				h_{sides}
	Thermal Conductivity (W/m*K)	k_1	Initial Temperature (°C)	T
		k_2	[1]Heat Transfer Conductance (W/m²*K)	htc
		k_3	[2]Thermal Expansion Coefficient	α_T
			[3]Forced Convection Coefficient (W/m²*K)	h_{forced}
Electromagnetic	Electrical Conductivity (S/m)	$\sigma_1, \sigma_2, \sigma_3$	Frequency (Hz)	Freq
	Relative Permeability	μ_r	Current Amplitude (A)	I
	Relative Permittivity	ε_r	[1]Contact Resistance (Ω.m)	R

[1]Necessary parameters in the case of double plate model simulations
[2]Significant for metal and dissimilar material joints and can be neglected for composite only welds
[3]Additional parameters required in the case of full continuous induction welding simulations with air-jet cooling

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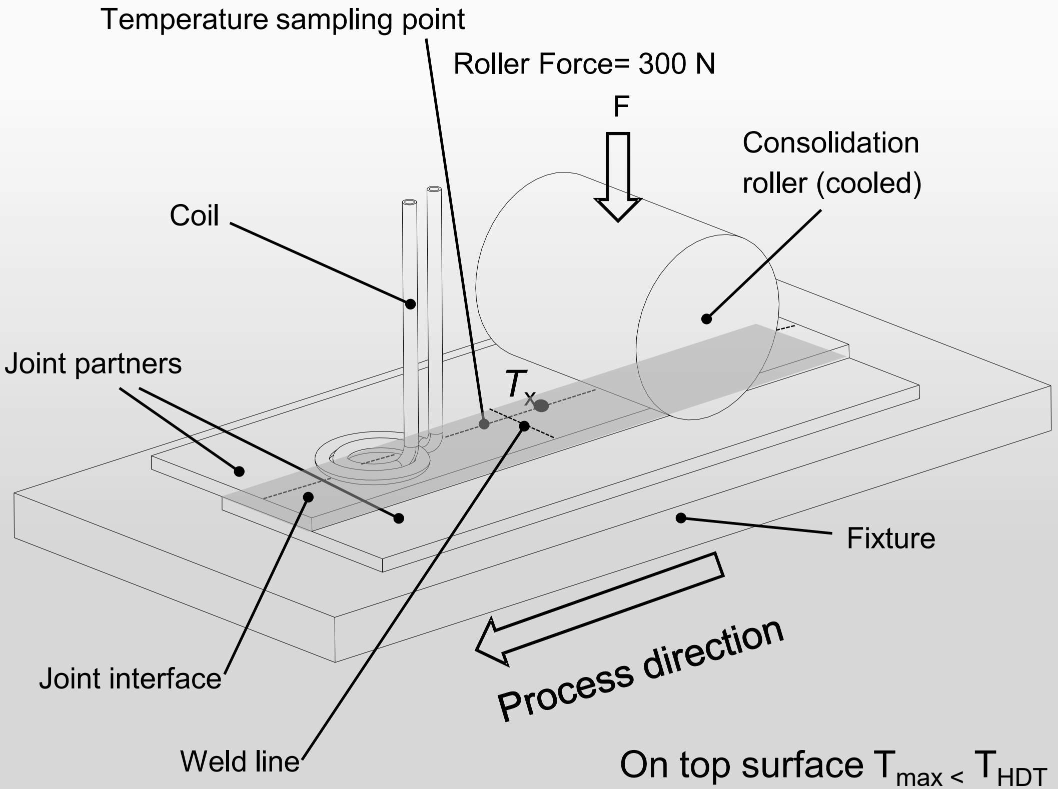
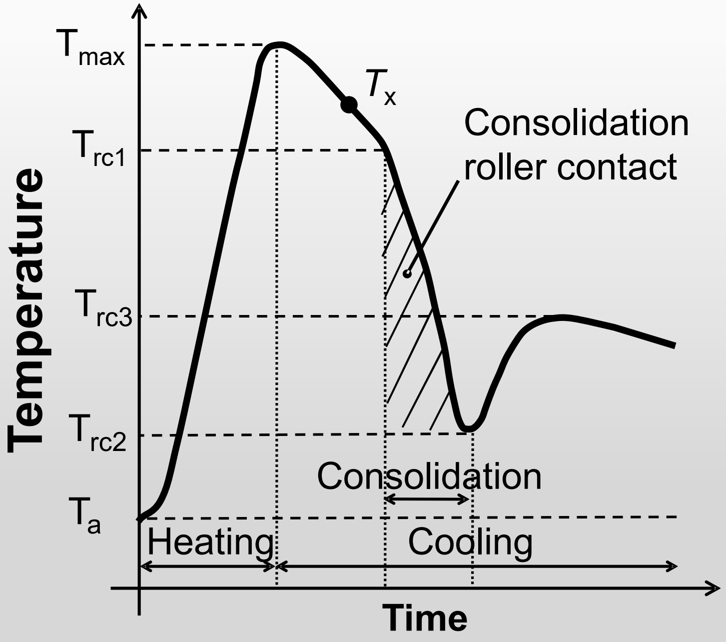
Understanding and Simulating Continuous Induction Welding





On top surface $T_{max} < T_{HDT}$

At joining interface $T_{melt} < T_{max} < T_{degradation}$

& $T_{rc1} > T_{melt}$; T_{rc2} & $T_{rc3} < T_{HDT}$

Processing Speed = 3 mm/sec (KVE Induct®: fabrics ~17 mm/sec, UD ~3 mm/sec) known to give excellent welding results with CF/CF combination but why? Plus we would like see what happens for other material combinations and in addition speed things up!

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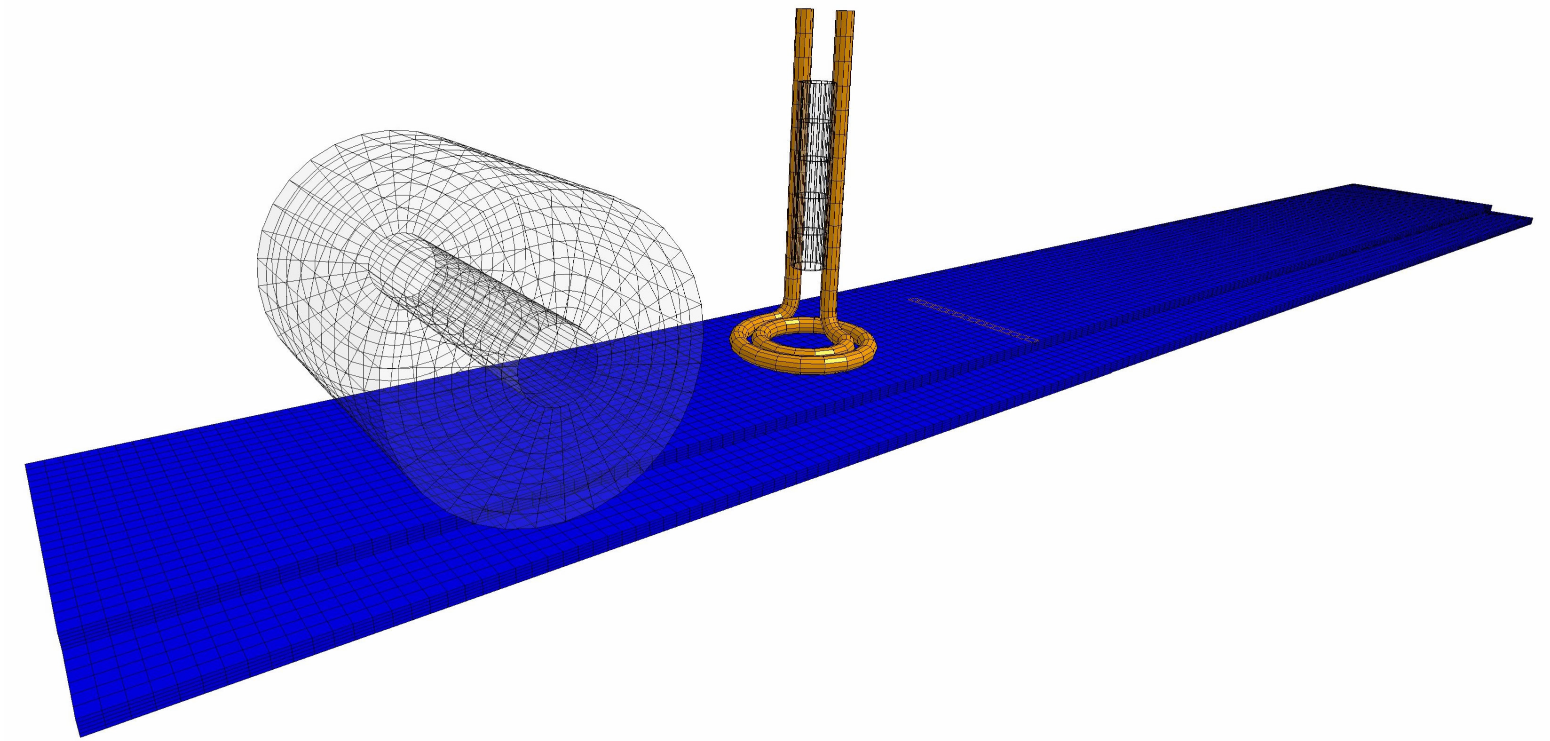
Understanding and Simulating Continuous Induction Welding: Model Setup in LS-DYNA®

Now we can examine temperature profiles at any location!

