Simulation of Thermoplastic Composite Induction Welding

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Introduction: Working Principle of Induction Welding

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

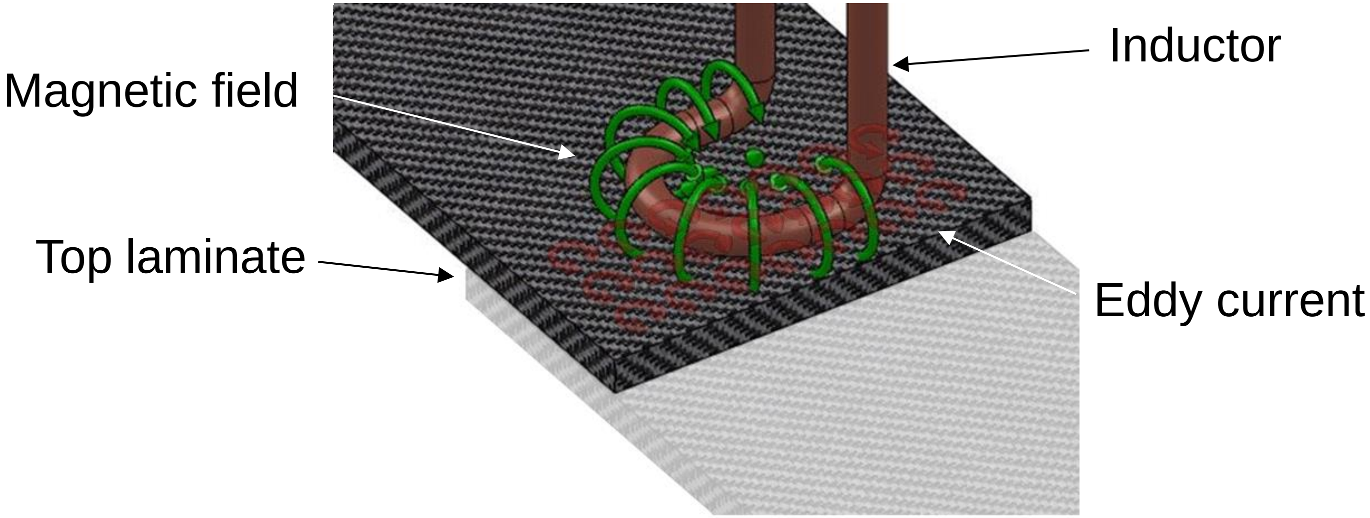

Image courtesy of Mrs. Mirja Didi
IVW GmbH

Mass production of “composite” automotive assemblies

- Development of the ability to join **thermoplastic carbon/glass fibre composite parts** to themselves and existing/future metal alloys
  - In the case of **composite – composite** we need conductive fibres (e.g. carbon) or matrix additives (e.g. conductive particles/fillers)
  - In the case of **metal – composite** conductivity of the metal part can be utilized

BMW‘s i3 carbon fiber composite passenger cell
(Image courtesy of auto-motor-und-sport.de)

BMW M-series front bumper
(Image courtesy of Jacob Composites GmbH)

What is Continuous Induction Welding of Thermoplastic Composites?

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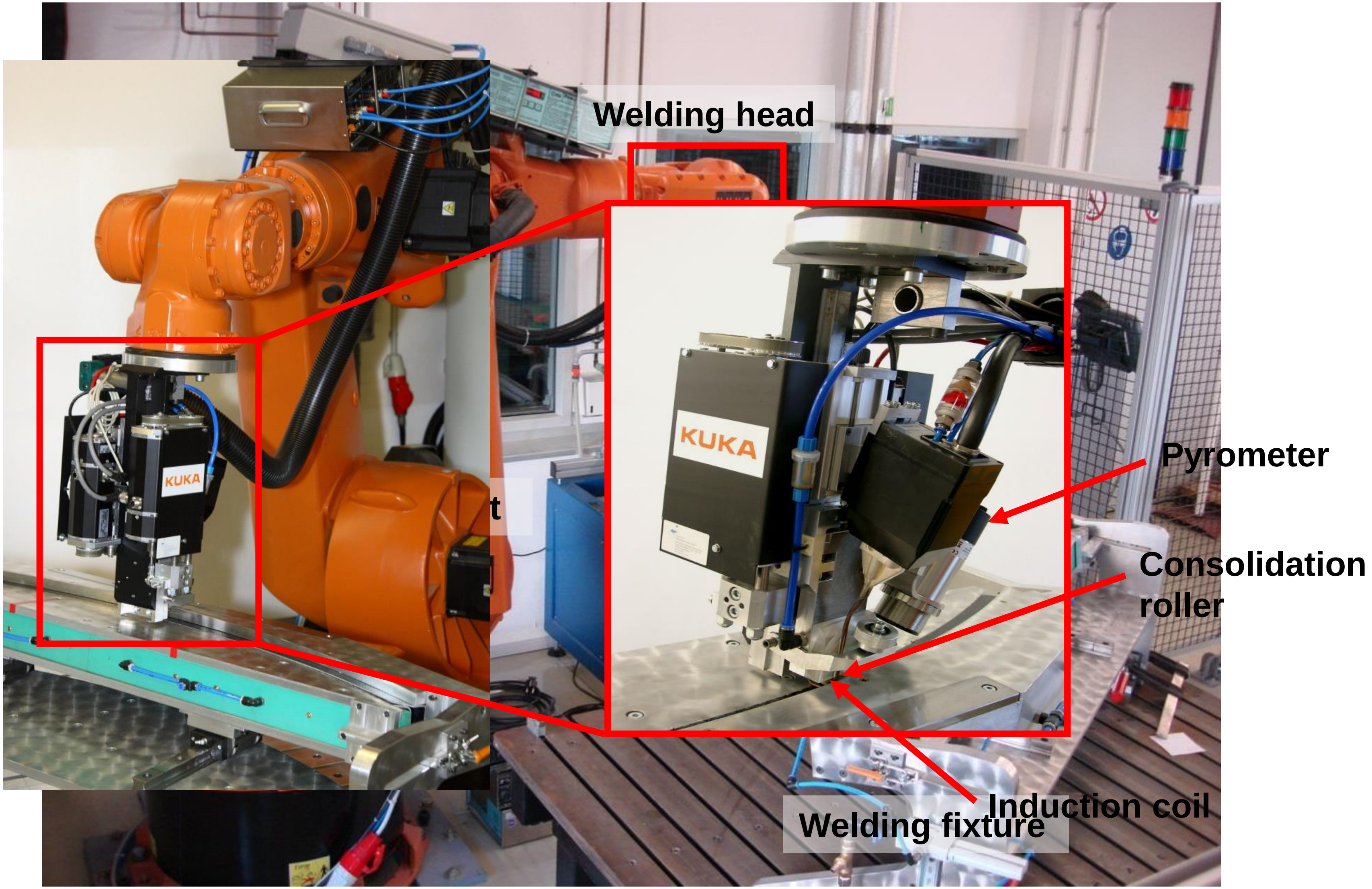

What is Continuous Induction Welding of Thermoplastic Composites?

