

# Towards Faster 3D Simulations of CFRTP Induction Welding



Leibniz-Institut für  
Verbundwerkstoffe

Miro Duhovic, Stefano Cassola, Thomas  
Hoffmann, Peter Mitschang

- **Introduction & Motivation**
- **Induction Welding Simulation Basics**
- **Material Properties and Process Inputs**
- **Understanding and Simulating Continuous Induction Welding**
  - **Model Setup in LS-DYNA®**
  - **Continuous Induction Welding Simulation Results**
  - **Parameter Studies with ODYSSEE CAE**
- **Summary**

# 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



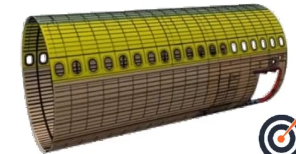
## → Induction WELDING : a key process for the TP Aircraft

Induction Welding on primary structure.

### What for ?

The **main target** for Dynamic Induction welding technologies seems to be the longitudinal stringer assembly :

- Important junction length : 800 meters (even more for Omega stringers)
- Relative constant geometry and low thickness
- Good accessibility at this stage of assembly



Use case : 10 meters long typical fuselage section

### Cost ?

#### Typical cost breakdown

Stringer Welded Thermoplastic fuselage

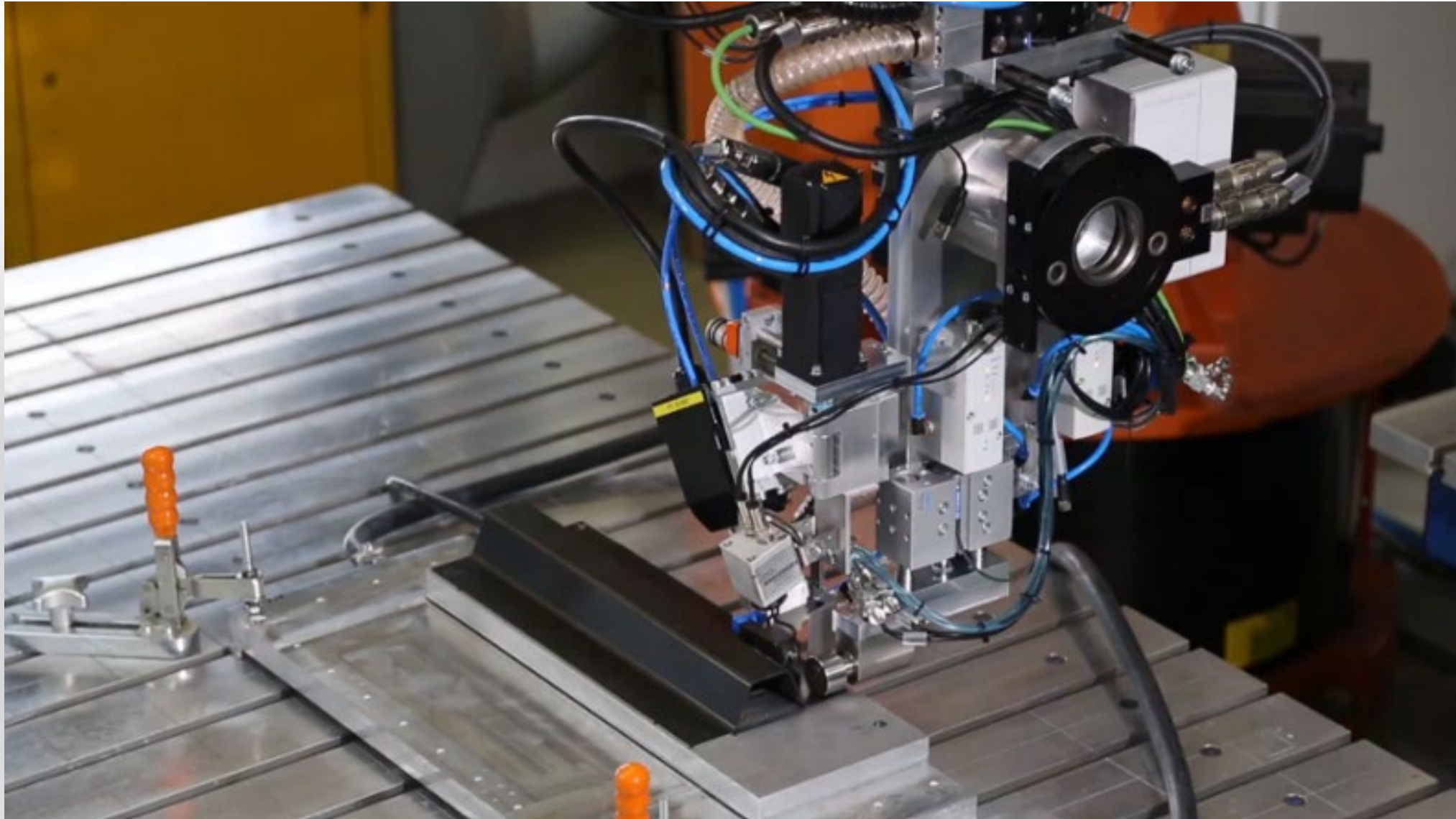


Holes & Fasteners Thermoplastic fuselage  
Typical metallic ratio : 70 (part) /30 (assy)

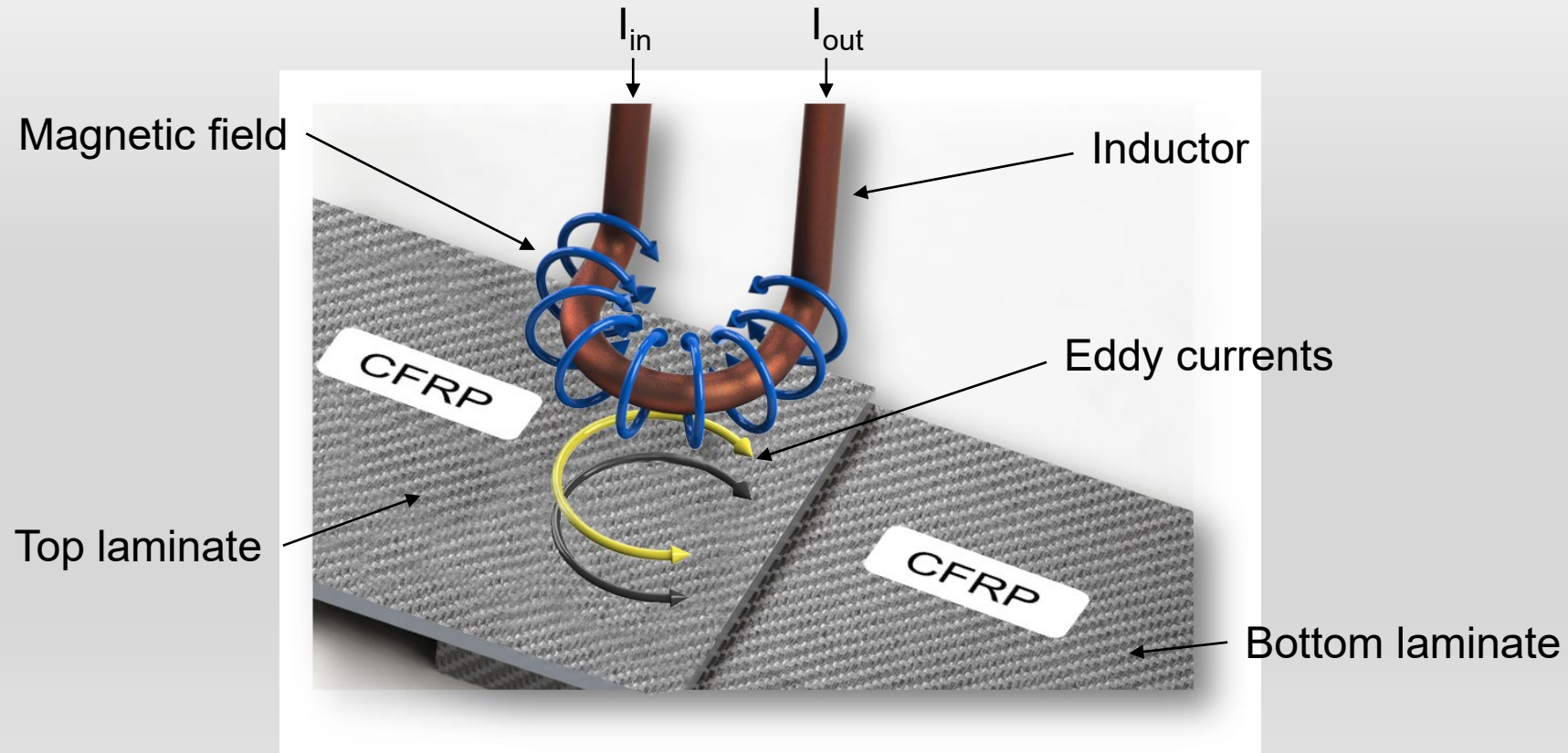
TP welding is more an enabler than a direct cost driver. Need to demonstrate quality, performance and reliability more than productivity.