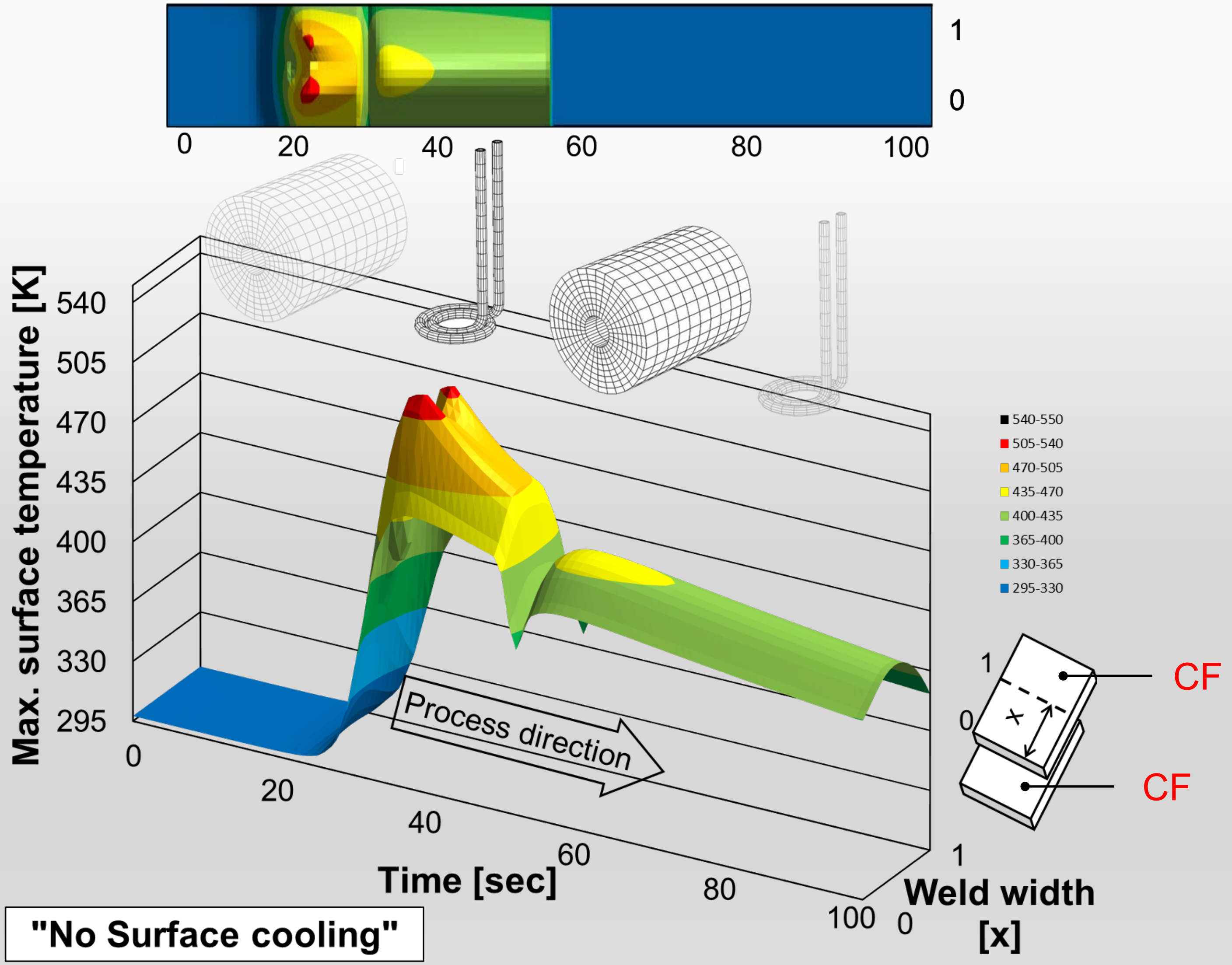


- The goal is to make sure we remain within the processing window of the material so that the top surface doesn't melt, the material anywhere does not degrade and the bond surface is hot enough for joining.

- A **P**roportional-**I**ntegral-**D**erivative controller (**PID** controller) is used to control the coil current based on temperatures sensed in the welding stack.

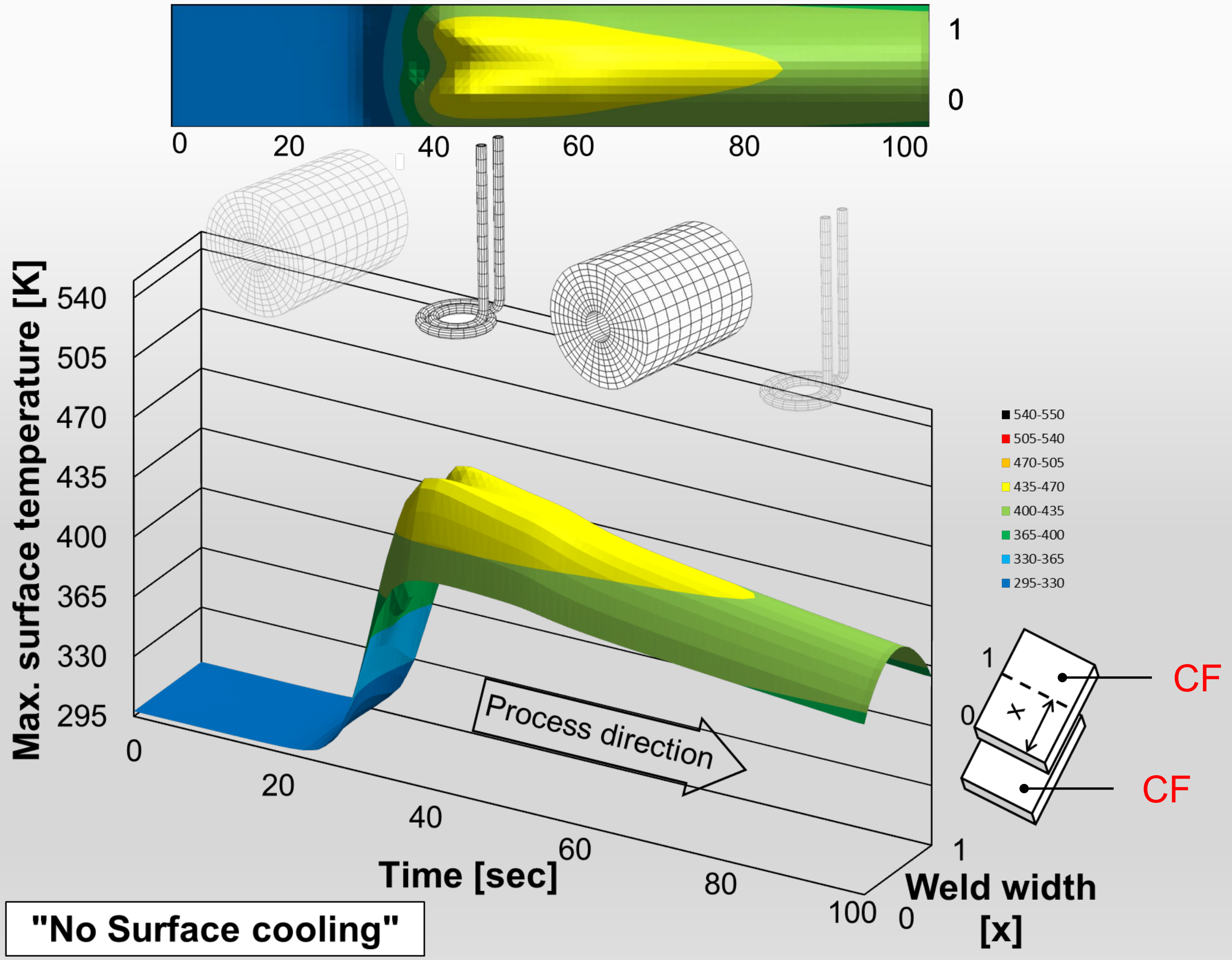
Duhovic M., Hausmann J., L'Eplattenier P., Caldichoury I. *A Finite Element Investigation into the Continuous Induction Welding of Dissimilar Material Joints*. In: Proceedings of the 10th European LS-DYNA® Users Conference, Process VII – Welding, 15.-17. June, 2015, Würzburg, Germany.
https://www.dynalook.com/conferences/10th-european-ls-dyna-conference/3%20Process%20VII%20-%20Welding/02-Duhovic-InstitutfuerVerbundwerkstoffe-P.pdf

Simulation Results: Actual Induction Welding Scenario Surface Temperature Plots – CF/CF



