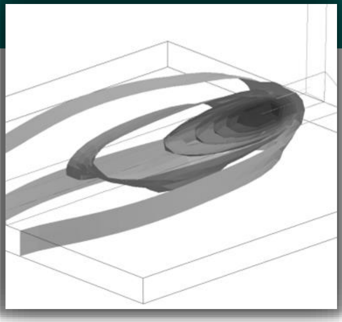
Möglichkeiten in LS-DYNA für die Simulation von Schweissprozessen und Wärmebehandlung



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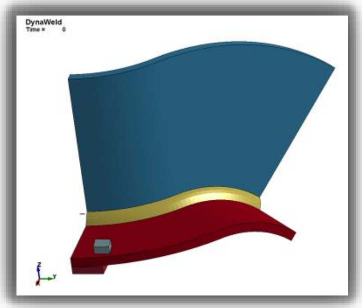
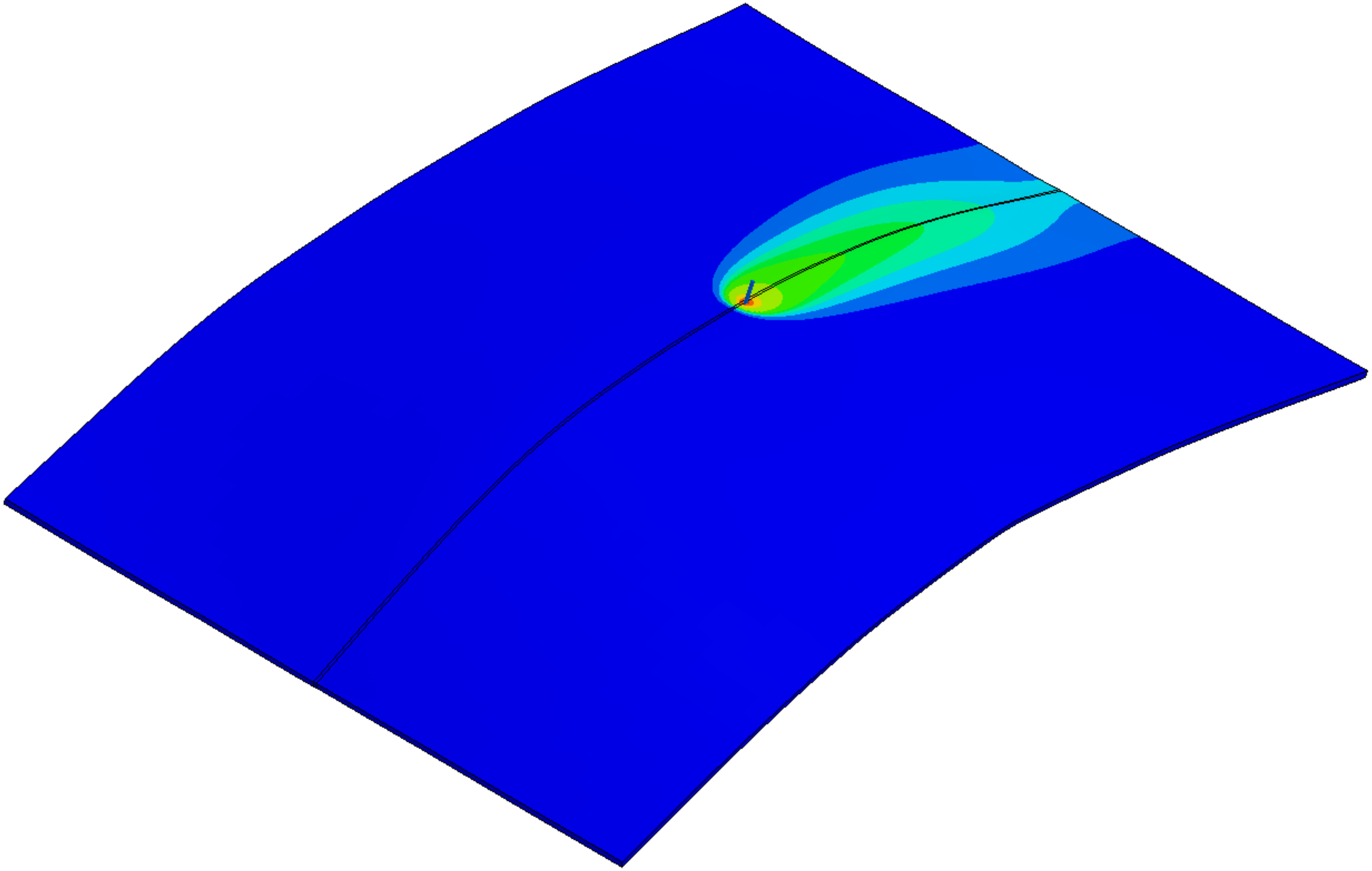


Welding simulation: What do we need?



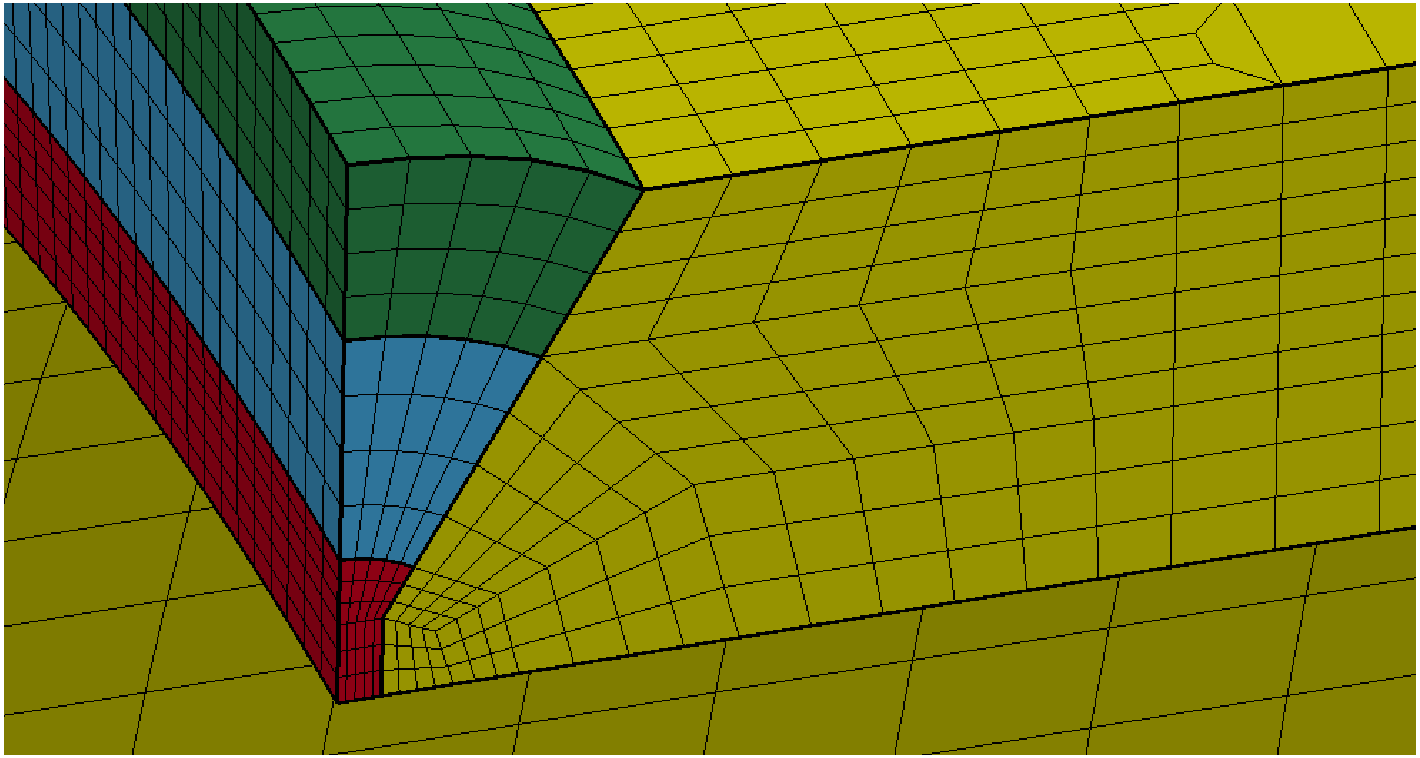
Welding simulation: What do we need?

- Finite element model
  - Geometry
  - Initial conditions (temperatures, stresses & strains)
  - Boundary conditions (thermal & mechanical)
- Coupling of thermal and mechanical problem
- Heat source (welding torch):
  - Geometry and power of the heat source
  - Movement of the heat source
- Material modeling
  - Distinction between **inactive** and **active** state of the material in the weld seam
  - Thermal and mechanical material parameters are **temperature dependent**
  - **Annealing** effects have to be considered
  - Material should be able to account for the **microstructure** of the alloy
  - **Phase changes** in heating and cooling
  - Transformation induced **strains**

Finite Element Model

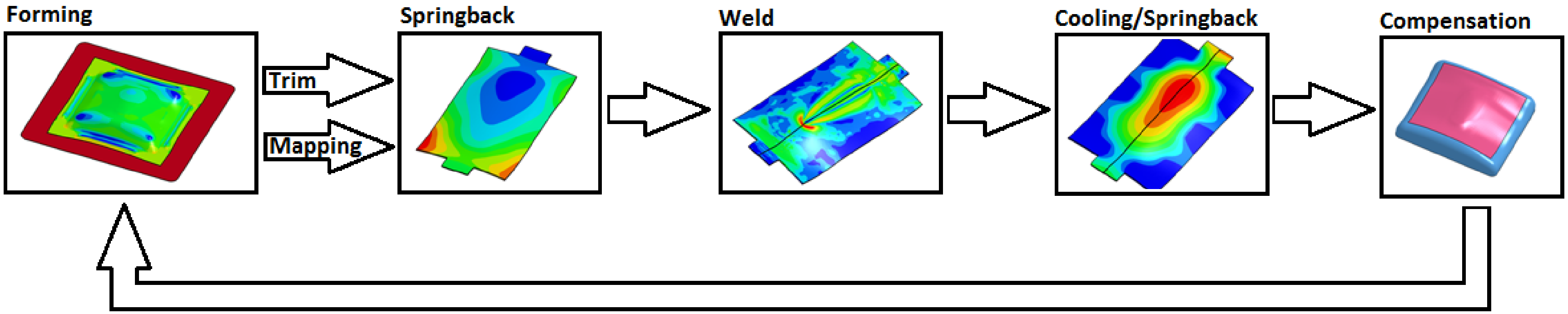
Geometry

- Mesh of parts and weld seam
- The mesh can be merged together using coincident nodes or with a tied contact with thermal properties.
- All weld passes are modeled from the beginning.



Initial conditions: consideration of manufacturing process

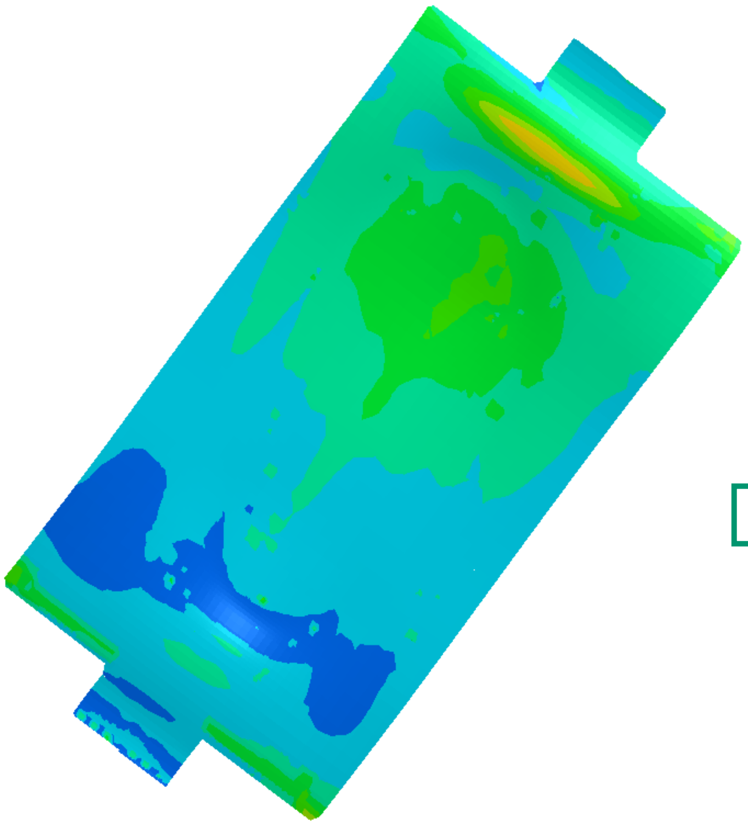
- if no initial conditions are defined, LS-DYNA will assign it to be zero
- properties of the finished part in general depend on the manufacturing chain
- Tooling has to be compensated for springback and shape distortions which occur in the fabrication chain