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>



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

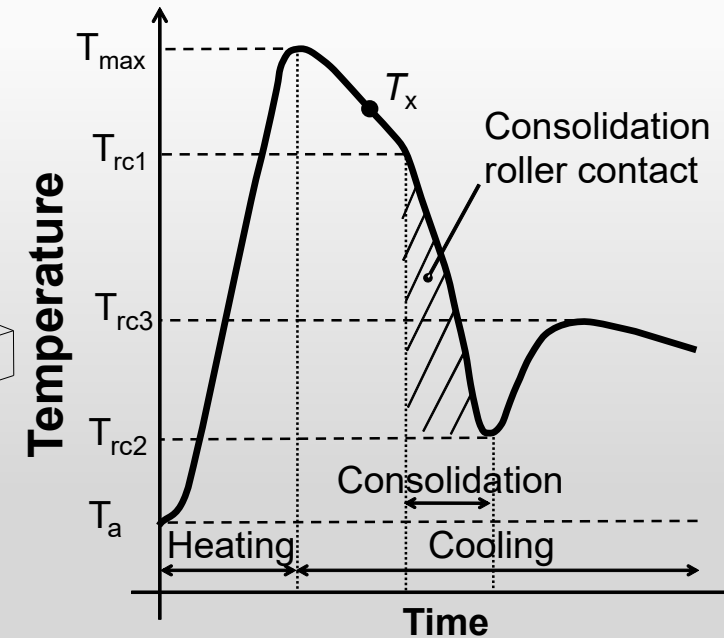
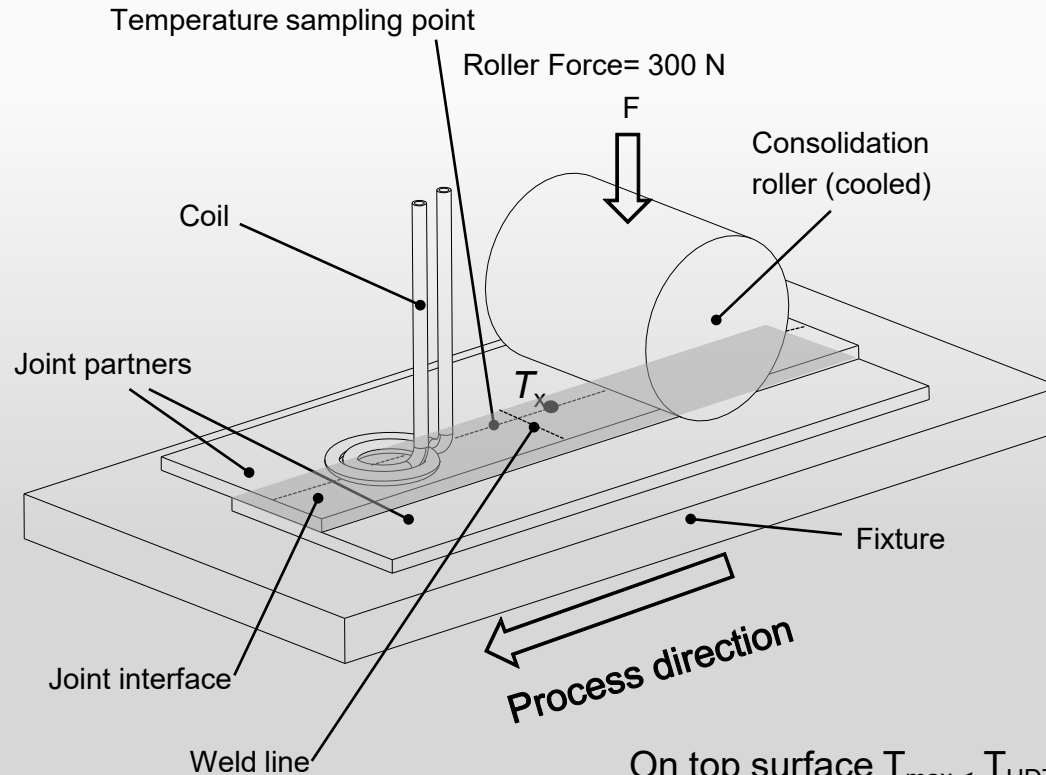


Type of Physics	Material Property		Process Inputs				
Mechanical	Stiffness (Pa)	$E_1, \nu_1$	Coupling Distance (m)	$d_1$			
		$E_2, \nu_2$	<sup>3</sup> Coil/Roller Velocity (m/s)	$v$			
		$E_3, \nu_3$	<sup>3</sup> Coil to Roller Distance (m)	$d_2$			
			<sup>3</sup> Roller Normal Contact Force (N)	$F_N$			
	Density (kg/m <sup>3</sup> )	$\rho$	<sup>3</sup> Roller Contact Friction Coefficient	$\mu_{fric}$			
Thermal	Heat Capacity (J/(kg*K))	Cp	Free Surface Convection Coefficients (W/m <sup>2</sup> *K)	$h_{top}$			
				$h_{bottom}$			
				$h_{sides}$			
	Thermal Conductivity (W/m*K)	$k_1$		Initial Temperature (°C)	T		
					$k_2$	<sup>1</sup> Heat Transfer Conductance (W/m <sup>2</sup> *K)	htc
							$k_3$
		<sup>3</sup> Forced Convection Coefficient (W/m <sup>2</sup> *K)	$h_{forced}$				
Electromagnetic	Electrical Conductivity (S/m)	$\sigma_1, \sigma_2, \sigma_3$	Frequency (Hz)	Freq			
	Relative Permeability	$\mu_r$	Current Amplitude (A)	I			
	Relative Permittivity	$\epsilon_r$	<sup>1</sup> Contact Resistance ( $\Omega.m$ )	R			

<sup>1</sup>Necessary parameters in the case of double plate model simulations

<sup>2</sup>Significant for metal and dissimilar material joints and can be neglected for composite only welds

<sup>3</sup>Additional parameters required in the case of full continuous induction welding simulations with air-jet cooling

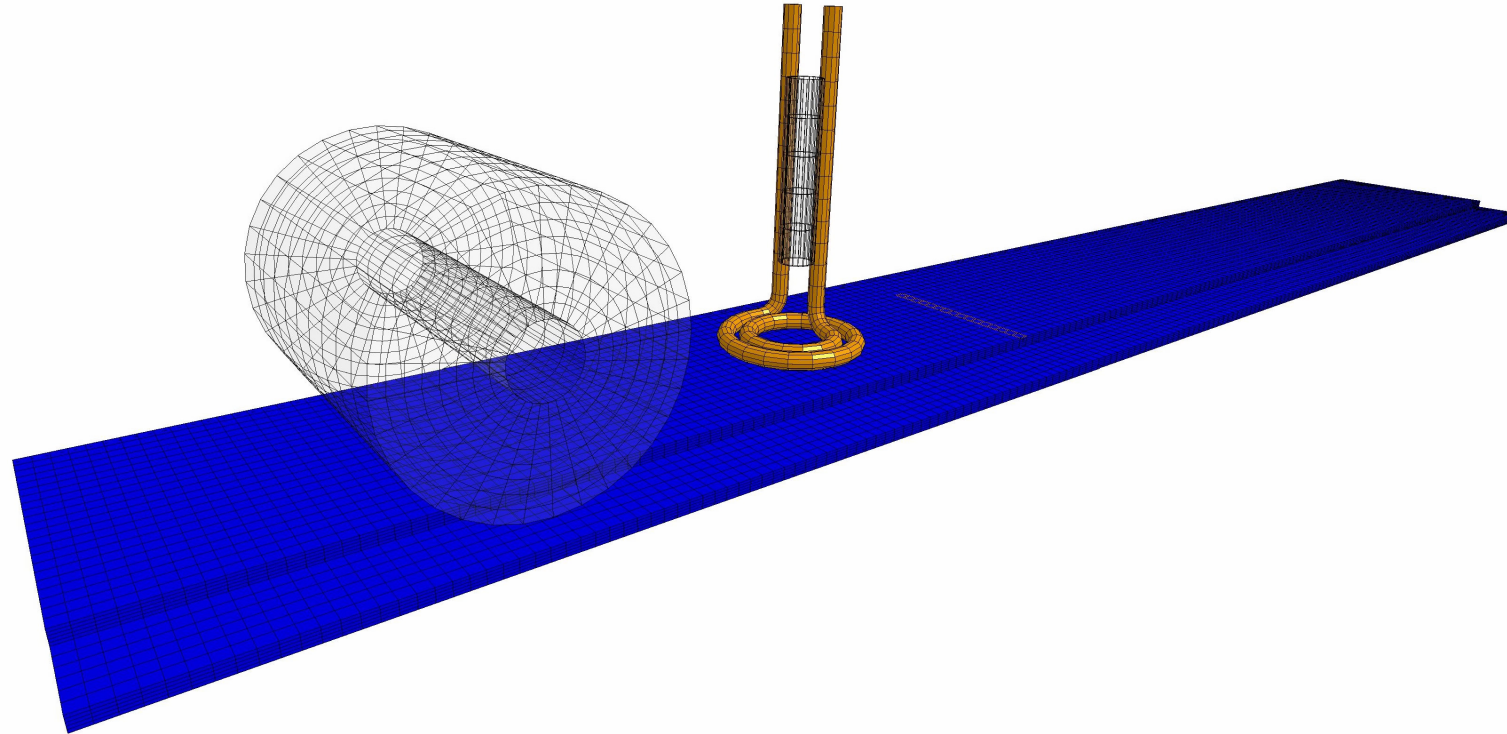


On top surface  $T_{max} < T_{HDT}$

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!

Now we can examine temperature profiles at any location!



