DYNAmore Express Webinar Series

Simulating Thermal-Mechanical Coupled Processes with LS-DYNA

- New Coupling Schemes, Boundary Conditions, Contact Algorithms and Materials -

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Motivation – Assembly Simulation

- State of the art digital process chain contains
  - (Hot) forming and press hardening simulations
  - Clamping simulations
  - Mechanical assembly steps, i.e. clinching, roller hemming, …
  - Thermal assembly steps, i.e. resistance spot welds, laser welds, line weld (MIG, MAG), …
  - Springback analysis

- Closed virtual process chain within LS-DYNA by data transfer from one stage to the next
  - Assembly of whole side-panel of a car
  - Hundreds of spot-welds, dozens of parts and multiple level of assemblies

- Tailored simulation strategies for each of the individual steps
  - As efficient as possible for each process, but without neglecting the critical effects
  - Keep track of material properties that might change significantly during process (e.g. phase evolution)

Content

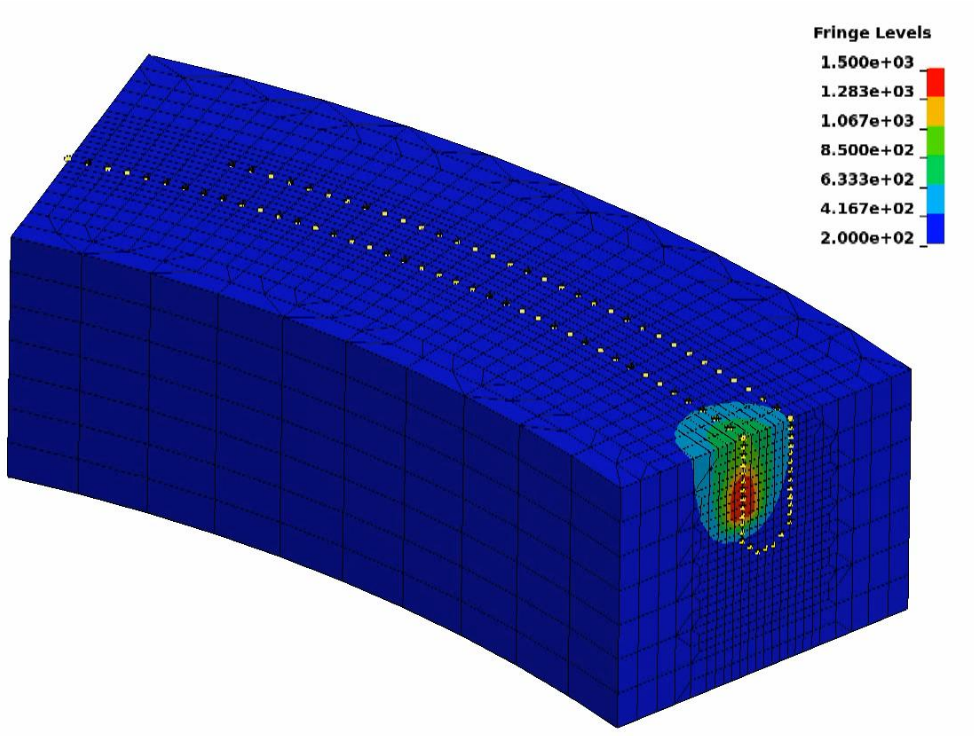
- Boundary Conditions I
- Coupling Strategies
- Boundary Conditions II
- Material Modelling
- Thermal Contact Algorithms

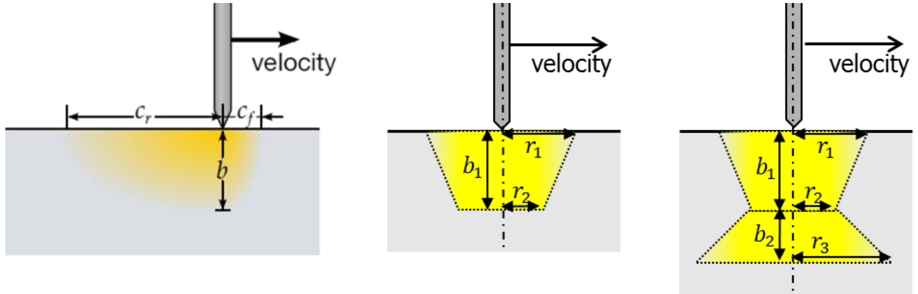
Content

- Boundary Conditions I
  - *BOUNDARY_THERMAL_WELD_TRAJECTORY
  - *BOUNDARY_FLUX_TRAJECTORY
  - *BOUNDARY_TEMPERATURE_RSW
- Coupling Strategies
- Boundary Conditions II
- Material Modelling
- Thermal Contact Algorithms

Modelling line welding processes

- *BOUNDARY_THERMAL_WELD_TRAJECTORY
  - defines a volumetric heat source
  - motion along a trajectory (nodal path)
  - prescribed velocity, possibly as function of time
  - user can choose from a list of equiv. heat sources
- Works in thermal-only and coupled analyses





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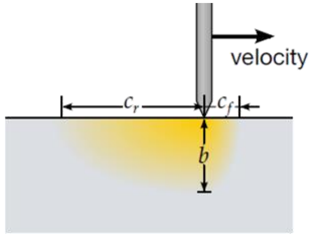
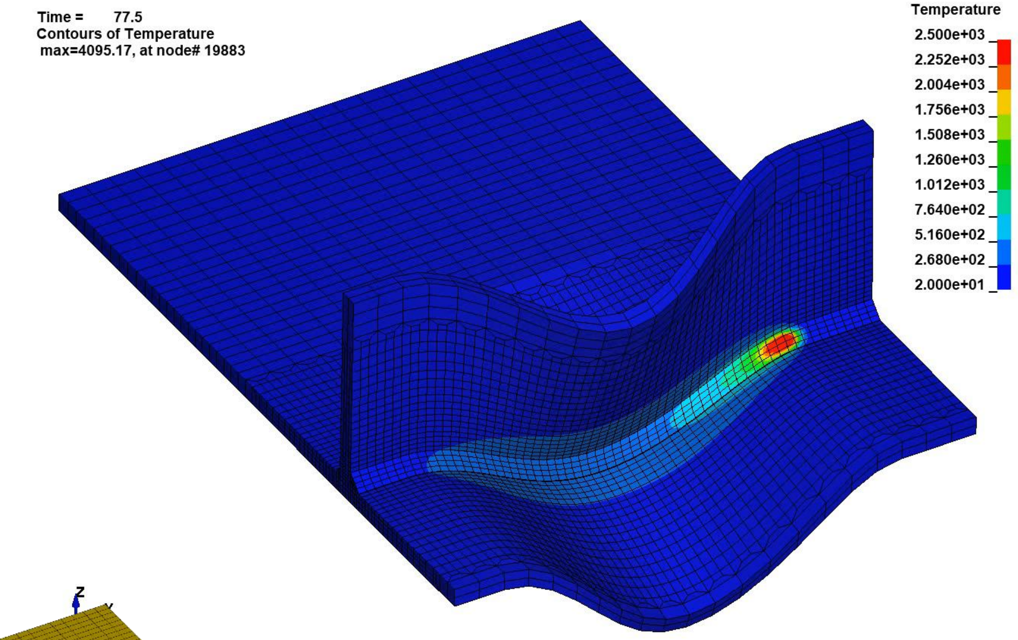
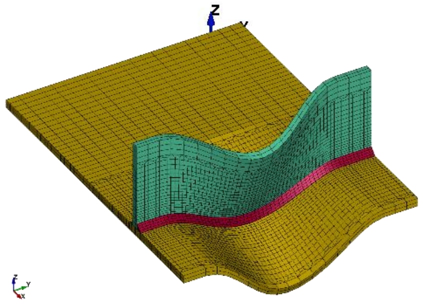
- Works in thermal-only and coupled analyses
- Applicable to solids and thermal thick shells
- Different possibilities to define aiming direction







Heat source orthogonal to weld seam surface (segment set)

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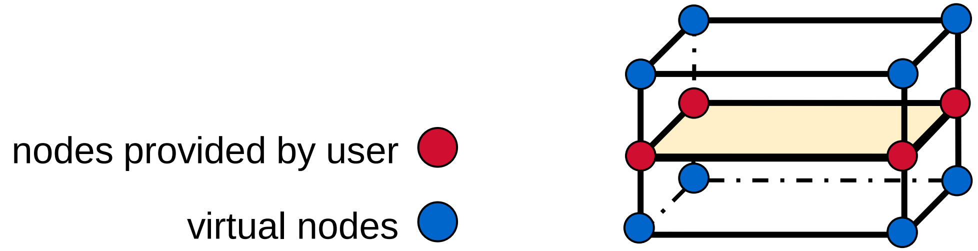

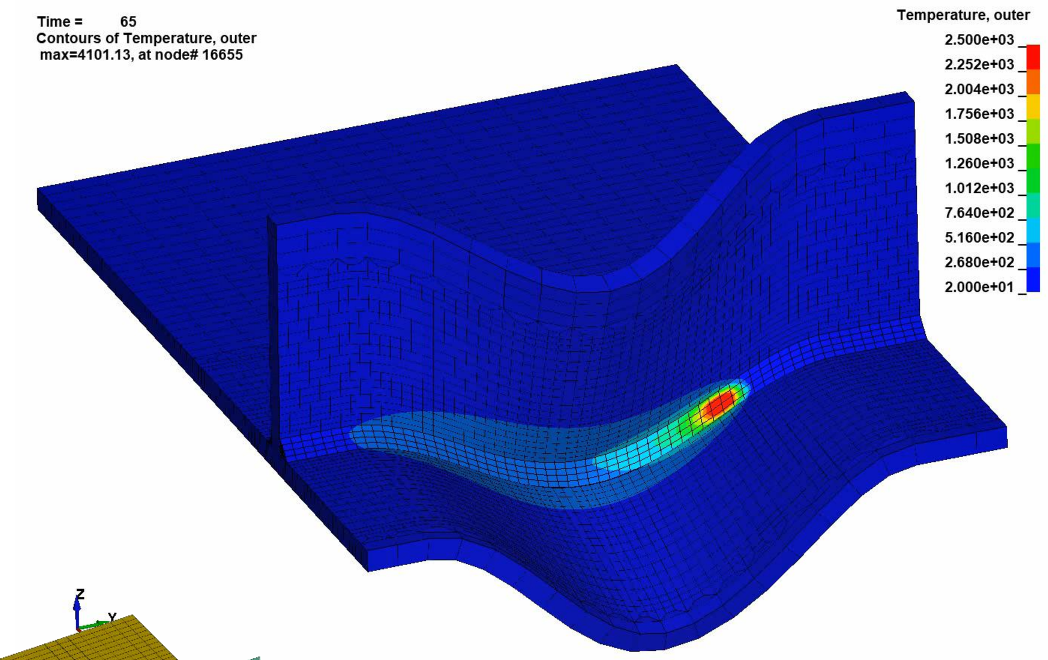

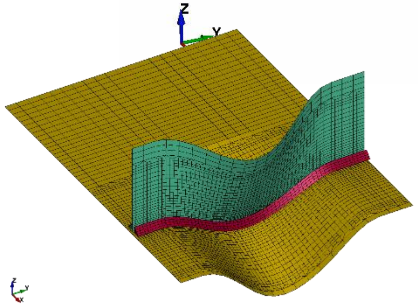

Heat source orthogonal to weld seam surface (segment set)