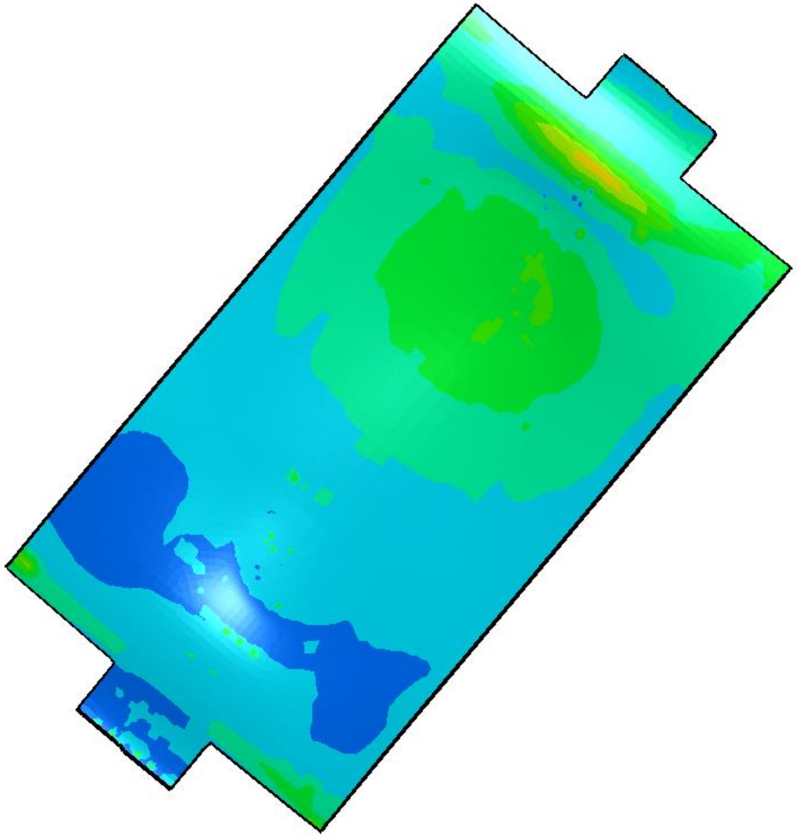
- Numerical simulations of the complete process chain necessary to predict finished geometry and properties
- The individual stages pose very different requirements on the numerical solver

LS-PrePost: Mapping from shell to solid elements

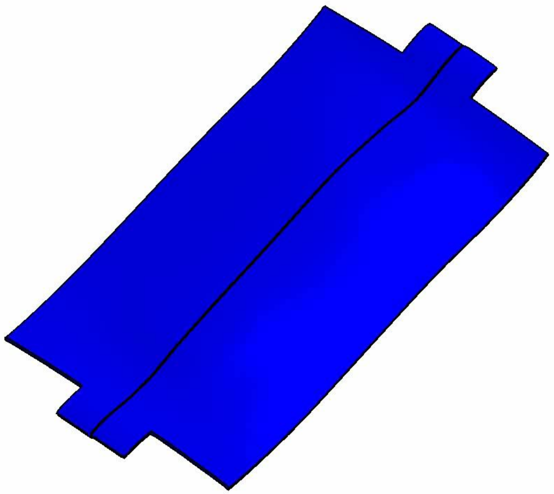
- Shells after forming

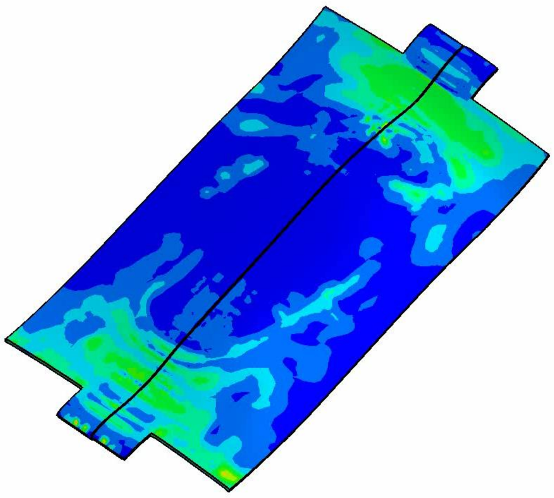


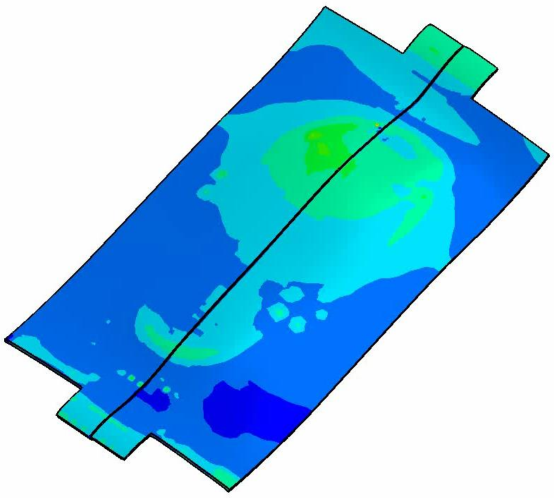
- Solids before welding



Welding simulation





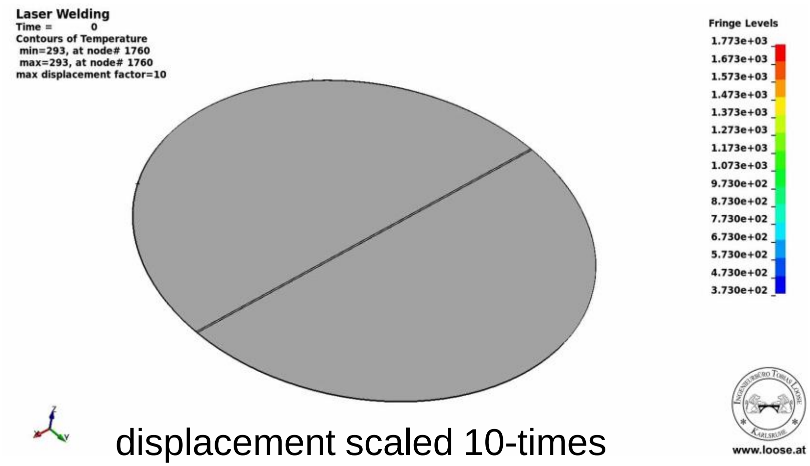


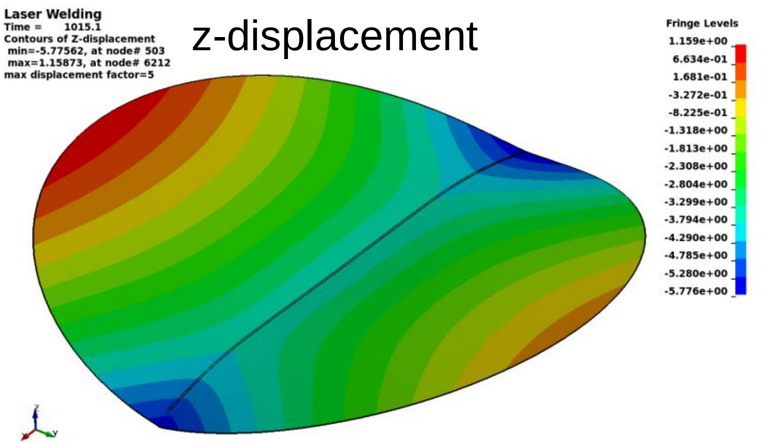
temperature

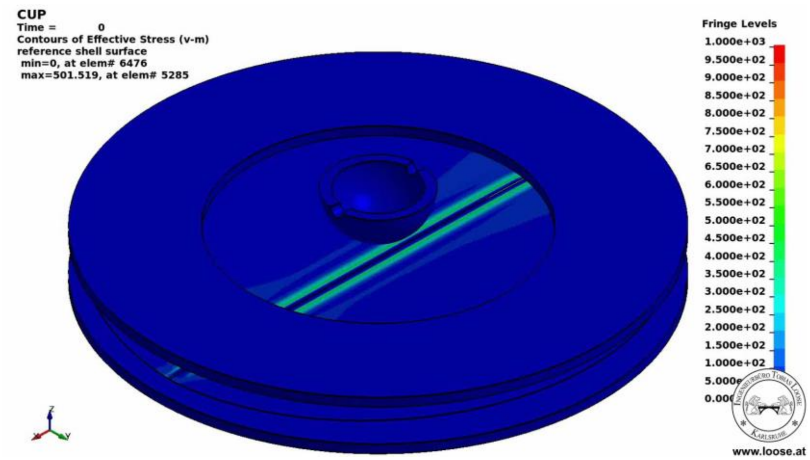
von Mises stress

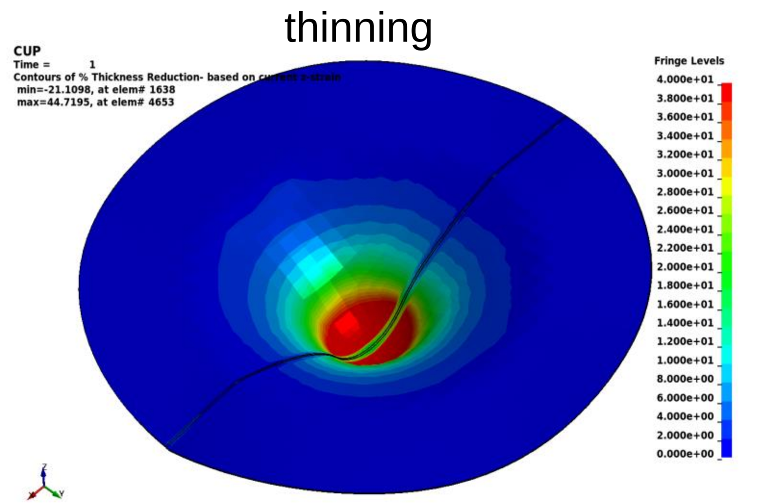
effective plastic strain

Manufacturing process chain including laser welds





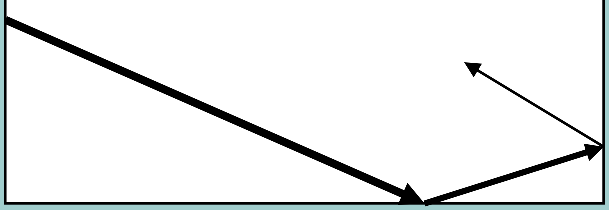




Thermal initial and boundary conditions

Temperature initial condition

radiation in a cavity
- diffuse
- specular



Boundary Conditions

temperature = f (time)

convection $q = hA\left(T - T_{\infty}\right)$

$$h = f(time, T_{film} = 0.5(T + T_{\infty}))$$

$$T_{\infty} = f(time)$$

radiation $q = \sigma\varepsilon FA\left(T^{4} - T_{\infty}^{4}\right)$

$$h = \sigma\varepsilon F = f(time, T)$$

$$T_{\infty} = f(time)$$

flux = f (time, T)

Thermo-mechanical coupling

Thermo-Mechanical Coupling

- Solvers are connected in a staggered solution scheme
  - Typical applications: welding simulation, hot stamping

Mechanical Solver

Based on the actual temperature
the mechanical solver calculates:

- Plastic work
- Contact gap and contact pressure
- Temperature dependent material properties
- Thermal expansion
- Update of the actual geometry

Explicit / Implicit (SMP & MPP)

Thermal Solver

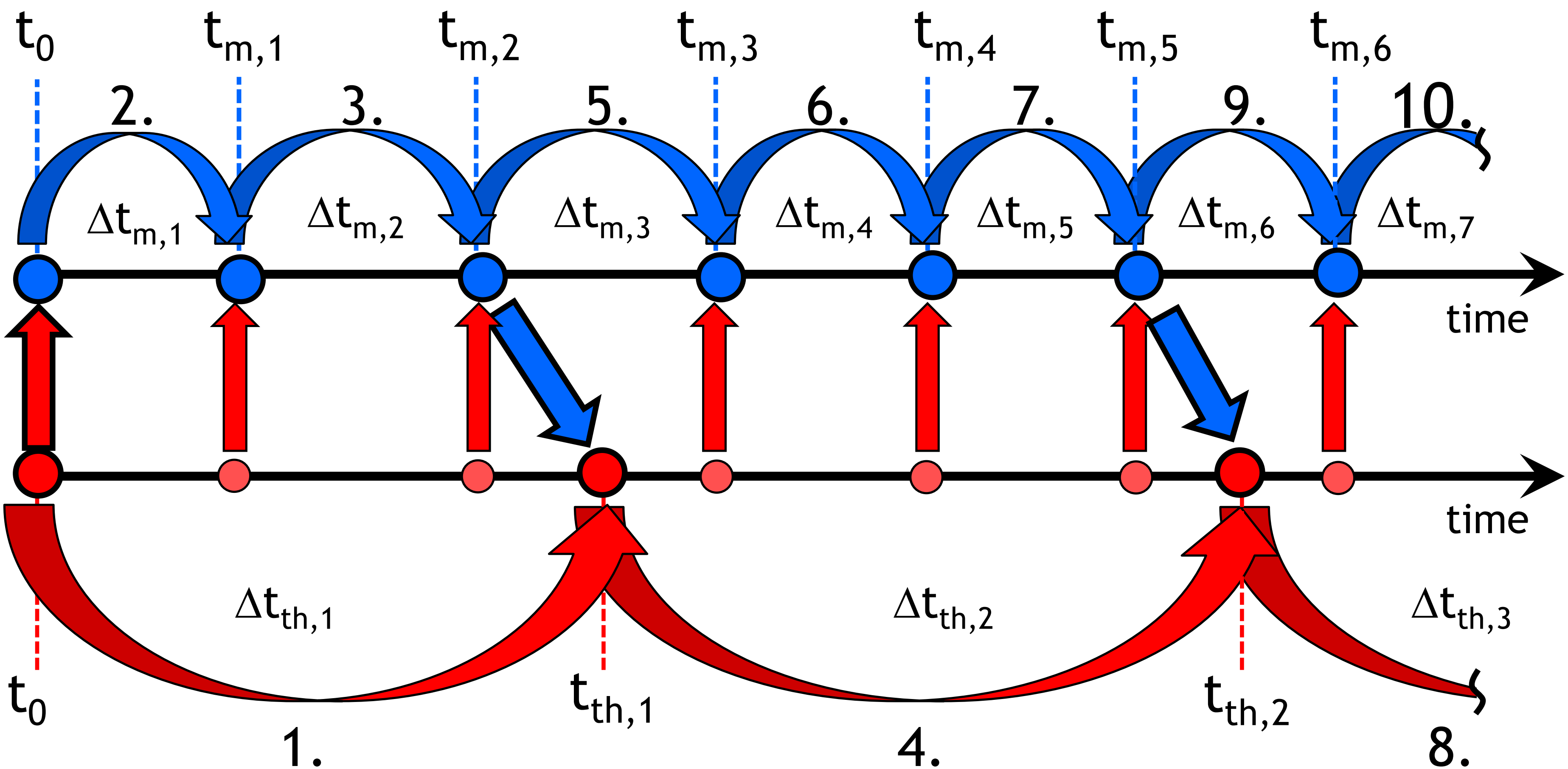
Based on the actual geometry
the thermal solver calculates:

- Heat source from plastic work
- Heat generated by sliding friction
- Contact heat transfer coefficient based on actual contact gap and pressure
- Update of the actual temperature

Implicit (SMP & MPP)

Thermo-Mechanical Coupling

Mechanical Problem

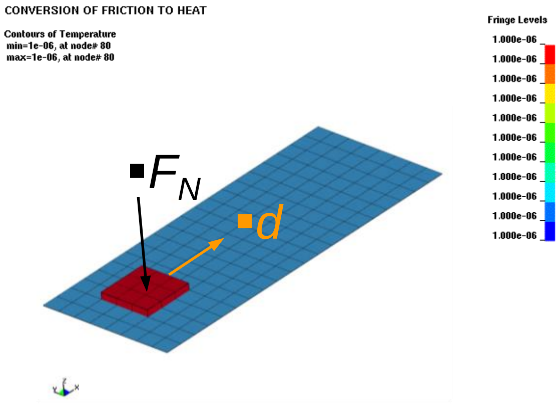


Thermal Problem

Thermal coupling effects

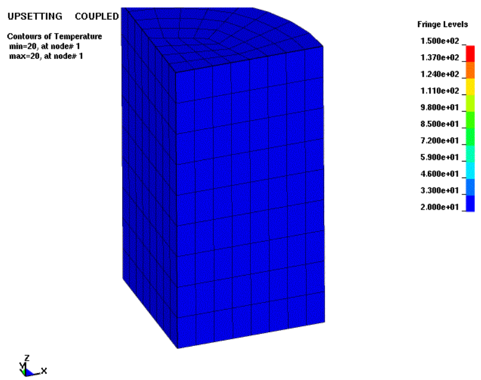
- Conversion of sliding friction energy into heat
  - Heat is distributed equally between contact surfaces
  - Energy calculation with

$$\mathcal{W}_{fric} = \mu \, F_N \, d$$



- Dissipation of plastic work into heat
  - Commonly 90 - 95% of plastic work is converted
  - Heat calculation using

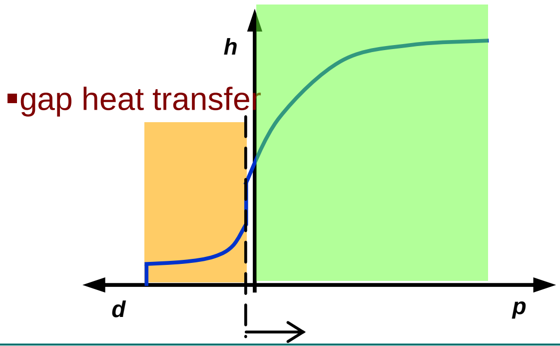
$$\mathcal{W}_{pl} = \rho \, c_p \, \Delta T = \eta \int_{\varepsilon_{pl}} \sigma^y \, \mathrm{d}\varepsilon_{pl}$$



- Thermal contact with heat transfer coefficient
  - heat transfer in gap

$$h_{gap} = \frac{k}{L_{gap}} + f_{rad} \, (T + T_\infty)(T^2 + T_\infty^2)$$

  - Heat transfer coefficient may depend on contact pressure , temperature of slave and master, …



Heat Sources

Goldak double ellipsoid heat source

- Double ellipsoidal power density distribution proposed in [Goldak2005]

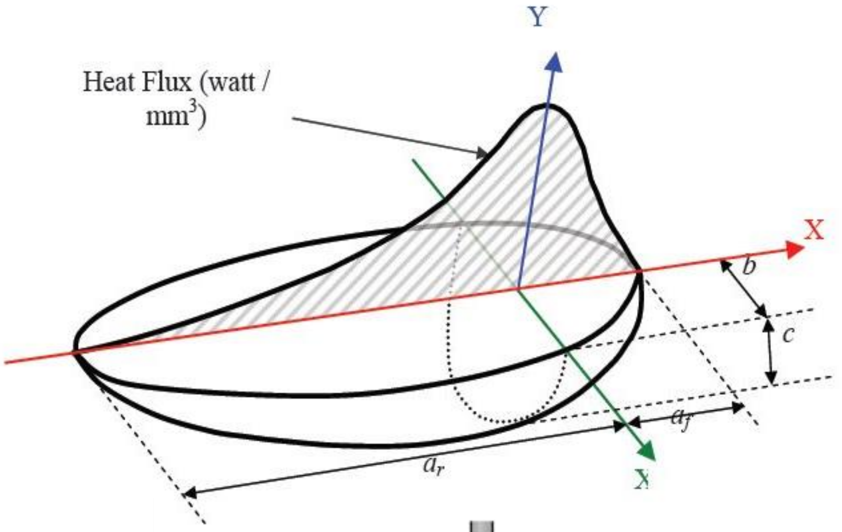
$$q = \frac{6\sqrt{3}FQ}{\pi\sqrt{\pi}abc}\exp\left(\frac{-3x^2}{a^2}\right)\exp\left(\frac{-3y^2}{b^2}\right)\exp\left(\frac{-3z^2}{c^2}\right)$$

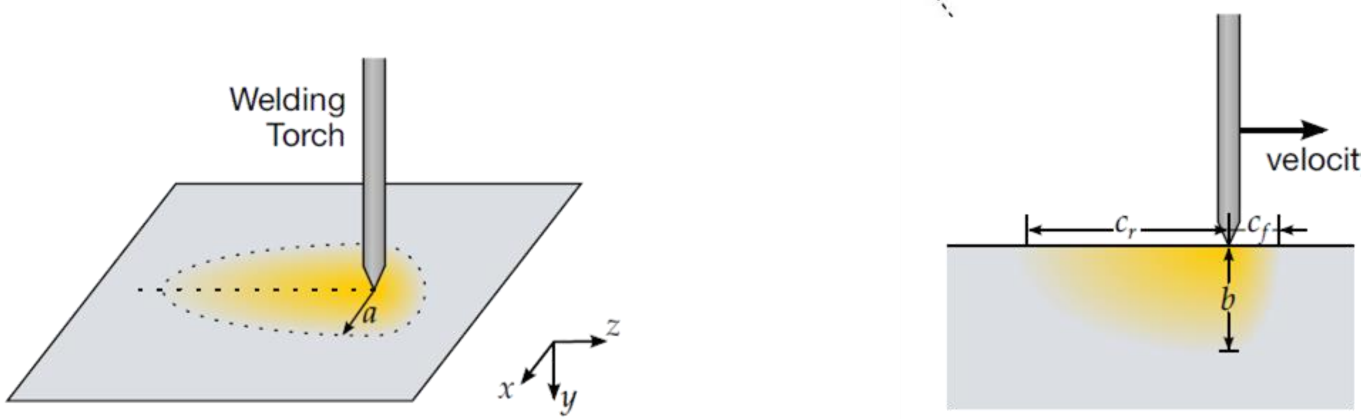
q = weld source power density

(x, y, z) = coordinates of point p in weld material

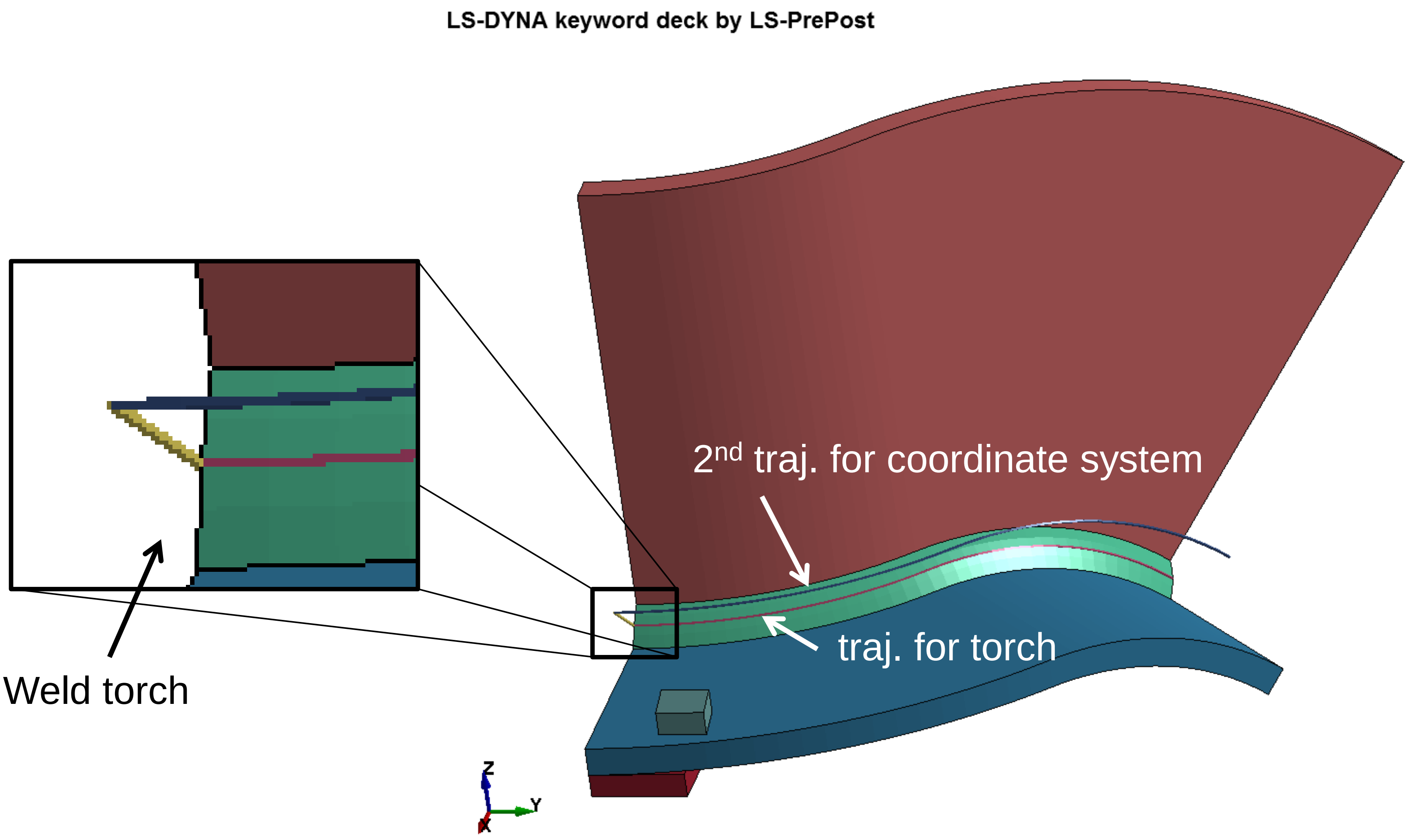
$$F = \begin{cases} F_f \text{ if point } p \text{ is in front of beam} \\ F_r \text{ if point } p \text{ is behind beam} \end{cases}$$

$$c = \begin{cases} c_f \text{ if point } p \text{ is in front of beam} \\ c_r \text{ if point } p \text{ is behind beam} \end{cases}$$