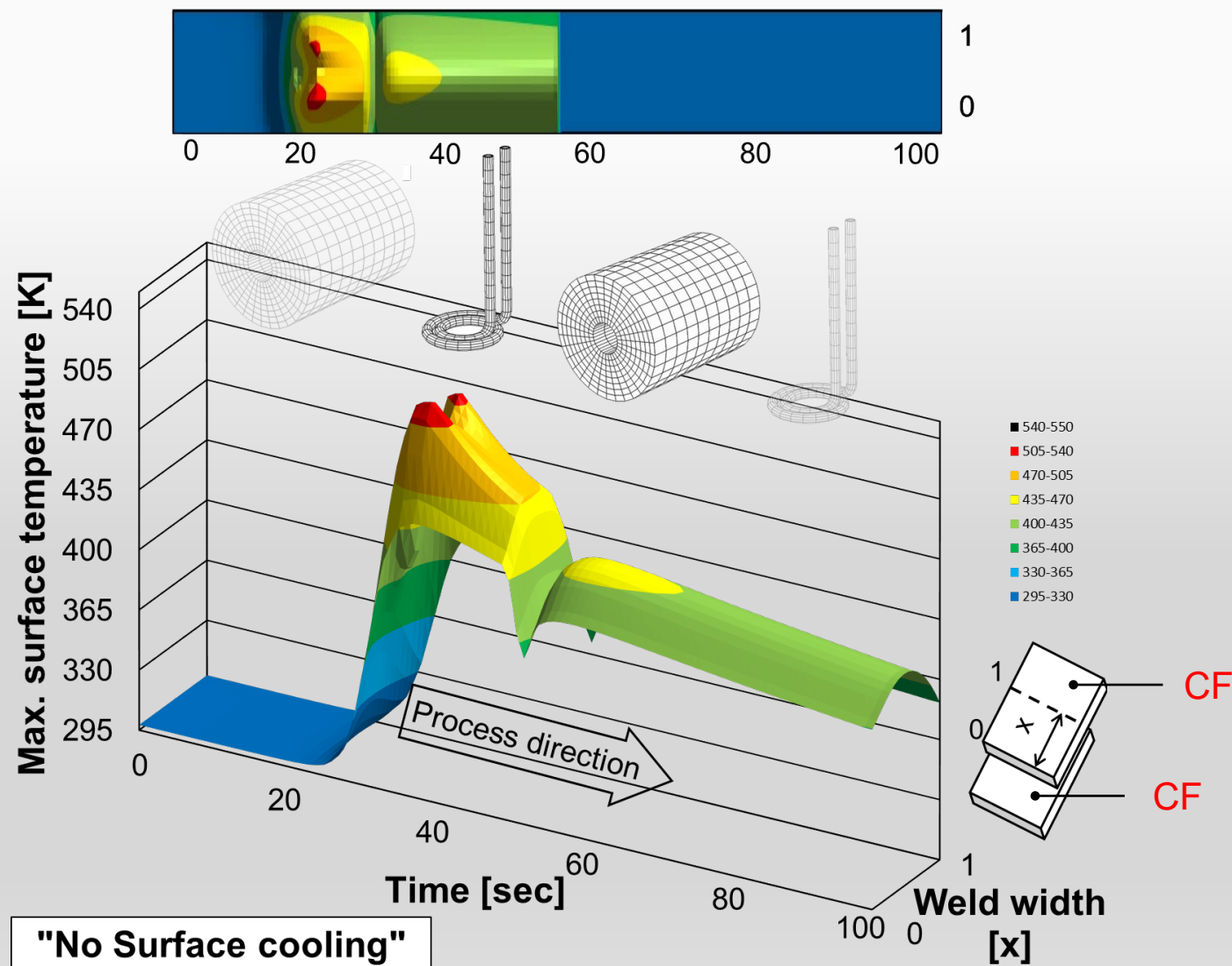
- The goal is to make sure we remain within the processing window of the material so that the top surface doesn't melt, the material anywhere does not degrade and the bond surface is hot enough for joining.
- A **Proportional-Integral-Derivative** controller (**PID** controller) is used to control the 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>