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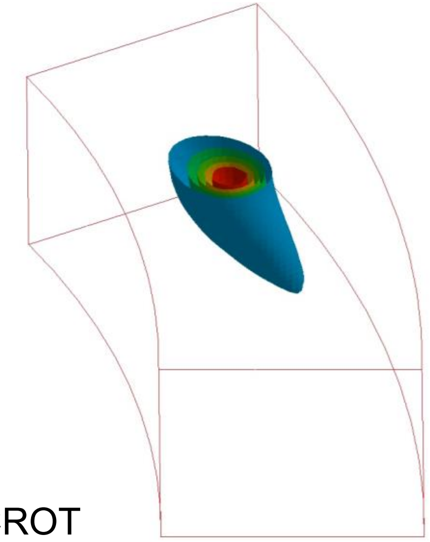
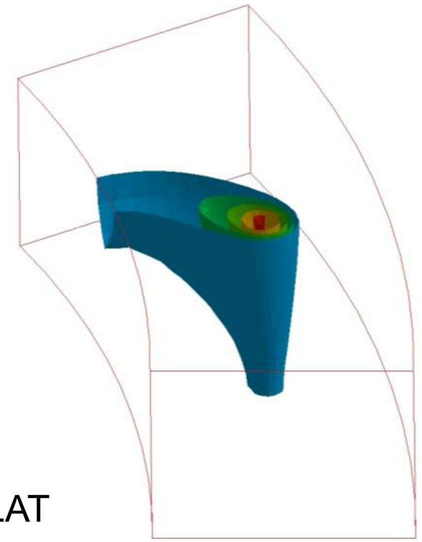
- Different possibilities to define aiming direction
- Additional rotation and translation (load curves)

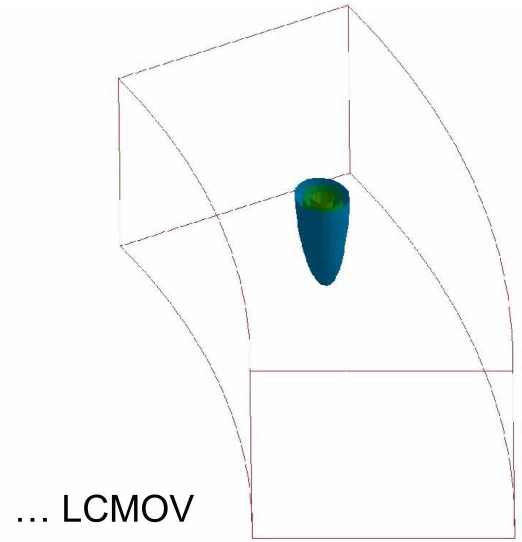
Influence of oscillations for…



… LCROT



… LCLAT



… LCMOV

Modelling line welding processes

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  - defines a volumetric heat source
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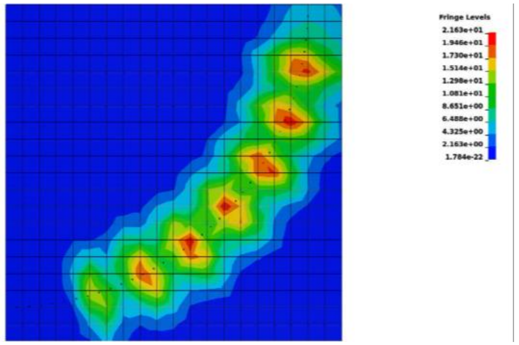
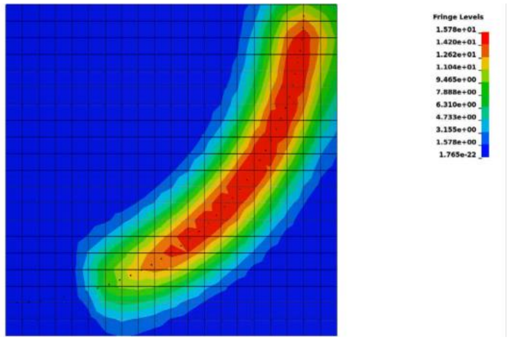
  - user can choose from a list of equiv. heat sources
- Works in thermal-only and coupled analyses
- Applicable to solids and thermal thick shells
- Different possibilities to define aiming direction
- Additional rotation and translation (load curves)
- Thermal dumping is possible

temperature field, NCYC = 1



Peak temperature = 21.6

temperature field, NCYC = 10

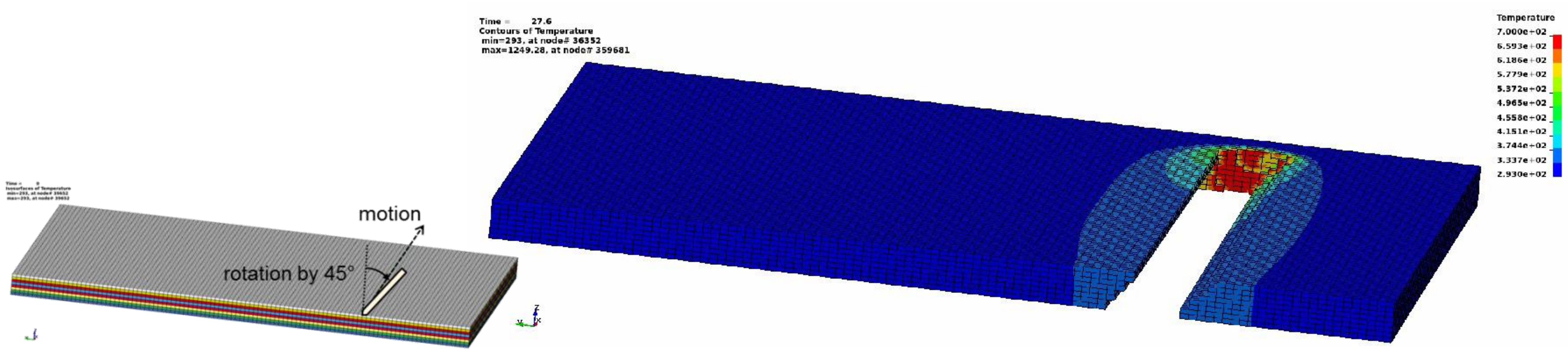


Peak temperature = 15.8

Laser heating and laser cutting

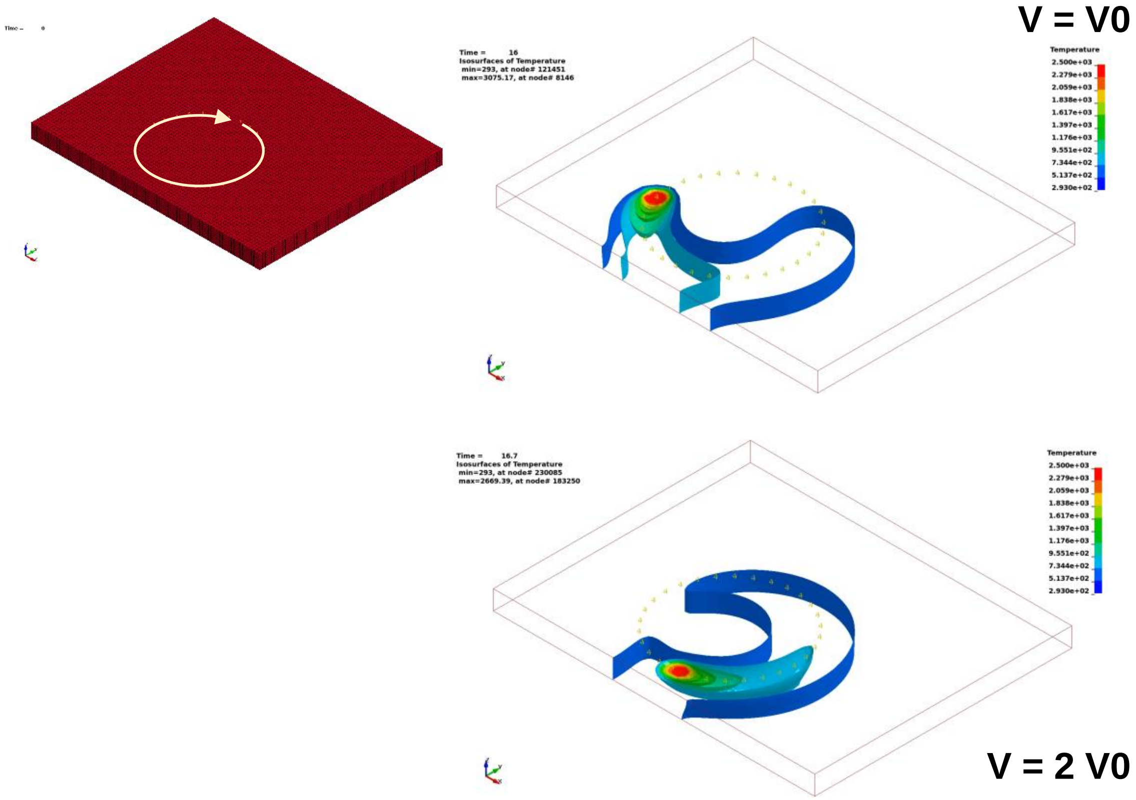
- Local heating of a surface by a laser with a certain position and orientation
- Material evaporates and topology of cut part changes

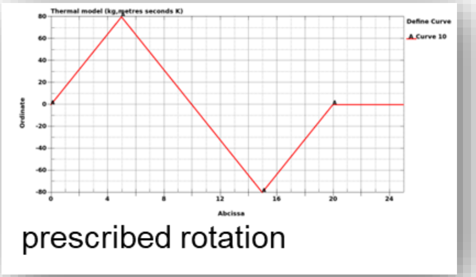
- LS-DYNA implementation with *BOUNDARY_FLUX_TRAJECTORY
  - surface flux boundary conditions that follows a prescribed path (node set)
  - resulting surface heat distribution depends on base distribution and current orientation of laser and surface
  - element erosion based on maximum temperature
  - newly exposed segments are accounted for

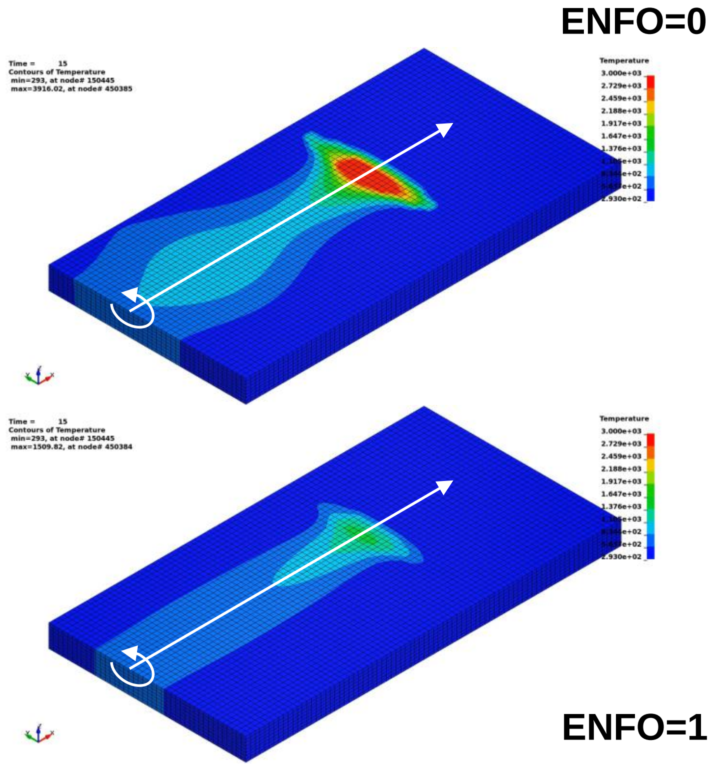


Laser heating and laser cutting

- *BOUNDARY_FLUX_TRAJECTORY
  - nodal path not necessarily defined on the cut part
  - tilting changes projection on the surface
  - change of intensity can be balanced