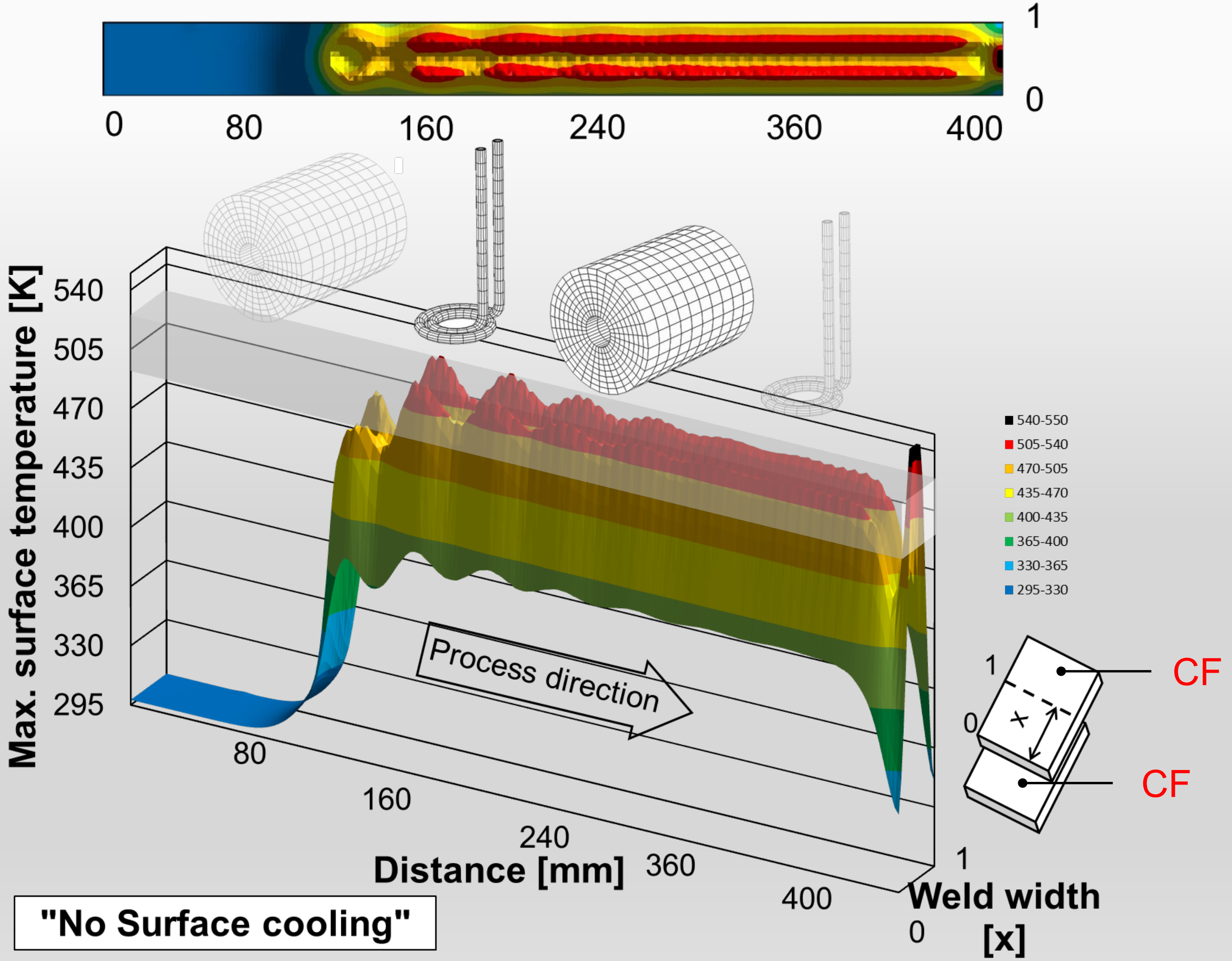
PIDCTL_SP250°C(523K)(170 A), 400 kHz **Top Surface Weldline** @ 3 mm/sec (0.18 m/min)

Simulation Results: Actual Induction Welding Scenario Surface Temperature Plots – CF/CF



PIDCTL_SP250°C(523K)(170 A), 400 kHz **Joint Interface Weldline** @ 3 mm/sec (0.18 m/min)

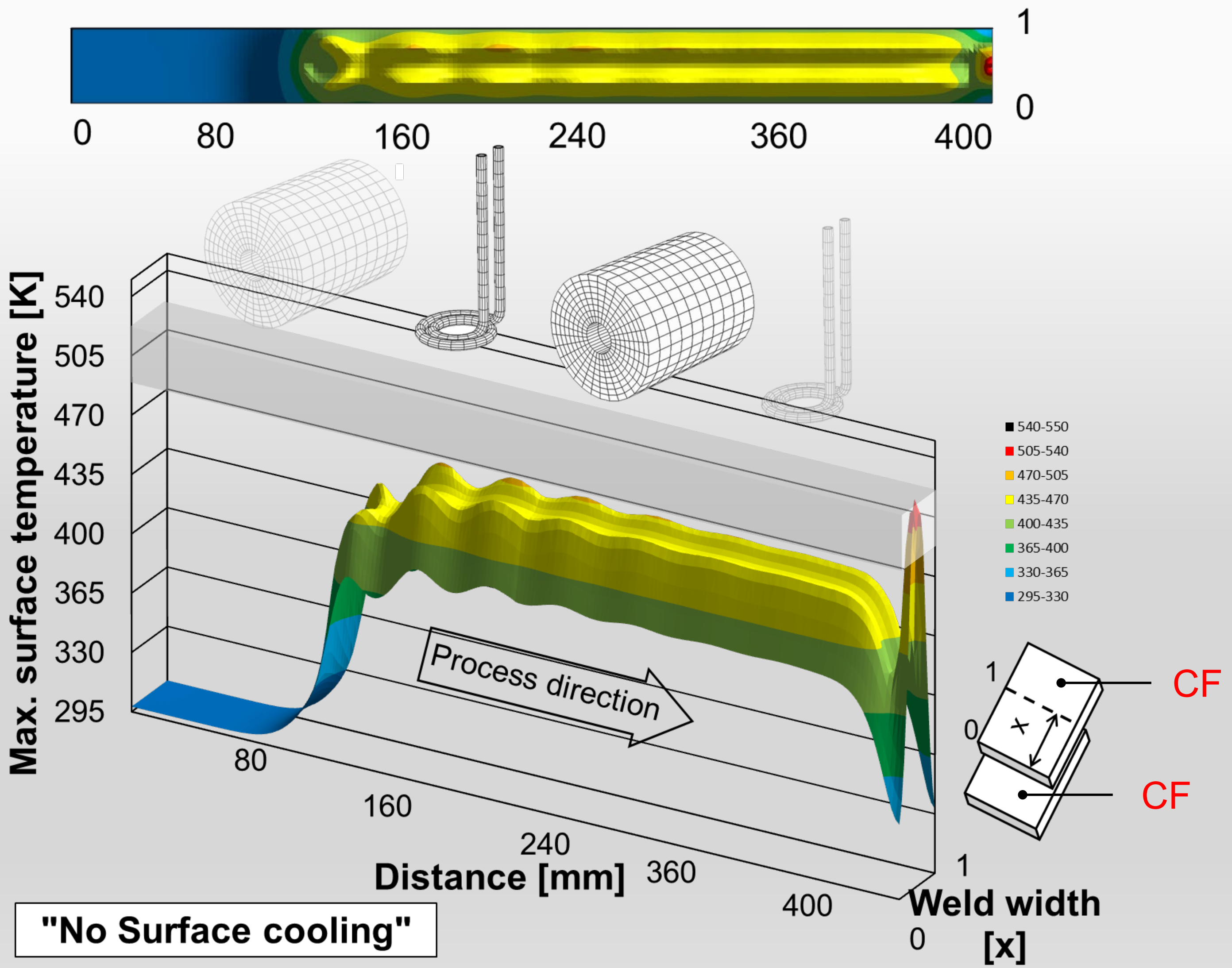
Simulation Results: Actual Induction Welding Scenario Surface Temperature Plots – CF/CF



"No Surface cooling"

PIDCTL_SP250°C(523K)(170 A), 400 kHz **Top surface** @ 3 mm/sec (0.18 m/min)

Simulation Results: Actual Induction Welding Scenario Surface Temperature Plots – CF/CF



PIDCTL_SP250°C(523K)(170 A), 400 kHz **Joint interface surface** @ 3 mm/sec (0.18 m/min)