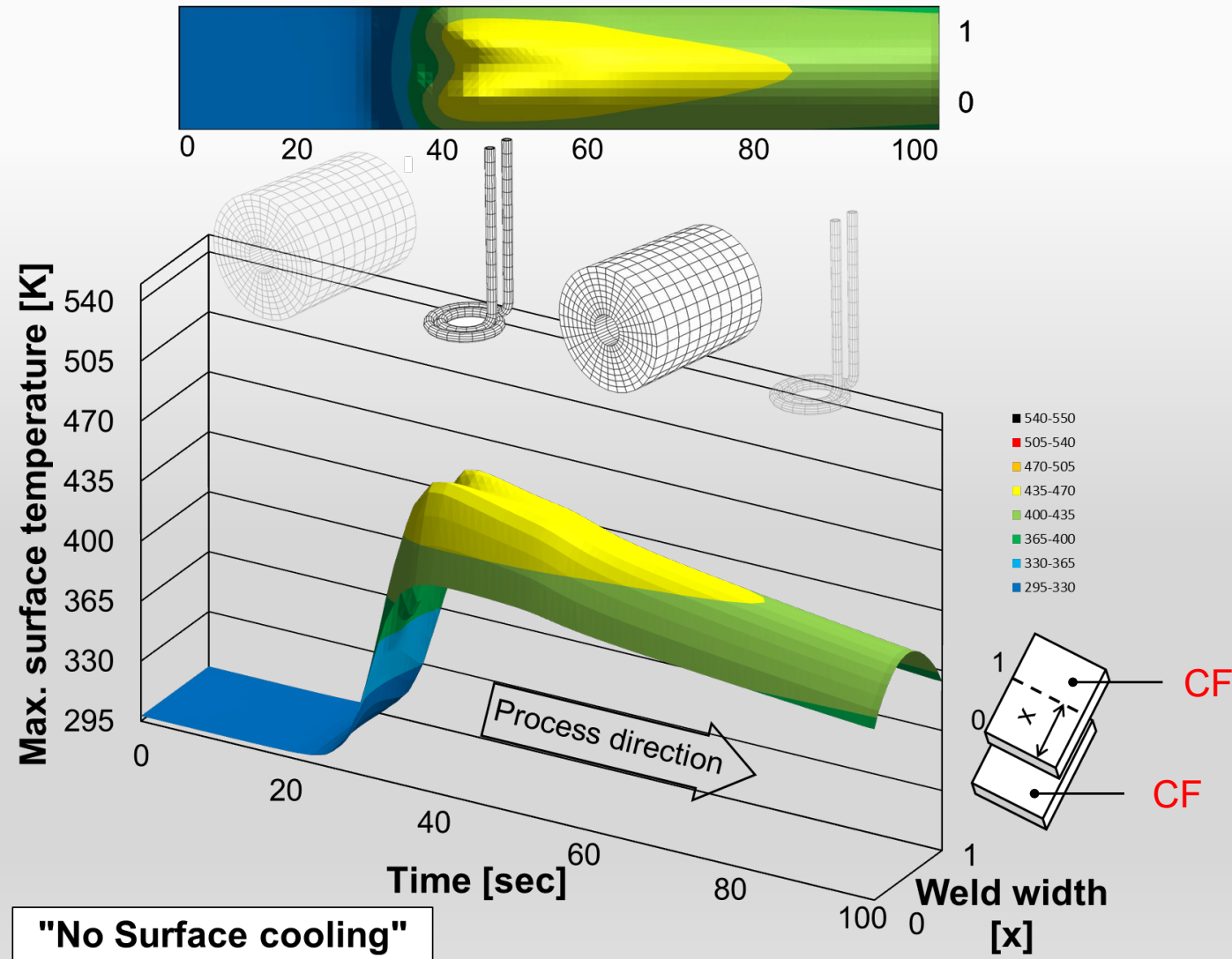


# Simulation Results: Actual Induction Welding Scenario Surface Temperature Plots – CF/CF



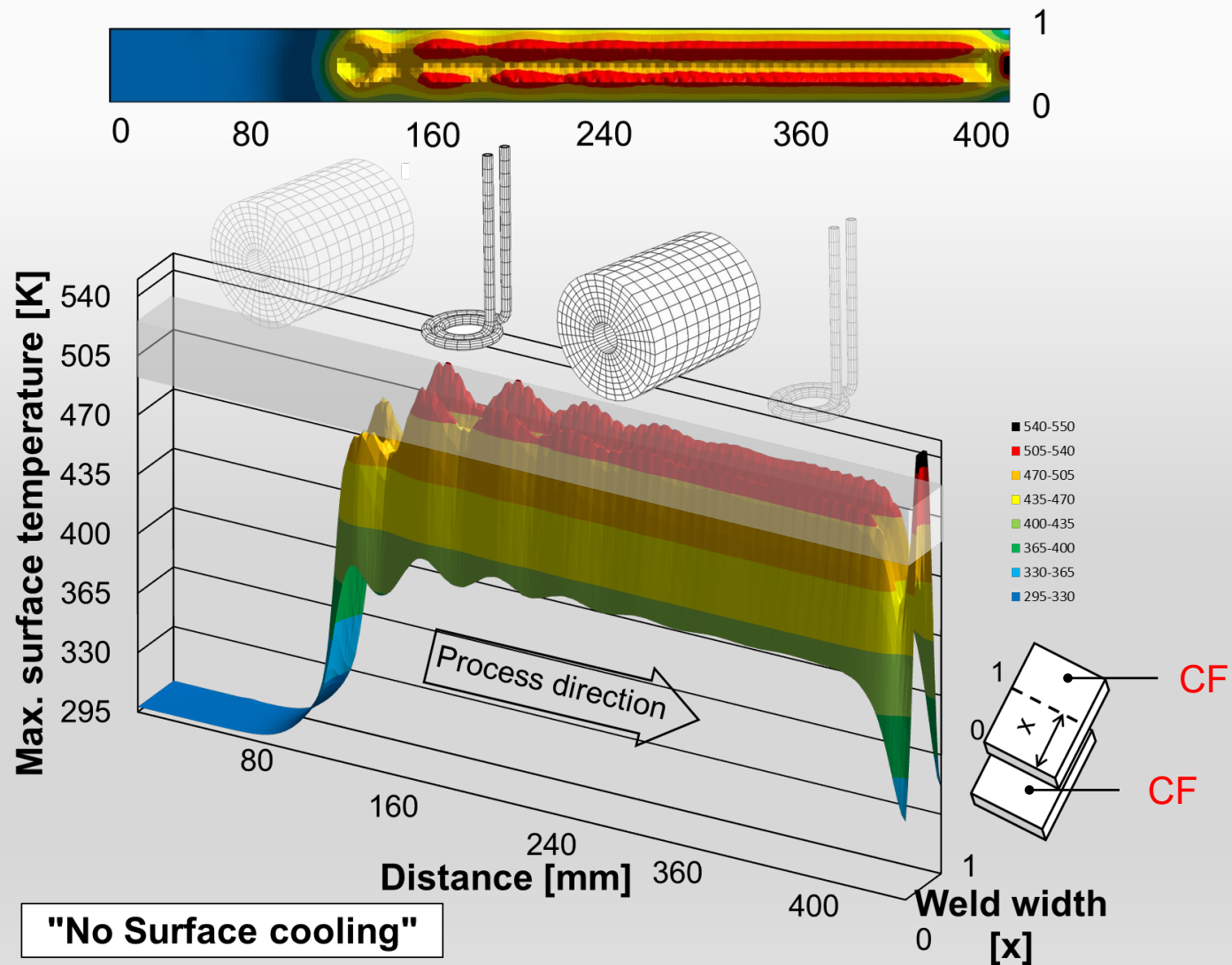
PIDCTL\_SP250°C(523K)(170 A), 400 kHz **Top Surface Weldline** @ 3 mm/sec (0.18 m/min)

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



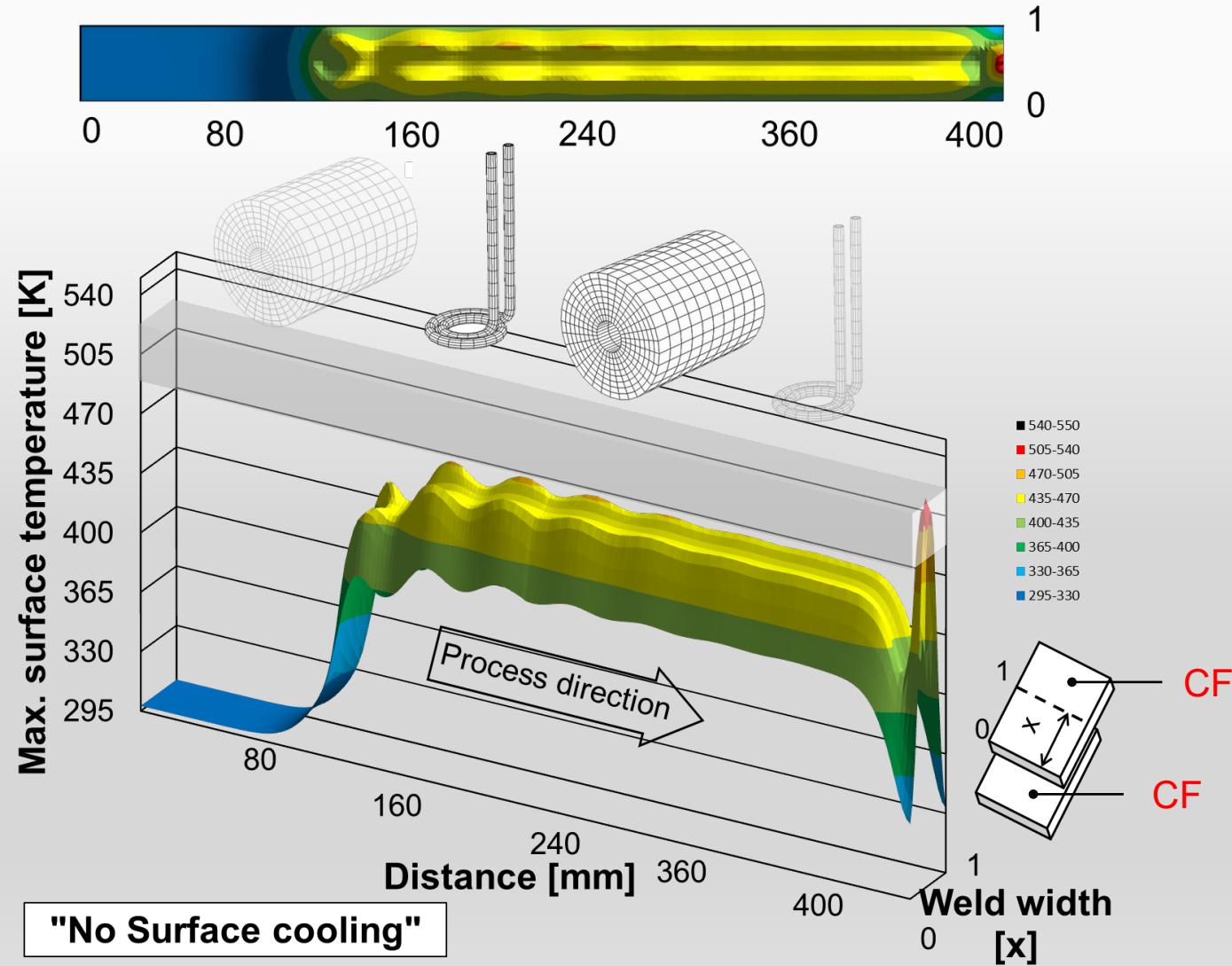
PIDCTL\_SP250°C(523K)(170 A), 400 kHz **Joint Interface Weldline** @ 3 mm/sec (0.18 m/min)

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



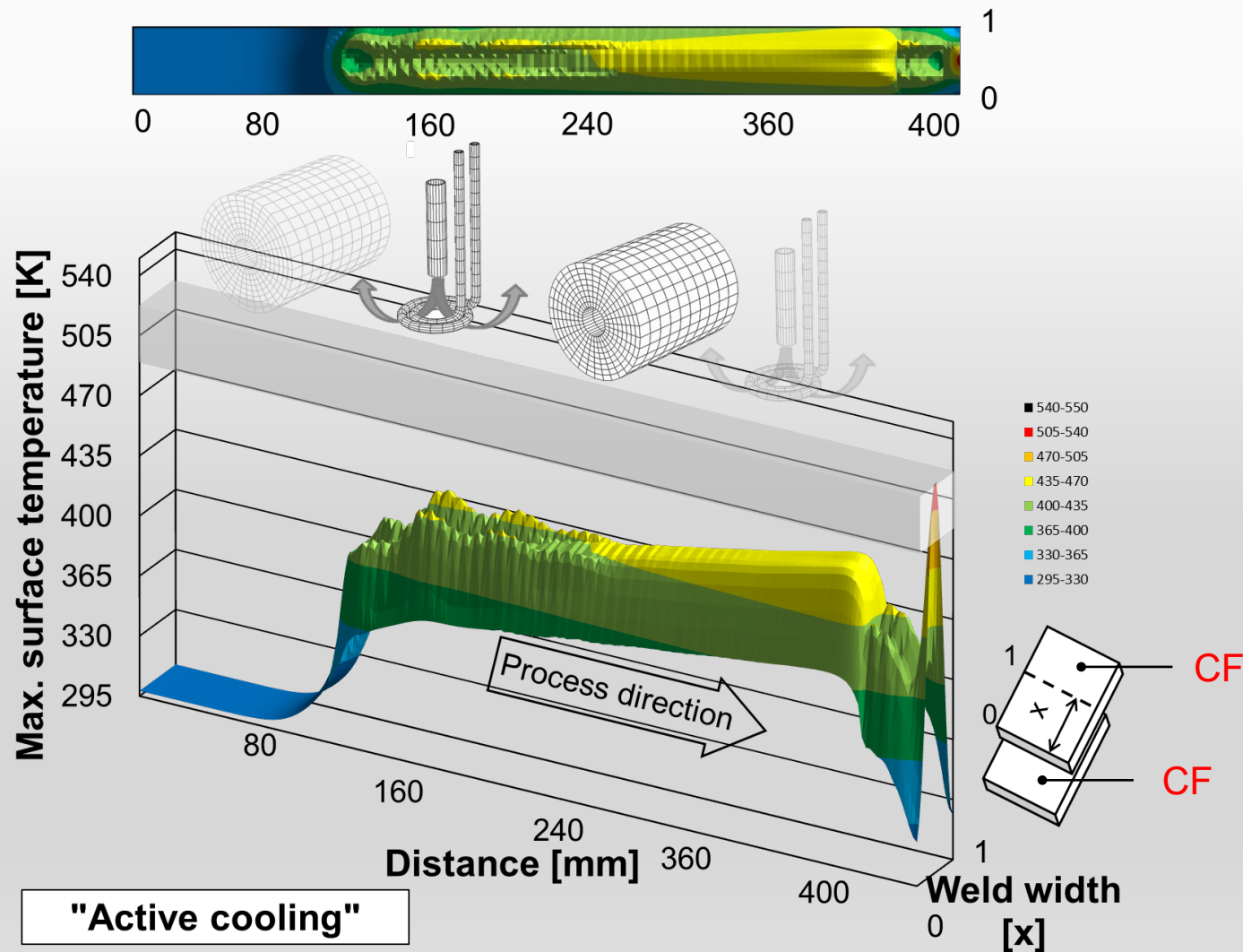
PIDCTL\_SP250°C(523K)(170 A), 400 kHz **Top surface** @ 3 mm/sec (0.18 m/min)