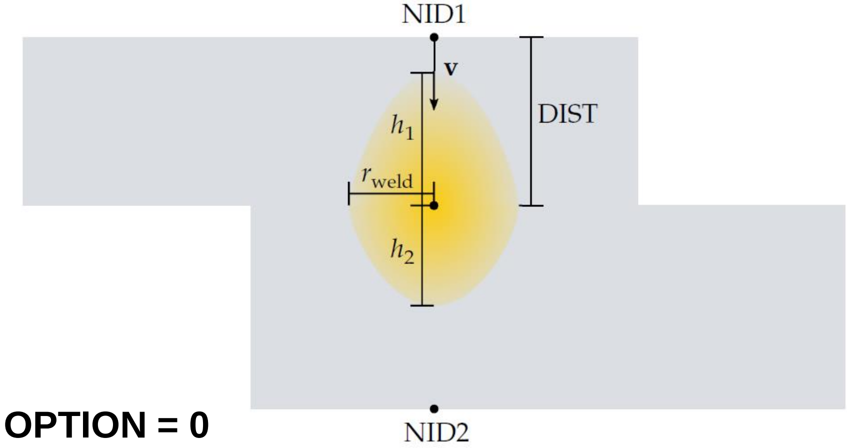




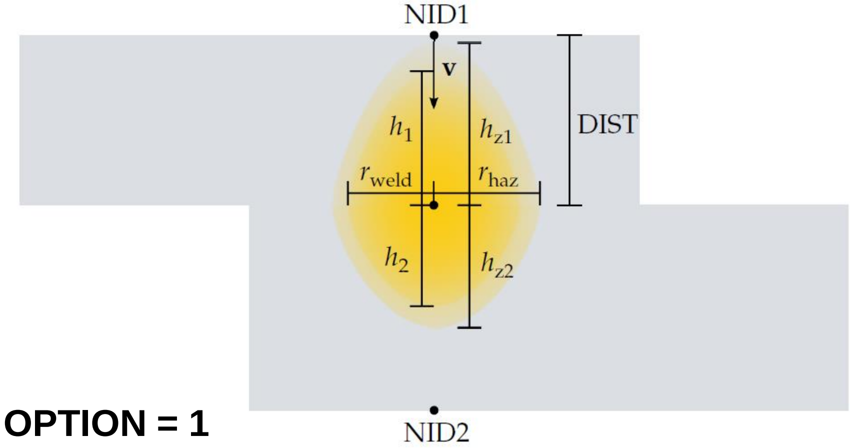
Resistance spot welding (RSW)

- Standard modelling approaches for RSW
  - Use a detailed and coupled (EM, thermal, structure) simulation
  - Use an equivalent heat source and calibrate its power and shape
  - **For large assemblies and hundreds of spot welds neither approach is feasible!**

- *BOUNDARY_TEMPERATURE_RSW
  - Direct temperature definition (Dirichlet condition) for the weld nugget and the heat affected zone for the **thermal** solver
  - Constraint condition only active during the welding
  - Very good prediction of deflections in large assemblies
  - A HAZ can be additionally accounted for



OPTION = 0

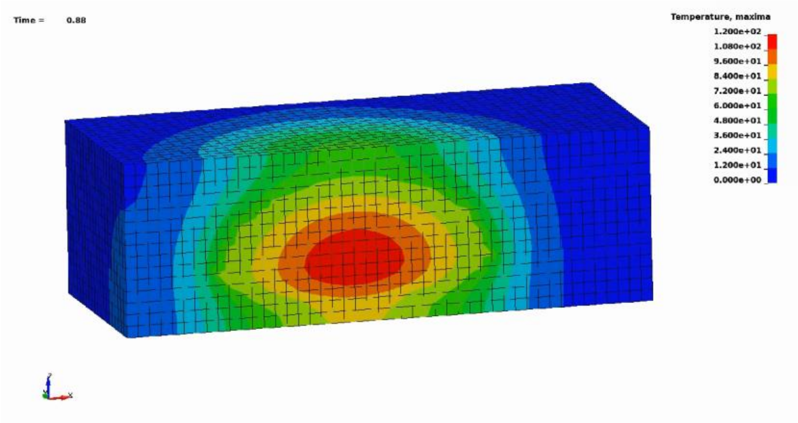


OPTION = 1

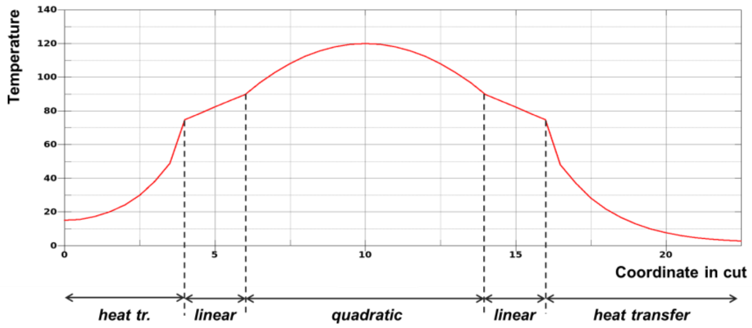
Resistance spot welding (RSW)

- Temperature in the weld nugget
  - prescribed at the center, boundary of nugget, and boundary of HAZ
  - quadratic approximation inside the nugget
  - linear approximation in the HAZ
- Boundary condition active between BIRTH and DEATH times
- Load curve input (LCIDT) for temperature scaling factor as function of normalized time

linear temp increase, BIRTH=0.1, DEATH=0.9



peak temp. profile, horizontal



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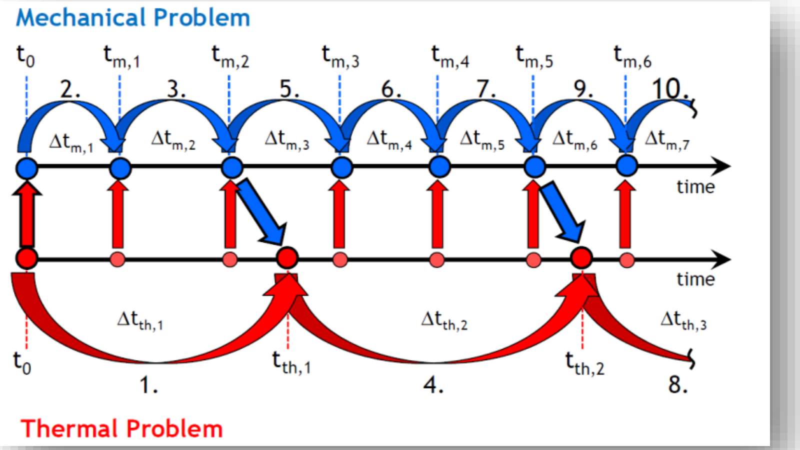
Content

- Boundary Conditions I
- Coupling Strategies
  - Standard Two-Way Coupling
  - One-Way Coupling with *LOAD_THERMAL_BINOUT
- Boundary Conditions II
- Material Modelling
- Thermal Contact Algorithms

Data Transfer and Simulation Principles

- Default strategy in LS-DYNA is a 2-way coupling
  - Staggered weak approach
  - Two solvers run in parallel and share data
  - Thermal time step is independent of the mechanical time step



- Data transfer

Mechanical Calculations

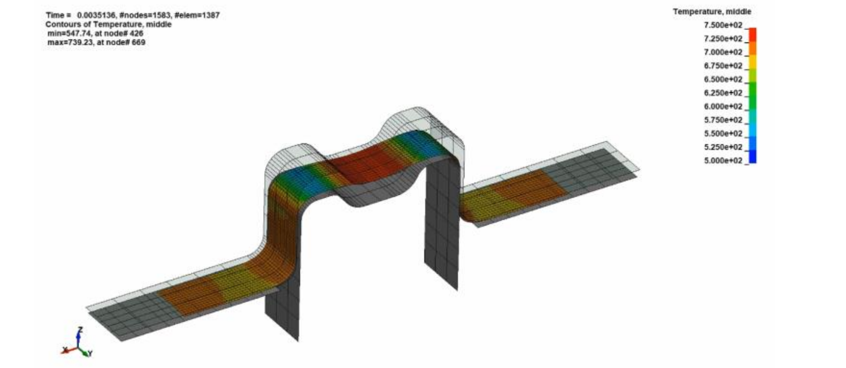
- Based on current temperature, calculate:
  - Plastic work
  - Part contact gap thickness
  - Temperature dependent material
  - Thermal expansion
- Update geometry

Thermal Calculations

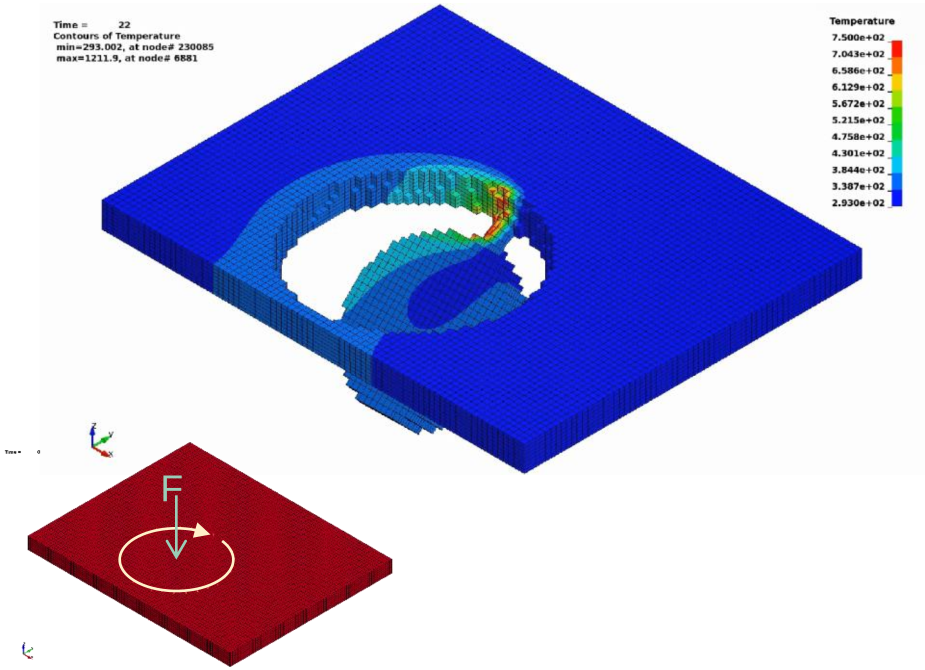
- Based on current geometry, calculate:
  - Heat from plastic work
  - Contact conductance from gap thickness and contact pressure
  - Heat from interface friction
- Update temperature