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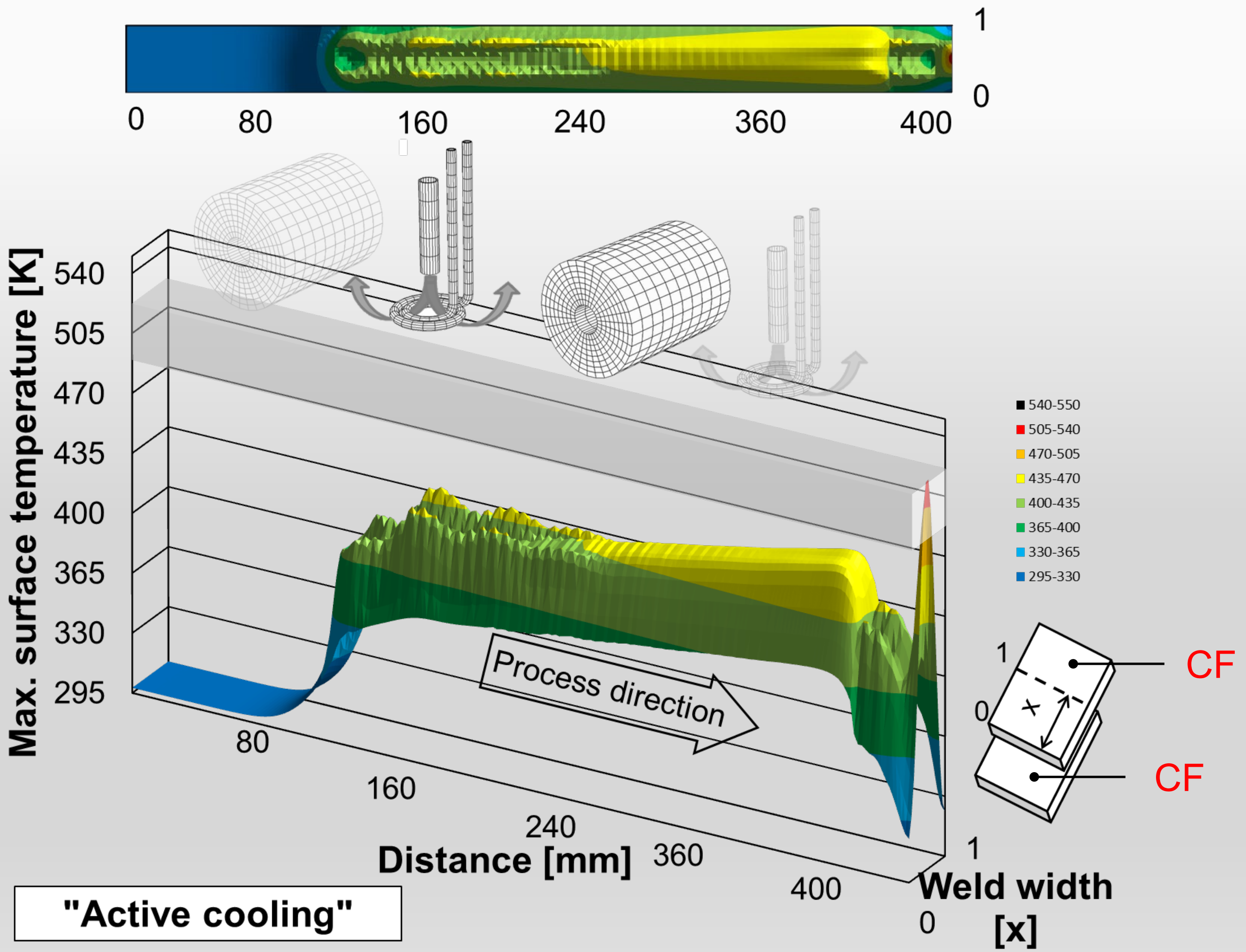
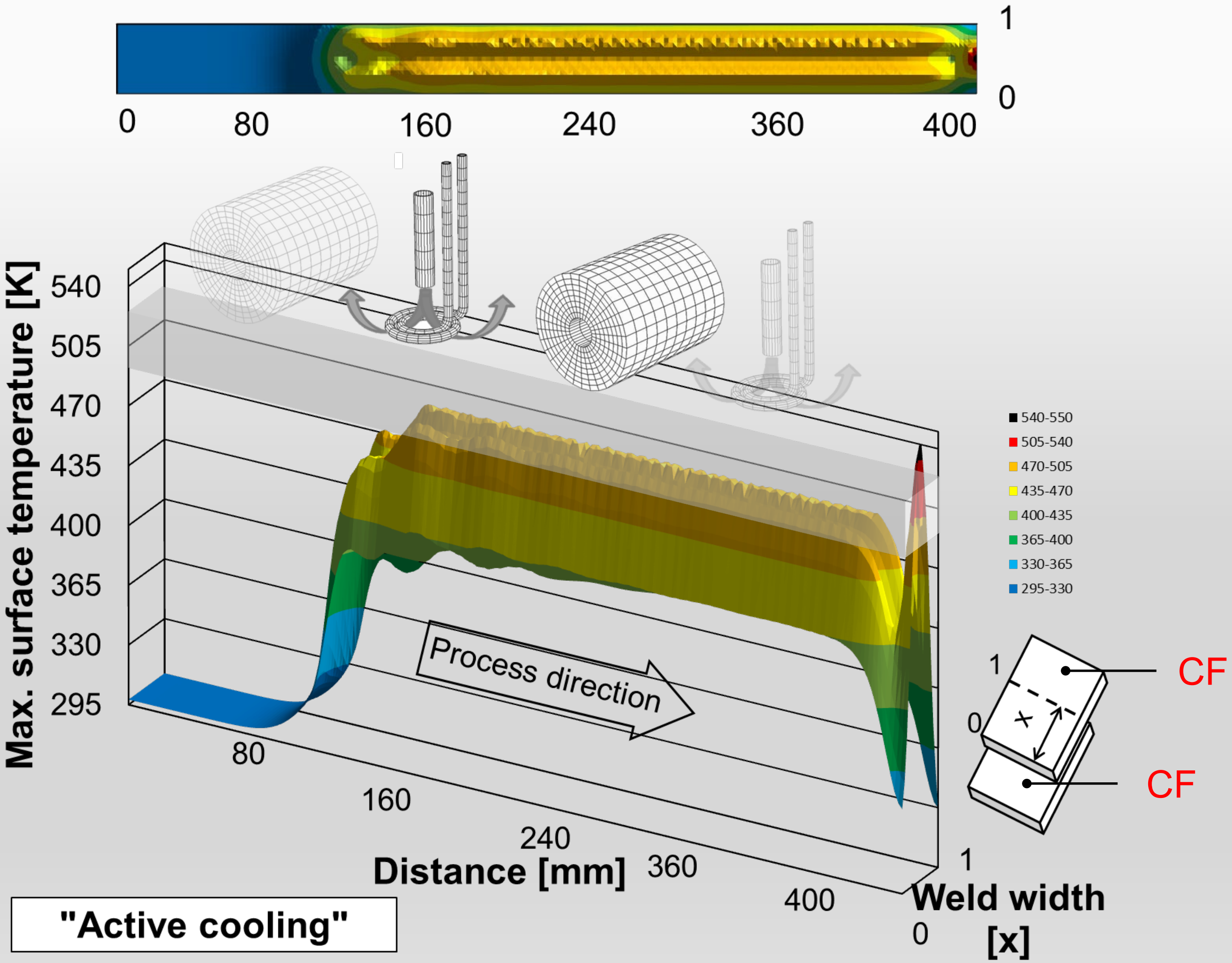
Simulation Results: Actual Induction Welding Scenario Surface Temperature Plots – CF/CF



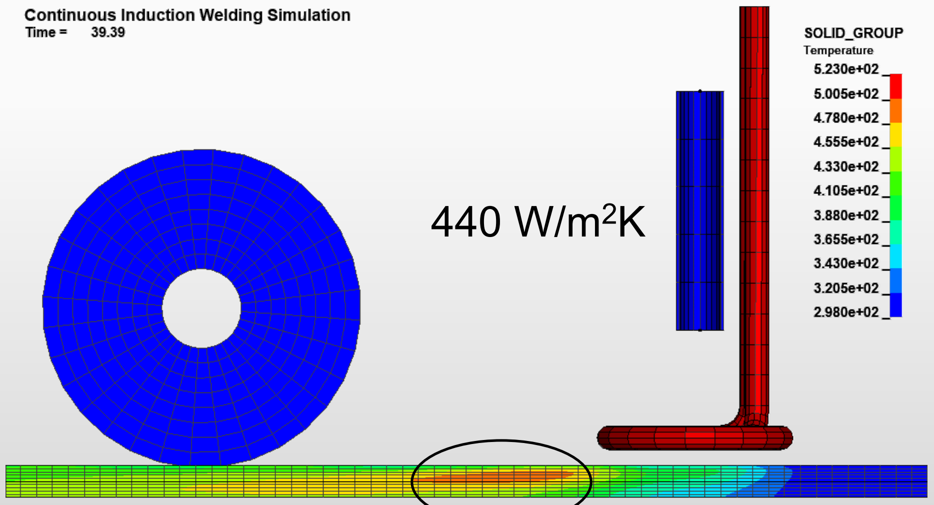
"Active cooling"

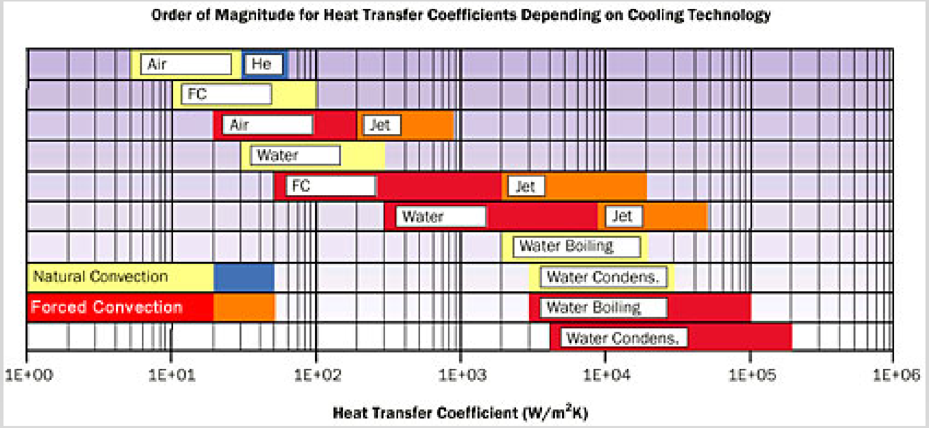
PIDCTL_SP250°C(523K)(195 A), 400 kHz **Top surface** @ 3 mm/sec (0.18 m/min) **(Cooling 440 W/m²K)**

Simulation Results: Actual Induction Welding Scenario Surface Temperature Plots – CF/CF



Where is the target 250°C (523 K)?