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



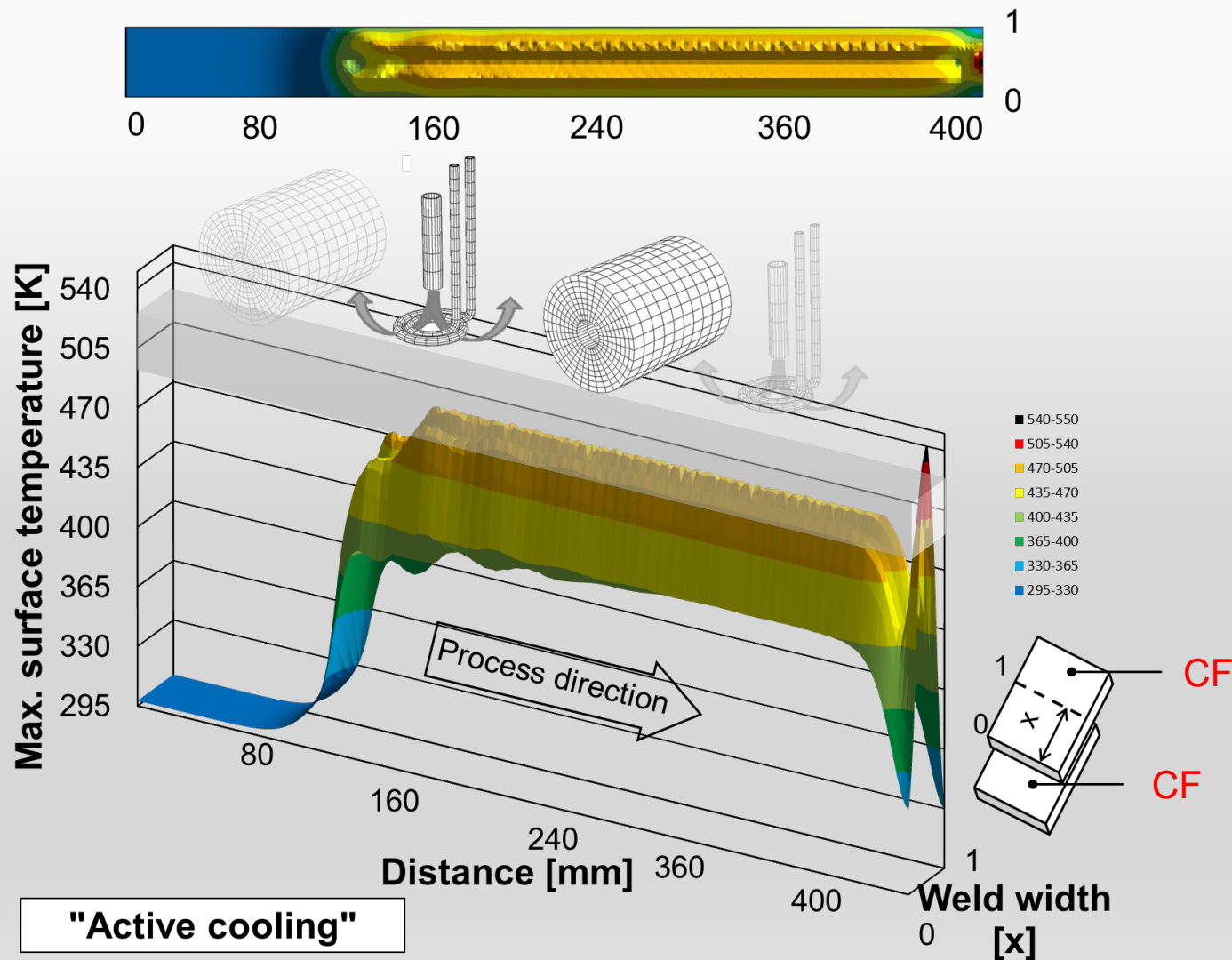
PIDCTL\_SP250°C(523K)(170 A), 400 kHz **Joint interface surface** @ 3 mm/sec (0.18 m/min)

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



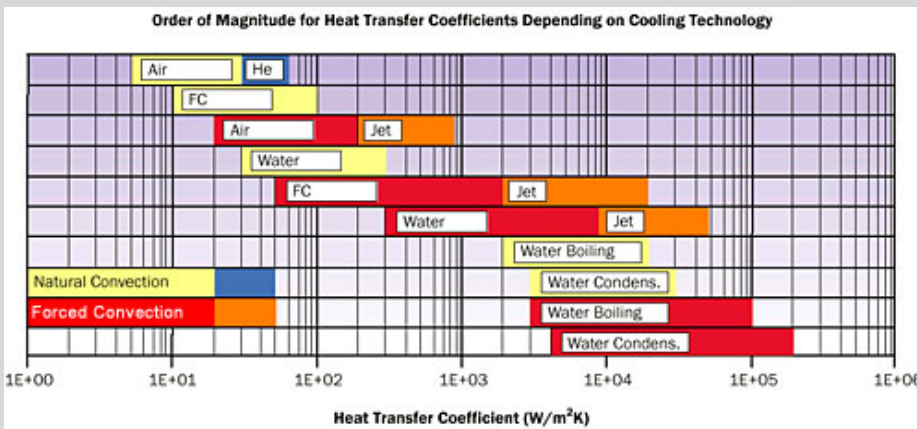
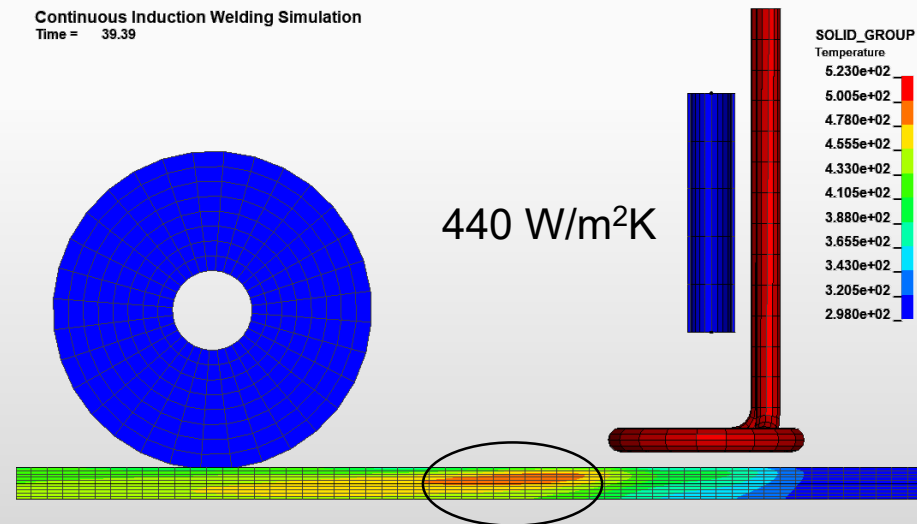
PIDCTL\_SP250°C(523K)(195 A), 400 kHz **Top surface** @ 3 mm/sec (0.18 m/min) (Cooling 440 W/m<sup>2</sup>K)

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



Where is the target 250°C (523 K)?

Continuous Induction Welding Simulation  
Time = 39.39



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**)

- 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.

- 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 <sup>2</sup> K)	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