2-way coupled Approach – Examples for possible Applications

- Hot forming
  - Constantly changing contact status
  - Heat transfer between blank and tools is pressure dependent
  - Heat generation from contact friction
  - Energy conversion from plastic work to heat

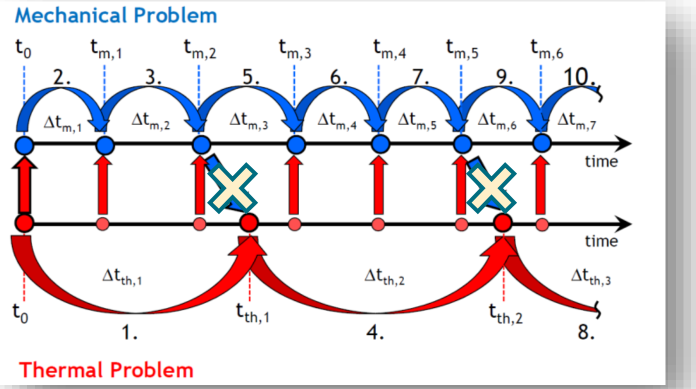


- Laser cutting
  - Surface heat source (*BOUNDARY_FLUX_TRAJECTORY) moving along a prescribed path
  - Propagation to newly exposed surfaces after element erosion
    - Element erosion is defined in mechanical solver
    - Constantly changing topology



Motivation for 1-way Coupling

- For some assembly stages the effect of structural deformation onto the thermal simulation is negligible
  - Distortion and/or material phase evolution due the thermal distribution are of interest to the user



- Results of a thermal run serves as loading for structure simulation with *LOAD_THERMAL_D3PLOT
  - Evolution in time of temperature distribution linearly interpolated between the output time steps
  - Thermal thick shell feature is supported also for the structure-only simulation
  - Temperature results are read from the d3plot file of the thermal run

  Challenges with this approach:
  - Complex input file format (d3plot) to be generated by a mapping tool
  - Meshes (models!) for both simulations have to coincide
  - Time scaling has to match as well

- Implemented more flexible *LOAD_THERMAL_BINOUT to read data from one or more LSDA database(s)

*LOAD_THERMAL_BINOUT

	1	2	3	4	5	6	7	8
Card 1	**DEFTEMP**							
Card 2	**Filename**							
Card 3	**START**	**TSF**						

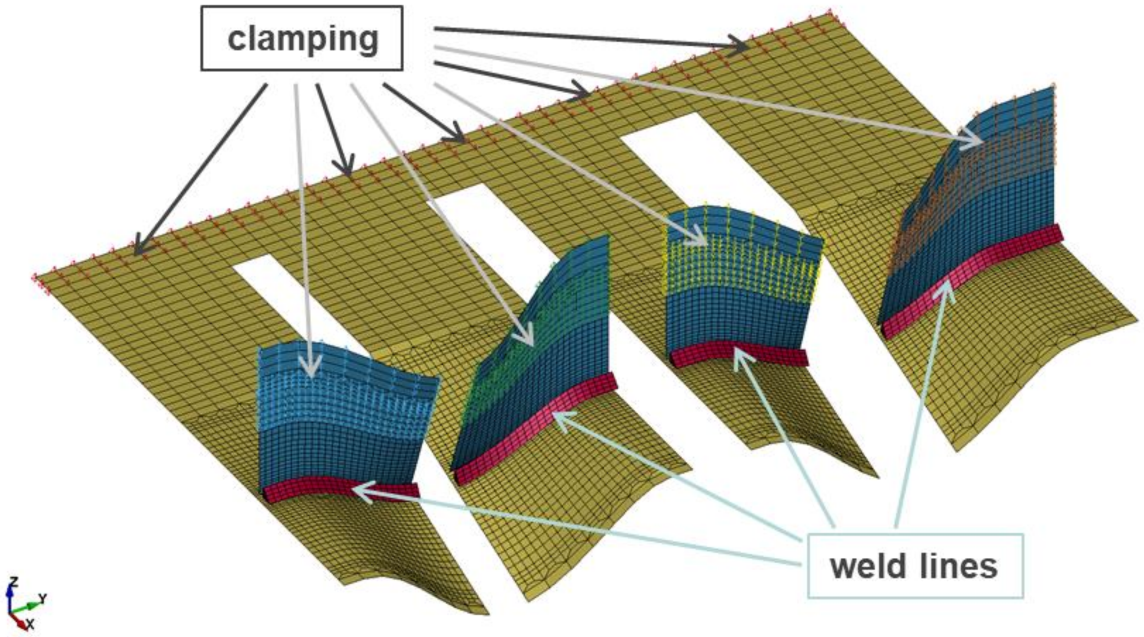
- Aims and scope of the new keyword
  - Use flexible and open LSDA data format to define thermal loading of a structure
  - Required structure of LSDA files matches the TPRINT section in LS-DYNA binout file, so results from thermal and from coupled LS-DYNA runs can be used without further modification
  - Only partial overlap between meshes should be required
  - Allow for a sequential thermal loading and for an easy modification of the sequence

*LOAD_THERMAL_BINOUT

	1	2	3	4	5	6	7	8
Card 1	DEFTEMP							
Card 2	Filename							
Card 3	START	TSF						

- File name of thermal run given in keyword
- Thermal thick shells are accounted for
- Time step sizes do not have to match

Welding Example:



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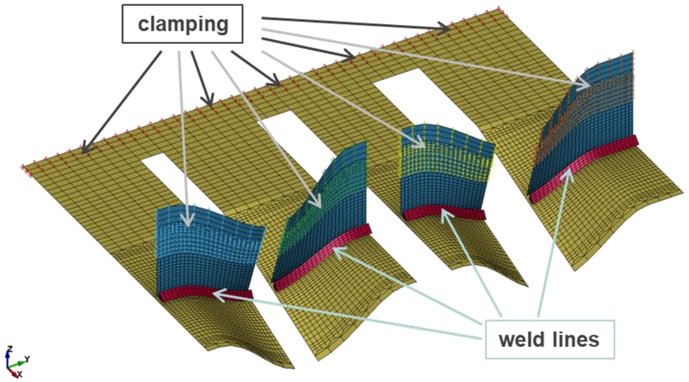

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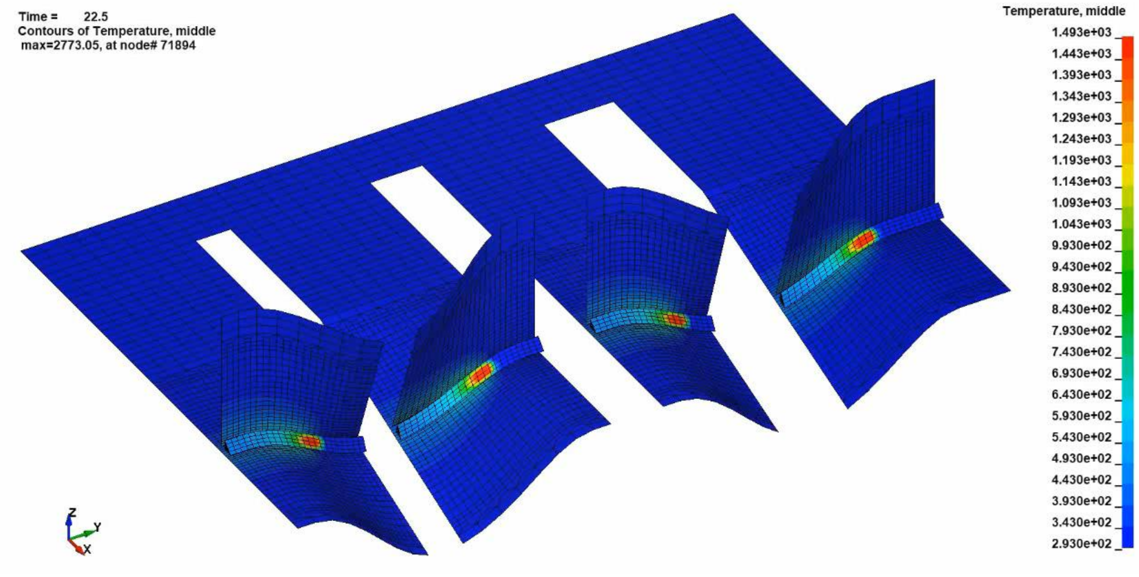
Thermal run:



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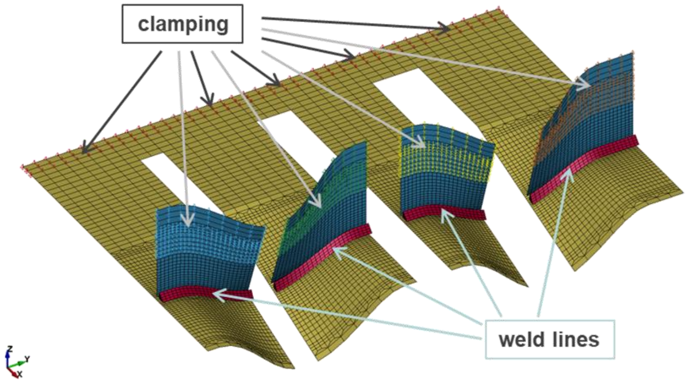
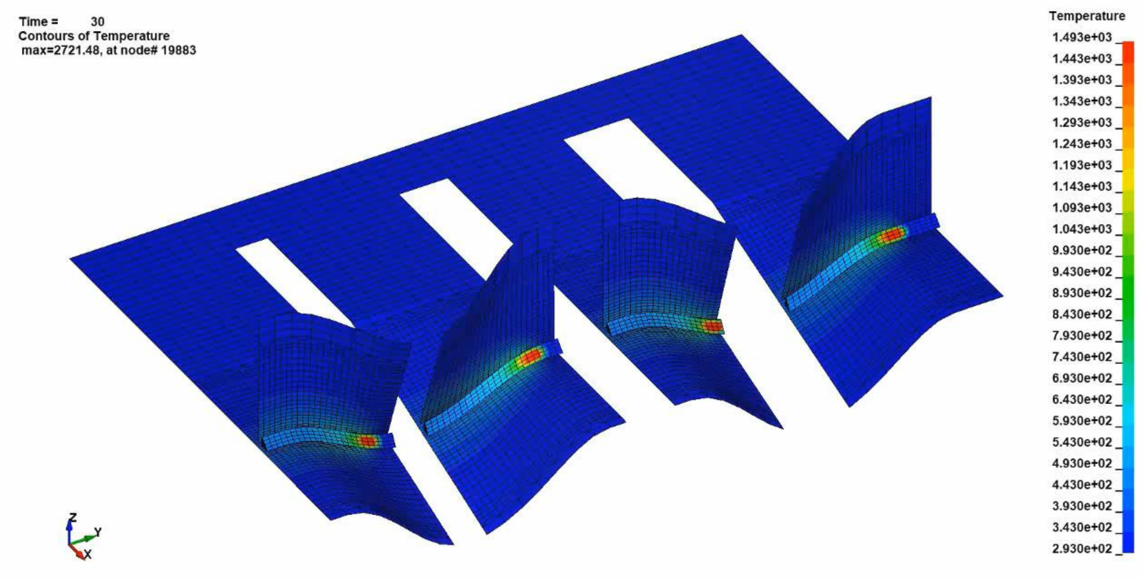
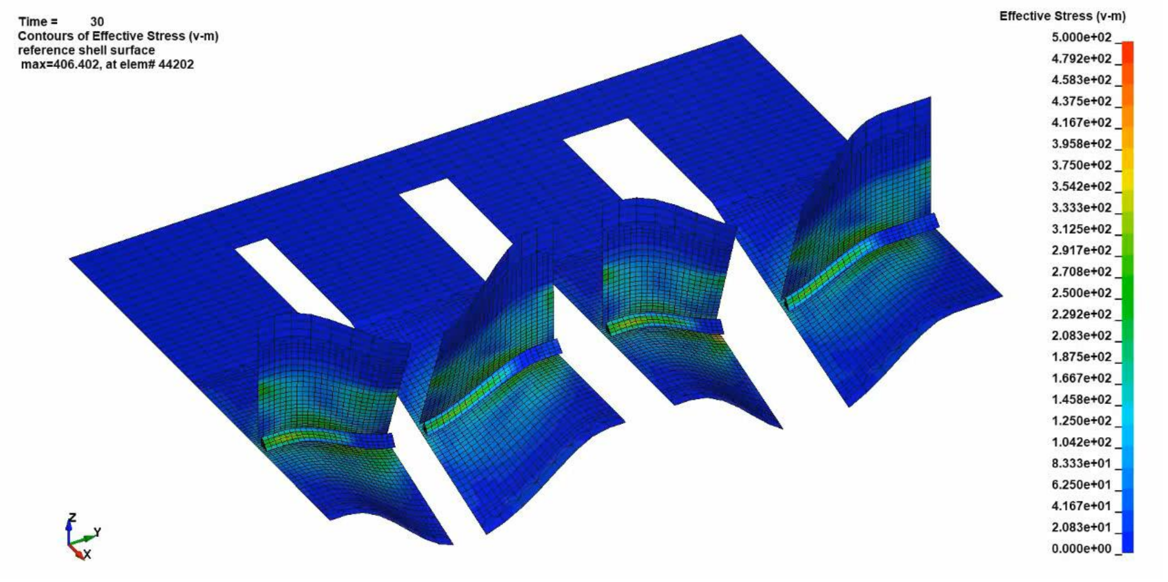


Structure run with thermal loading:



Temperature



von Mises stress

*LOAD_THERMAL_BINOUT

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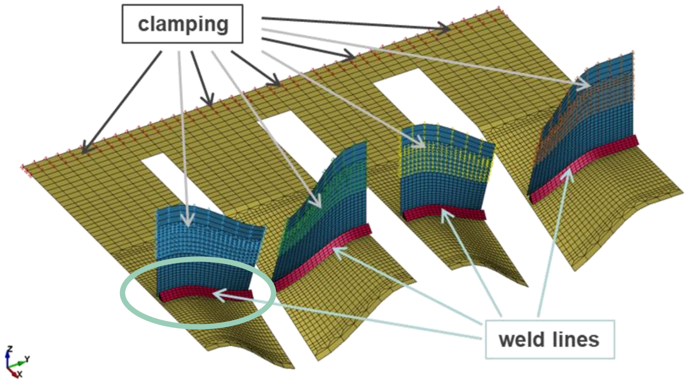
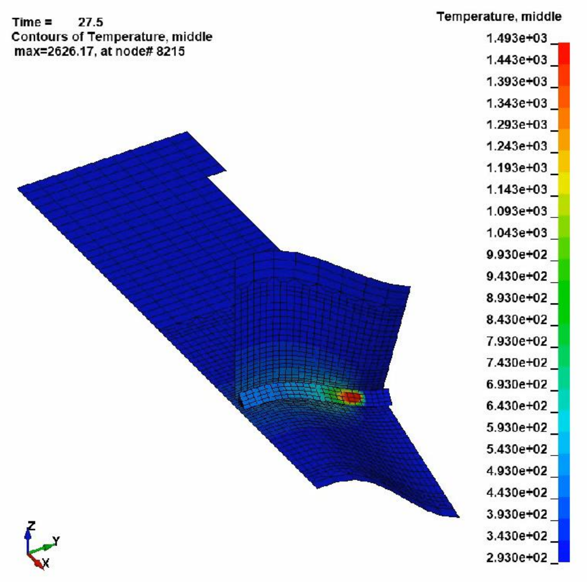


- File name of the input is to be given in the keyword
- Thermal thick shells are accounted for
- Time step sizes do not have to match

- Only partial overlap of the meshes is required
  - Data transfer based on user given ID of the nodes
  - Default temperature is used for those nodes of the structure simulations that are not included in the thermal run

Thermal Run:



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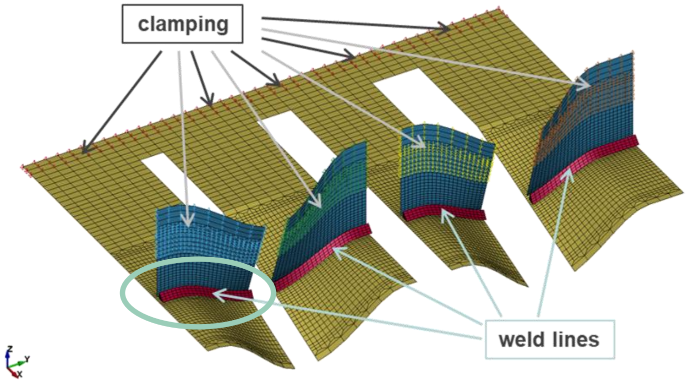

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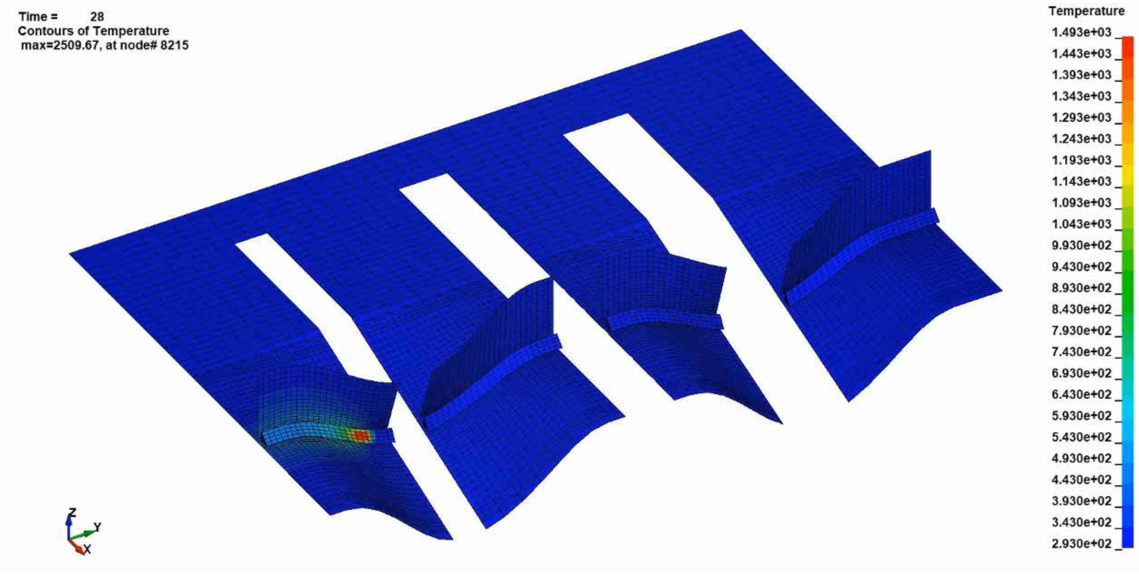
Mechanical Run:



Temperature

*LOAD_THERMAL_BINOUT

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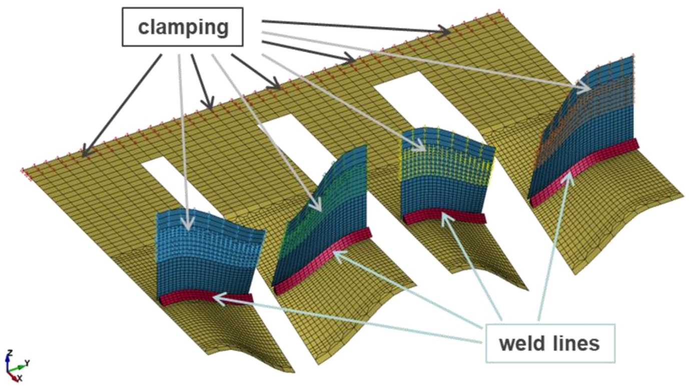
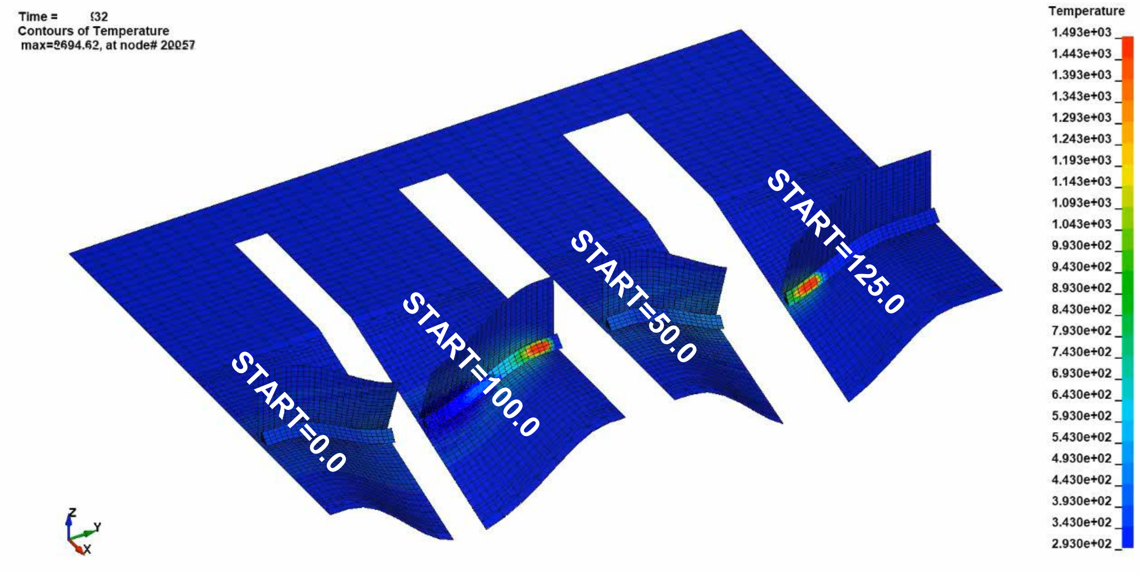
Card 3	START	TSF						