Experimental Equipment at IVW

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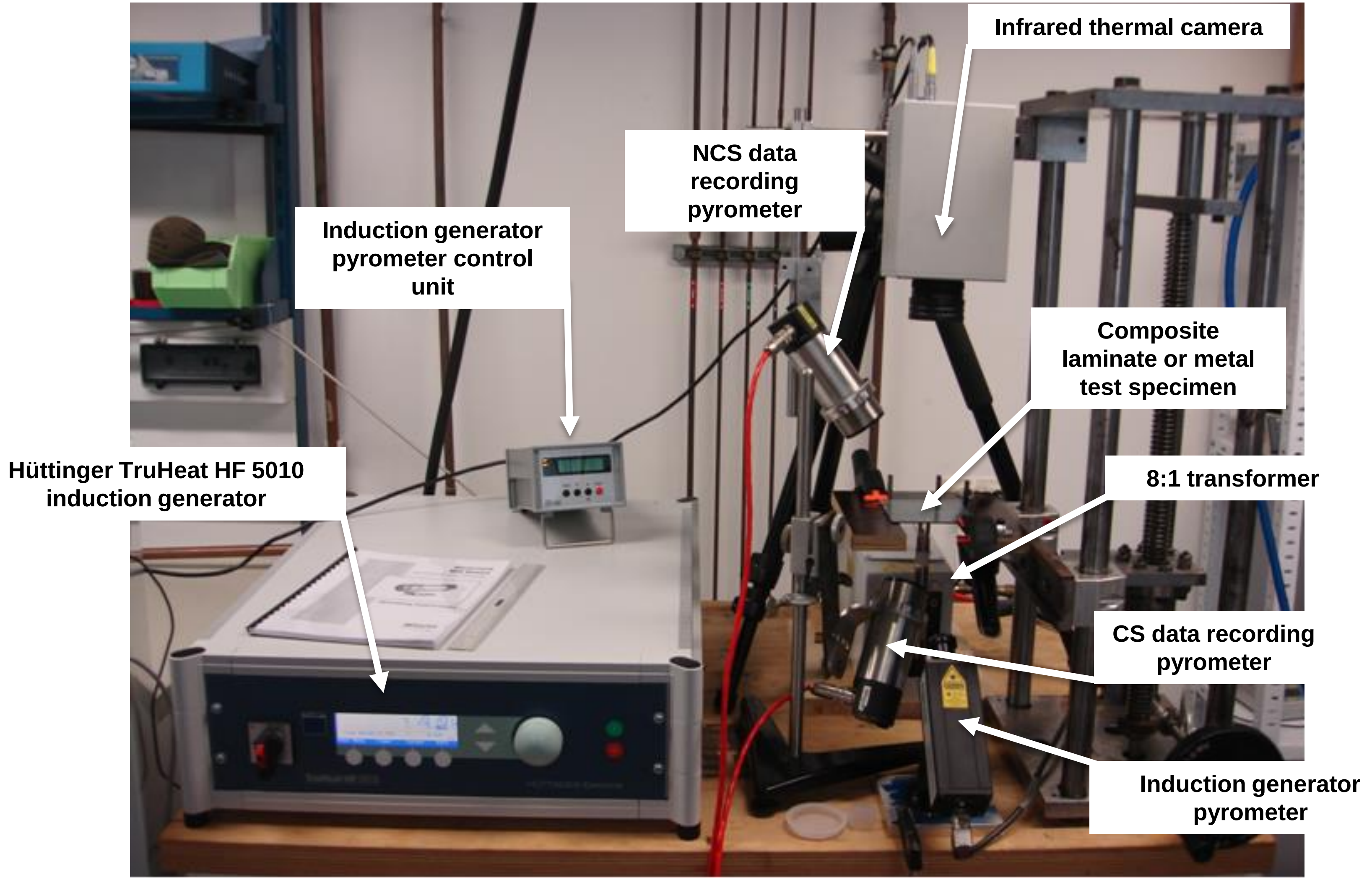
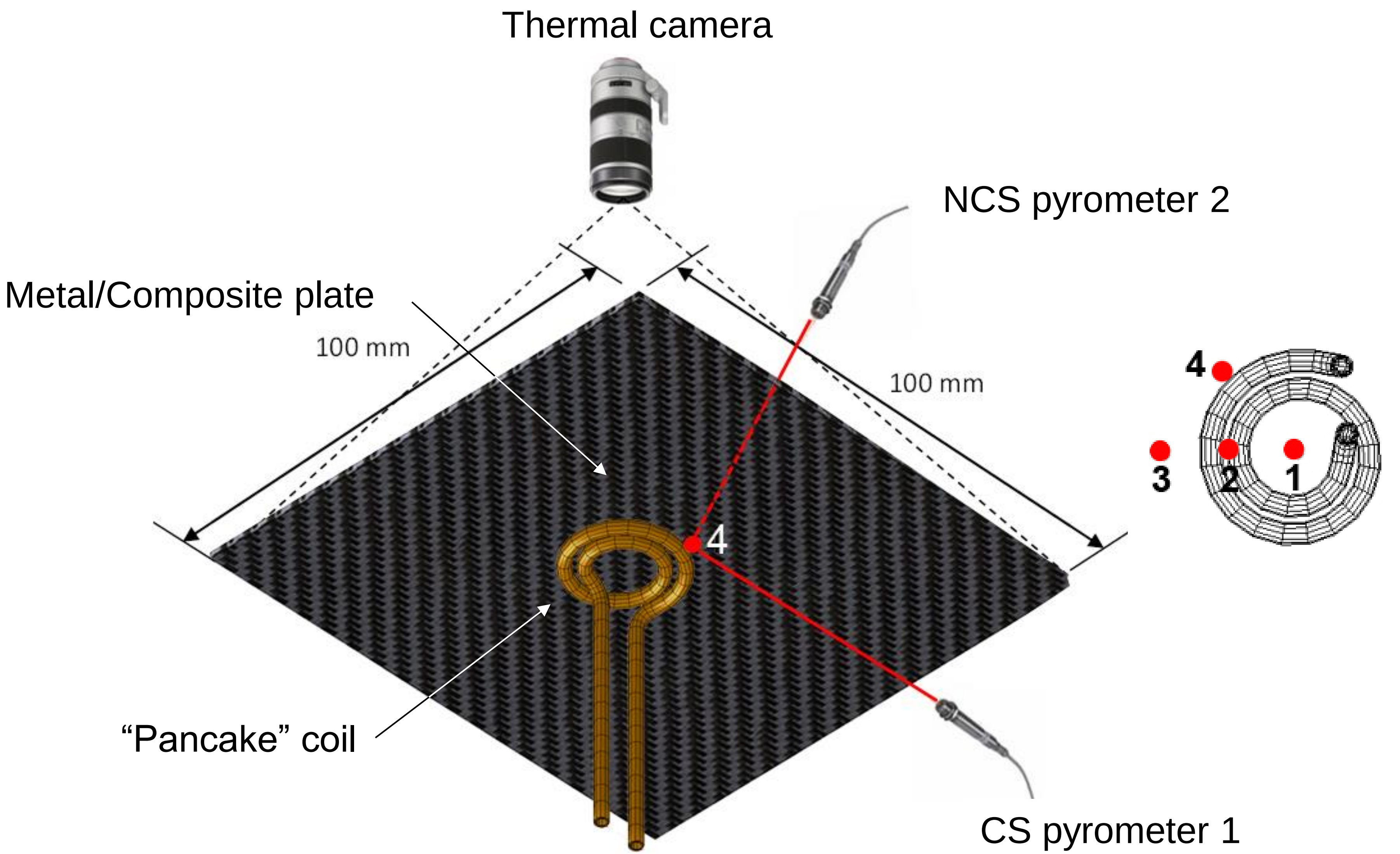
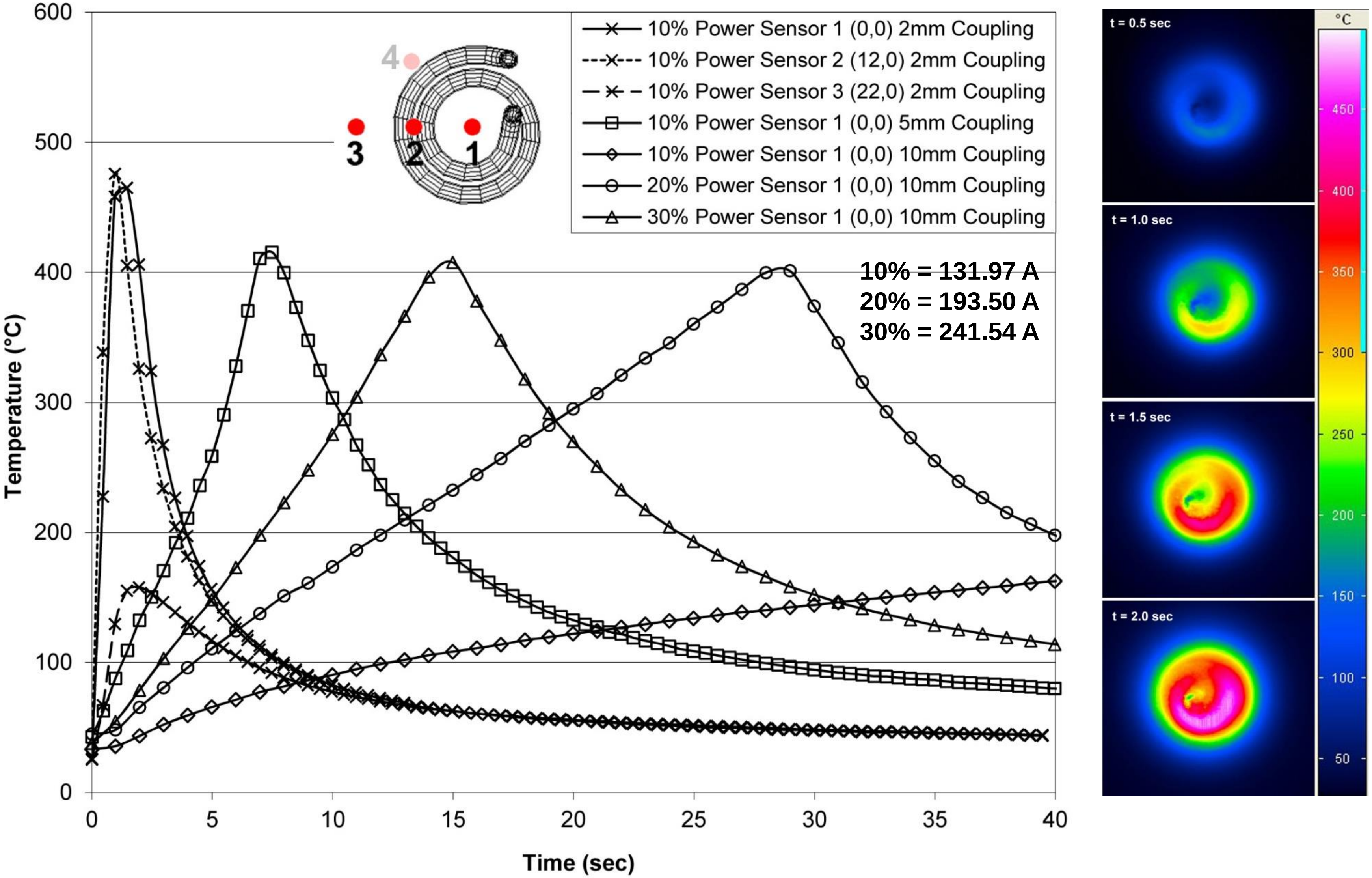


Material Characterization:
Metal and Composite Plate Specimens



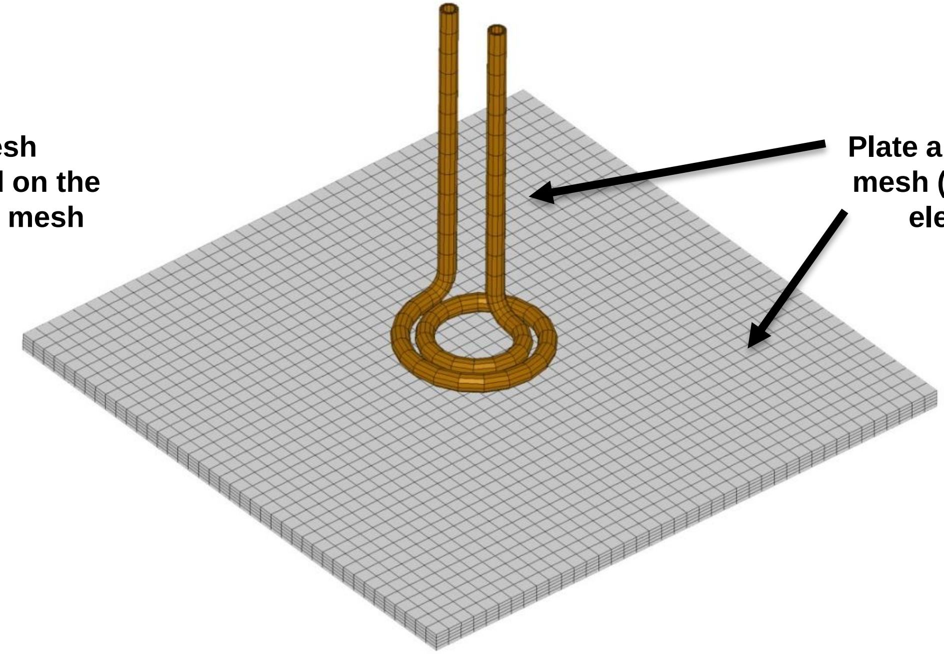
Material Characterization:
0.8 mm Thick Structural Steel Plate (400kHz)