- 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

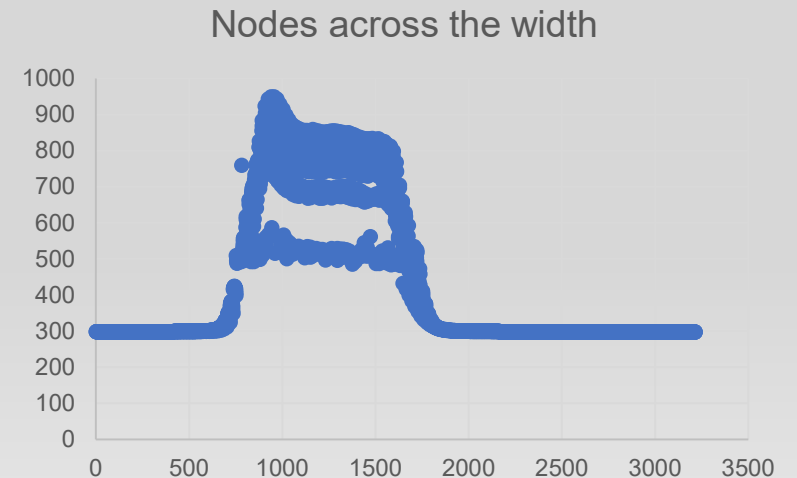
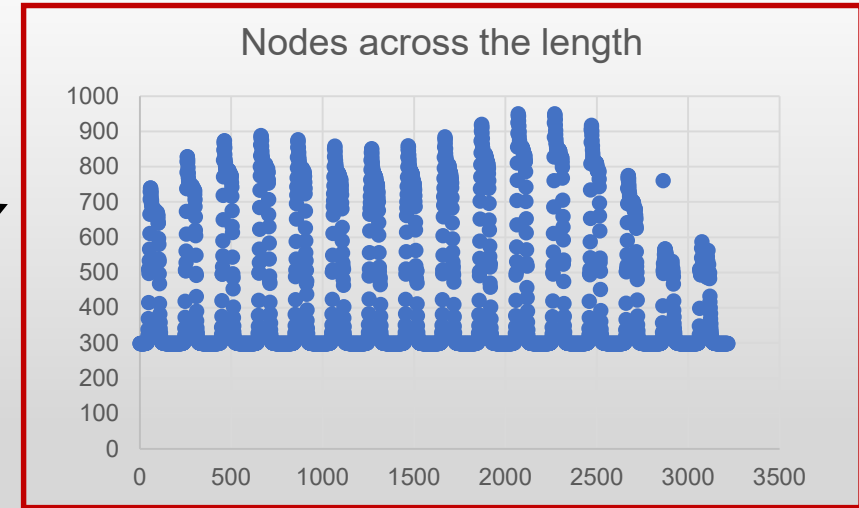
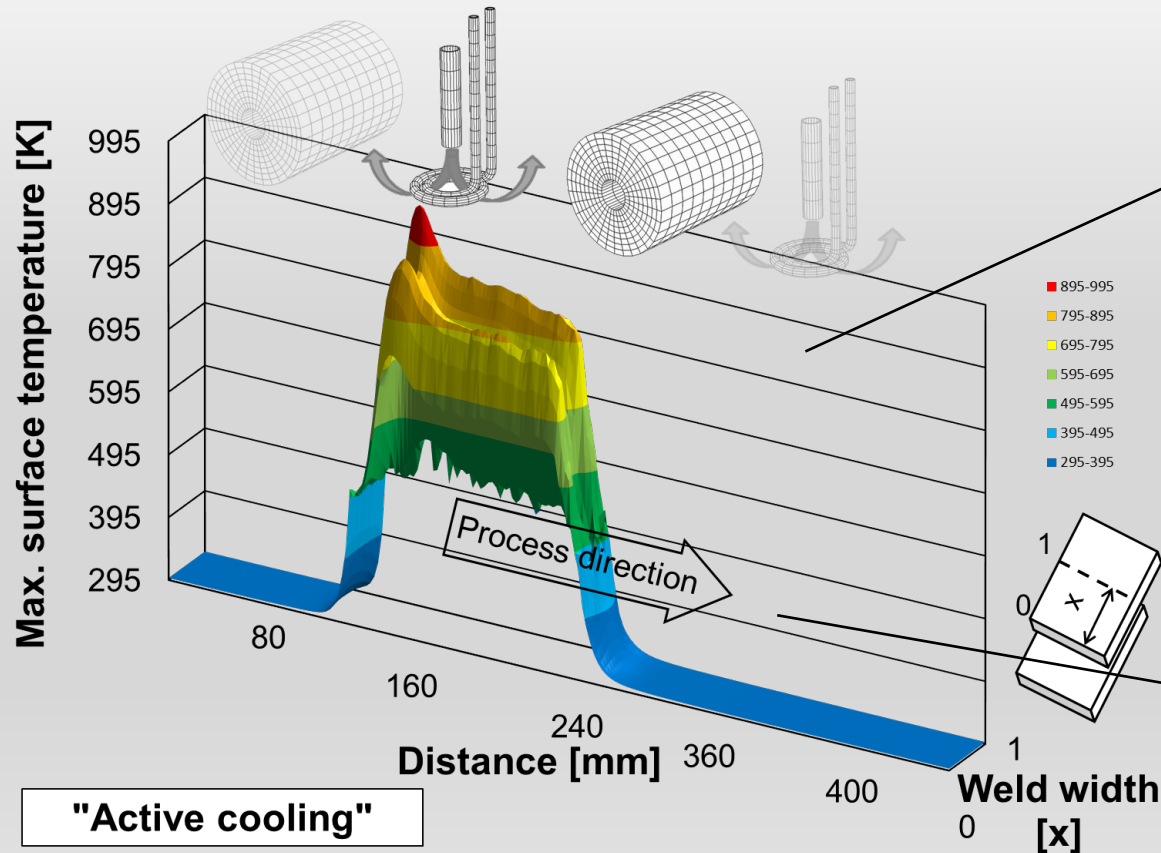
Final4\_Xn.csv

	B	C	D	E
1	0.322657	417.989	7444.39	28985.7
2	0.162956	121.102	289.862	22132
3	0.349939	306.555	5000	23000
4	0.138008	121.669	3988.28	22284.4
5				6.39971

Final4\_Yn.csv

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	
1	298.6063	298.5963	298.612	298.6166	298.6212	298.6272	298.6351	298.6451	298.6573	298.6717	298.6881	298.7065	298.727	298.7494	298.7739	298.8006	298.8296
2	298.0814	298.0812	298.0808	298.0812	298.082	298.0834	298.0851	298.0872	298.0896	298.0924	298.0956	298.0992	298.1032	298.1075	298.1123	298.1175	298.1232
3	298.238	298.2345	298.2396	298.2413	298.2441	298.2483	298.2542	298.2615	298.2702	298.2803	298.2917	298.3044	298.3184	298.3338	298.3506	298.3691	298.3893
4	297.26	297.257	297.263	297.266	297.269	297.273	297.278	297.283	297.289	297.296	297.303	297.312	297.321	297.331	297.342	297.355	297.368

- 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...



Lunar v2022.2 - test

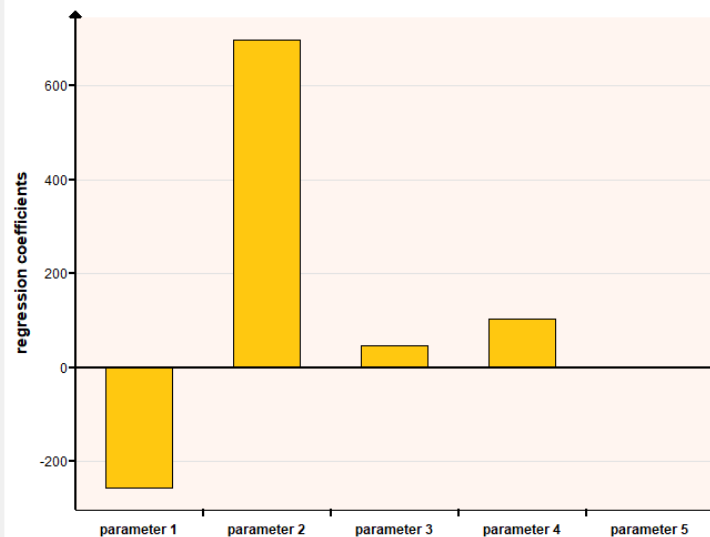
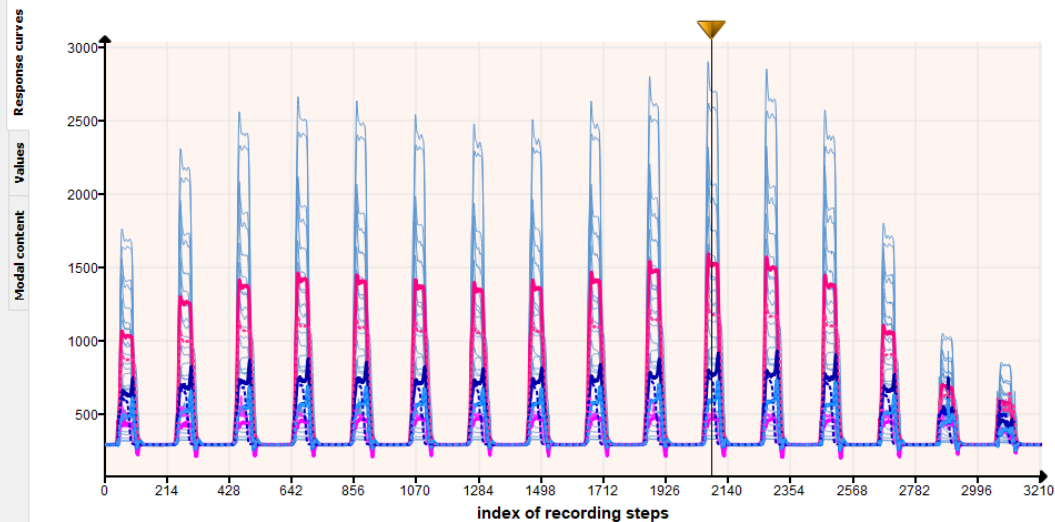
File Export Tools Preferences Help

1-Project 2-Data 3-Sensitivity 4-Interpolation 5-Optimization 6-Animation User script



### Sensitivity

Dataset\_1 Animation



Solver : POD (all modes) with ARBF

**Legend**

- New case #1
- New case #2
- New case #3
- New case #4
- imported curve #1
- imported curve #2
- imported curve #3
- imported curve #4

Display all curves Hide all curves  
Hide base curves Graph settings  
Import curves Clear imported curves

adjust parameter set generate range statistics parameters' effects

Base parameter set : Base case #1  
reset values  
Parameter to vary : parameter 1  
Number of samples : 2