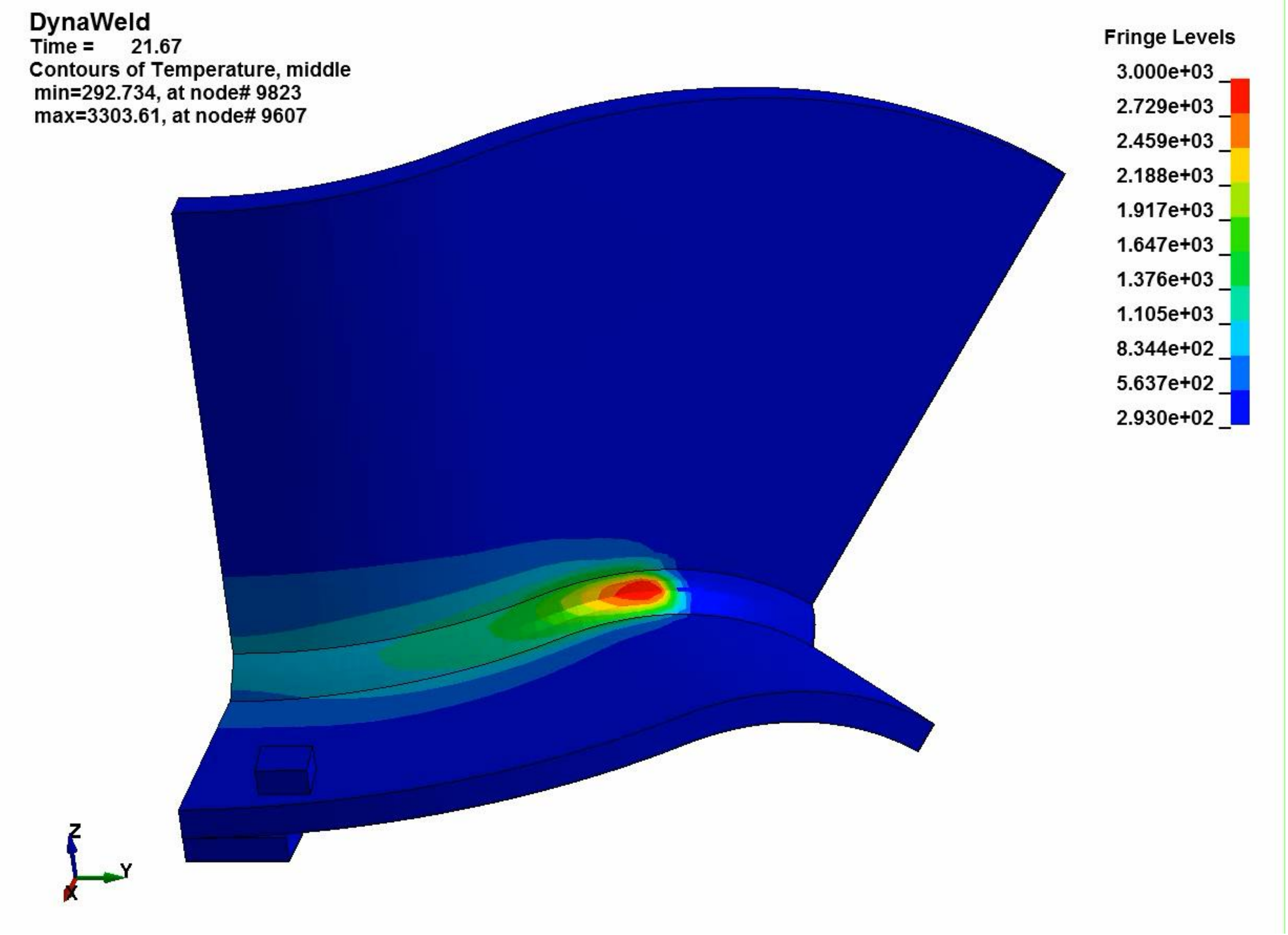




Movement of the heat source - example

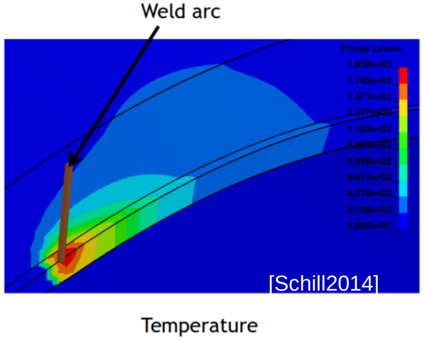


Movement of the heat source - example



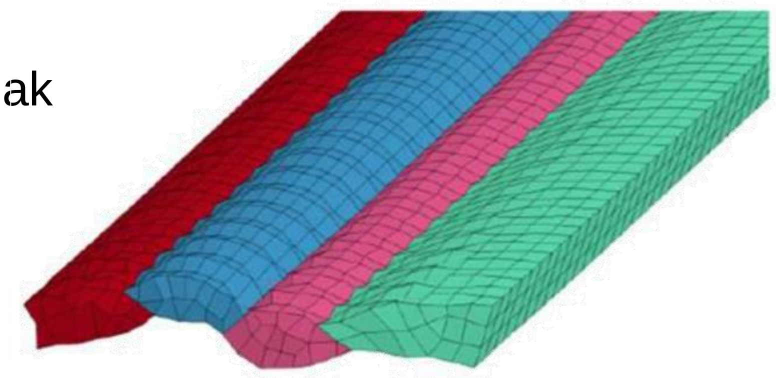
Discussion of the standard Goldak heat source

- Beam motion allows defining the translation and rotation of the heat source



- For previously deformed or curved structures, the description of the heat source is NOT straight-forward

- Movement of the part has to be compensated for



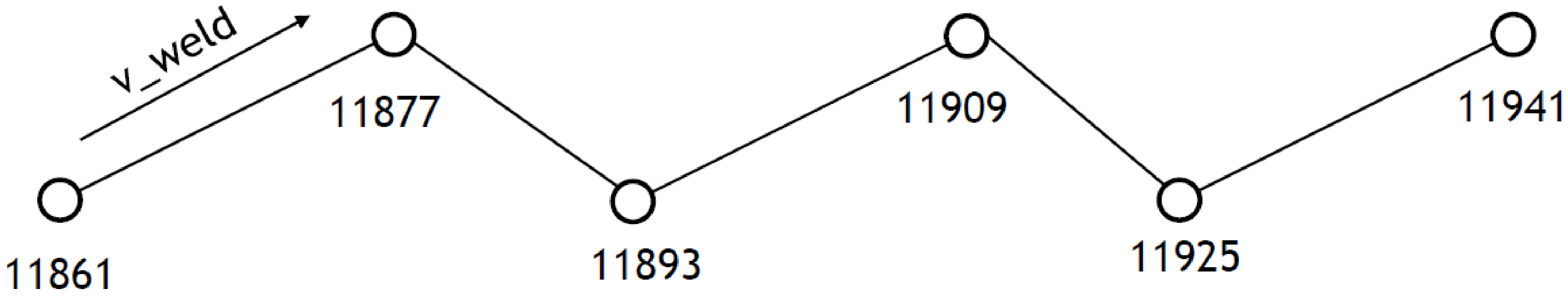
- The incremental heating when using the Goldak heat source leads to element distortion when a too large timestep is used.

- The mechanical solver is needed to move the heat source even though this should be solvable using only the thermal solver.

A new heat source approach

- Define heat source and movement within one definition
- New possibilities to define weld path:
  - The heat source follows a prescribed velocity along a node path (*SET_NODE)
  - The heat source is perpendicular to surface (*SET_SEGMENT)
- The weld path is continuously updated
- No need to include the mechanical solver

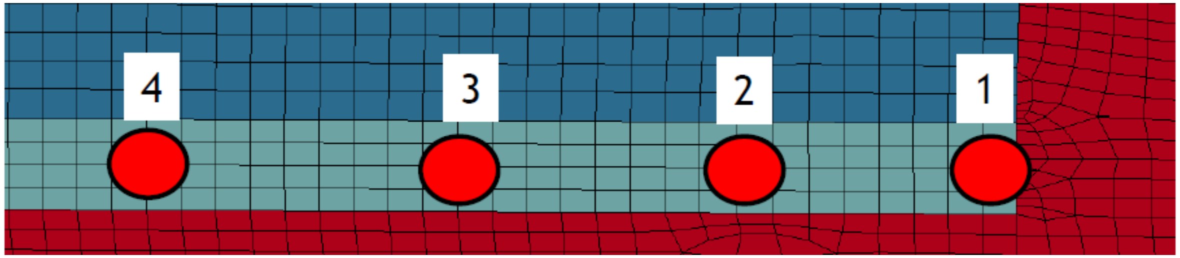
```
*SET_NODE_LIST
1
11861,11877,11893,11909,11925,11941
```



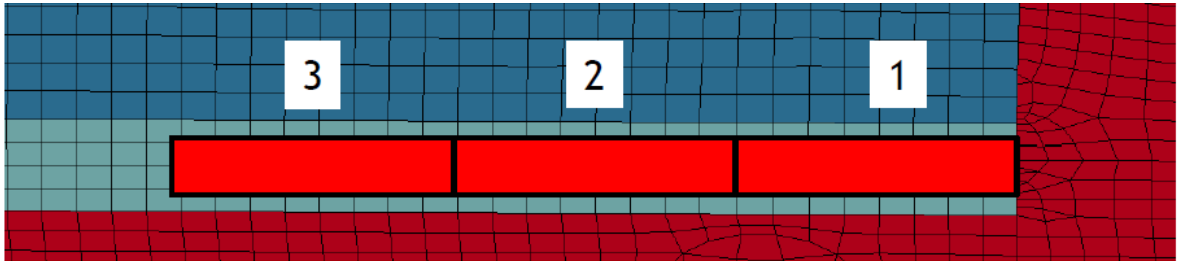
A new heat source approach

- Use “sub-timesteps” for integration of heat source

Weld source evaluated at thermal timesteps

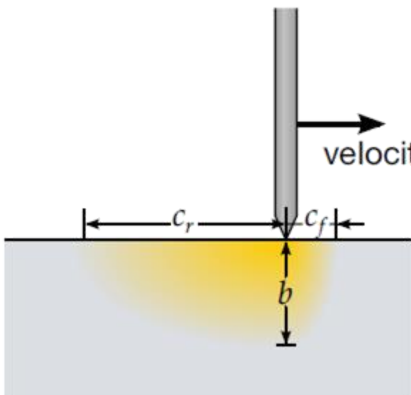


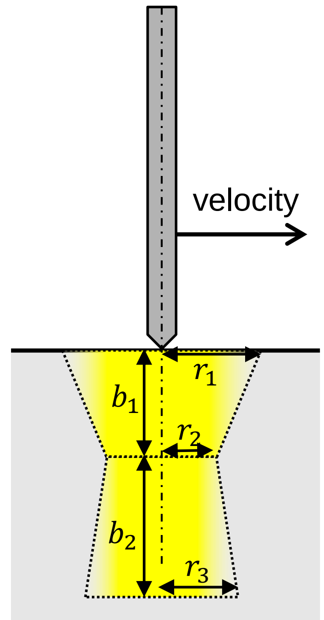
Weld source integrated between thermal time steps

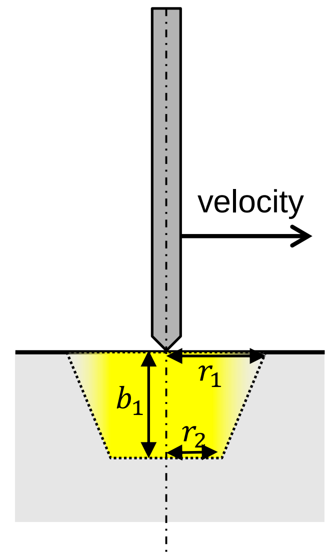


A new heat source approach

- More options for geometry of energy rate density distribution
  - EQ.1. Goldak-type heat source
  - EQ.2. double ellipsoidal heat source with constant density
  - EQ.3. double conical heat source with constant density
  - EQ.4. conical heat source

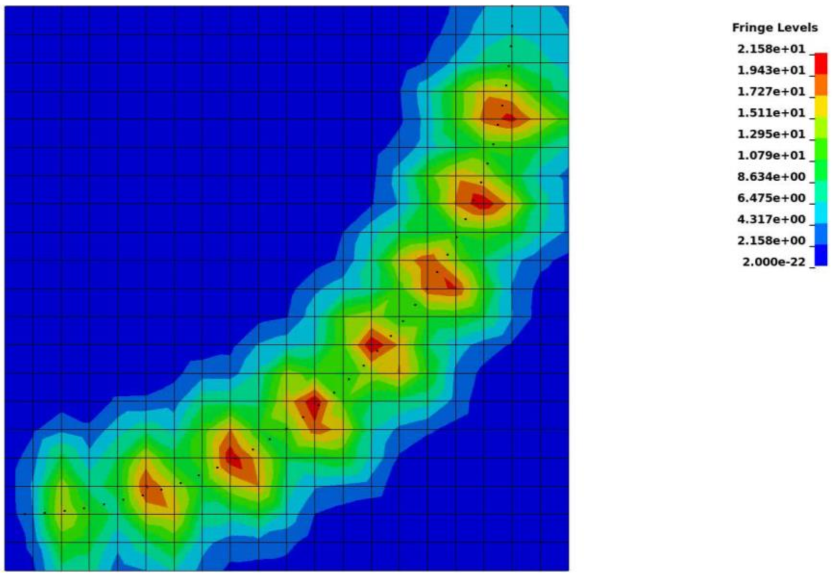






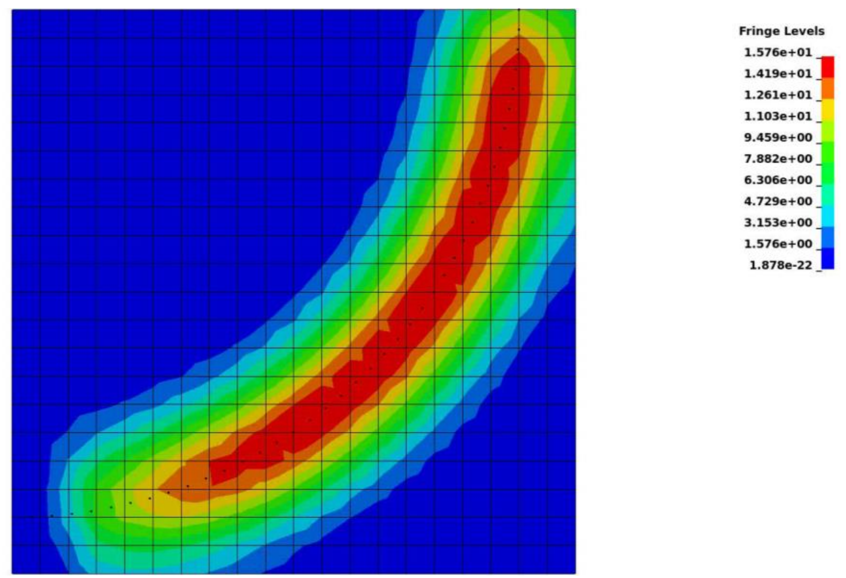
Example

- Welding on a circular trajectory
  - Thermal-only analysis with a large time step