Source: Lasance, C., Technical Data column, Electronics Cooling, January 1997

PIDCTL_SP250°C(523K)(195 A), 400 kHz **Joint interface surface** @ 3 mm/sec (0.18 m/min) **(Cooling 440 W/m²K)**

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ODYSSEE CAE

- ODYSSEE CAE uses knowledge of a model's time-dependent behavior to:
  - Predict the response of the model in parametric studies
  - Use this prediction as an initial guess for improving the model or to test the model via a reduced-order-modeling (ROM) simulation coupled with optimization.

- ➢ Lunar: The main GUI of ODYSSEE CAE
- ➢ Quasar: An AI/AML/ROM solver allowing for predictive modeling and data mining analysis.
- ➢ Nova: Optimizer to extract the optimal variables of a model allowing minimization of a given objective function, and associated constraints.
- ➢ Pulsar: A general-purpose parser to create the inputs for Lunar.

ODYSSEE CAE: Definition of Parameters

- We chose five of the most important parameters which influence heating behavior during continuous induction welding
  - A total of 42 simulations were carried out considering 21 to 42 DOEs generated using the Latin Hyper Cube approach (better for low sample sizes)

Priority	Parameter	Min value	Max value
1	Welding speed (m/min)	0.1	0.5
2	Power (current amplitude) (A)	70 (10% Power)	700 (100% Power)
3	Top surface cooling rate (W/m^2K)	0	10000
4	Laminate in-plane electrical conductivity, K1/K2 (combined) (S/m)	16000	30000
5	Laminate through thickness electrical conductivity, K3 (S/m)	0.03	10

  - Not all simulations worked: 25 training models – 4 validation models
  - Each simulation takes an average of 12 days to solve using 4 Cores of an Intel® Xeon® Ice Lake Gold 6326, 2.9 GHz, 16-Core CPU

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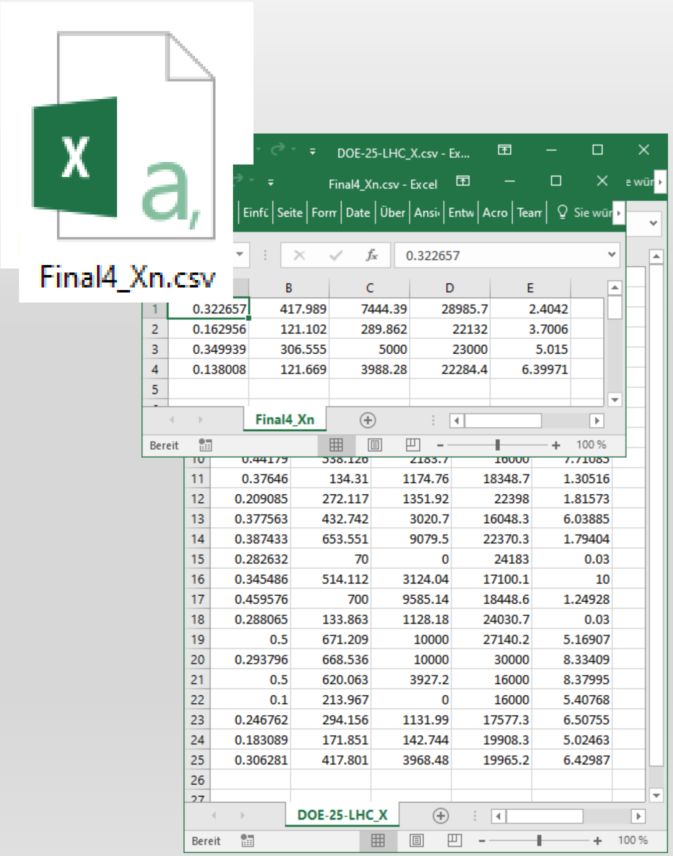
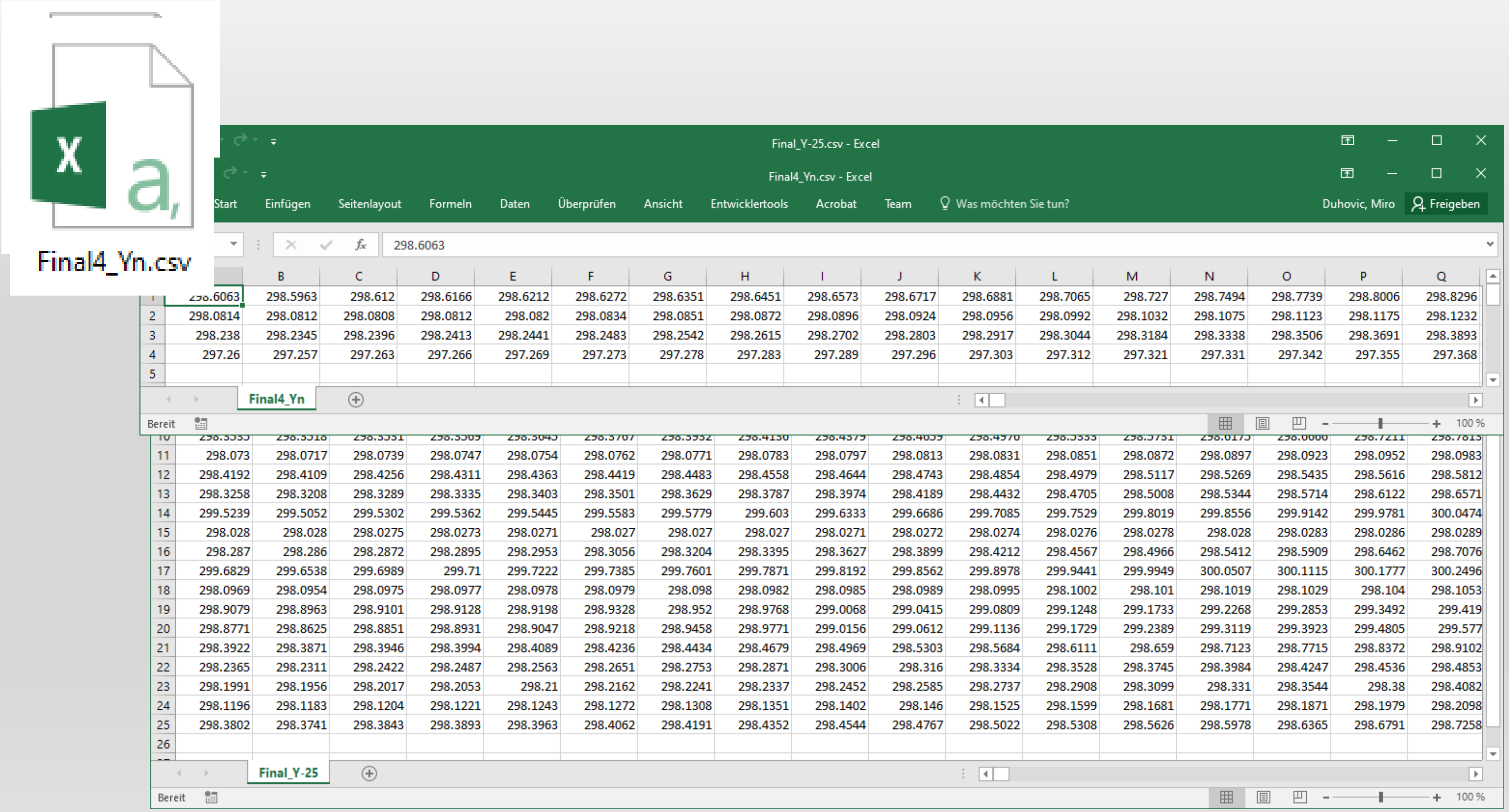
ODYSSEE CAE: Inputs

- X (input) and Y (output) .csv database files are selected for the Reduced Order Model (ROM)
  - Additional Xn (input) and Yn (output) .csv files are given as validation sets