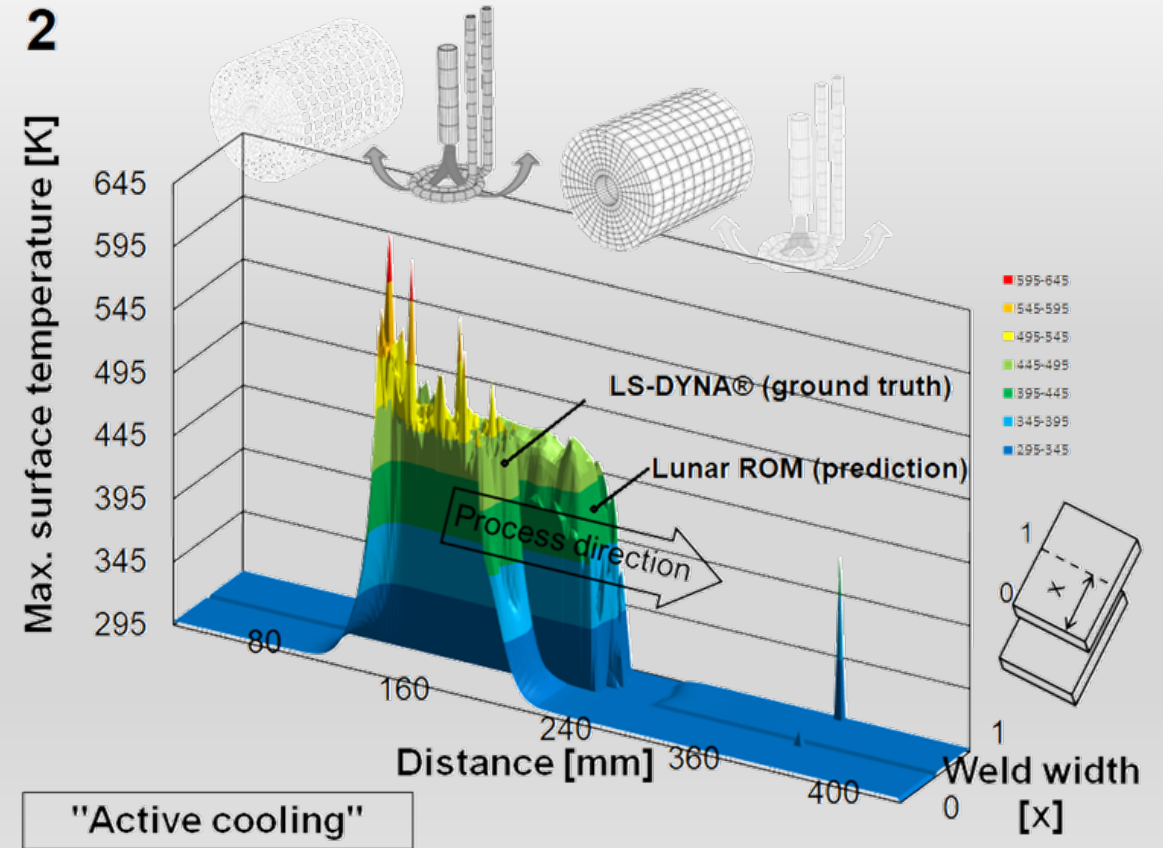
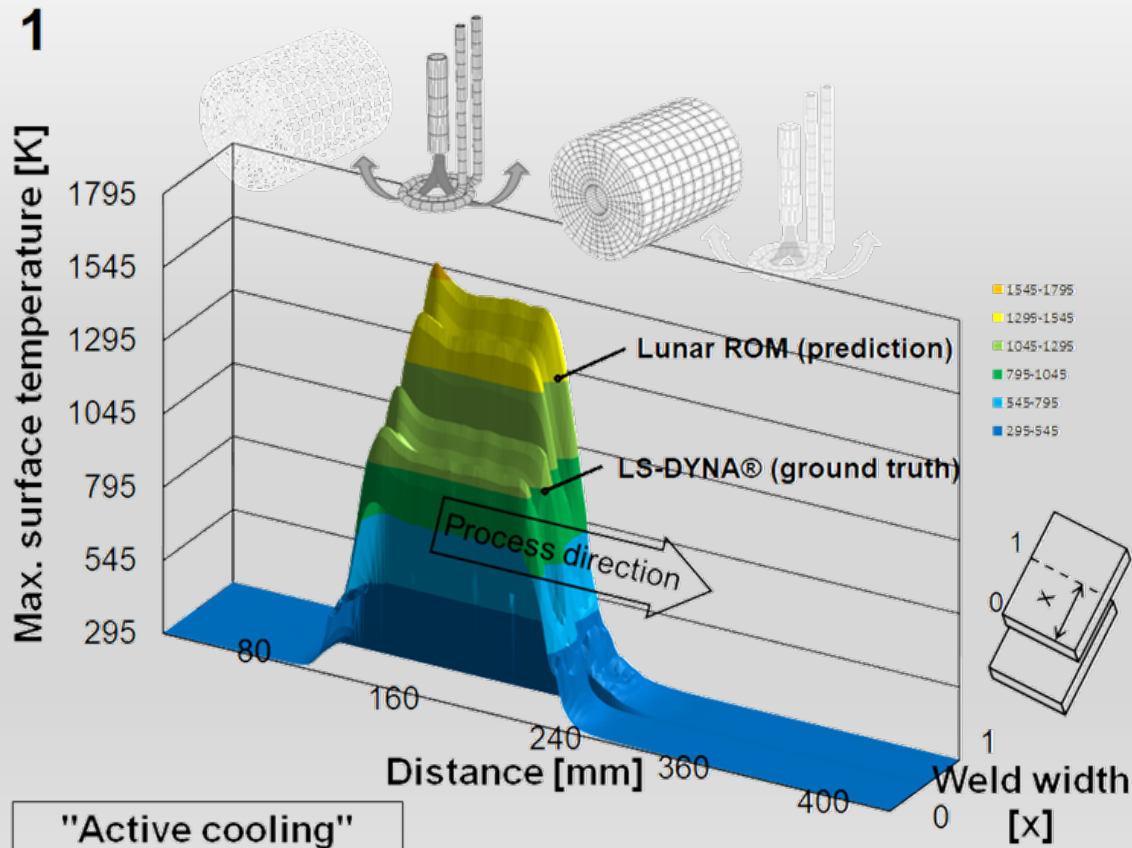
parameter 1: 0.198781 (range 0.1 to 0.5)  
parameter 2: 540.171 (range 70 to 700)  
parameter 3: 5765.15 (range 0 to 10000)  
parameter 4: 27273.6 (range 16000 to 30000)  
parameter 5: 4.33237 (range 0.03 to 10)

```
0.322657;417.989;7444.39;28985.7;2.4042
0.162956;121.102;289.862;22132;3.7006
0.349939;306.555;5000;23000;5.015
0.138008;121.669;3988.28;22284.4;6.39971
```

New XN set editor  
Import Clear Save as Run

Parameter	Val. Set 1
Welding speed (m/min)	0.322657
Power (current amplitude) (A)	417.989
Top surface cooling rate (W/m <sup>2</sup> K)	7444.39
Laminate in-plane electrical conductivity, K1/K2 (combined) (S/m)	28985.7
Laminate through thickness electrical conductivity, K3 (S/m)	2.4042

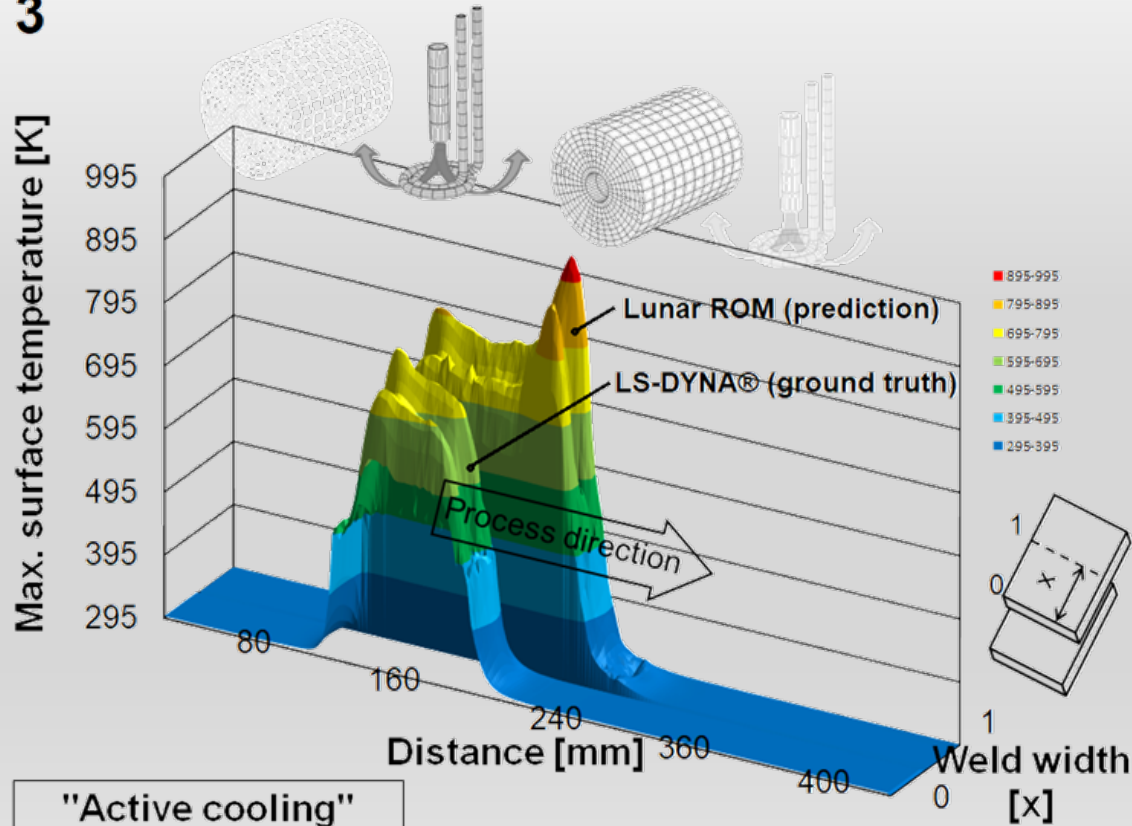
Parameter	Val. Set 2
Welding speed (m/min)	0.162956
Power (current amplitude) (A)	121.102
Top surface cooling rate (W/m <sup>2</sup> K)	289.862
Laminate in-plane electrical conductivity, K1/K2 (combined) (S/m)	22132
Laminate through thickness electrical conductivity, K3 (S/m)	3.7006