Finite Element Models: LS-DYNA® R7 Induction Heating Solver

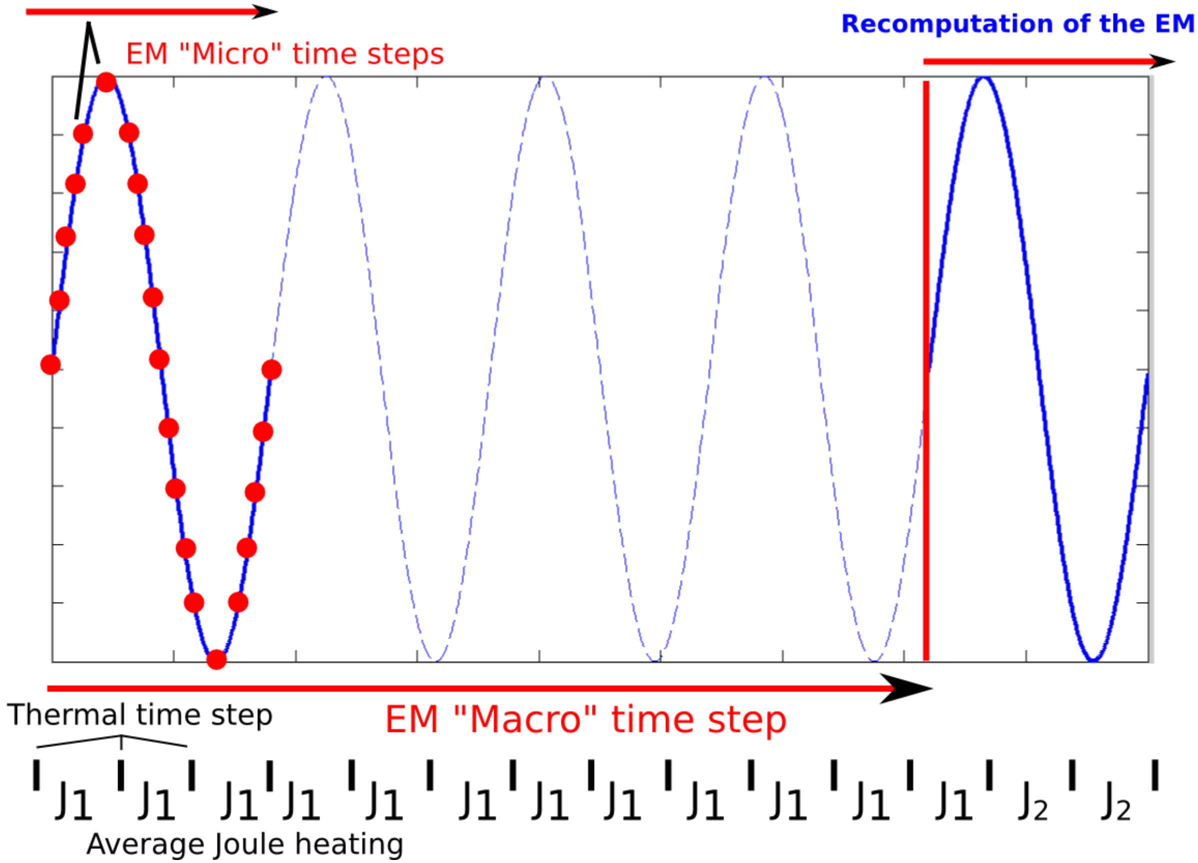
Solves Maxwell's equations in the Eddy current (induction-diffusion approximation)

- Is **fully coupled** with the **structural and thermal** mechanics solvers (Lorentz forces, Ohmic heating) and now even **fluid dynamics!**
- Uses a combination of FEM (conductors e.g. coil, workpiece) and BEM (insulators e.g. air, insulators) methods, **no air mesh is necessary**



Finite Element Models: LS-DYNA® R7 Induction Heating Solver

- Assumes a **rapidly oscillating current** compared to the total process time
- Eddy current problem solved over **two periods** with a “micro” EM time step
- **Average** of EM field used for calculations within the “macro” EM time step



Finite Element Models: Material Properties

Material Property	Air	Coil (Copper)	Steel Plate (0.9% Carbon Structural Steel)	Composite Plate (CF/PEEK)
Density, ρ (kg/m^3)	1.293 (1.217)	8960	7850	1790
Heat Capacity at (const. pressure), Cp [J/(kg*K)]	1010 (1006)	385	475 **Cp vs. T curve**	1803 **Cp vs. T curve**
Thermal Conductivity, k (W/m*K) k_1	0.026 (0.025)	390	44.5 **k vs. T curve**	2.50
Thermal Conductivity, k (W/m*K) k_2	-	-	-	2.50
Thermal Conductivity, k (W/m*K) k_3	-	-	-	0.32
Electrical Conductivity, σ (S/m)	1	5.998×10^7	1.032×10^6 **σ vs. T curve**	1.389×10^4 **σ vs. T curve**
Relative Permittivity, ε_r	1	1	1	3.7
Relative Permeability, μ_r	1	1	150 **B vs. H curve** **μ_r vs. T curve**	1
Surface Emissivity	-	0.5	(0.95)	(0.95)
Skin Depth (mm) (automatically calculated)	-	~ 0.1	~ 0.8	~ 3.5

A Lot of Parameters!

Simulation Results Static Heating: 0.8 mm Thick Structural Steel Plate (400kHz)

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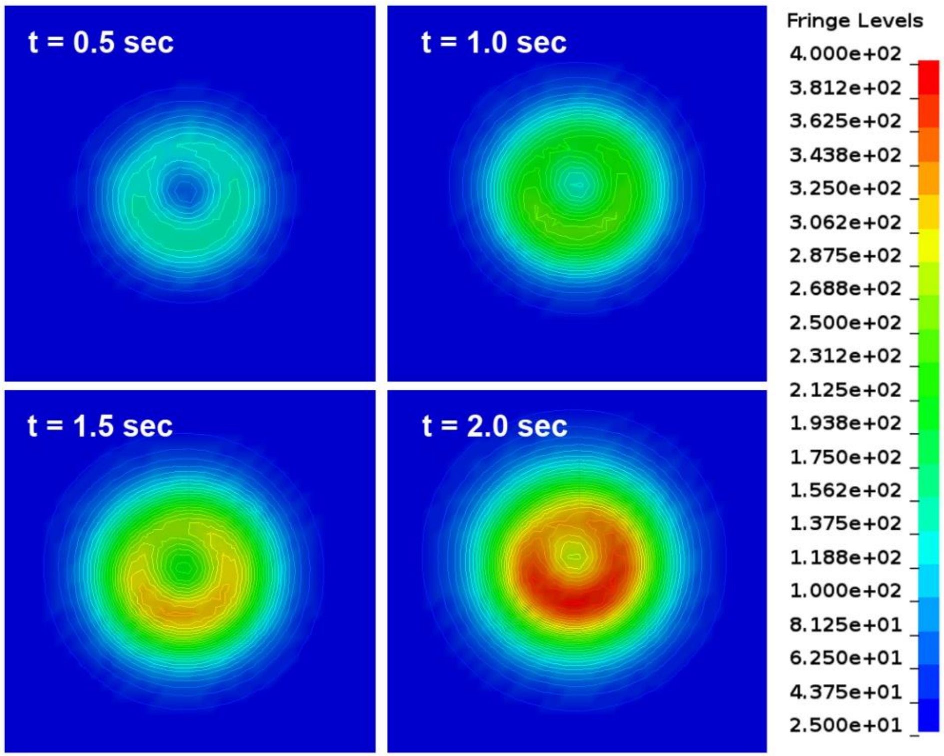

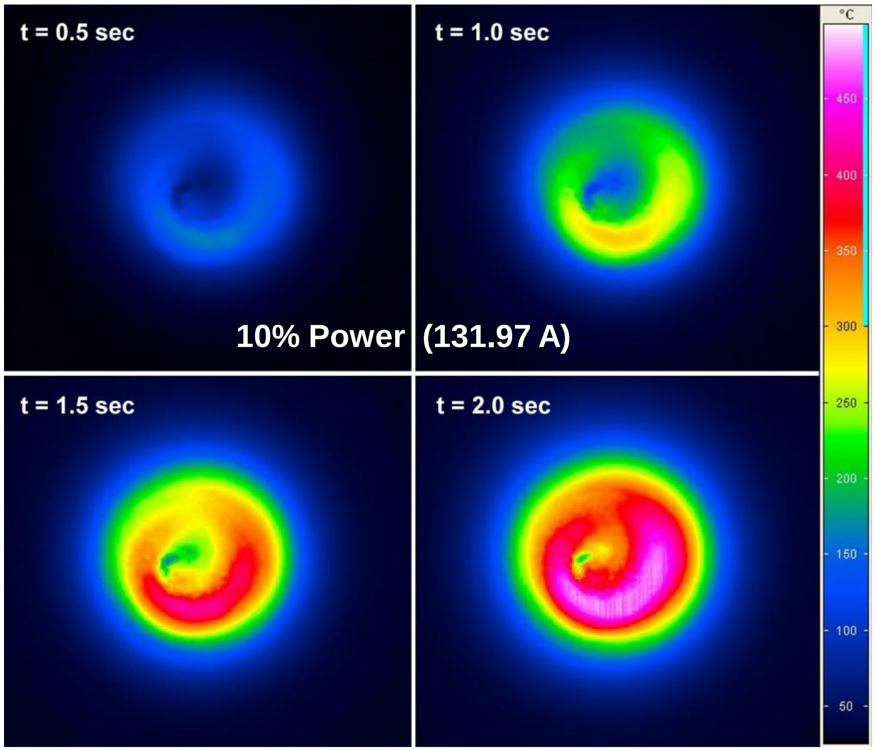

LS-DYNA

Max temperatures @ t = 0.5 sec = 150°C
t = 1.0 sec = 263°C
t = 1.5 sec = 343°C
t = 2.0 sec = 400°C

Experiment

Max temperatures @ t = 0.5 sec = 145±5°C
t = 1.0 sec = 267±5°C
t = 1.5 sec = 399±3°C
t = 2.0 sec = 482±1°C