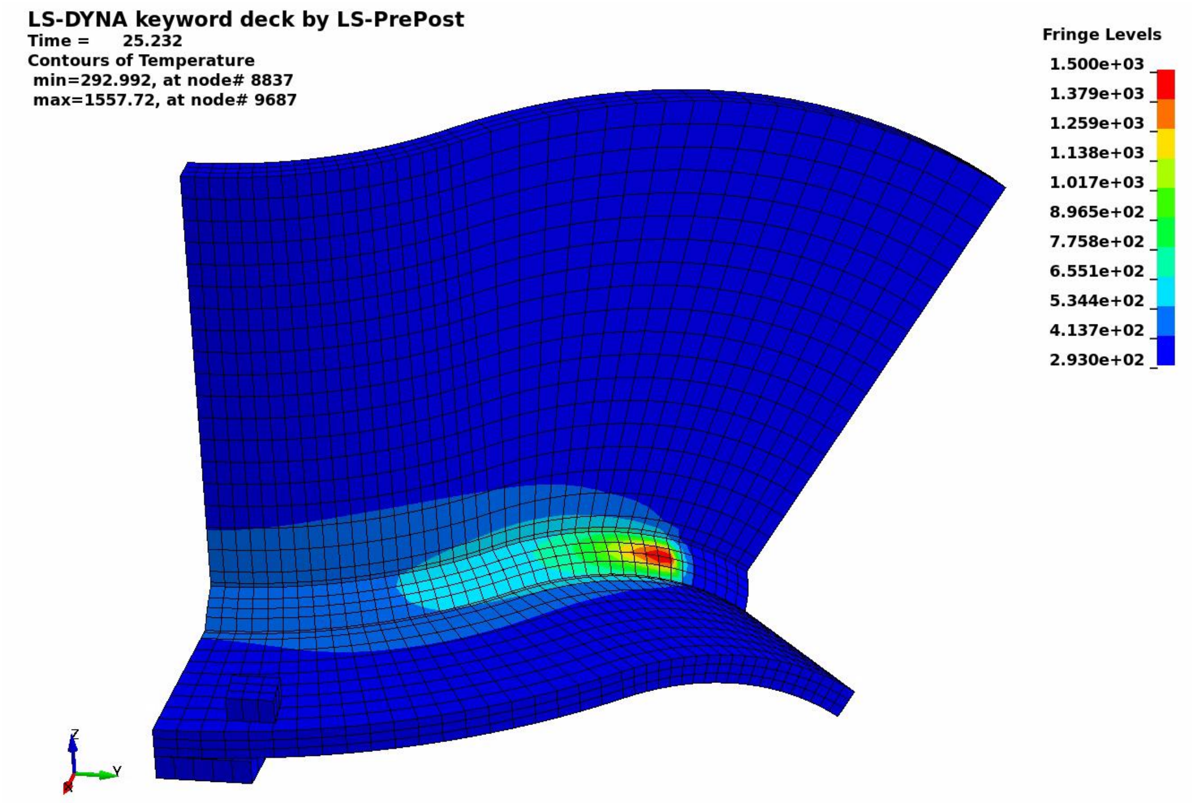
temperature field, NCYC = 1

temperature field, with 10 subtimesteps



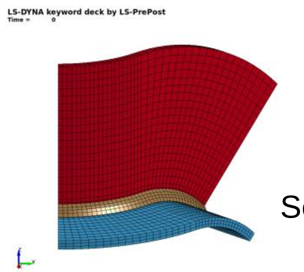
Example: curved T-Joint

- Welding of a three-dimensionally curved T-Joint
  - Coupled analysis
  - Weld source direction defined with a segment set

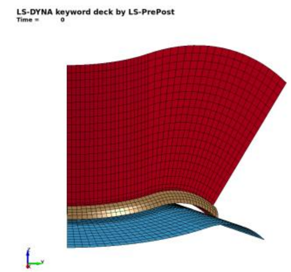


Example: curved T-Joint

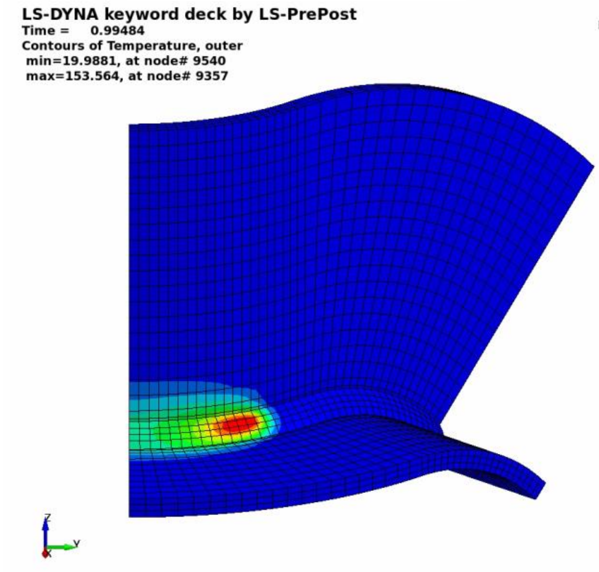
- New approach is also applicable to thermal thick shells
- Three-dimensional curved T-Joint, thermal-only analysis



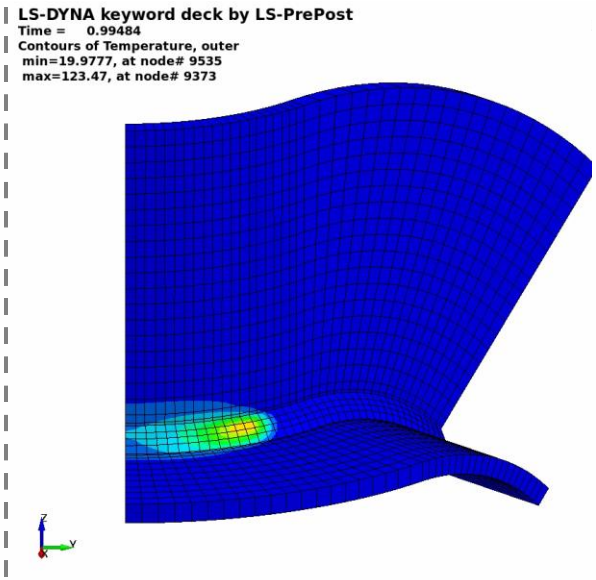
Solids



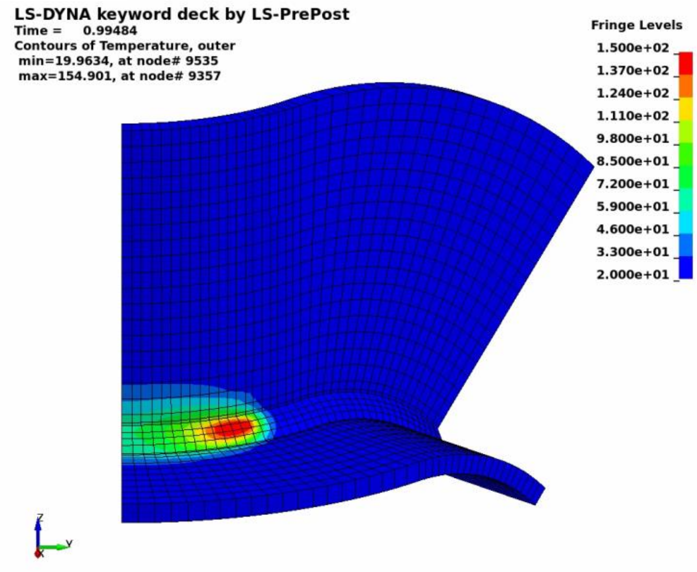
Solids and shells



BC on all solids



BC on solids only



BC on solids and shells

Heat sources with arbitrary shape

- In some cases the pre-defined heat sources are not suitable
- *LOAD_HEAT_GENERATION_*OPTION* might be useful

	1	2	3	4	5	6	7	8
Card 1	SID	LCID	CMULT	WBLCID	CBLCID	TBLCID		

  - LCID accepts a function id, that returns `heat(t,x,y,z)`

- *DEFINE_FUNCTION
  - Define arithmetic expressions involving a combination of independent variables and other functions
  - Function name must be unique (`heat` for heat generation)
  - Can be referenced in other functions
  - C-type or FORTRAN-style code is possible

LOAD_HEAT_GENERATION_*OPTION

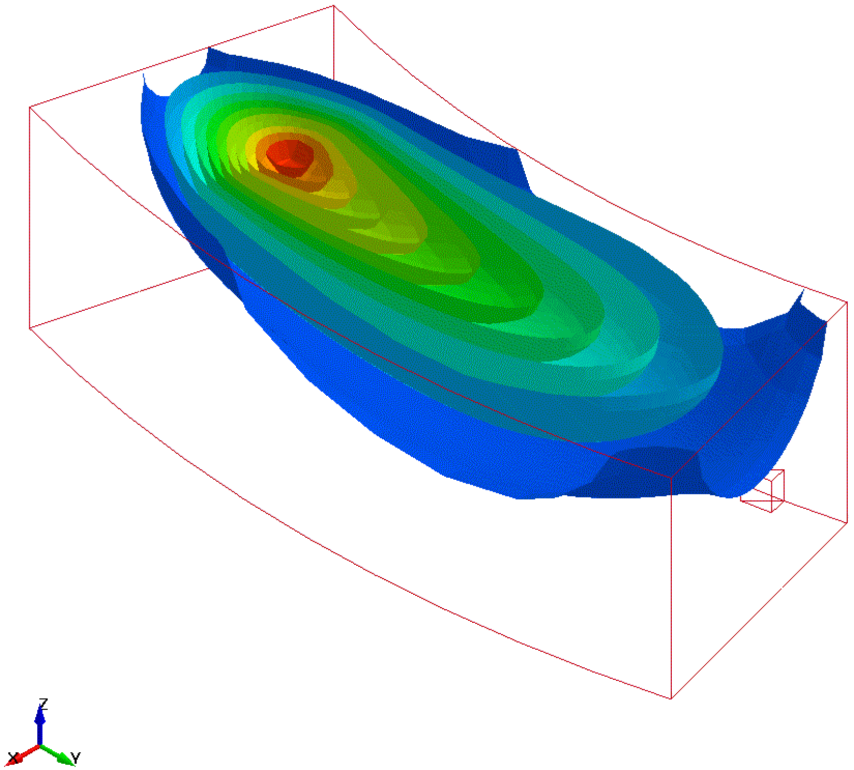
- Example: Define moving (along x) spherical heat source

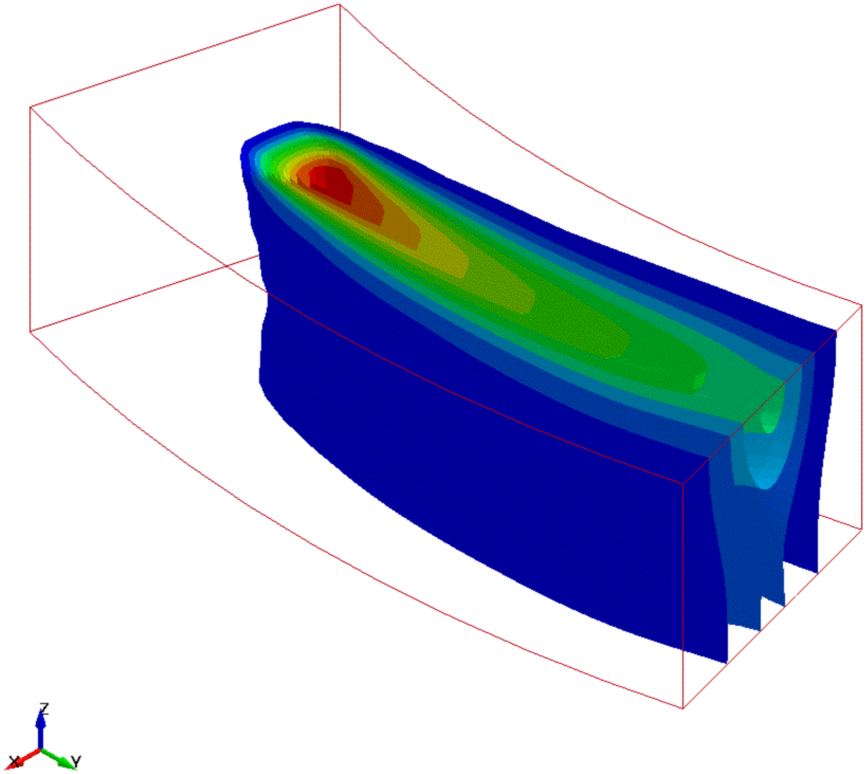
```
*LOAD_HEAT_GENERATION_SET
      1001      1001       1.0         0         0         0
*DEFINE_FUNCTION
      1001
float heat(float time, float x, float y, float z)
{   float xl,rl,f;
    xl=x-xt(time);
    if (xl**2+y**2+z**2>=1) f=0;
     else f= sqrt(1- xl**2+y**2+z**2);
     return f;}
*DEFINE_FUNCTION
      4001
float xt(float time)
{  float f = 10*time;
   return f;}
```

- `xl=x-xt(time);` ← x distance from center (reference)
- `if (xl**2+y**2+z**2>=1) f=0;` ← No heat generation outside sphere
- `else f= sqrt(1- xl**2+y**2+z**2);` ← Spherical heat source
- `float xt(float time)` ← Motion along x-axis with v=10

*LOAD_HEAT_GENERATION_OPTION

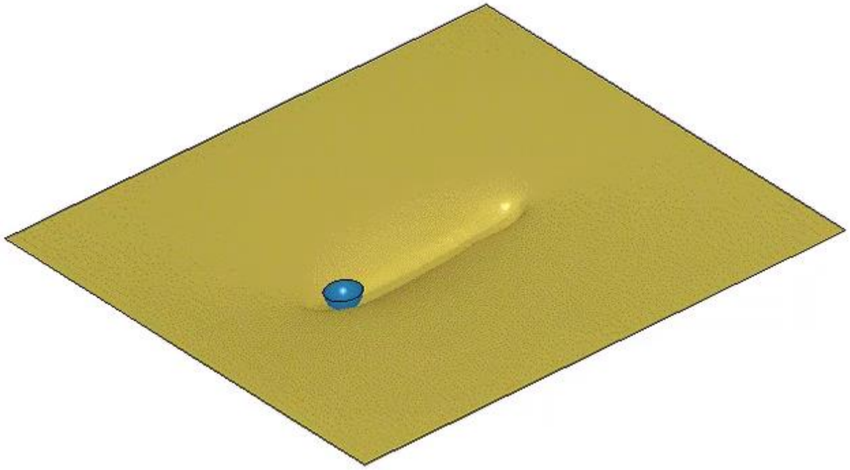
- Example:
  Temperature fields for a Goldak and a double cone-shaped heat source



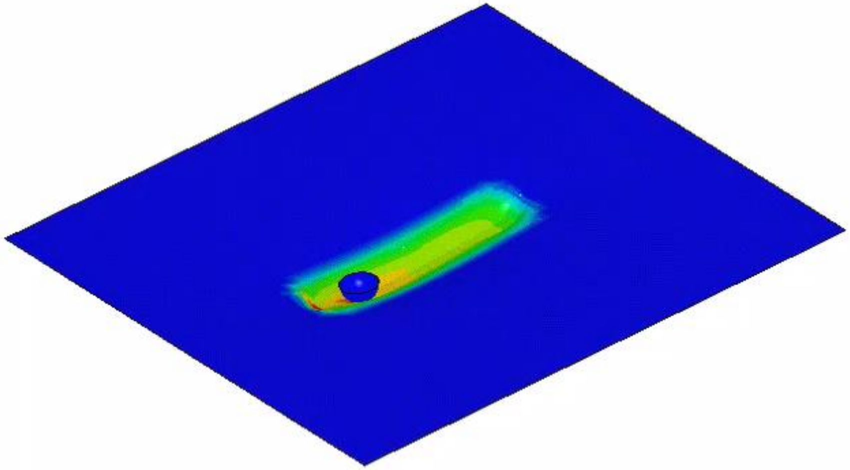


Heat source defined by flux boundary condition

- Laser assisted sheet forming:
  - the laser heats the material and softens it for forming
  - Energy from the laser is modeled using a flux boundary condition