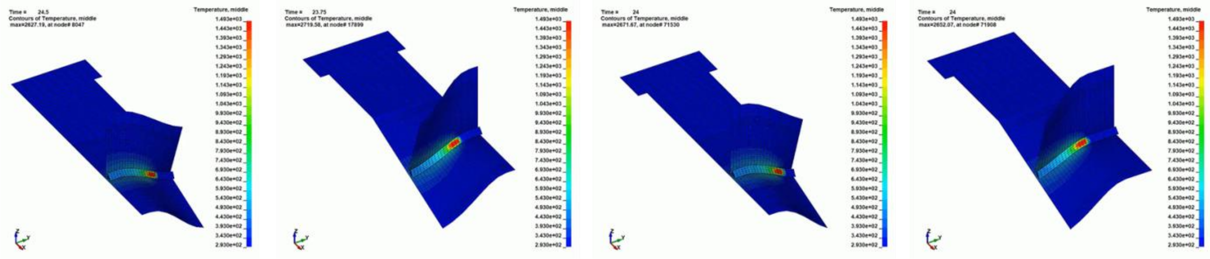
- Multiple thermal runs can be read in
- Each thermal run with time offset START
- Compensation for a scaling in time with TSF

Structure Run:



Temperature

Thermal Runs:



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- Boundary Conditions II
  - *LOAD_THERMAL_RSW
- Material Modelling
- Thermal Contact Algorithms

Resistance spot welding (RSW)

- Successfully tested one-way coupled approach:
  - *BOUNDARY_TEMPERATURE_RSW as boundary condition in thermal-only simulation
  - *LOAD_THERMAL_BINOUT as loading condition in structure-only simulation

- In early design phases this approach might be numerically too expensive

- Further simplification
  - Skip the calculation of heat transfer altogether
  - Imprint the temperature field of the weld nugget directly as thermal load
  - Structure-only simulation
  - Adapt the HAZ, because there is no heat transfer into the surroundings

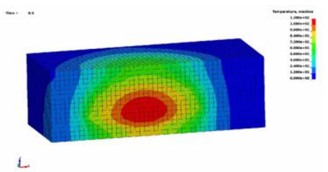
Resistance spot welding (RSW)

- Keyword *LOAD_THERMAL_RSW implemented

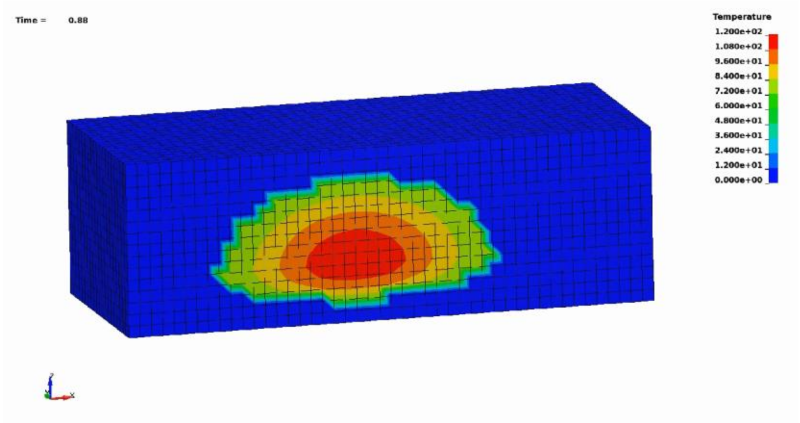
- Temperature profile in the weld nugget same as in the temperature boundary condition
  - Prescribed at the center, boundary of nugget, and boundary of HAZ
  - Quadratic approximation inside the nugget
  - Linear approximation in the HAZ

- Default temperature to be defined
  - Assumed outside the HAZ
  - Used before birth and after death of loading condition

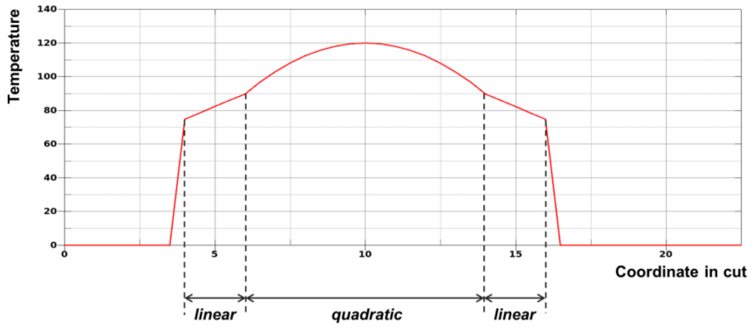
- No heat transfer into surroundings
- Sharp edges in temperature distribution



linear temp increase, BIRTH=0.1, DEATH=0.9



peak temp. profile, horizontal



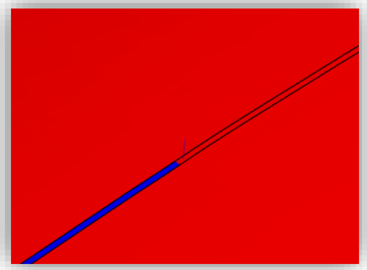
Content

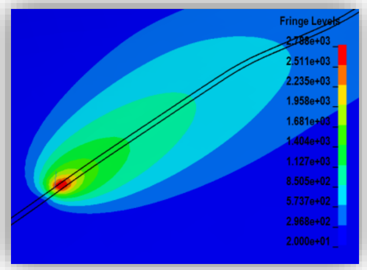
- Boundary Conditions I
- Coupling Strategies
- Boundary Conditions II
- Material Modelling
  - *MAT_CWM / *MAT_270
  - *MAT_THERMAL_CWM / *MAT_T07
  - *MAT_GERNALIZED_PHASE_CHANGE / *MAT_254
- Thermal Contact Algorithms

*MAT_270 – Ghosting approach for welding

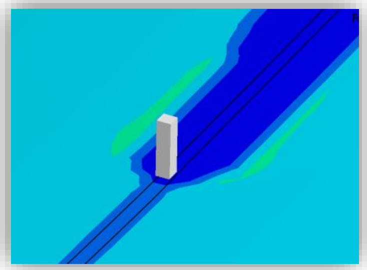
- Material has two diferent states
  - Elements are initialy ”Ghost” or ”Silent” until activated at a specific temp.
    - Low stiffness
    - Negligible thermal expansion
  - After activation, material with temperature dependend
    - Mechanical properties of the base material
    - Von-Mises plasticity with mixed isotropic/kinematic hardening
    - Thermal expansion

- Anneal at specific temperature
  - Reset of plastic strain data
  - Perfect plasticity without accumulation of plastic strains


activation



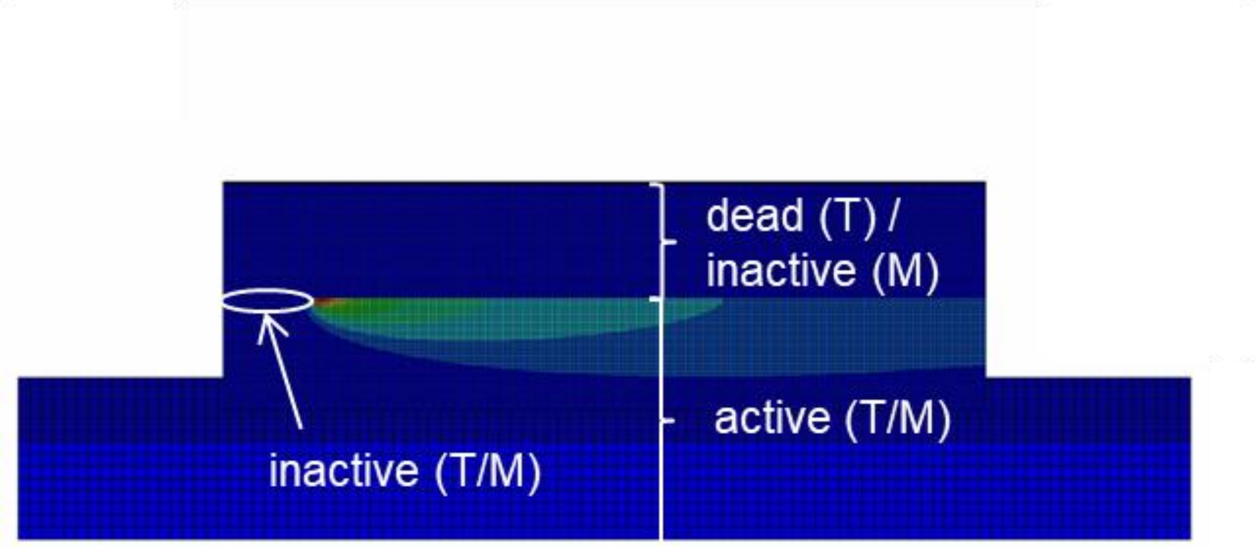
temperatures


annealing

*MAT_T07 – Ghosting approach for welding

- Material has three different states
  - Material has a birth time
  - Elements are born as ”Ghost” or ”Silent” until activated at a specific temp.
  - For all three states, specific heat and thermal conductivity are to be defined

- The formulation allows to simulate multiple weld paths and additive manufacturing processes



*MAT_254 – Overview

- up to 24 individual phases (= 552 possible phase change scenarios)
- phase changes in heating, cooling or in a temperature window
- user can chose from a list of phase change models for each scenario

- basic mechanical features:
  - elasto-plastic material with a von-Mises plasticity model
  - temperature and strain-rate effects
  - transformation induced strains and plasticity
  - thermal expansion
- any mechanical quantity α is determined by a rule of mixtures based on the current phase fractions x_i and the quantity α_i of phase i:

$$\alpha = \sum_{i=1}^{24} x_i \alpha_i$$

*MAT_254 – Overview

- elaborate features:
  - latent heat algorithm
  - calculation and output of additional pre-defined post-processing histories
  - calculation and output of additional user-defined history values
    - refers to *DEFINE_FUNCTION keyword
    - Possible input:
      time, user-defined histories, phase concentrations, temperature, peak temperature, temperature rate, stress state, plastic strain data
  - enhanced annealing option by evolution equation for plastic strain depending on time and temperature

*MAT_254 – Phase transformation

	1	2	3	4	5	6	7	8
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5			

- microstructural phase evolution
  - up to 24 individual phases
  - parametrization of the phase transformation to be given in a matrix-like structures (*DEFINE_TABLE_2D/3D)
  - matrix input for
    - phase transformation law (2D)
    - start and end temperatures (2D)
    - transformation constants (2D)
    - temperature (rate) dependent parameters (3D)
    - parameters depending on eqv plastic strain (3D)

from \ to	ph. 1	ph. 2	ph. 3	…	ph. n
ph. 1	--	data	data	…	data
ph. 2	data	--	data	…	data
ph. 3	data	data	--	…	data
⋮	⋮	⋮	⋮	--	⋮
ph. n	data	data	data	…	--