Simulation Results Static Heating: 0.8 mm Thick Structural Steel Plate (400kHz)

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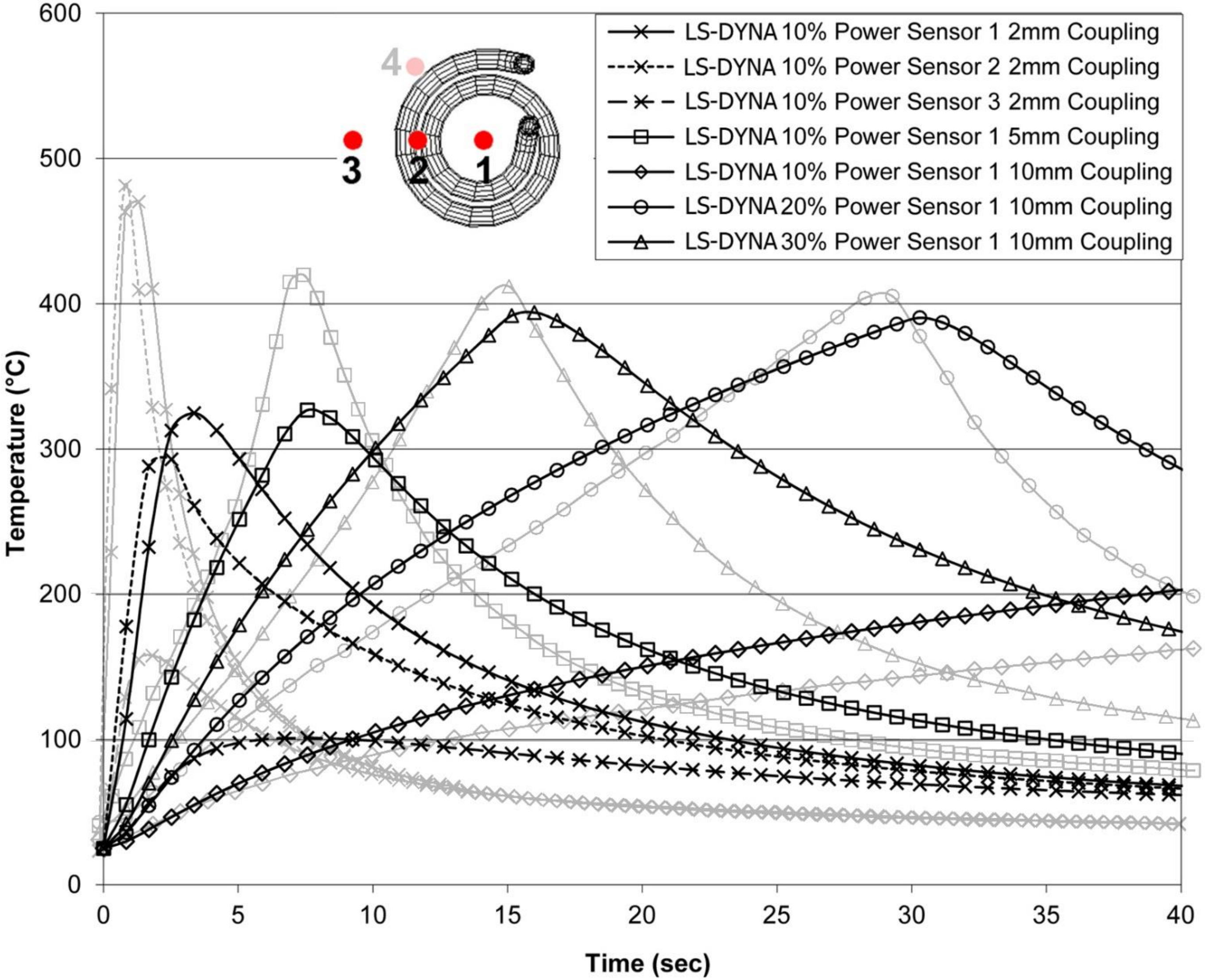
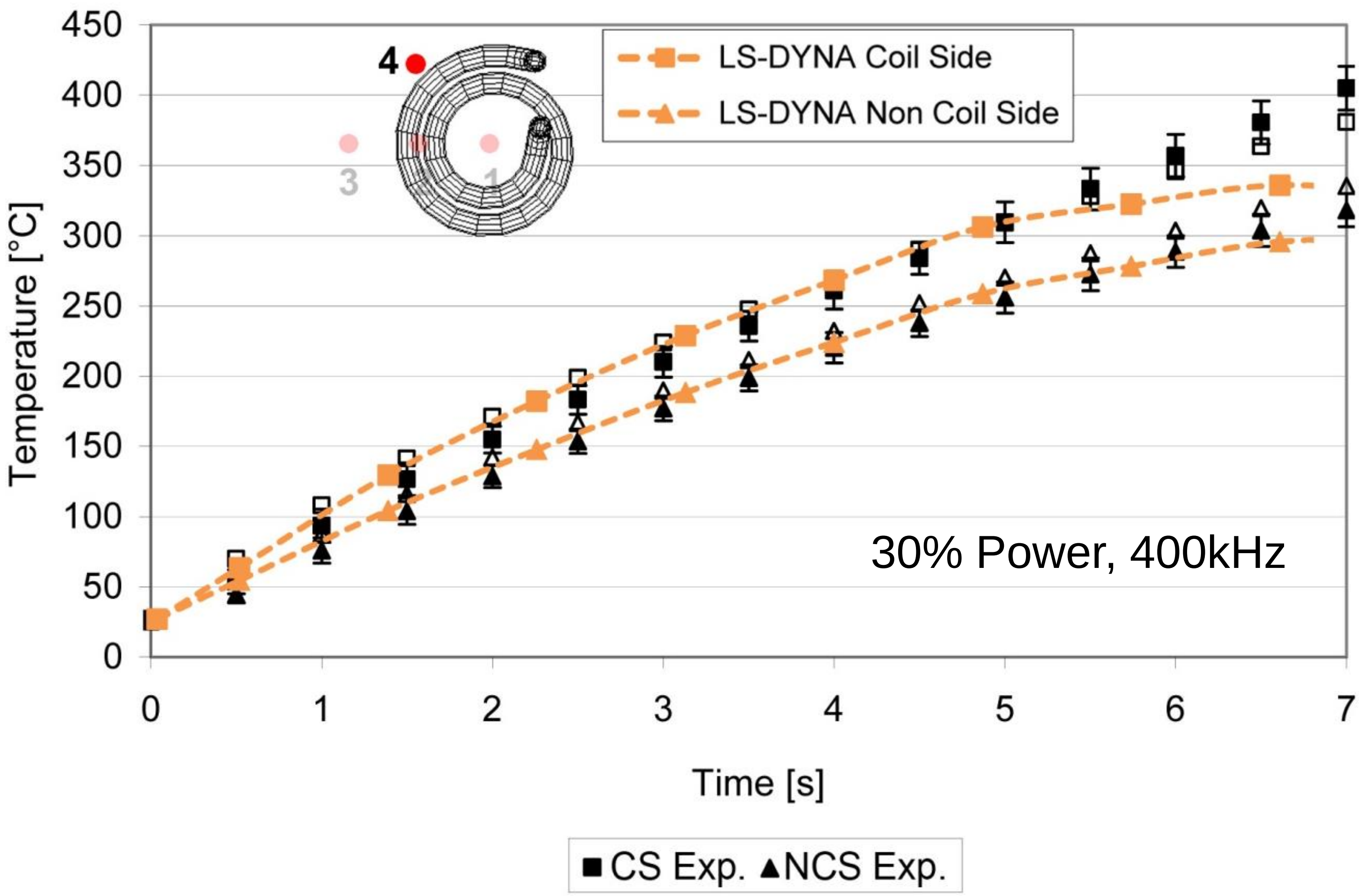


Simulation Results Static Heating: 2.0 mm Thick CF/PEEK Composite Plate



Simulation Results Actual Induction Welding Scenario: Test-Bed Model Setup

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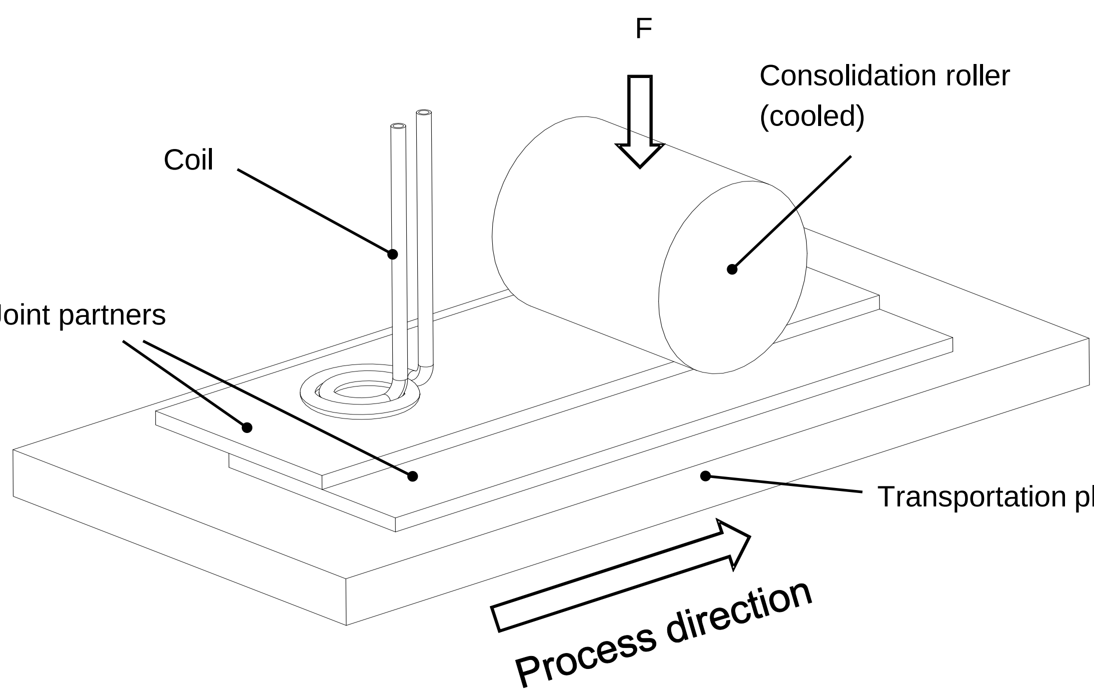
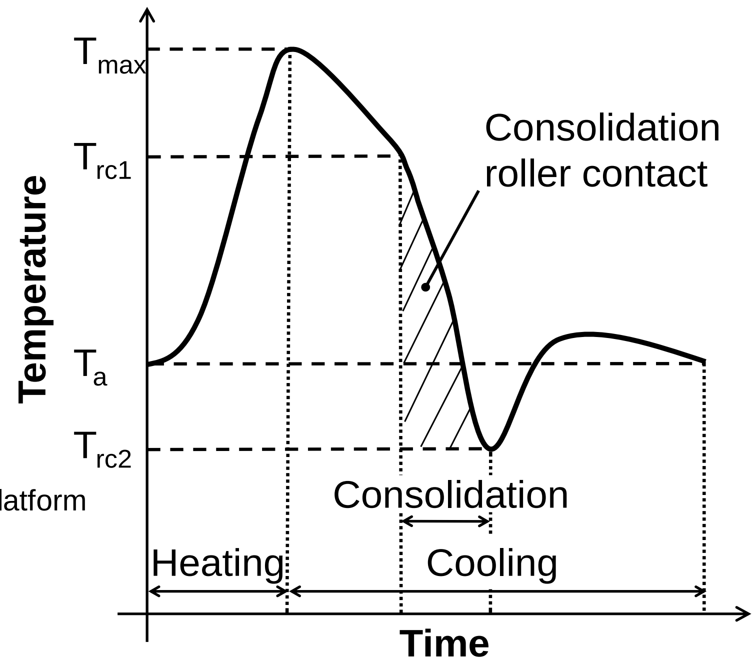
Roller Force= 300 N