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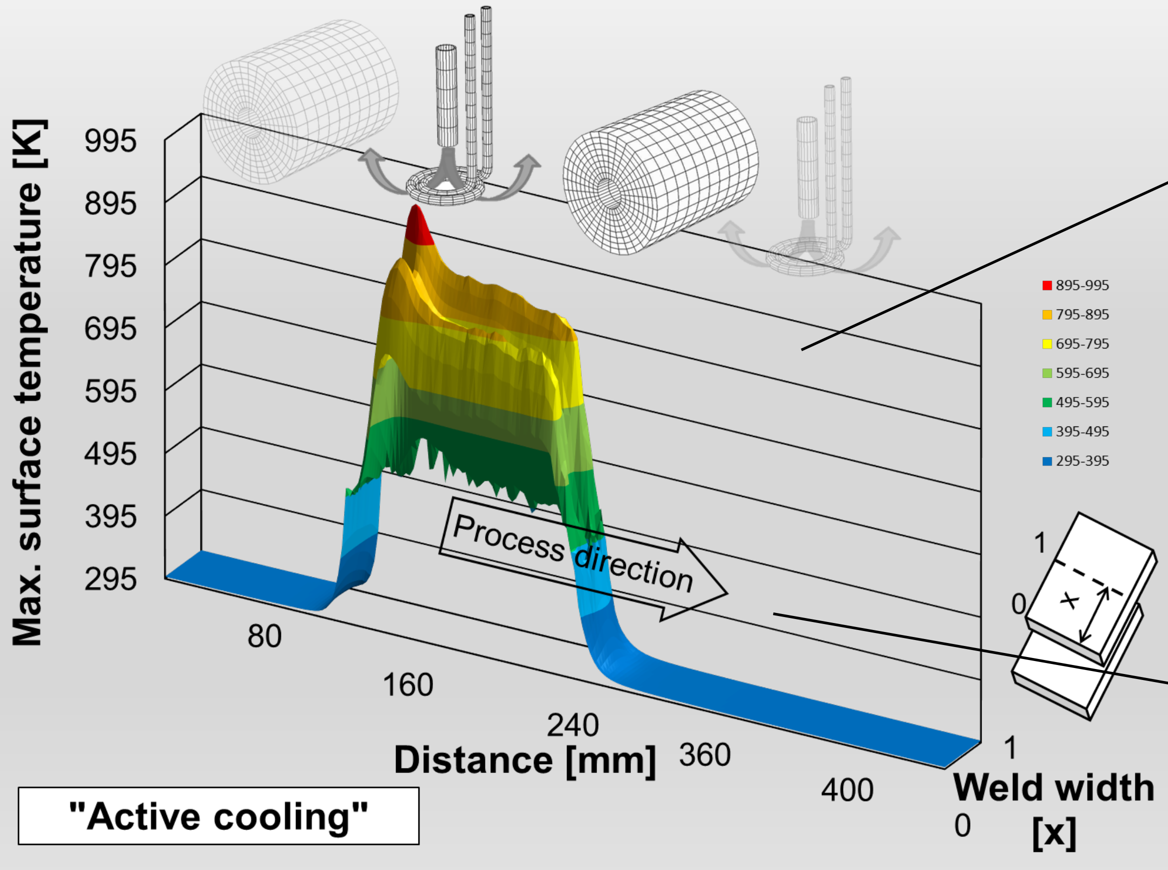
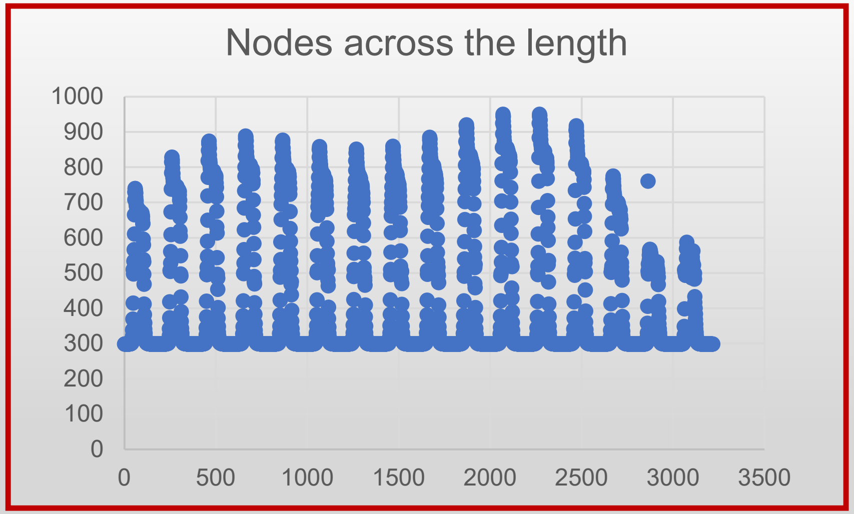
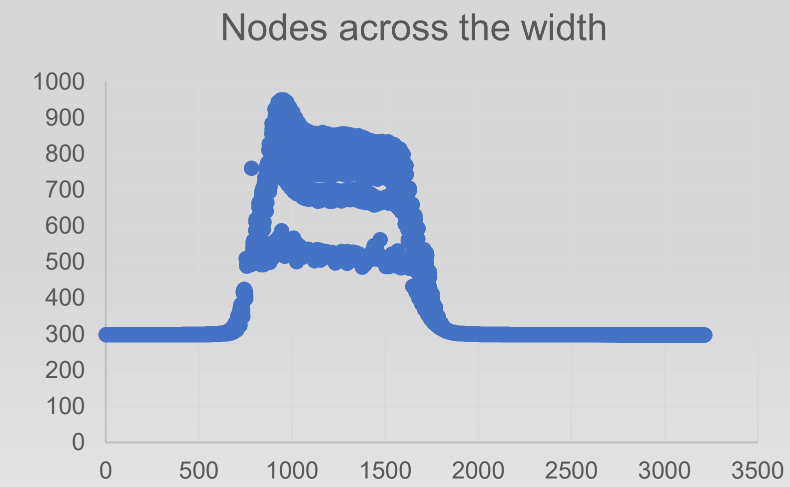
ODYSSEE CAE: Inputs

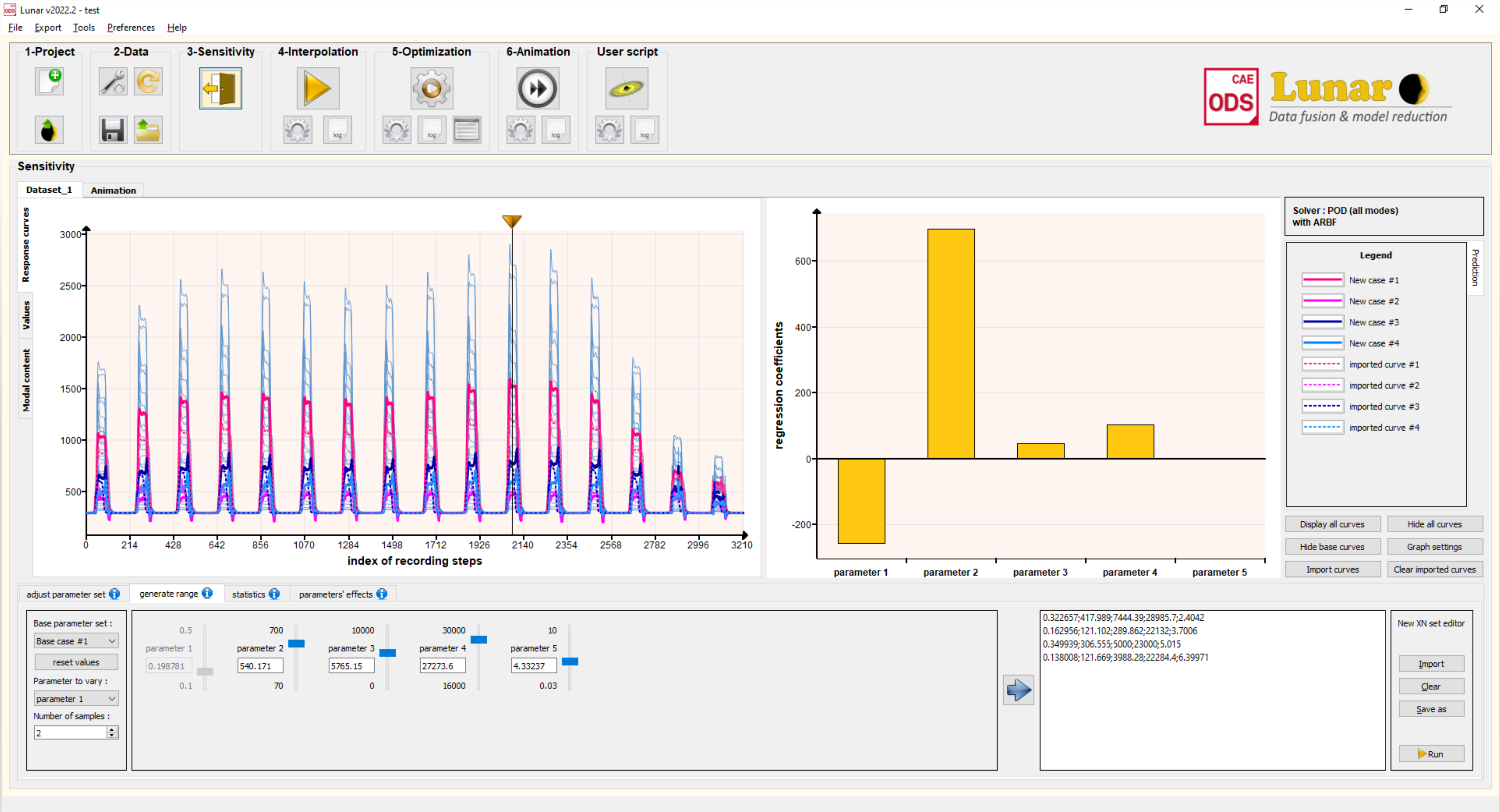
- Y database (joint interface temperature) data must be given in the form of a 1D array (single row of temperature values)
  - There are two options…