*MAT_254 – Phase transformation

	1	2	3	4	5	6	7	8
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5			

- Available phase transformation laws
  - Koistinen-Marburger
  - generalized Johnson-Mehl-Avrami-Kolmogorov (JMAK)
  - Akerstrom (only cooling, *MAT_244)
  - Oddy (only heating, *MAT_244)
  - Phase Recovery I (only heating, Titanium)
  - Phase Recovery II (only heating, Titanium)
  - Parabolic Dissolution I (only heating, Titanium)
  - Parabolic Dissolution II (only heating, Titanium)
  - incomplete Koistinen-Marburger (only cooling, Titanium)

from \ to	ph. 1	ph. 2	ph. 3	…	ph. n
ph. 1	--	data	data	…	data
ph. 2	data	--	data	…	data
ph. 3	data	data	--	…	data
⋮	⋮	⋮	⋮	--	⋮
ph. n	data	data	data	…	--

*MAT_254 – Phase transformation

	1	2	3	4	5	6	7	8
Card 3	**PTLAW**	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	**PTTAB1**	**PTTAB2**	**PTTAB3**	**PTTAB4**	**PTTAB5**	**PTTAB6**		

- Johnson-Mehl-Avrami-Kolmogorov (JMAK):
  - Evolution equation:

$$\frac{dx_b}{dt} = n(T)(k_{ab}x_a - k'_{ab}x_b)\left(\ln\left(\frac{k_{ab}(x_a + x_b)}{k_{ab}x_a - k'_{ab}x_b}\right)\right)^{\frac{n(T)-1.0}{n(T)}}$$

$$k_{ab} = \frac{x_{eq}(T)}{\tau(T,\varepsilon^p)}f(\dot{T}), k'_{ab} = \frac{1.0-x_{eq}(T)}{\tau(T,\varepsilon^p)}f'(\dot{T}),$$
$$\tau(T,\varepsilon^p) = \tau^0(T)\cdot\alpha(\varepsilon^p)$$

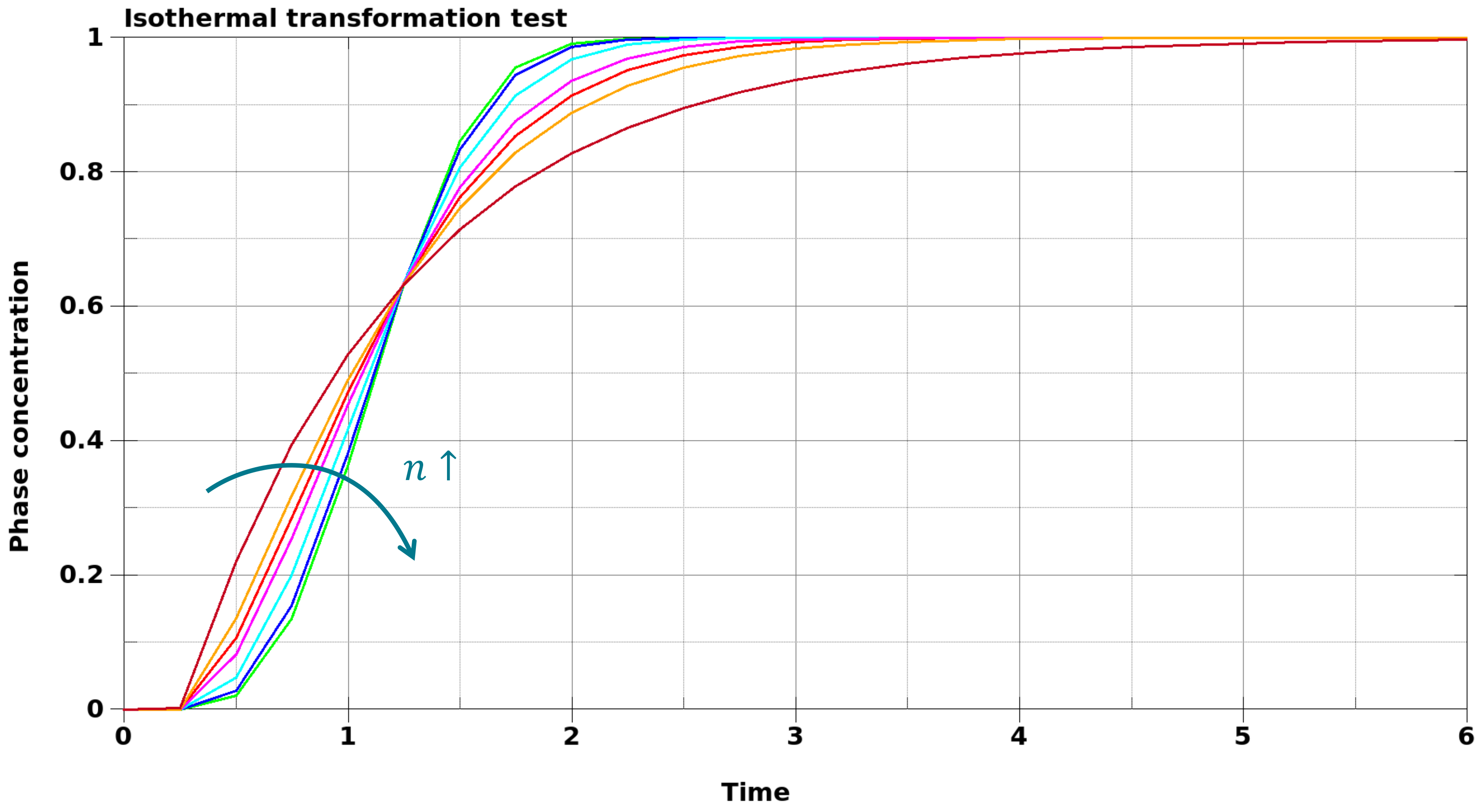
  - incremental form (isothermal case)

$$x_b = x_{eq}(T)(x_a + x_b)\left(1 - e^{-\left(\frac{t}{\tau(T,\varepsilon^p)}\right)^{n(T)}}\right)$$

- Parameter:
  - PTTAB1: $n(T)$
  - PTTAB2: $x_{eq}(T)$
  - PTTAB3: $\tau^0(T)$
  - PTTAB4: $f(\dot{T})$
  - PTTAB5: $f'(\dot{T})$
  - PTTAB6: $\alpha(\varepsilon^p)$

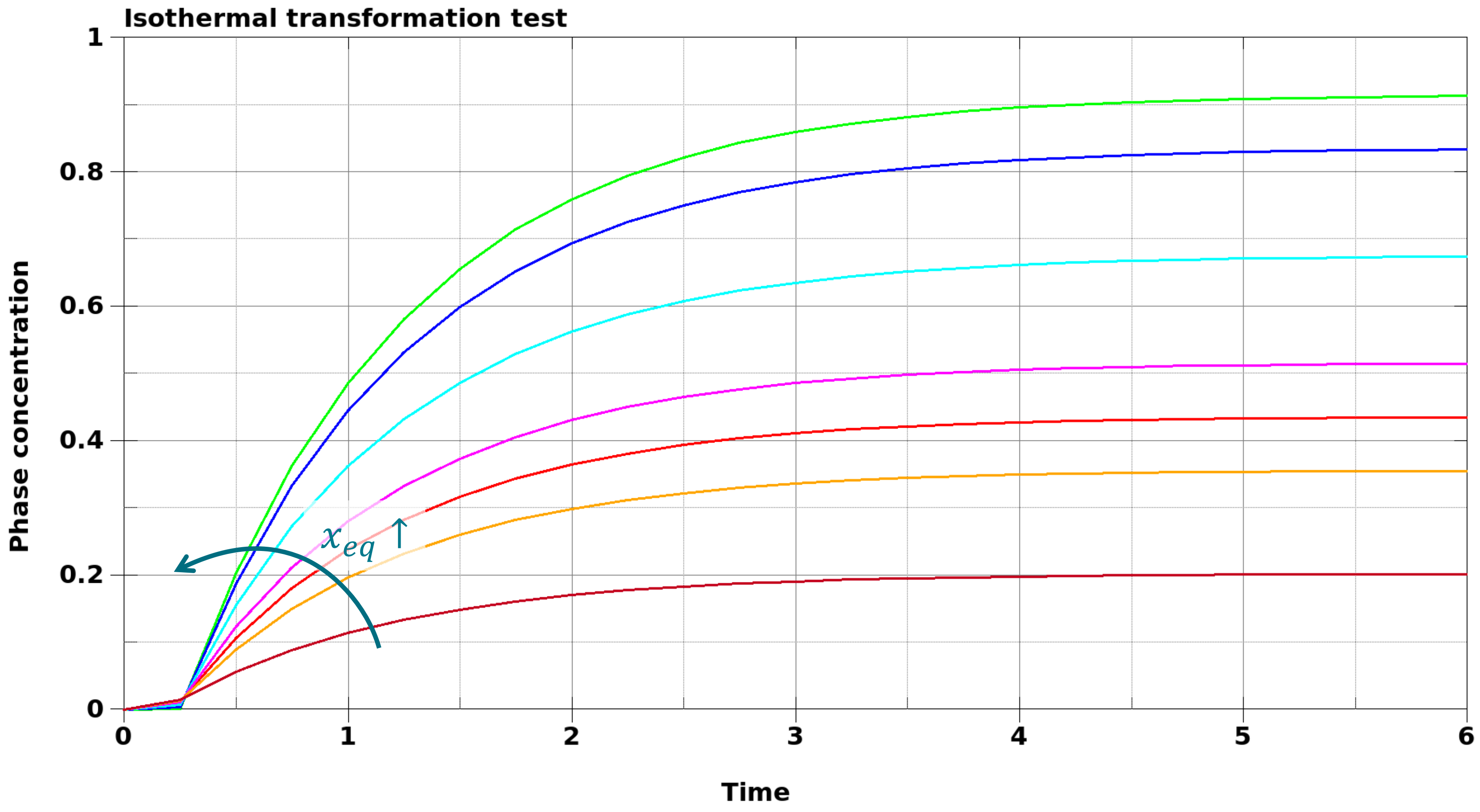
*MAT_254 – Phase transformation validation