Deformation

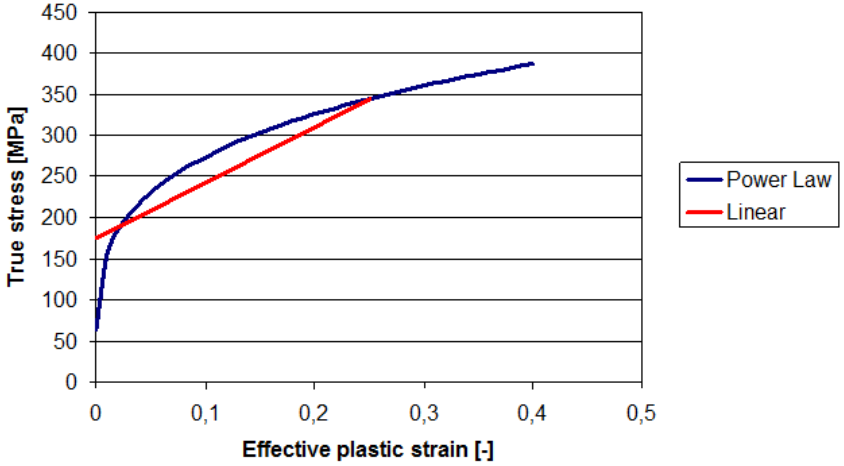


Temperature

Material Modeling

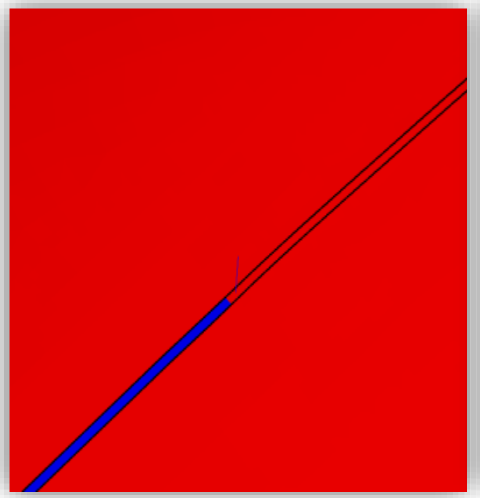
*MAT_CWM: Computational Welding Mechanics

- Both mechanical and thermal CWM model available
- Elements are initialy ”Ghost” or ”Silent” until activated at a specific temperature
  - typically very low stiffness, zero poissons ratio
  - neglible thermal expansion
  - low thermal conductivity
- After activation, material with temperature dependent
  - mechanical properties
  - Von-Mises plasticity with mixed isotropic/kinematic hardening
  - thermal expansion
  - thermal properties

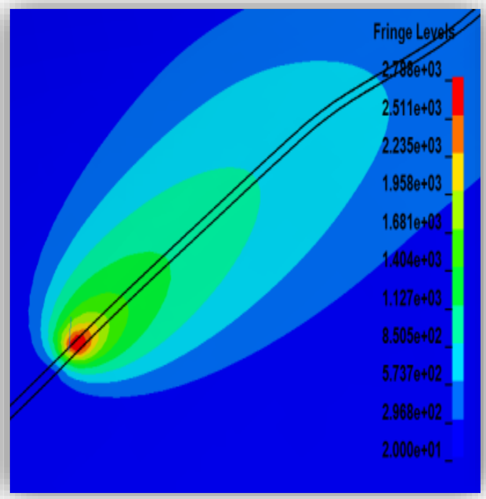


*MAT_CWM: Computational Welding Mechanics

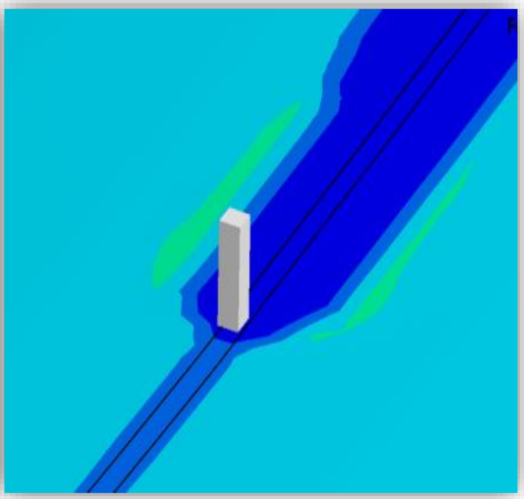
- Annealing at specific temperature
- Available for shell and solid elements



activation



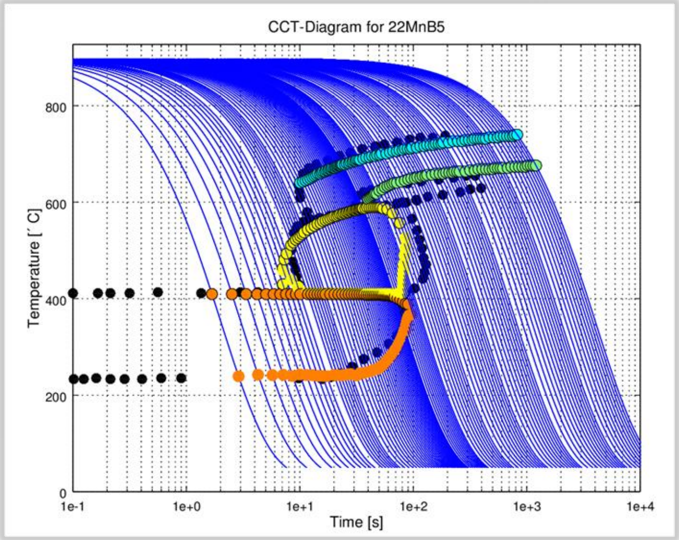
temperatures



annealing

*MAT_UHS_STEEL/*MAT_244

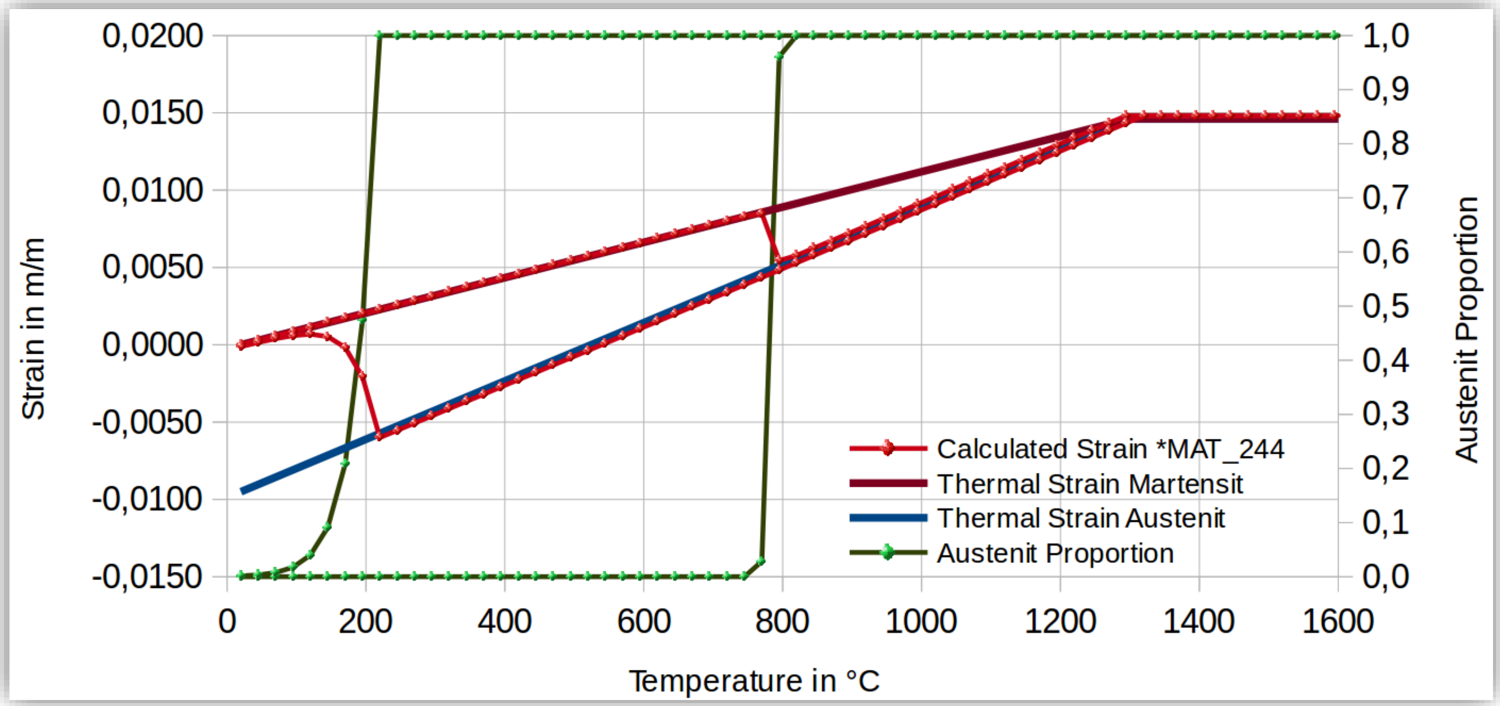
- Material tailored for hot stamping / press hardening processes
  - Phase transition of austenite into ferrite, pearlite, bainite and martensite for cooling
  - Strain rate dependent thermo-elasto-plastic properties defined for individual phases
  - Transformation induced plasticity algorithm
  - Re-austenitization during heating
  - User input for microstructure computations is chemical composition alone



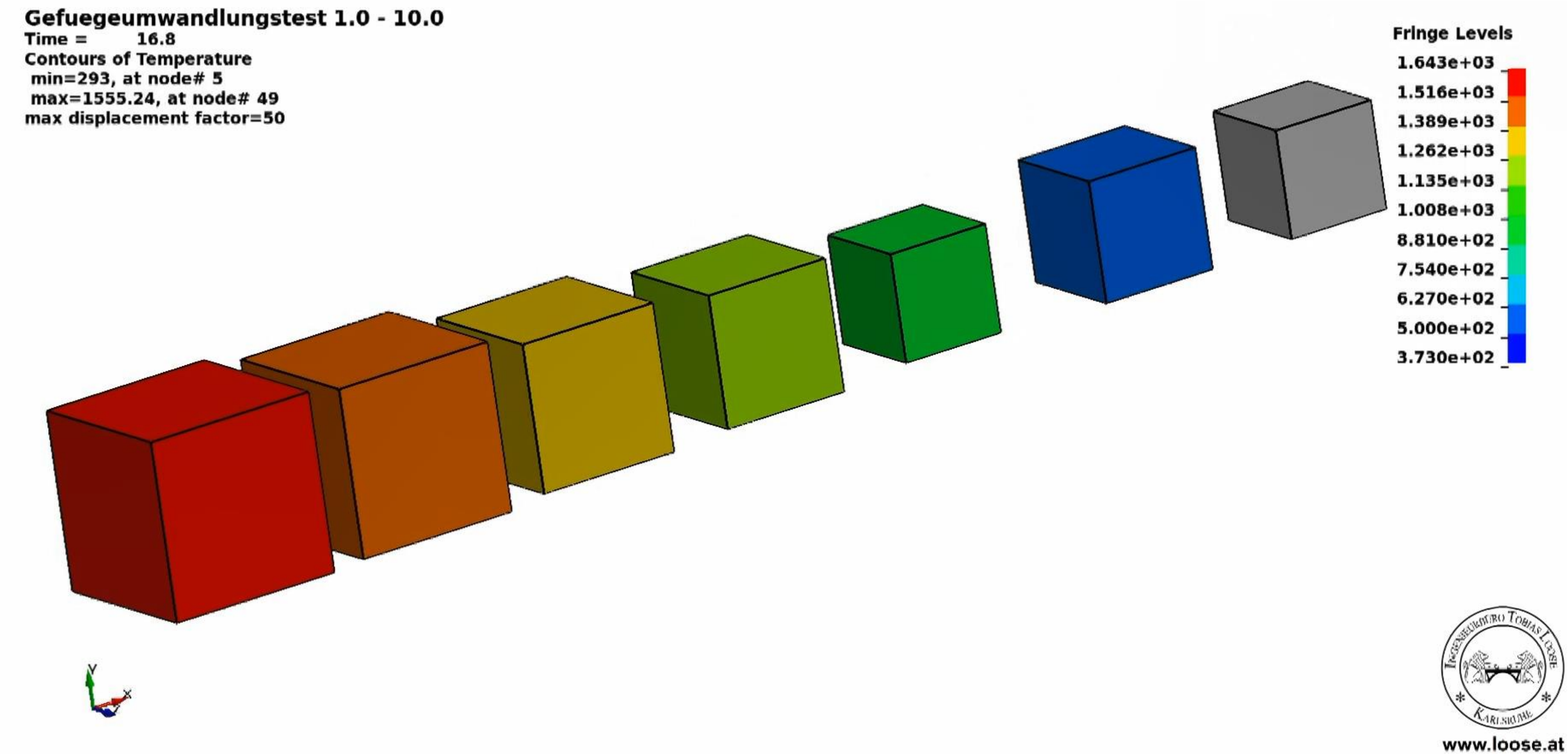
- Added:
  - Transformation induced strains
  - Welding functionality (“ghost” state)
  - Different transformation start temperatures for heating and for cooling

*MAT_UHS_STEEL / *MAT_244

- Temperature dependent definition for thermal expansion for austenite and the hard phases
- Dilatometer experiments show transformation induced strains as temperature dependent jumps