ODYSSEE CAE: Lunar GUI



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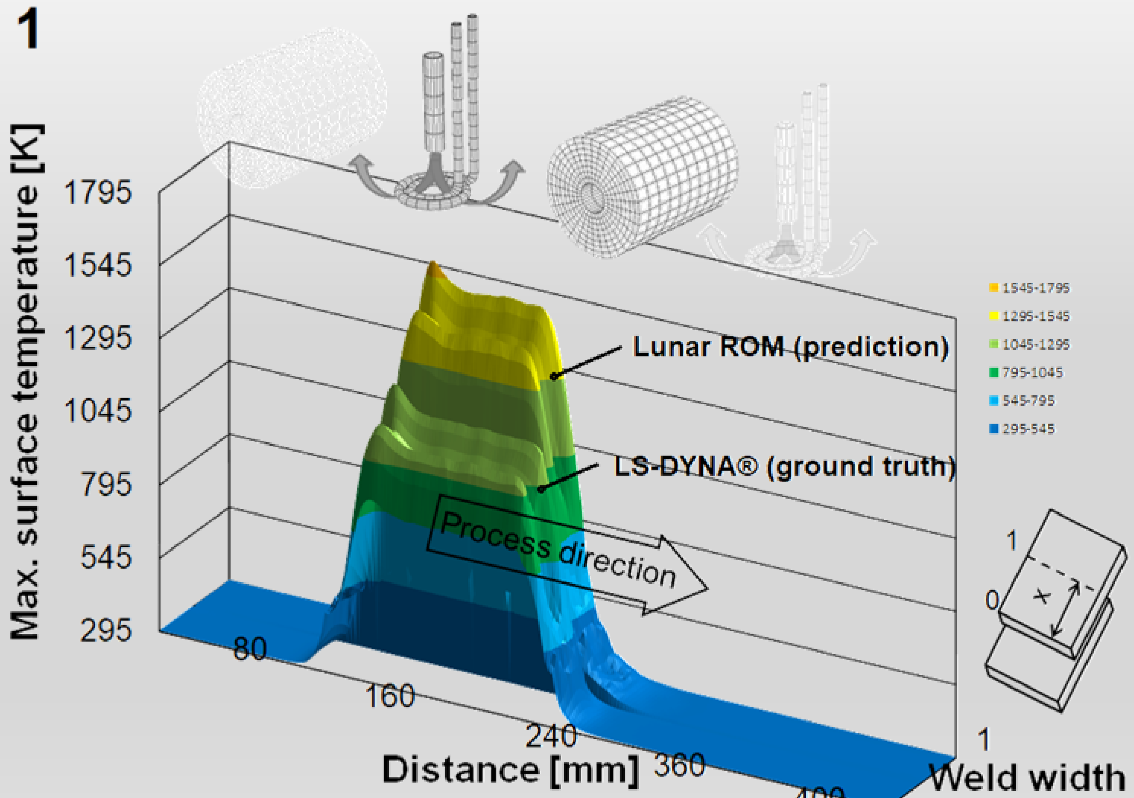
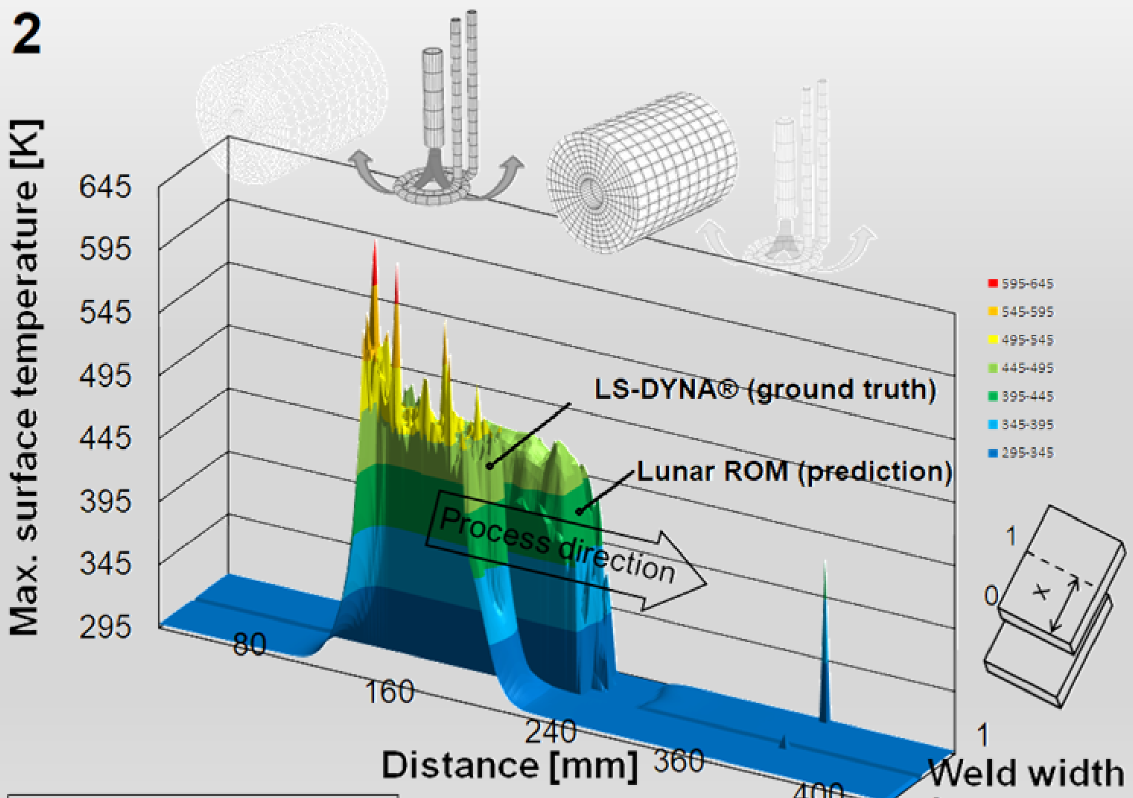
ODYSSEE CAE: Results

Parameter	Val. Set 1
Welding speed (m/min)	0.322657
Power (current amplitude) (A)	417.989
Top surface cooling rate (W/m²K)	7444.39
Laminate in-plane electrical conductivity, K1/K2 (combined) (S/m)	28985.7
Laminate through thickness electrical conductivity, K3 (S/m)	2.4042

Parameter	Val. Set 2
Welding speed (m/min)	0.162956
Power (current amplitude) (A)	121.102
Top surface cooling rate (W/m²K)	289.862
Laminate in-plane electrical conductivity, K1/K2 (combined) (S/m)	22132
Laminate through thickness electrical conductivity, K3 (S/m)	3.7006



"Active cooling"



"Active cooling"