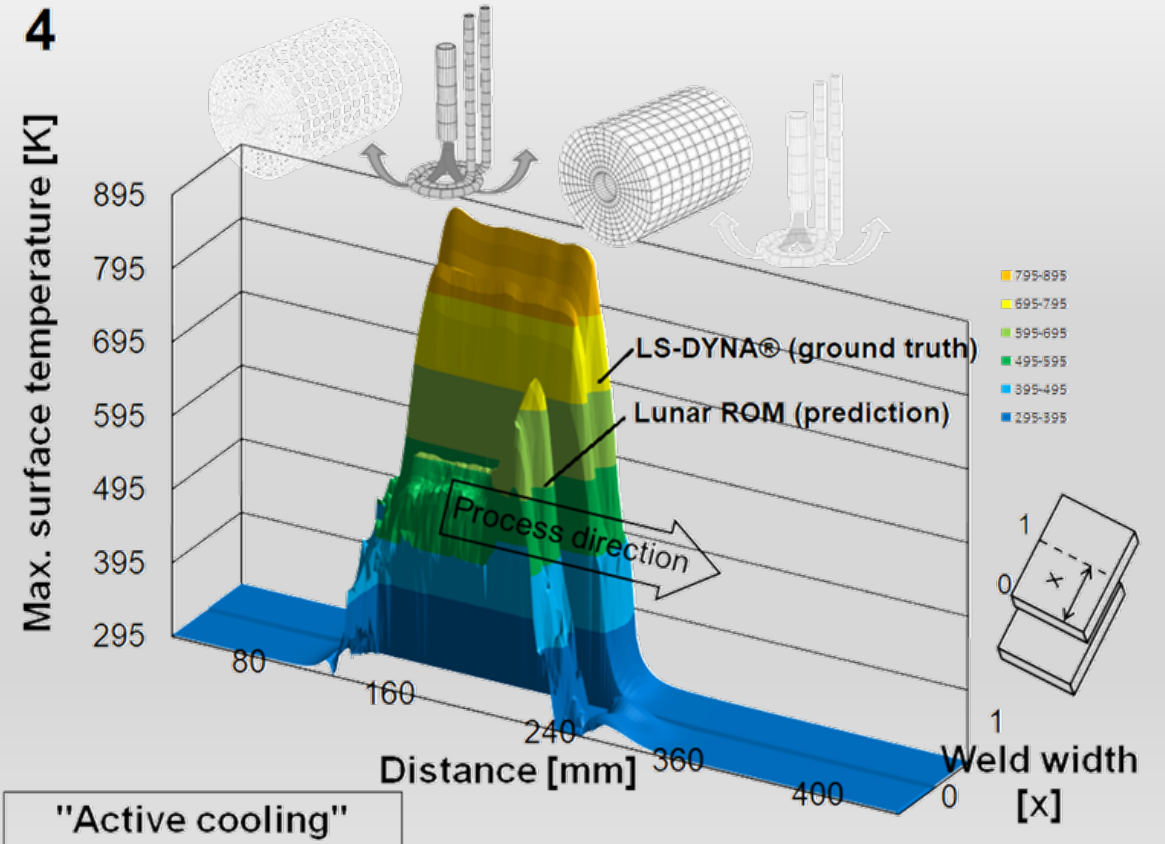
Parameter	Val. Set 3
Welding speed (m/min)	0.349939
Power (current amplitude) (A)	306.555
Top surface cooling rate (W/m <sup>2</sup> K)	5000
Laminate in-plane electrical conductivity, K1/K2 (combined) (S/m)	23000
Laminate through thickness electrical conductivity, K3 (S/m)	5.015

Parameter	Val. Set 4
Welding speed (m/min)	0.138008
Power (current amplitude) (A)	121.669
Top surface cooling rate (W/m <sup>2</sup> K)	3988.28
Laminate in-plane electrical conductivity, K1/K2 (combined) (S/m)	22284.4
Laminate through thickness electrical conductivity, K3 (S/m)	6.39971

3



4

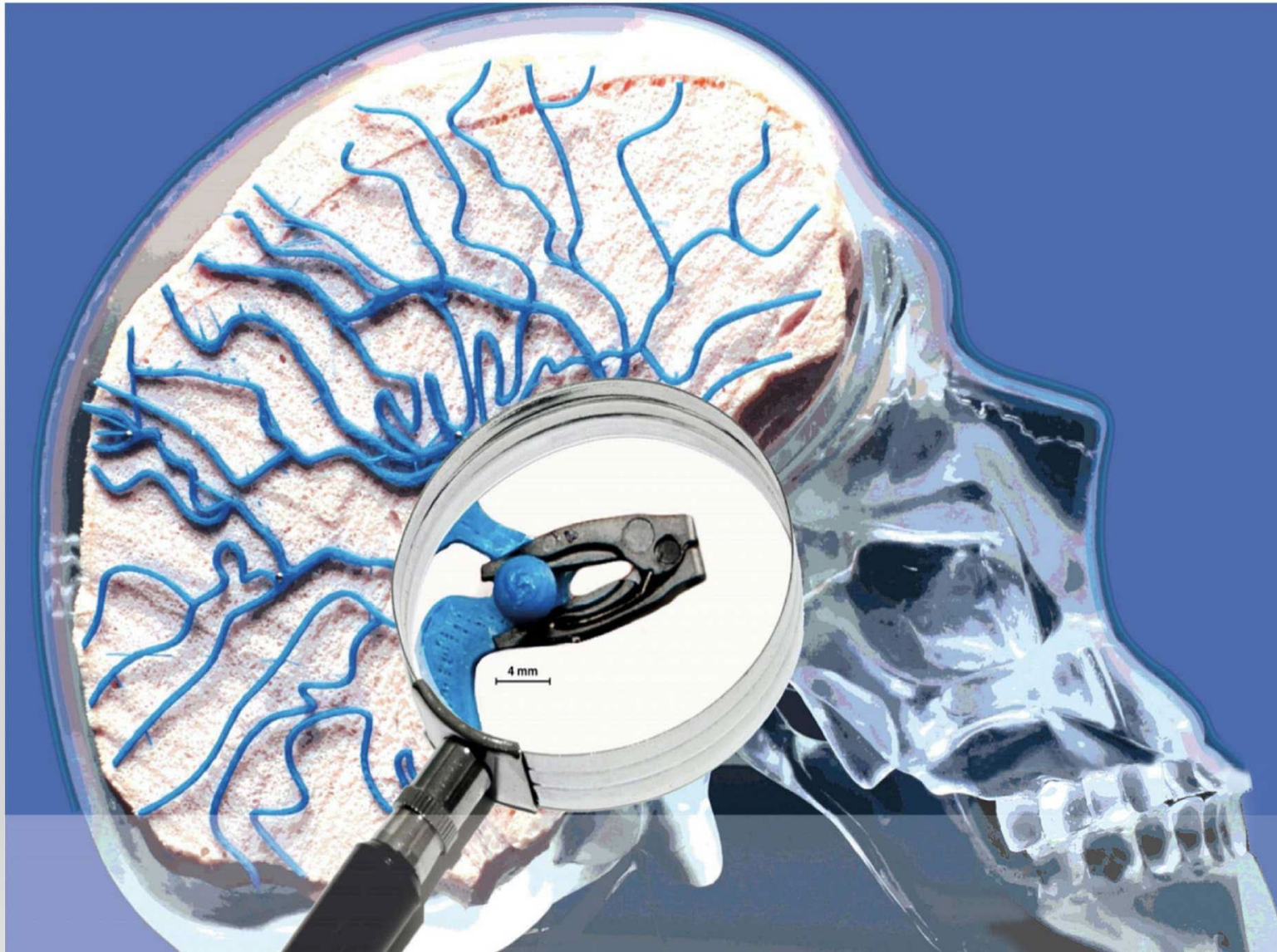


- The process of continuous induction welding has been modeled using advanced 3D finite element modelling techniques
- Temperature profiles at the bonding interface for different processing conditions can be examined and optimized to ensure they remain within material processing limits, however full 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

## DYNAmore

- Nikolay Lazarov
- Steffen Frik

## MSC Software



## Contact details:

Miro Duhovic

[miro.duhovic@ivw.uni-kl.de](mailto:miro.duhovic@ivw.uni-kl.de)

[www.ivw.uni-kl.de](http://www.ivw.uni-kl.de)

Tel: +49 (0) 631 2017-363

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Composite Aneurysm Clip

Photo: Thorsten Becker & Sylvain Fotouk Foiso

www.thefutureiscomposite.com