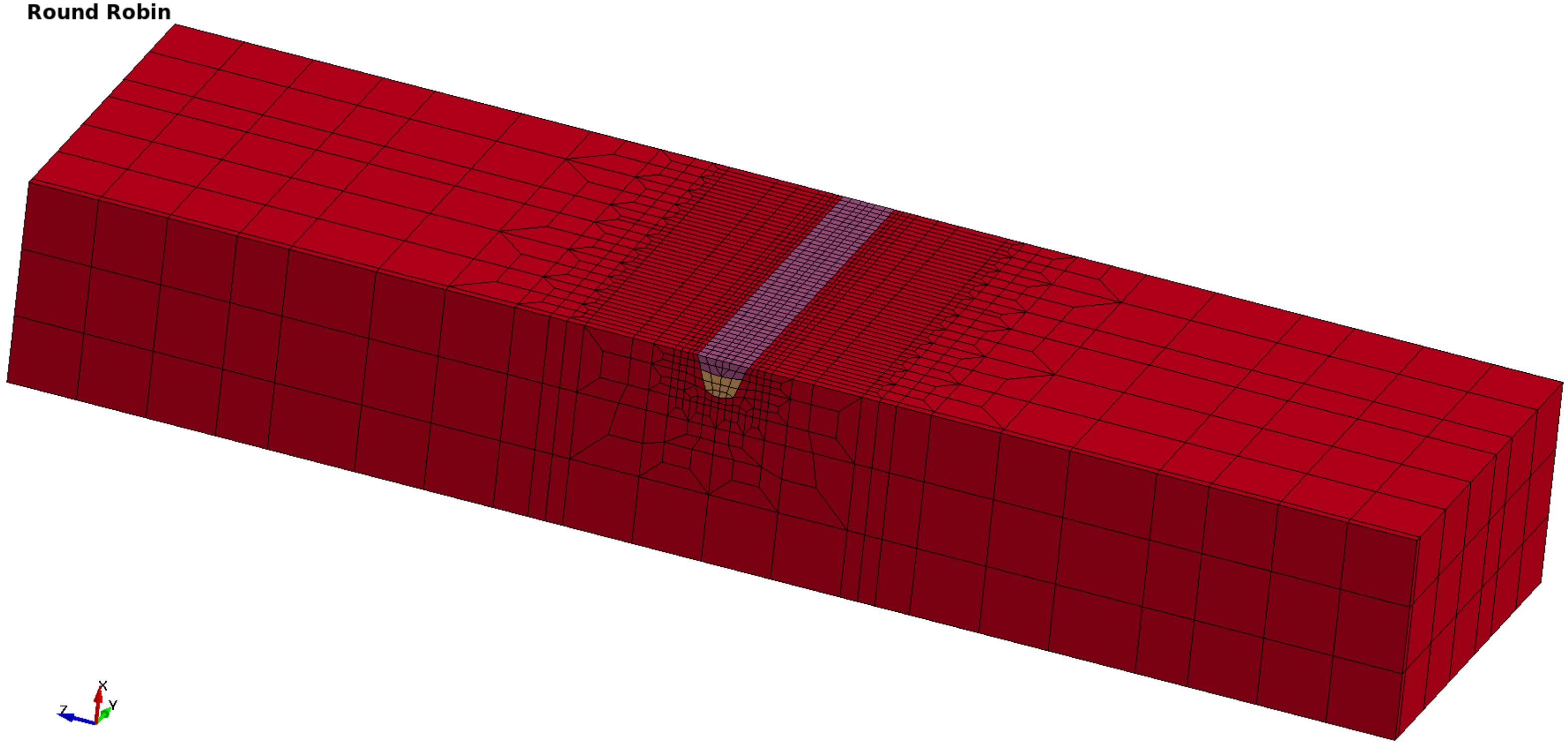
*MAT_UHS_STEEL / *MAT_244



*MAT_UHS_STEEL / *MAT_244

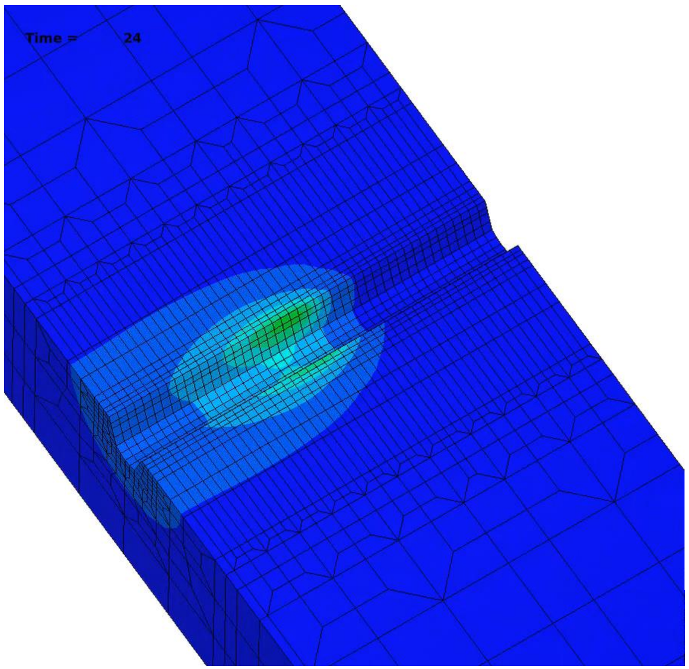
Example: Round Robin

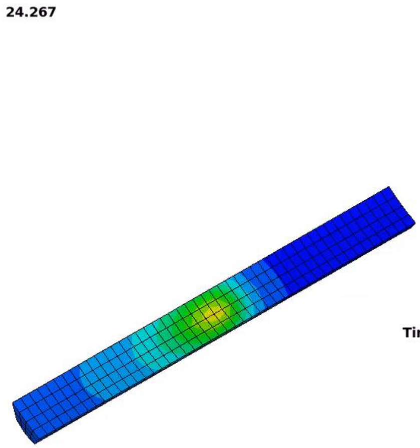
- Geometry: notched block with 2 weld seams
- All materials are initialized in ferrite phase