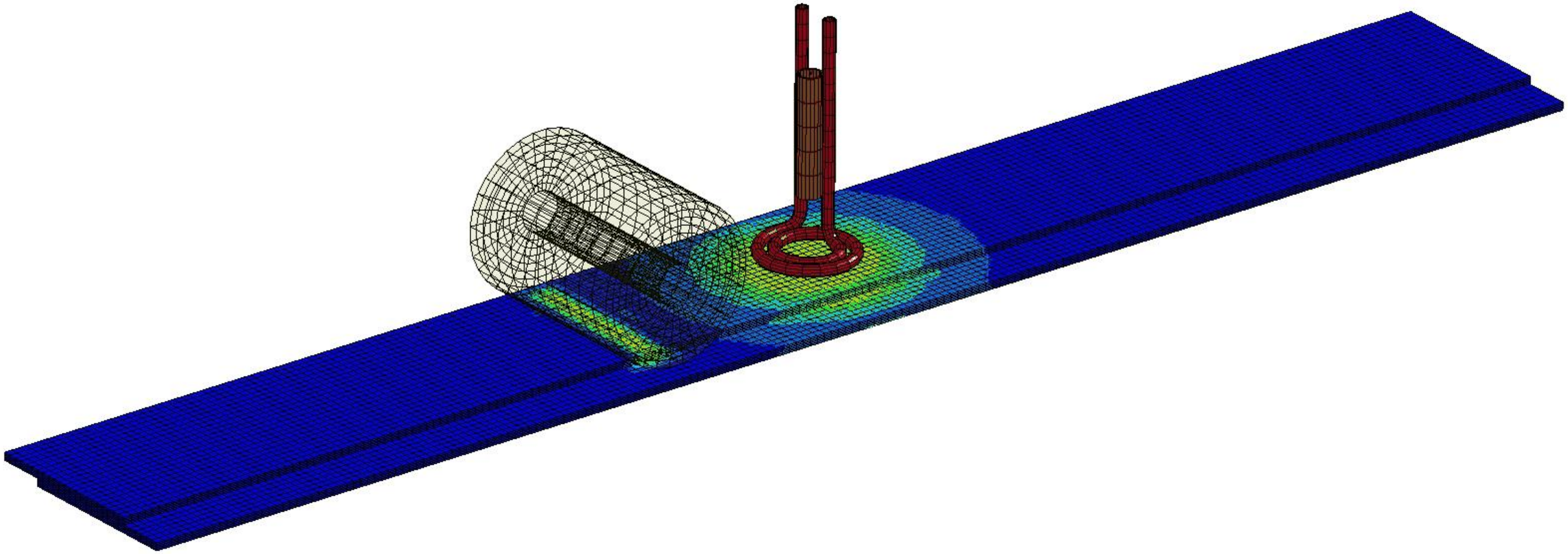




Processing Speed = 3 mm/sec known to give excellent welding results but why? Plus we would like to speed things up!

Simulation Results Actual Induction Welding Scenario: Test-Bed Model Setup

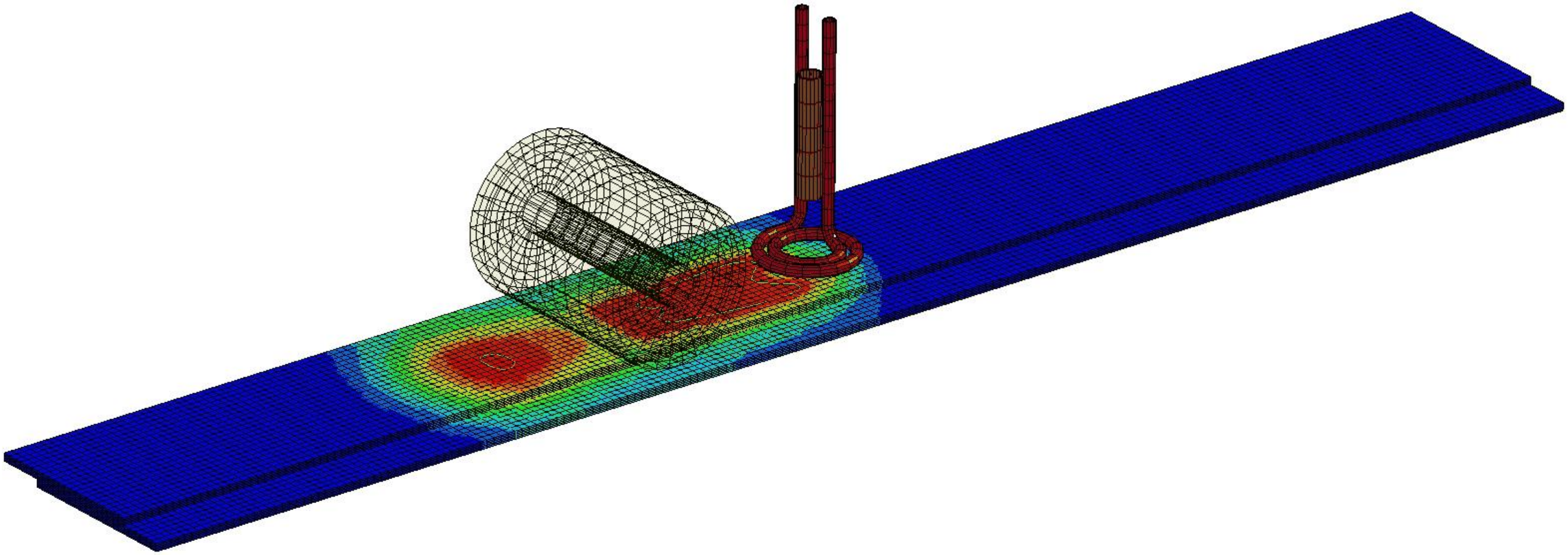
- Rolling contact (with prescribed z-direction load, friction and heat transfer)
- Moving air jet pressure (*LOAD_MOVING_PRESSURE)



Stresses

Simulation Results Actual Induction Welding Scenario: Test-Bed Model Setup

- Moving coil with updated electromagnetic fields and joule heating effect
- Moving air jet convection heat flux (*DEFINE_FUNCTION)