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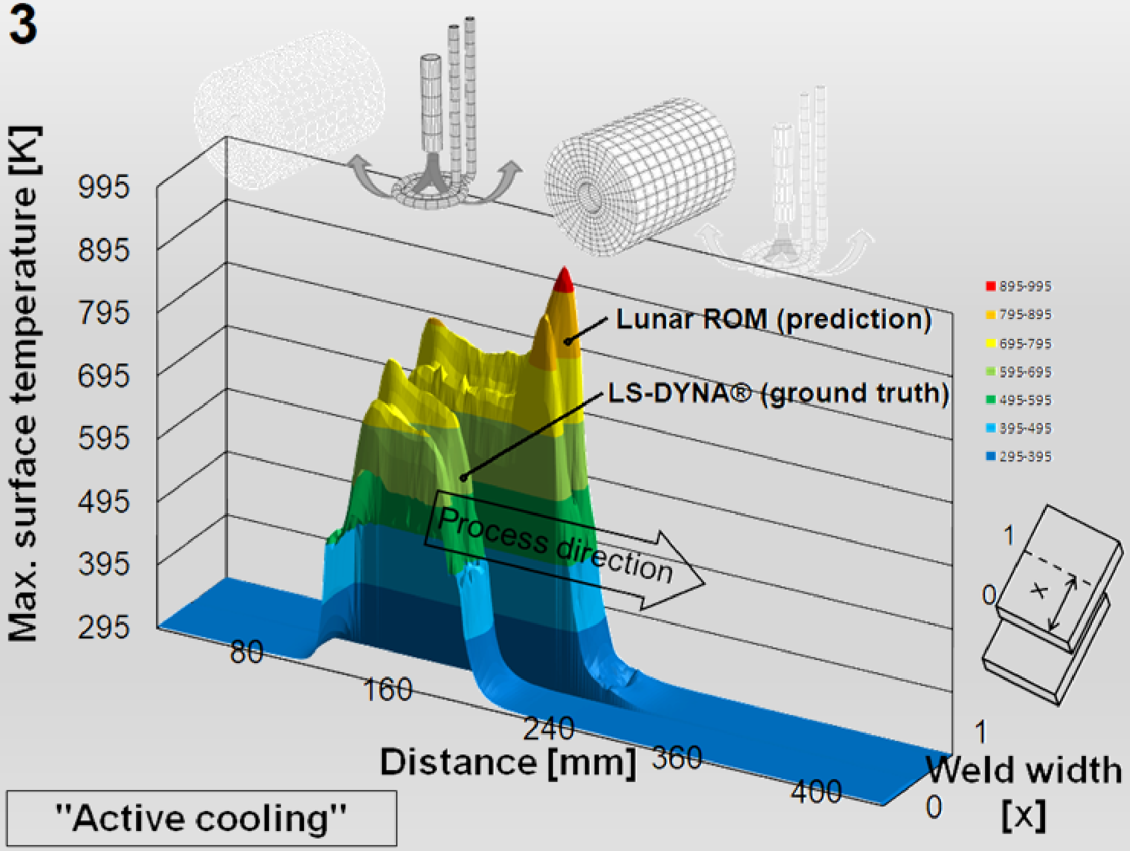
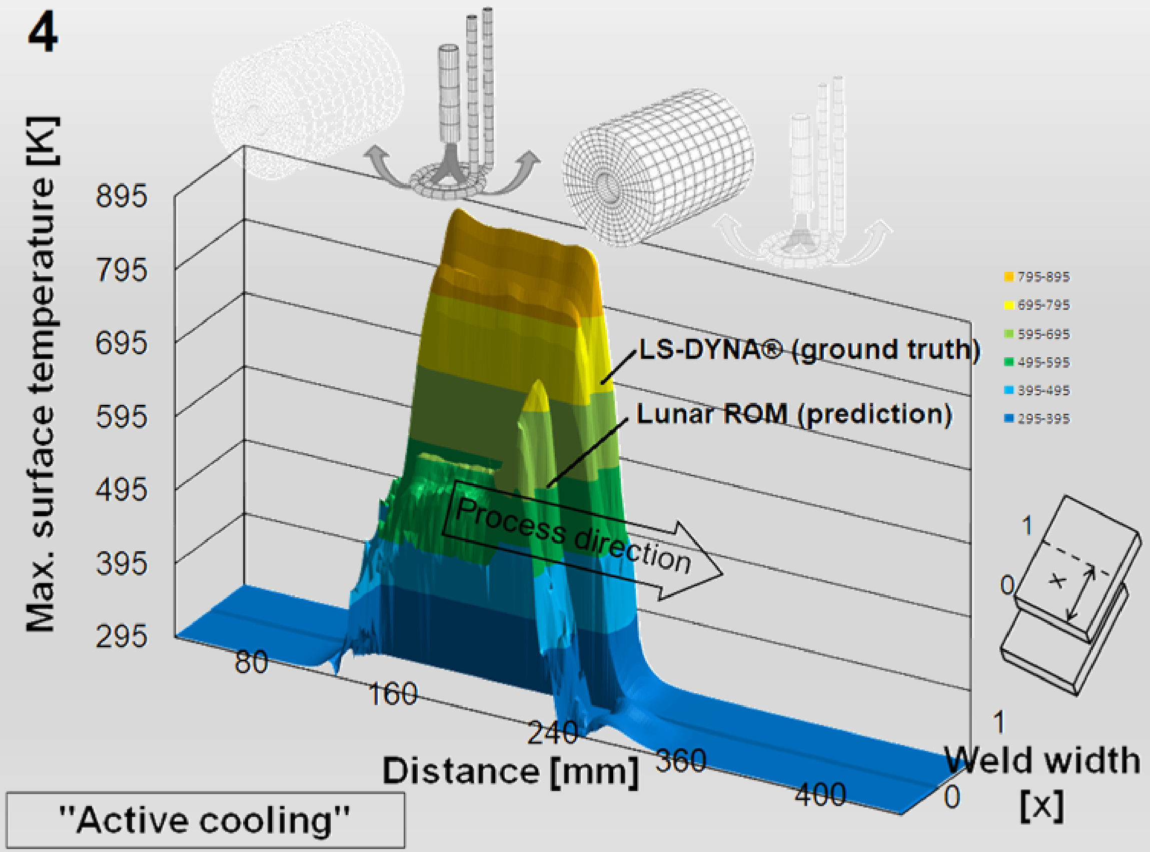
ODYSSEE CAE: Results

Parameter	Val. Set 3
Welding speed (m/min)	0.349939
Power (current amplitude) (A)	306.555
Top surface cooling rate (W/m²K)	5000
Laminate in-plane electrical conductivity, K1/K2 (combined) (S/m)	23000
Laminate through thickness electrical conductivity, K3 (S/m)	5.015

Parameter	Val. Set 4
Welding speed (m/min)	0.138008
Power (current amplitude) (A)	121.669
Top surface cooling rate (W/m²K)	3988.28
Laminate in-plane electrical conductivity, K1/K2 (combined) (S/m)	22284.4
Laminate through thickness electrical conductivity, K3 (S/m)	6.39971





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Summary

- The process of continuous induction welding has been modeled using advanced 3D finite element modelling techniques
- Temperature profiles at the bonding interface for different processing conditions can be examined and optimized to ensure they remain within material processing limits, however full simulations take far too long!
- An initial ODYSSEE CAE parameter study using 5 of the most important parameters has been carried out
- A first attempt at creating a ROM for the induction welding simulation models shows that some of the parameter ranges need to be refined
- Once properly trained the ROM can be used to instantly generate results and even full LS-DYNA output decks (d3plot data)
- The intention is to use the ROM and generator d3plot data to find the parameter set providing the optimum maximum temperature shift towards the joint interface

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Acknowledgments

DYNAmore

- Nikolay Lazarov
- Steffen Frik

MSC Software

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Thank you for your attention!

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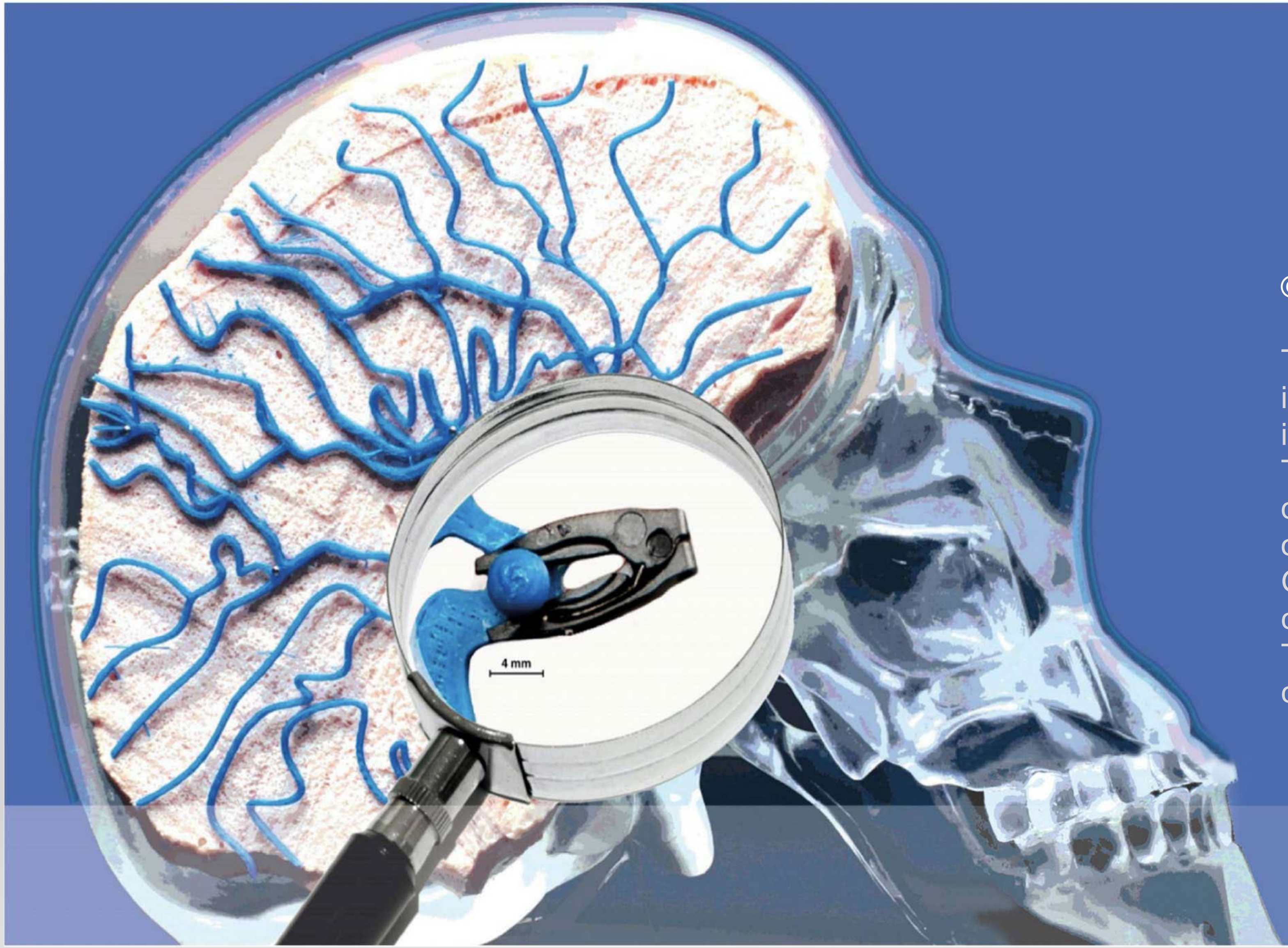

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Composite Aneurysm Clip

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