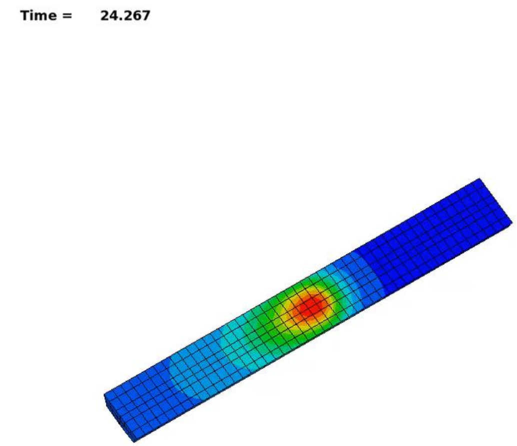


*MAT_UHS_STEEL / *MAT_244

- Temperature

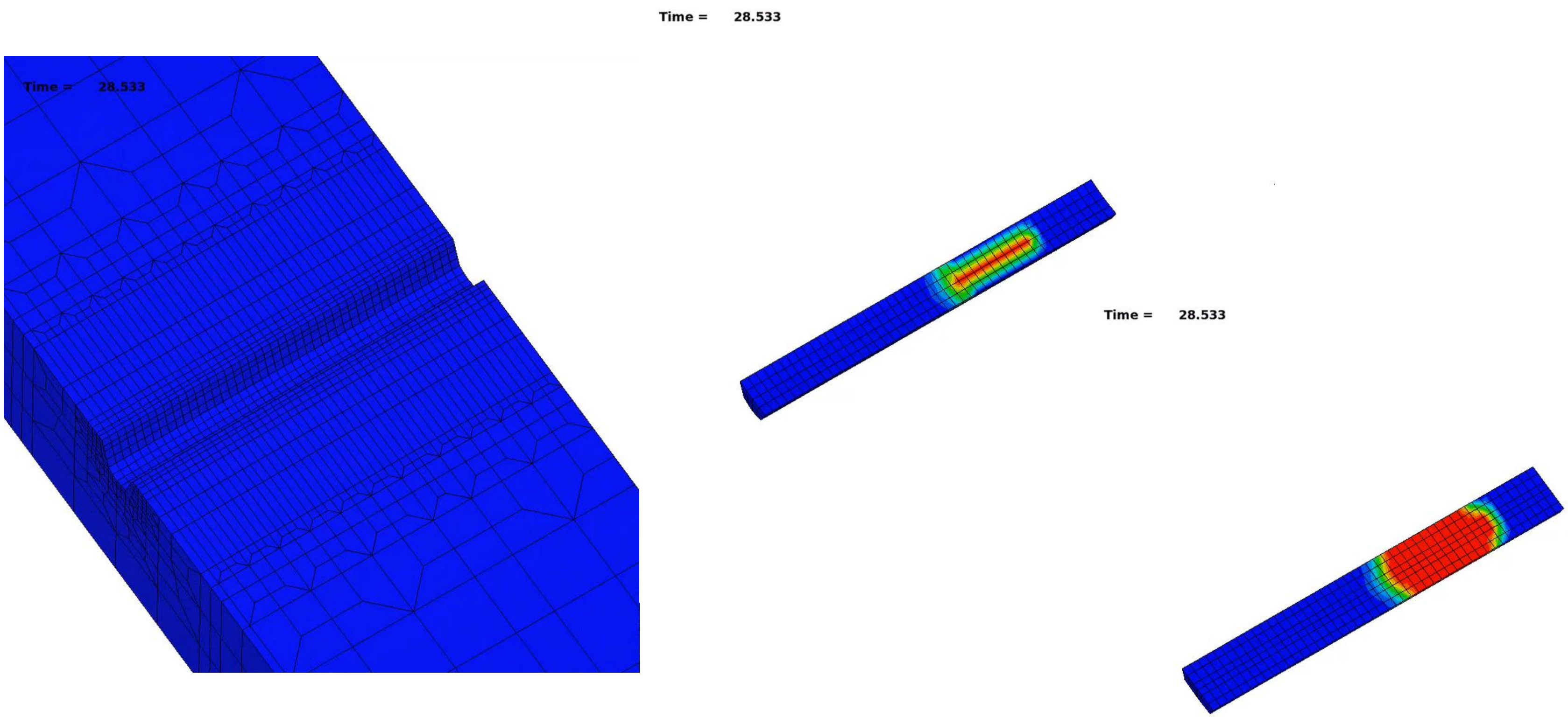






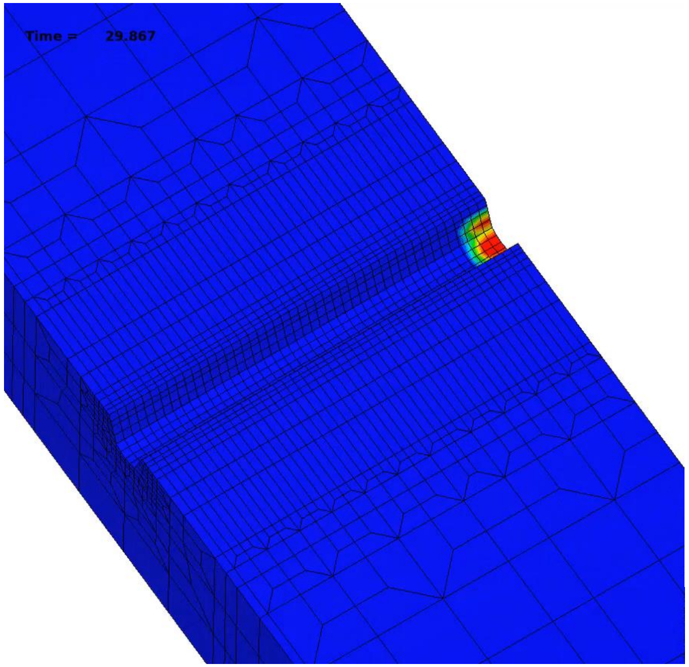
*MAT_UHS_STEEL / *MAT_244

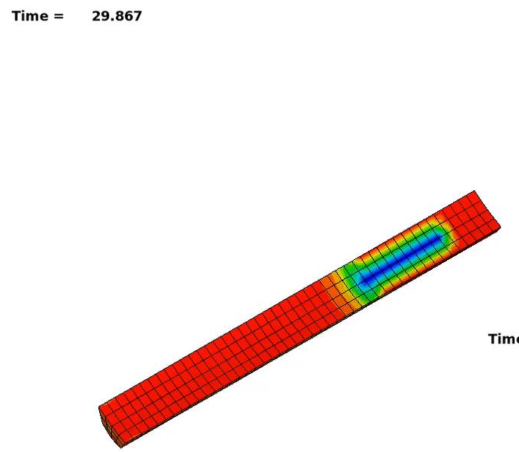
- Austenite concentration

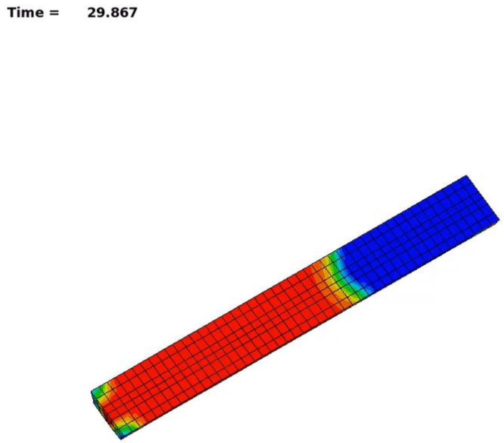


*MAT_UHS_STEEL / *MAT_244

- Martensite concentration

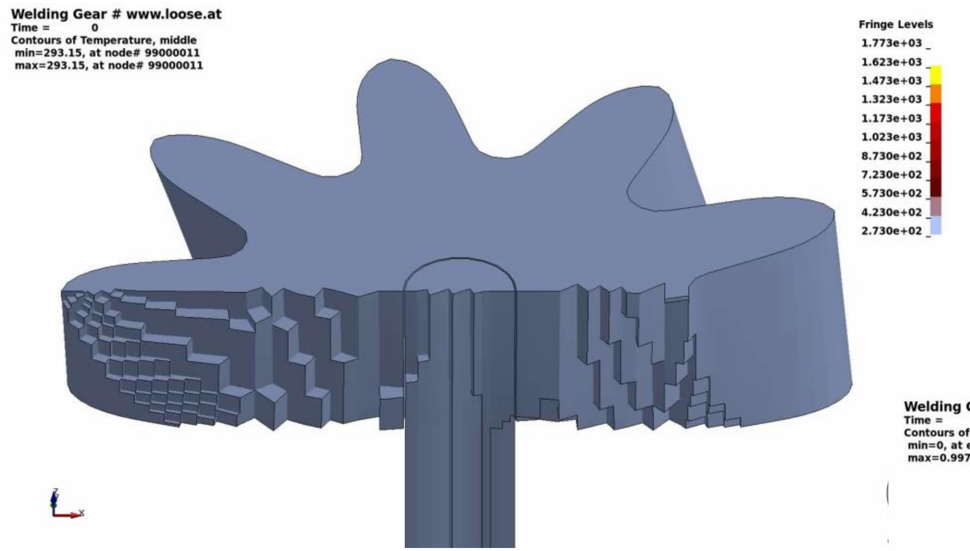






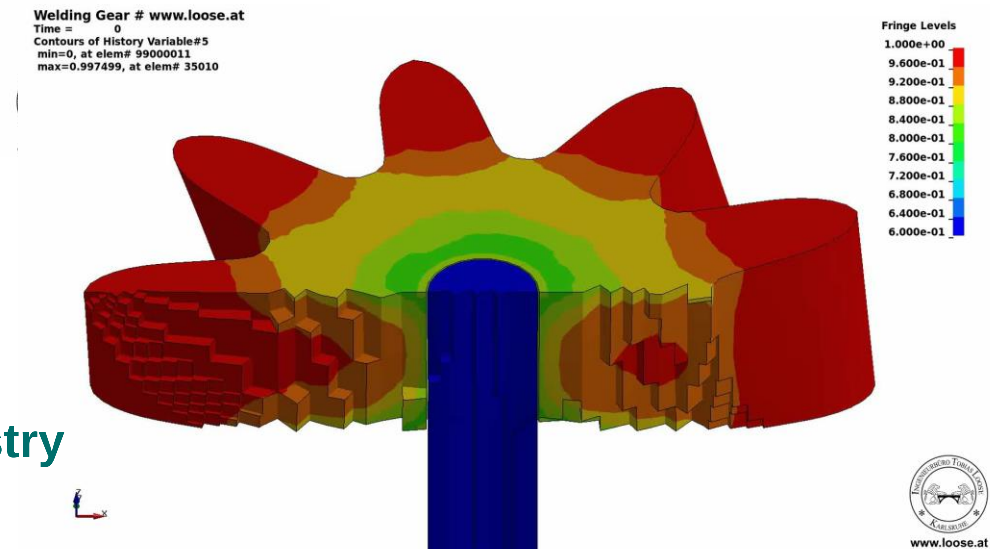
Example with *MAT_UHS_STEEL

- A gear is heated, quenched, welded to a joint



Temperature field

Martensite concentration



***MAT_244 is only valid for a narrow range of steel alloys!**

Heuristic formulas connecting chemistry with mechanics fail otherwise!

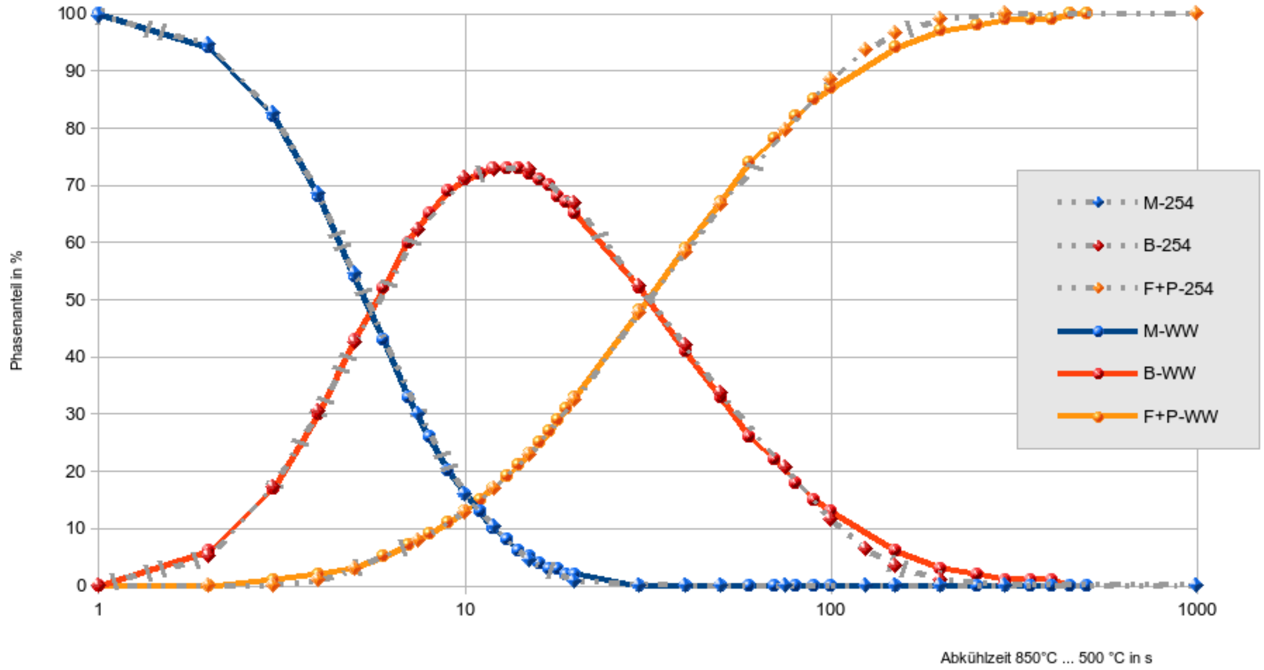
Latest Developments

*MAT_254

- Implementation of **`*MAT_GENERALIZED_PHASE_CHANGE`**
- Features
  - Up to 24 individual phases
  - User can choose from generic phase change mechanisms (Leblond, JMAK, Koistinen-Marburger,…) for each possible phase change
  - Material will incorporate all features of *MAT_244
  - Phase change parameters are given in tables and are not computed by chemical composition
- Will be suitable for a wider range of steel alloys and aluminum alloys
- Parameter of the material might come from a material database or a microstructure calculation

*MAT_254 with JMAK

- First example: Phase change test for steel S420



Welding without filler elements

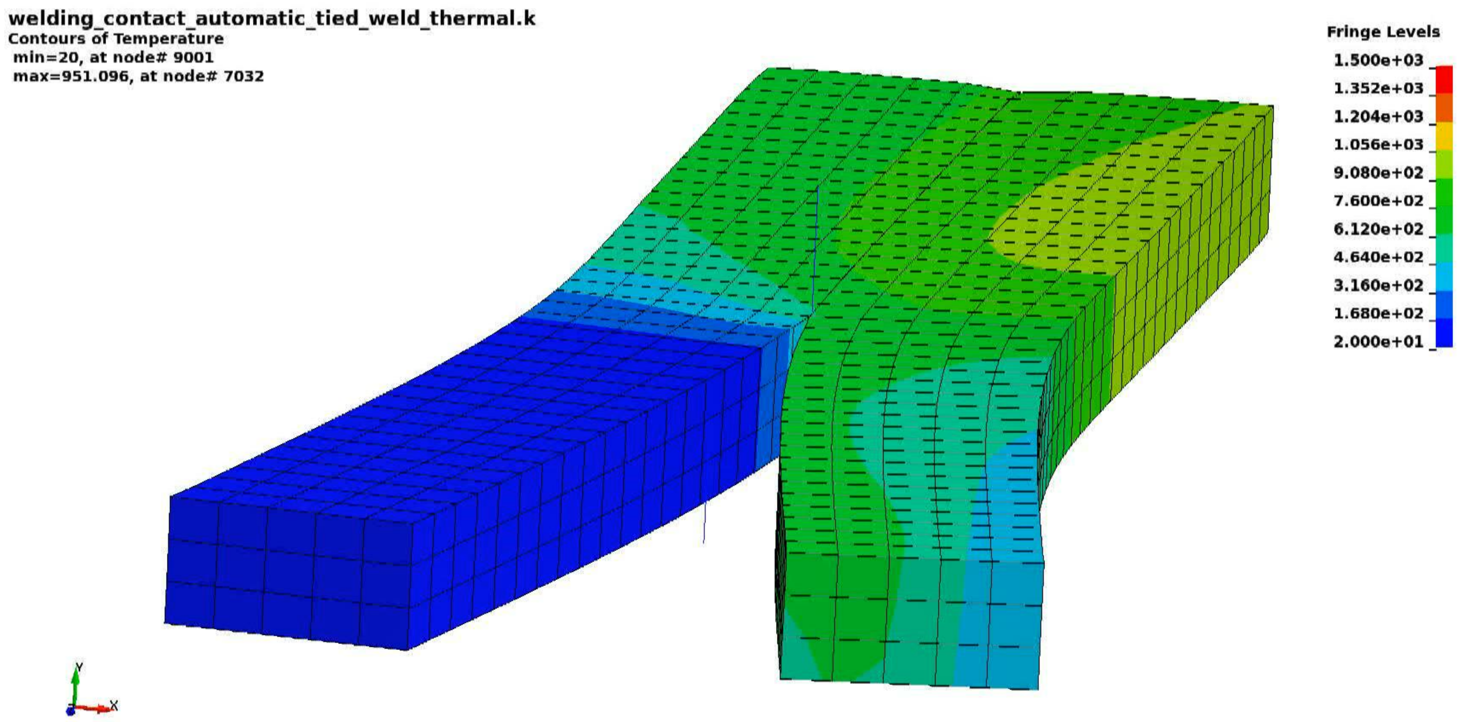
- Ghost element approach is not suitable for all welding processes
  - No material might be added in the process
  - Significant sliding of parts before welding

- New contact formulation *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL
  - As regions of the surfaces are heated to the welding temperature and come into contact, the nodes are tied
  - Regions in which the temperature in the contact surface is always below the welding temperature, standard sliding contact is assumed
  - Heat transfer in the welded contact zones differs as compared to unwelded regions

  - Right now, only implemented for contact between solid elements

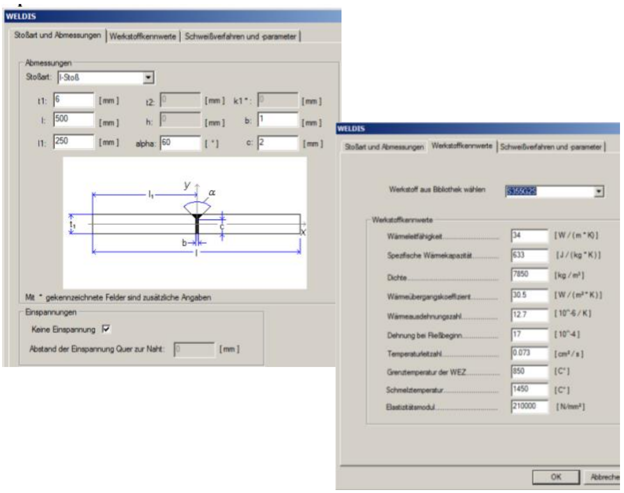
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL

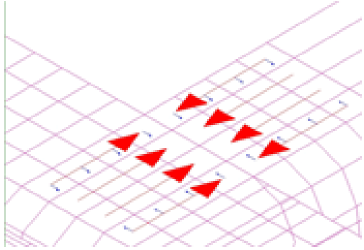
- Example: butt weld
  - During welding the blocks are allowed to move
  - Assumption: Insulation in unwelded state, perfect heat transfer after welding

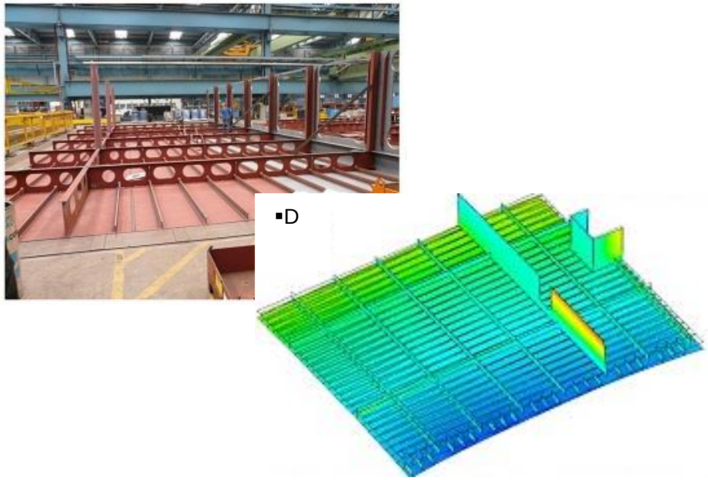


Hybrid welding simulation

- Analytic-numerical hybrid approach for calculating welding distortions developed at the BTU Cottbus







▪*Courtesy of BTU Cottbus*

- Analytical model calculates longitudinal and transversal strains and their distribution for every single weld.
- Mechanical loads are applied on an elastic FE-model of the structure.

→ Prediction of distortions for large structures with long weld seams

→ well suited for optimization of welding process

Summary

LS-DYNA offers many special features for welding simulations:

- Realistic modeling of welding heat source
  - Goldak and other heat source geometries
  - Flexibility for arbitrarily shaped heat sources
- Material modeling for welding:
  - Ghosting approach that allows to deal with filler materials in weld seams
    - MAT_CWM: Computational Welding Mechanics
  - Comprehensive material formulations including microstructure phase changes
    - MAT_244 for certain UHS steel alloys
    - MAT_254 under development for a large variety of different metals
- Special welding contact

➔ **LS-DYNA is a general purpose (Finite Element) solver that can be used to simulate the complete manufacturing process chain.**

Thank you for your attention!

Your LS-DYNA distributor and more