Temperatures

Simulation Results Actual Induction Welding Scenario: Test-Bed Model Setup

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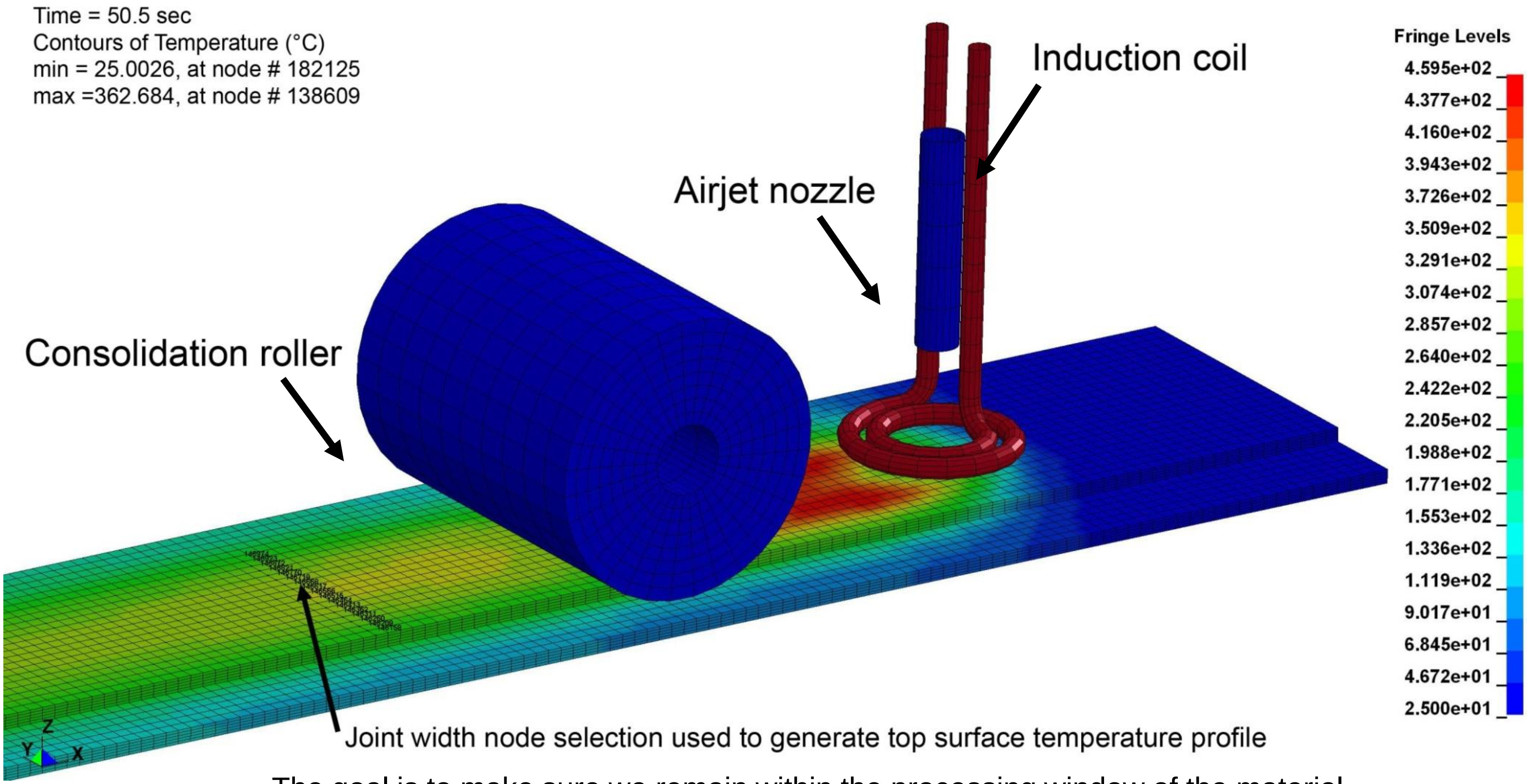
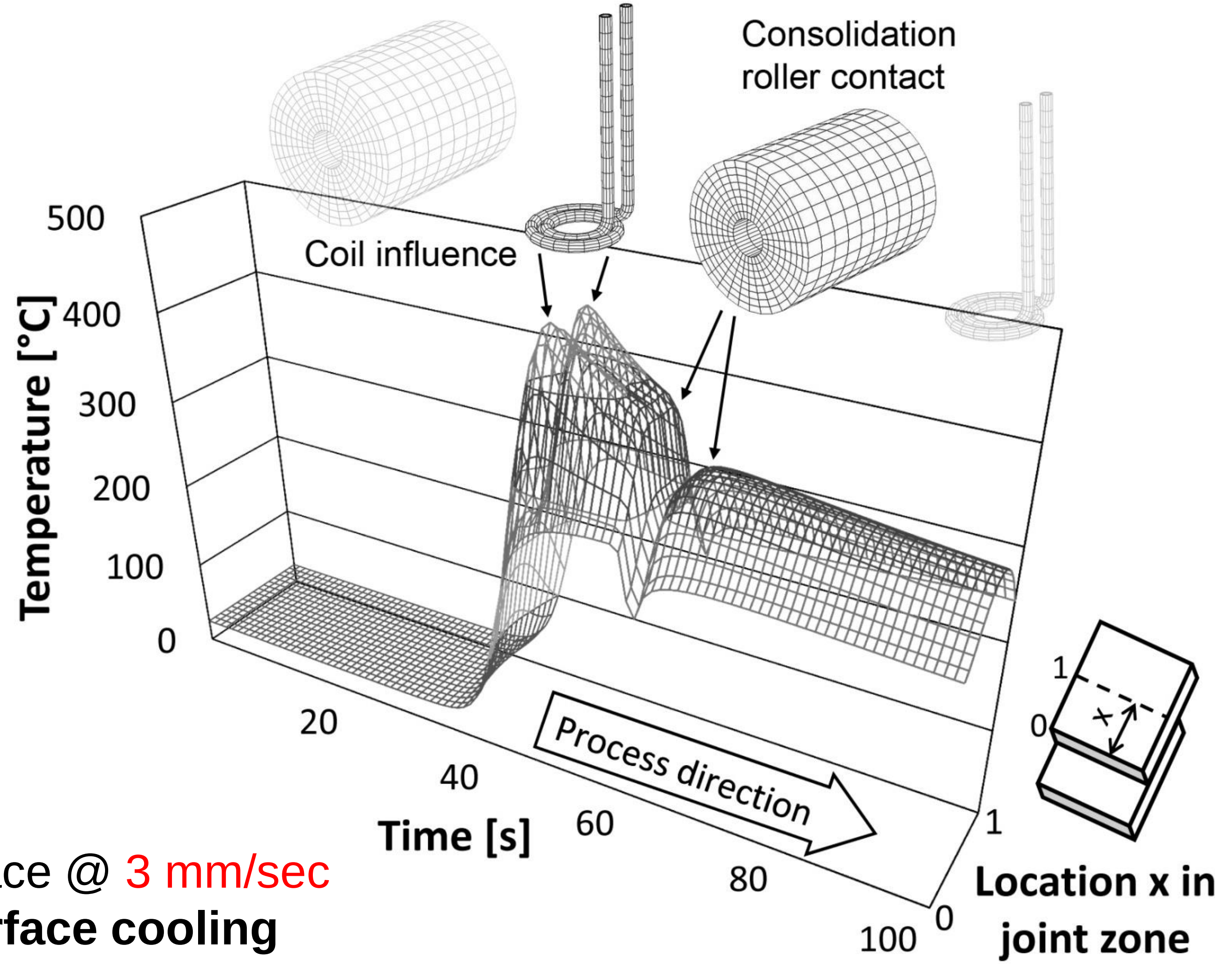
We can now examine temperature profiles at any location!



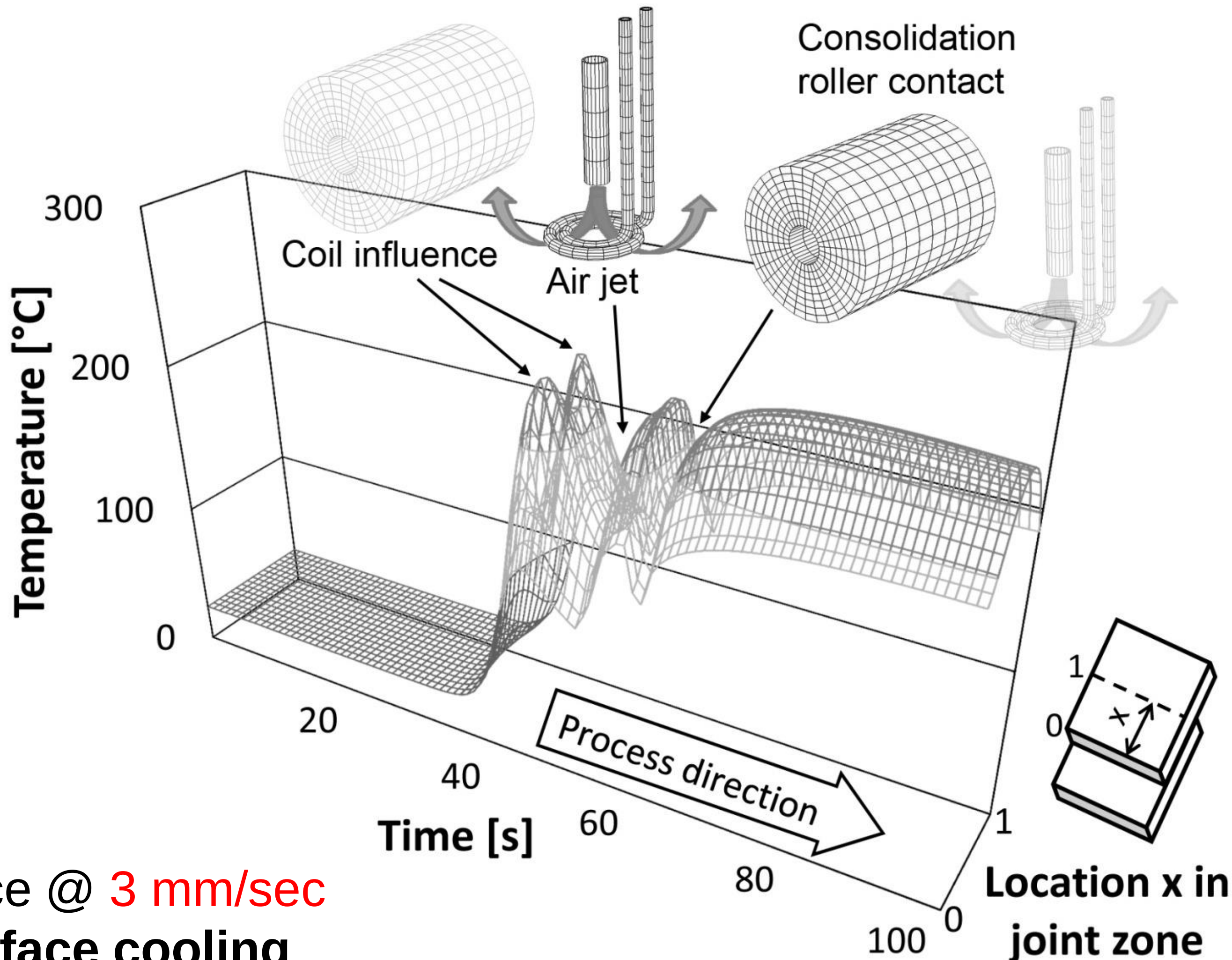
The goal is to make sure we remain within the processing window of the material so that the top surface doesn't burn and the bond surface is hot enough for joining

