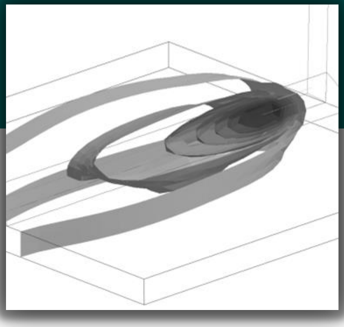
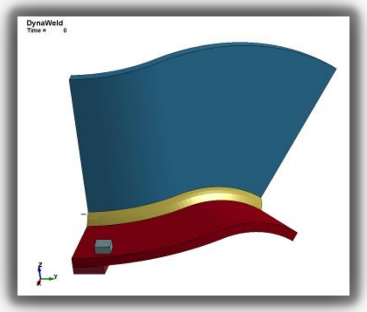


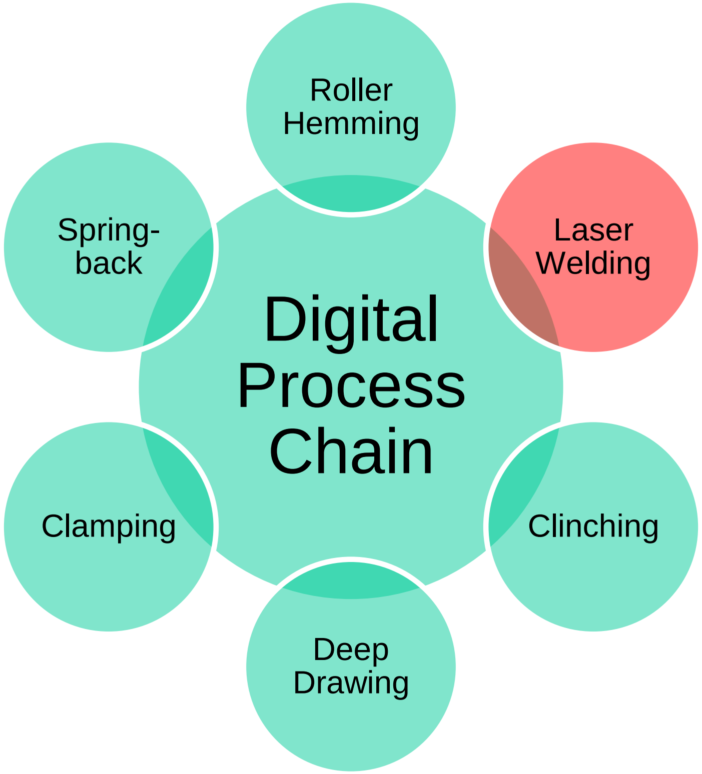


Using LS-DYNA for Simulation of Welding and Heat Treatment

Dr.-Ing. Thomas Klöppel

DYNAmore GmbH

Motivation – Process chain

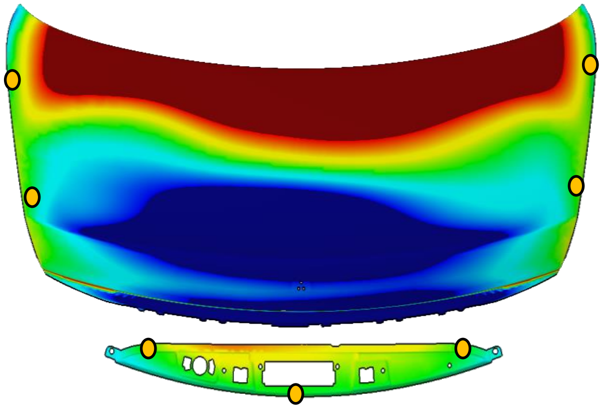


- For modern processes and materials, the mechanical properties of the finished part highly depend on the fabrication chain
- Numerical simulations of the complete process chain necessary to predict finished geometry and properties
- Welding stages particularly important
  - Locally very high temperature gradients
  - Large distortions
  - Changes in the microstructure of the material in the heat affected zone
- Compensation for springback and shape deflections