- influence of parameter $n(T)$ on isothermal transformation



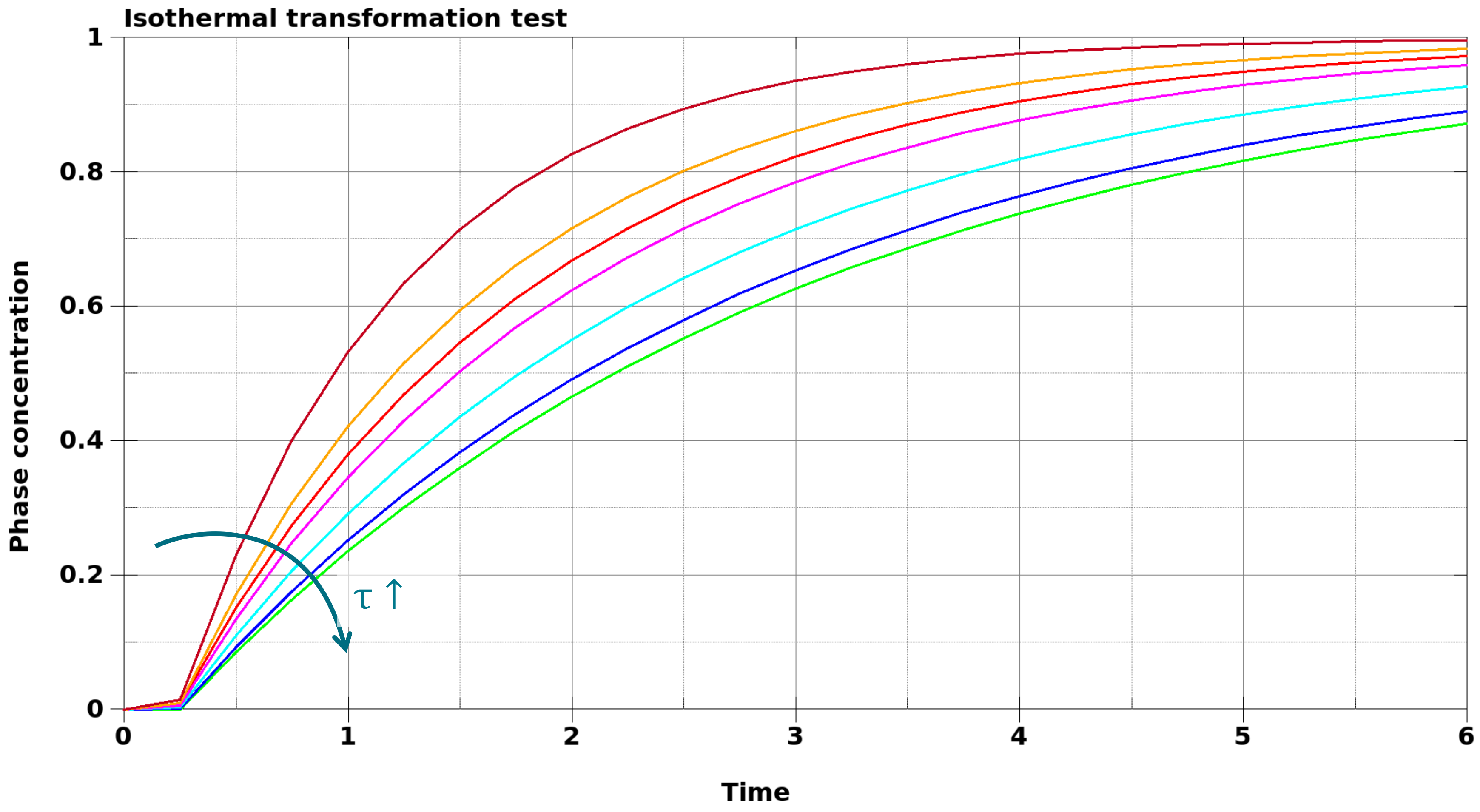
*MAT_254 – Phase transformation validation

- influence of parameter $x_{eq}(T)$ on isothermal transformation



*MAT_254 – Phase transformation validation

- influence of parameter $\tau(T)$ on isothermal transformation



Content

- Boundary Conditions I
- Coupling Strategies
- Boundary Conditions II
- Material Modelling
- Thermal Contact Algorithms
  - _TIED_WELD option
  - thermal shell edge contacts

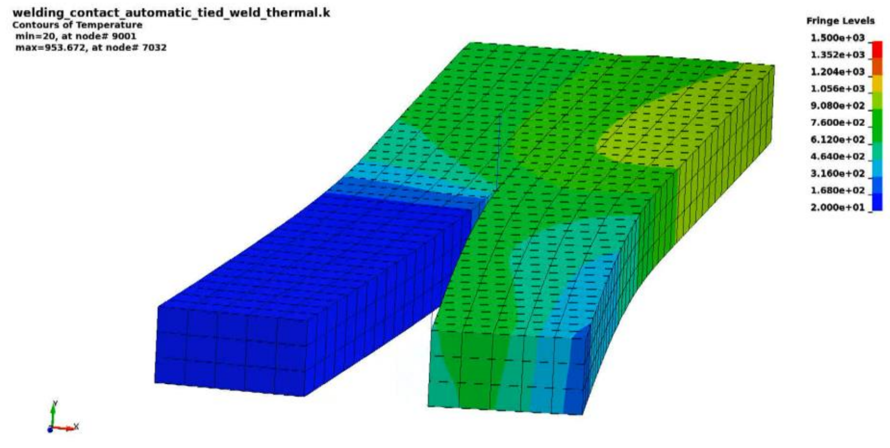
TIED_WELD contact formulations

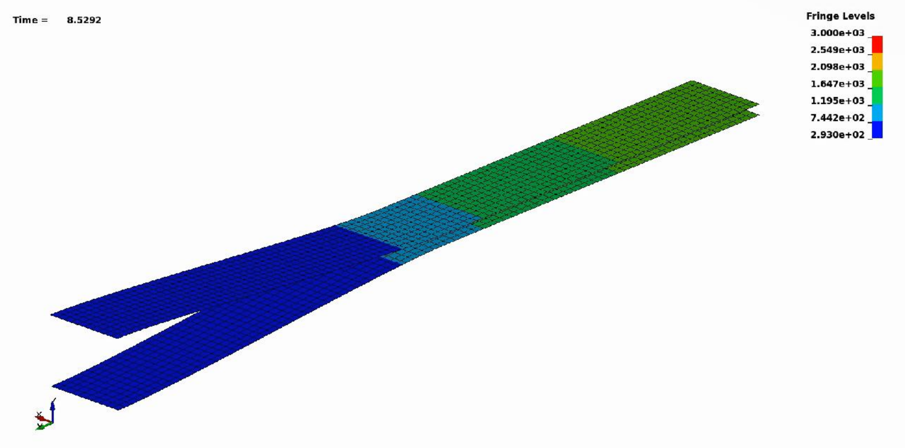
- Motivation:
  For welding processes without filler material, ghost approach is not applicable

- Basic features
  - Formulation can locally switch from sliding (un-welded) to tied (welded)
  - Switch is triggered by a temperature criterion
  - Welding only considered, if the gap between the contact partners are below a certain limit
  - Heat transfer coefficient also changes with welding

- MORTAR version available and recommended

- Available for solids and shells

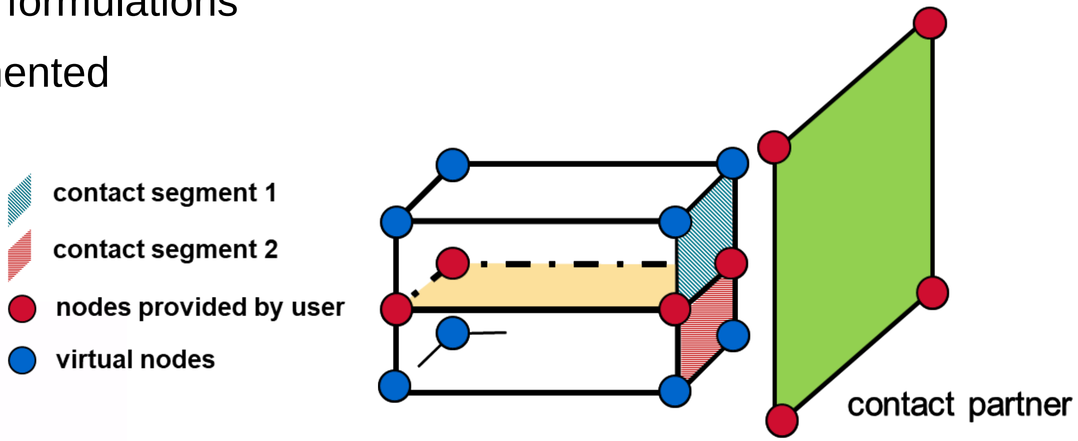


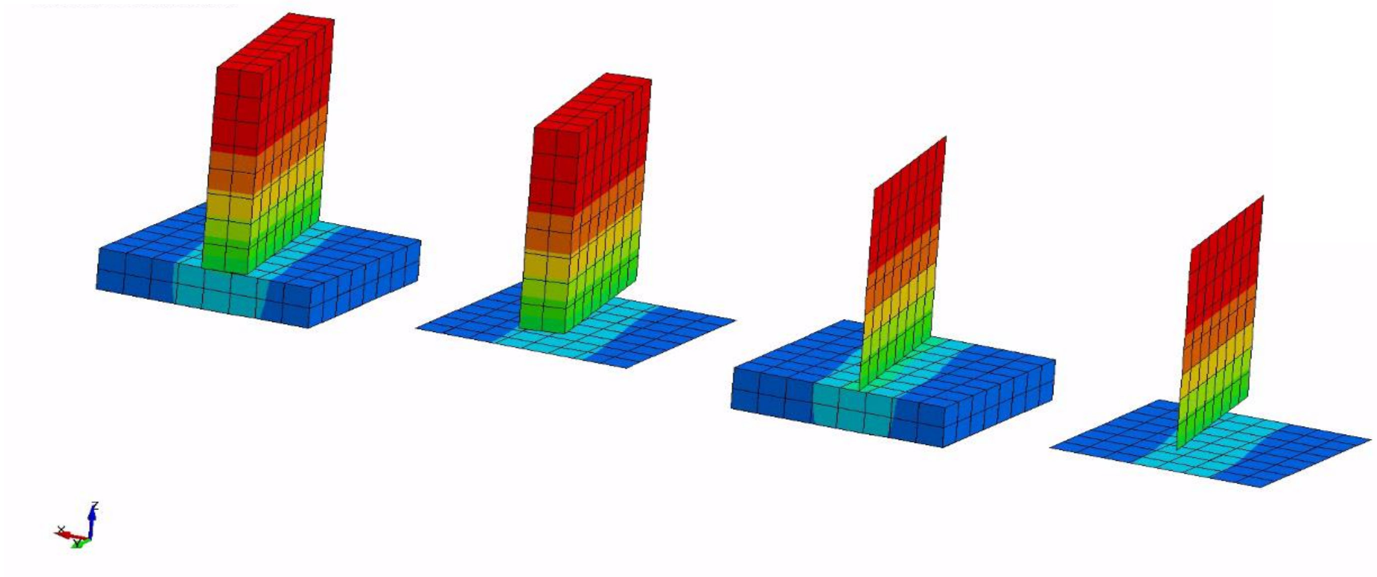


Heat Transfer over Shell Edges in Contact

- Situation so far:
  - heat transfer only available for surface to surface type contact formulations
  - for shell contacts only heat flux normal to shell surface implemented

- Thermal thick shells allow for reconstruction of two four-node surfaces at each shell edges for contact





Summary

- Introduced tailored boundary conditions to comfortably simulate heat generation in welding processes
  - *BOUNDARY_THERMAL_WELD_TRAJECTORY for line welding
  - *BOUNDARY_FLUX_TRAJECTORY for laser heating and laser cutting
  - *BOUNDARY_TEMPERATURE_RSW / *LOAD_THERMAL_RSW for resistance spot welds
- Presented new coupling keyword ‘LOAD_THERMAL_BINOUT
  - Flexible input in LSDA fromat
  - Input of multiple thermal runs with easy modification of the input order
- Discussion on different material formulations for assembly simulations
  - *MAT_THERMAL_CWM as temporally and thermally activated thermal material
  - *MAT_CWM / *MAT_270 as thermally activated temperature dependent structure material
  - *MAT_254 as state-of-the-art material formulation for phase transformations (UHS, Al6xxxx, Ti6Al4V, …)
- Brief summary of new features in the thermal contacts
  - TIED_WELD option to locally switch from sliding to tied contact
  - Heat transfer across shell edges can be accounted for

Thank you for your attention!

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