Simulation Results Actual Induction Welding Scenario: Surface Temperature Plots



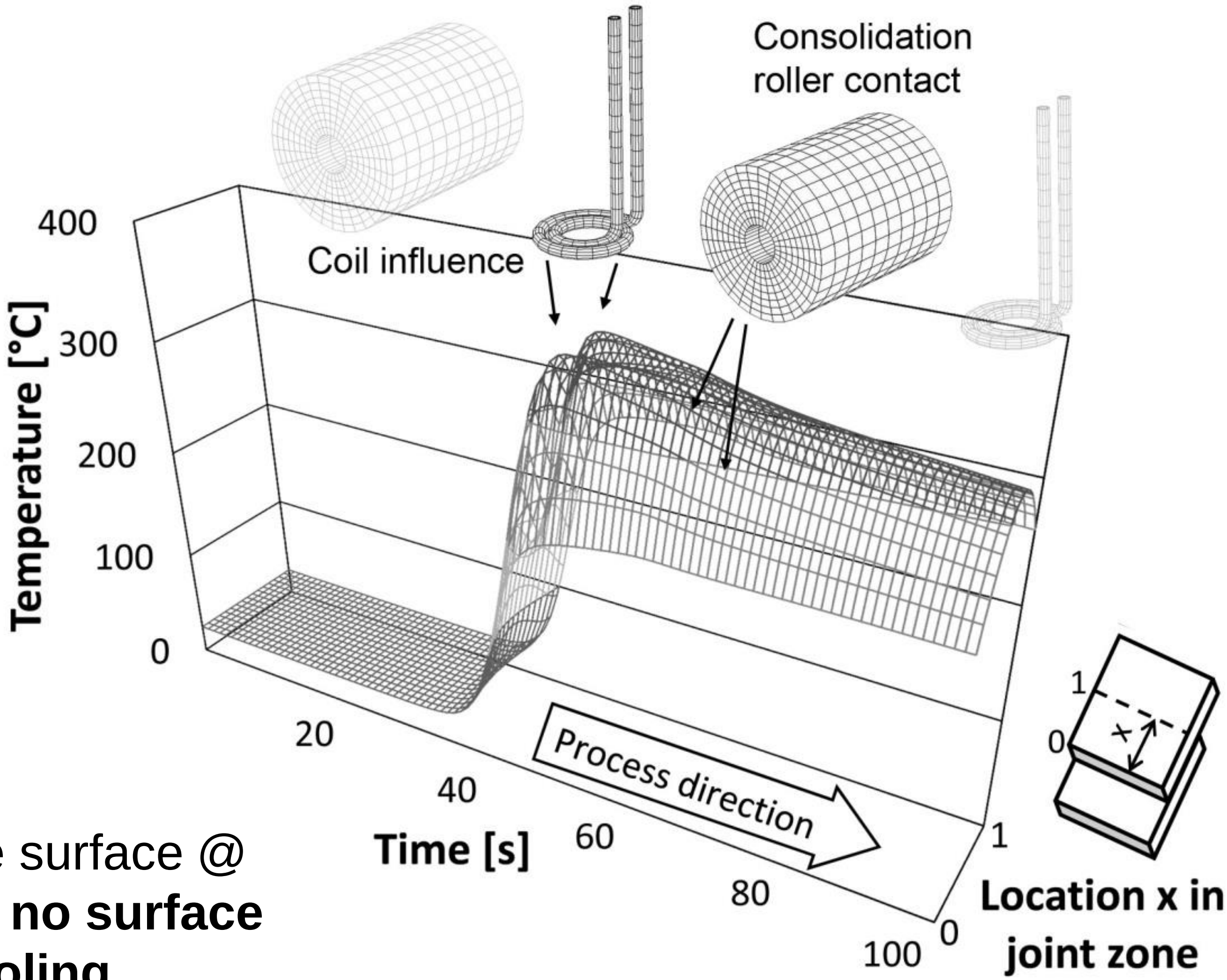
Top surface @ 3 mm/sec
no surface cooling

Simulation Results Actual Induction Welding Scenario: Surface Temperature Plots



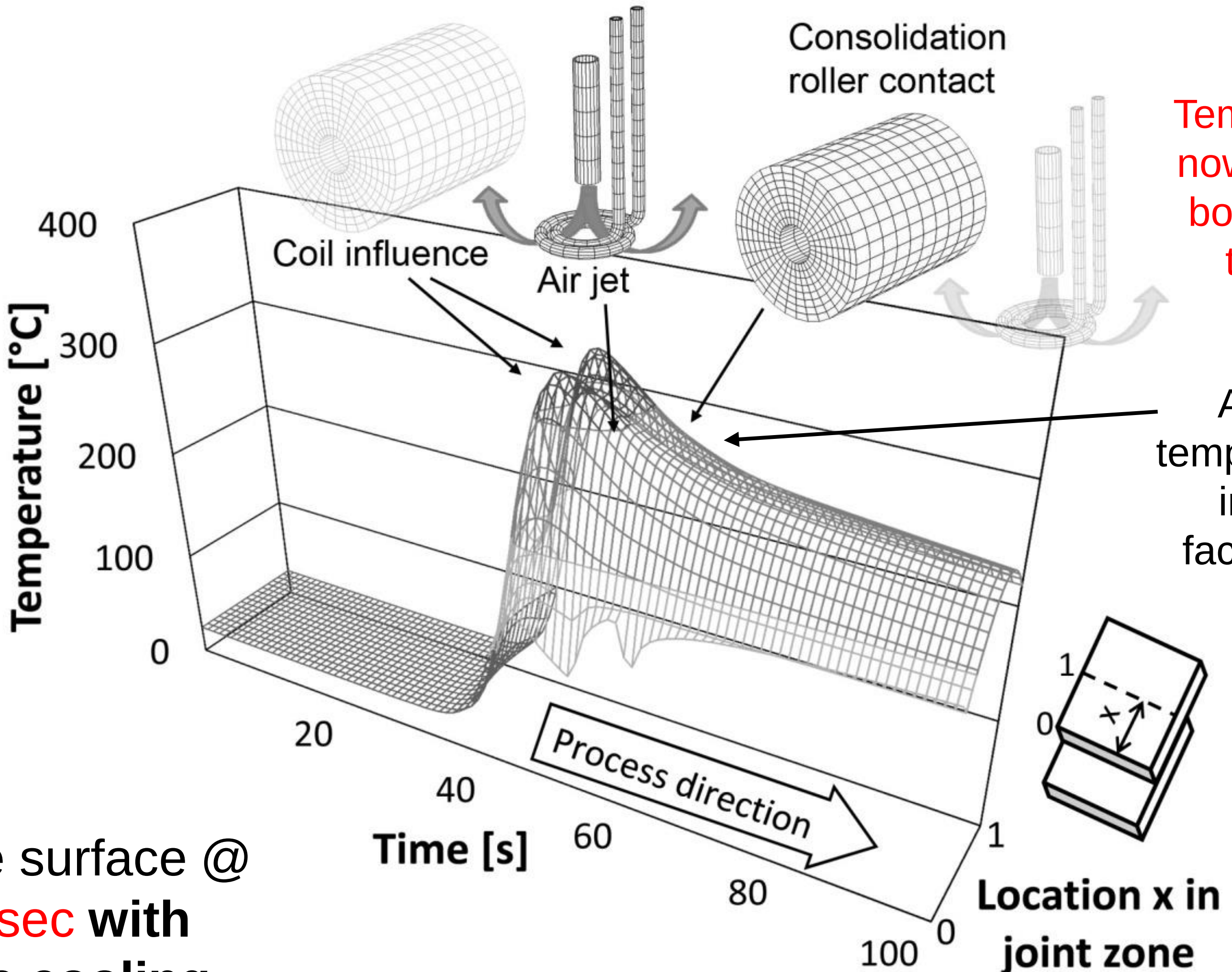
Top surface @ 3 mm/sec
with surface cooling

Simulation Results Actual Induction Welding Scenario: Surface Temperature Plots



Bond line surface @ 3 mm/sec **no surface cooling**

Simulation Results Actual Induction Welding Scenario: Surface Temperature Plots

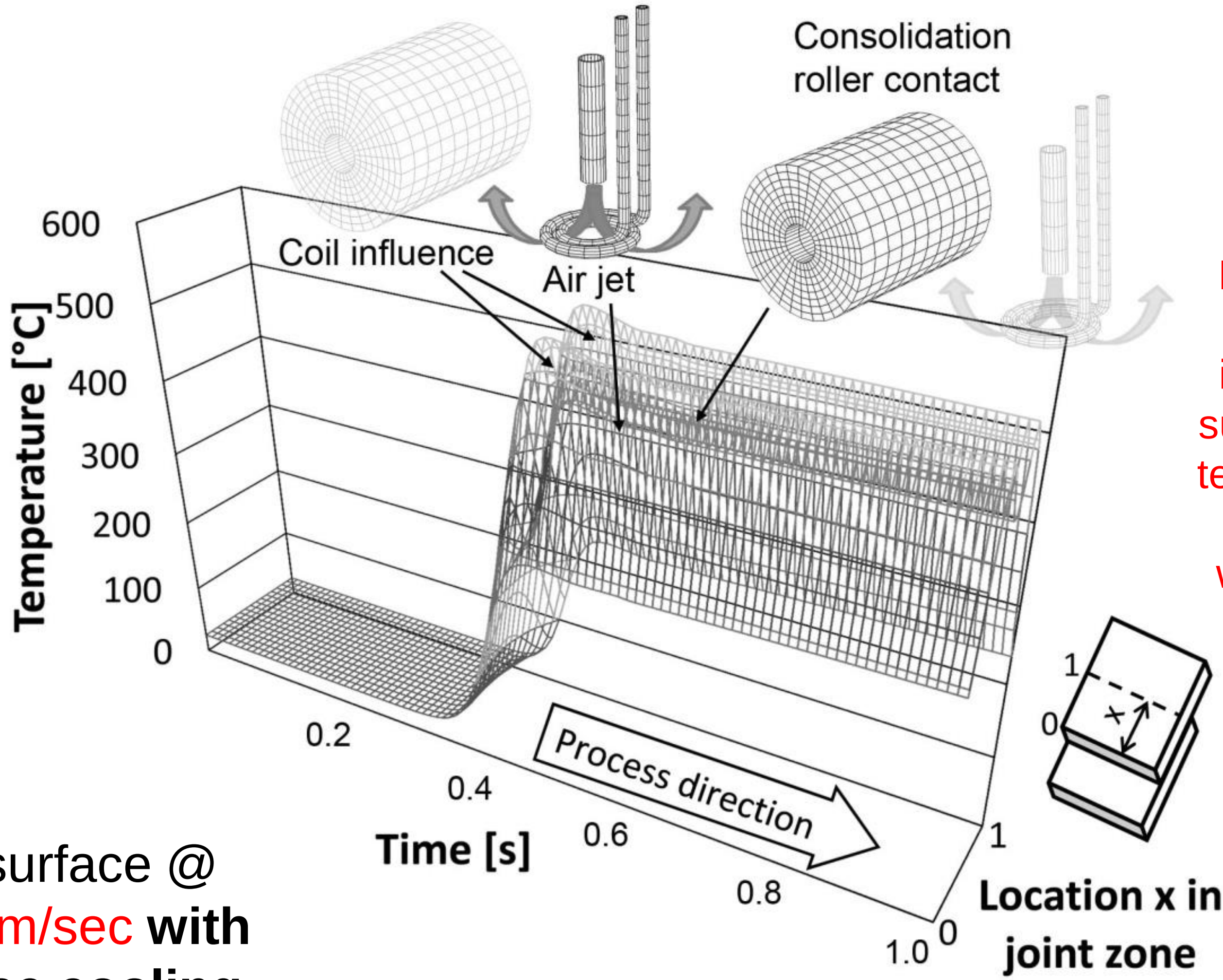


Temperatures are now higher at the bonding surface than the top surface!