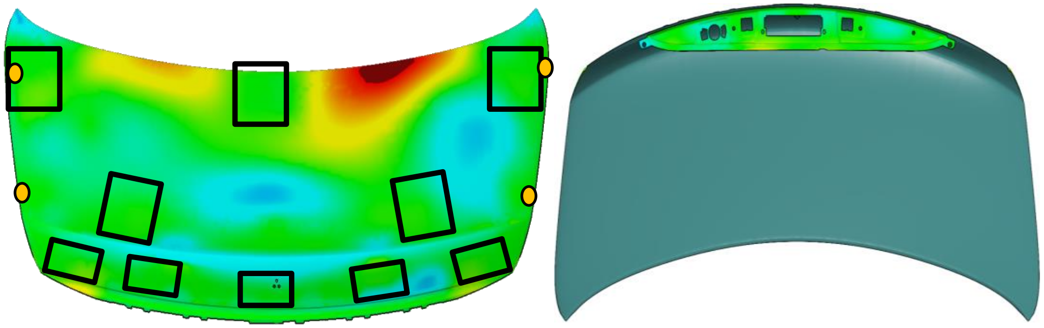
Motivation - Example

● alignment points

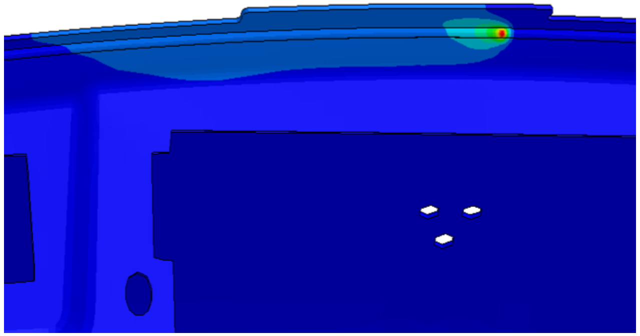
1 Deep drawing



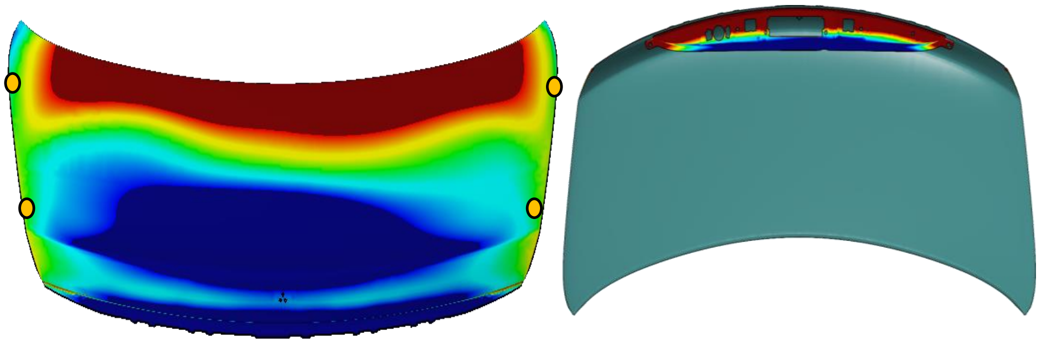
2 Clamping



3 Welding

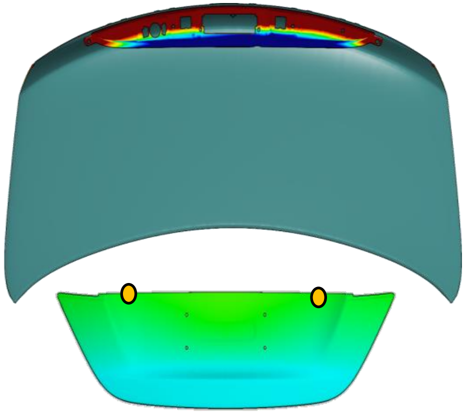


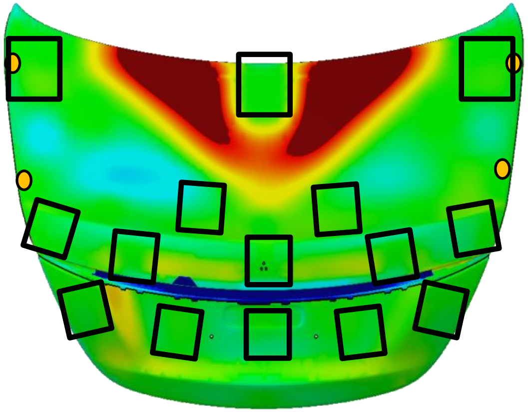
4 Springback

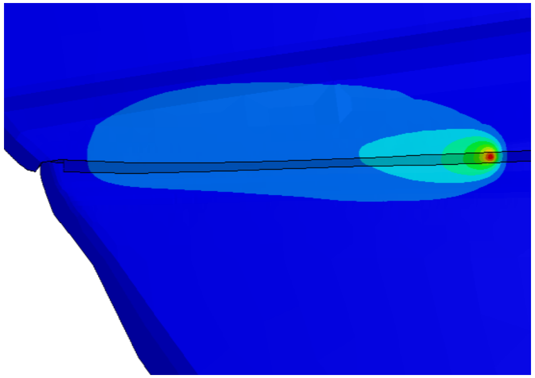


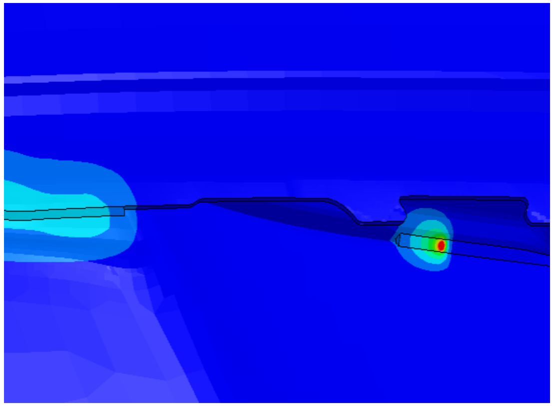
Motivation - Example

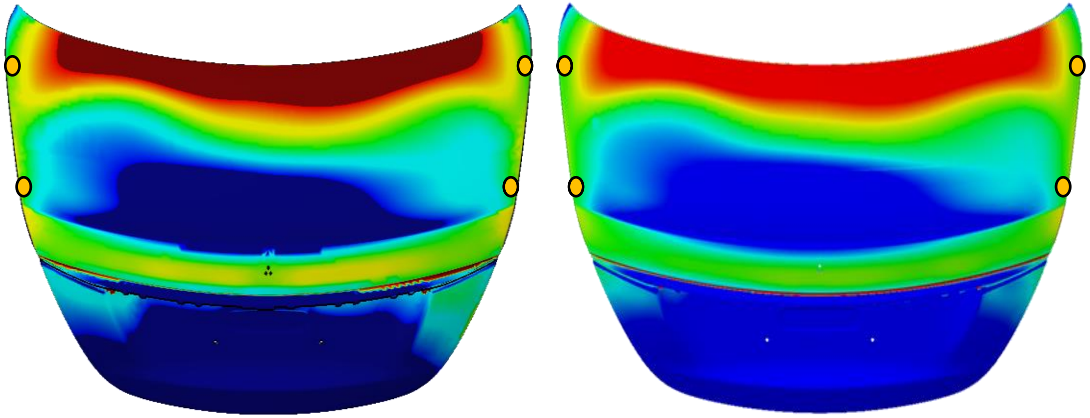
● alignment points


5 Deep drawing

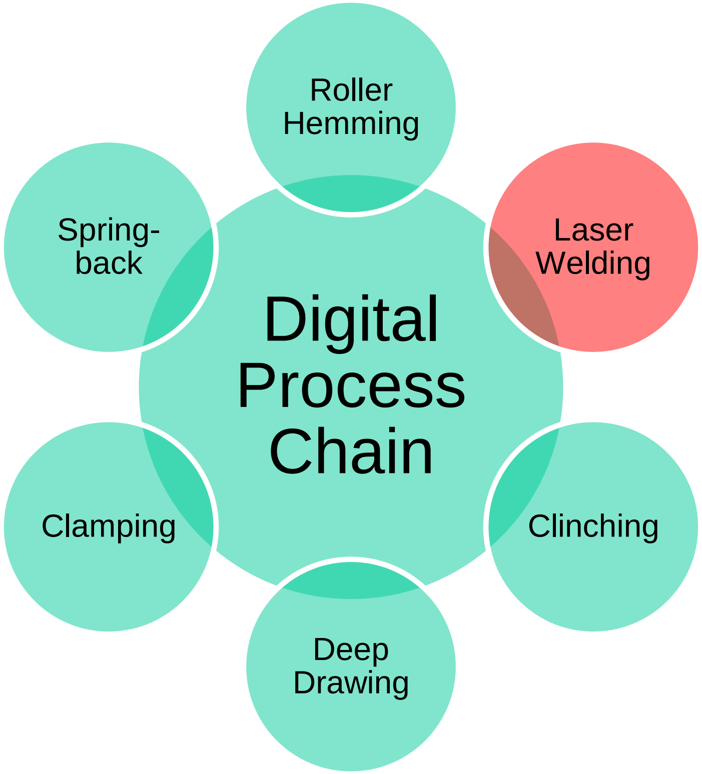

6 Clamping


7 Welding hollow seams


8 Welding flanged seams


9 Springback (left) vs. measurement (right)

Motivation - Conclusions



- Need a powerful multi-physics solver to simulate the welding process