An adequate temperature drop is important for facilitating a joint

Bond line surface @ 3 mm/sec **with surface cooling**

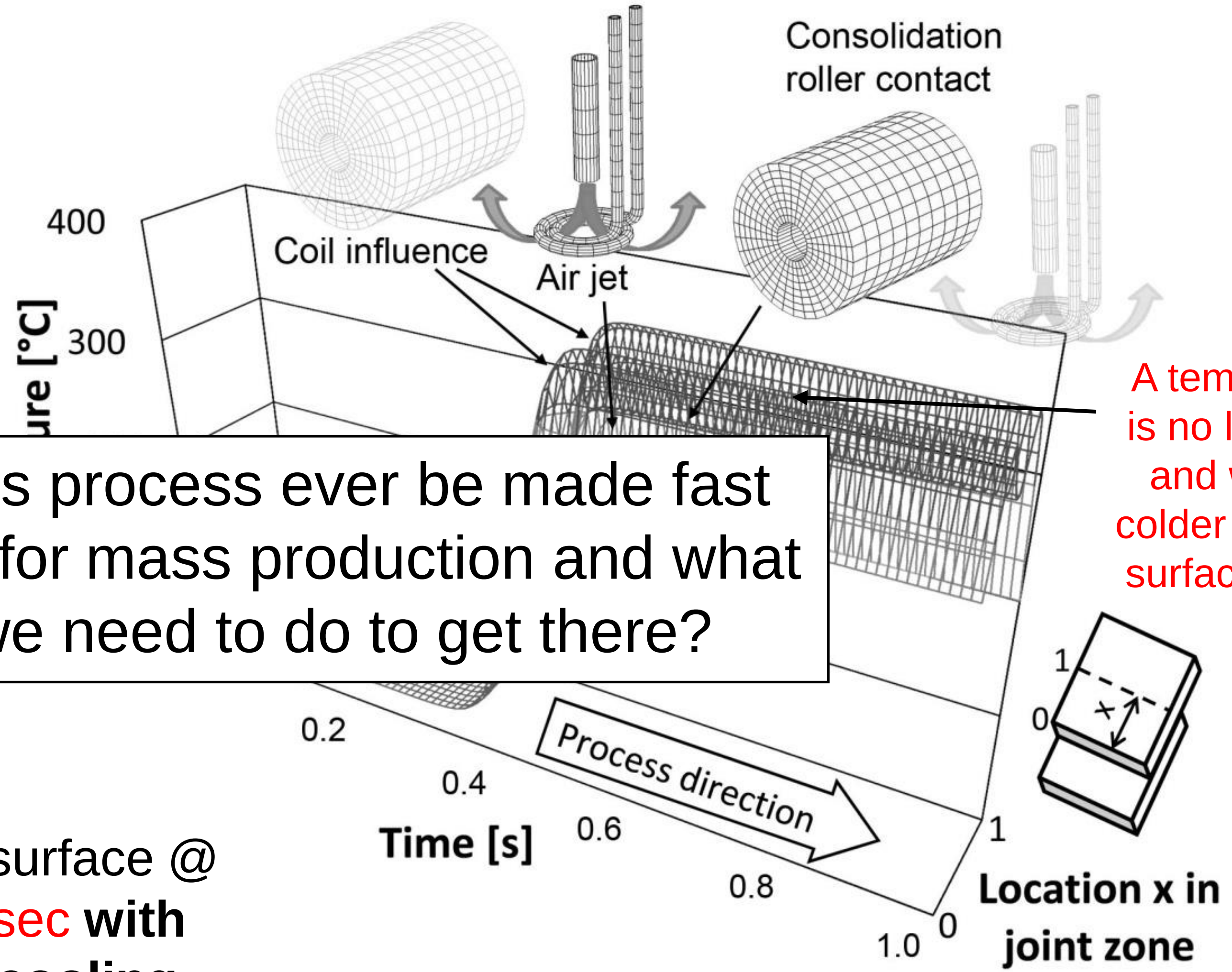
Simulation Results Actual Induction Welding Scenario: Surface Temperature Plots



Induction heating power has been increased to give suitable processing temperature but we now have a very wide temperature range

Top surface @
300 mm/sec **with surface cooling**

Simulation Results Actual Induction Welding Scenario: Surface Temperature Plots



A temperature drop is no longer present and we are again colder at the bonding surface than the top surface!

Can this process ever be made fast enough for mass production and what do we need to do to get there?

Bond line surface @ 300 mm/sec **with surface cooling**

Summary

- Thermoplastic composite continuous induction welding is a materials joining process with high potential to enable mass production manufacturing techniques for such materials in both the automotive and aerospace sectors
- The process is relevant for both composite to composite and composite to metal/metal alloy joints
- The method uses the phenomena of *electromagnetic induction* and the *joule heating effect* together with additional heat transfer mechanisms to effectively heat the interface of the two joining partners
- Currently, research level state of the art can produce seamless quality joints between composite to composite parts but only at very low welding speeds (~3 - 5 mm/sec)
- For the process to become industrially acceptable welding speeds of up to 300 mm/sec are desirable

Summary

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- To help understand the 3-way interacting physics involved and realize the goal of faster processing speeds the process has been modeled using LS-DYNA R7's Multiphysics Solver
- Initially, static plate induction heating characterization experiments are performed and used to verify simulations of the same nature for both composite (CF/PEEK) and metal (structural steel) plates
- The simulations are then extended to the case of an actual welding scenario involving dynamic conditions (i.e. a moving induction coil)
- With the help of a "Simulation Test-Bed" temperature profiles at the bonding interface for different processing conditions and coil geometries can be examined and optimized to ensure they remain within material processing limits
- The model has provided unprecedented information about the process characteristics, the answer is near, standby for more….
- The future is composite! www.thefutureiscomposite.com

Future Analyses with LS-DYNA®: Continuous Induction Welding Simulation Test-Bed

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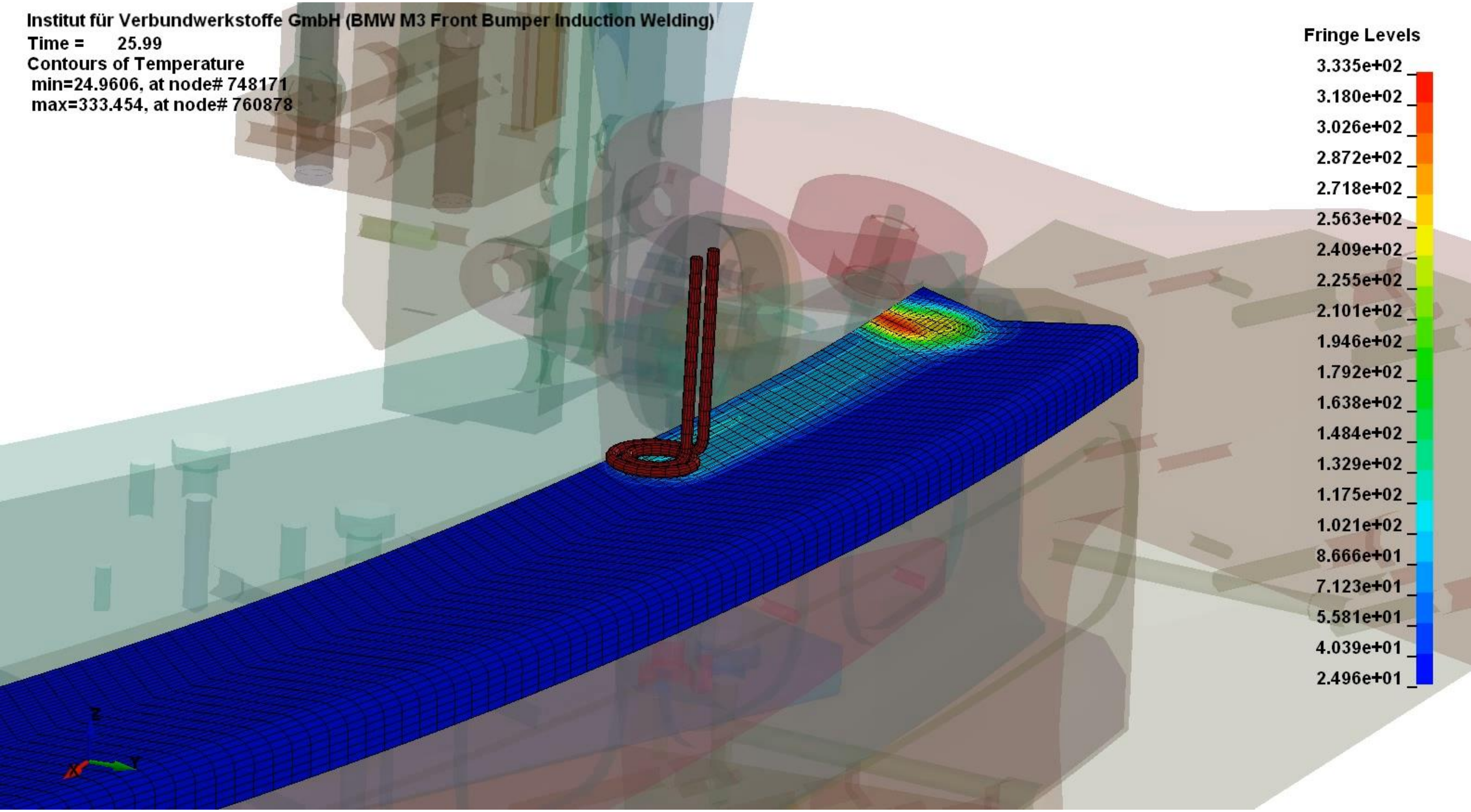

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