- As stand-alone process welding is most often simulated with solid discretizations
- In automotive industries, welding is only one stage in the process chain
  - Seamless transition of date from one stage to the next
  - Typically, forming and spring-back analyses are done using shell discretizations
- All new developments are to be done for solid and shells!

Necessary developments

- Realistic description of the heat source applied to the weld seam
  - For curved and deforming structures (thermal expansion during welding)
  - For different processes and different discretizations (particularly shell discretizations)

- Material formulation with microstructure evolution
  - Phase changes due to heating and cooling alter mechanical and thermal properties
  - Transformations induced strains and plasticity
  - Strain rate and temperature dependent plasticity
  - Valid description for a wide range of steel and aluminium alloys

- Special contact capabilities
  - Material fusion due to heating
  - Thermal contact at T-joints for shells

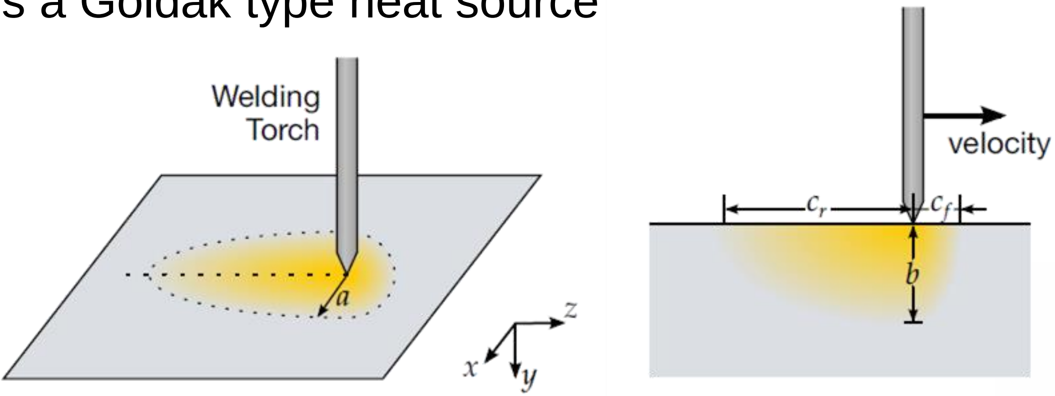
CONTENT

- Motivation
- *BOUNDARY_THERMAL_WELD_TRAJECTORY
- *MAT_GENERALIZED_PHASECHANGE / *MAT_254
- New contact options in LS-DYNA
- Remarks on Simulation Strategies

*BOUNDARY_THERMAL_WELD

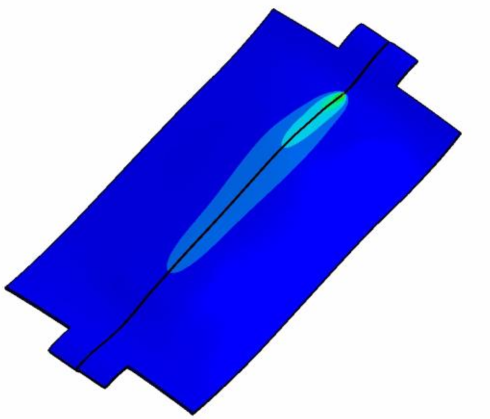
	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NID	NFLAG	X0	Y0	Z0	N2ID
Card 2	a	b	cf	cr	LCID	Q	Ff	Fr
Opt.	Tx	Ty	Tz					

- Defines a Goldak type heat source



- Weld source motion possible, follows motion of node NID

- Only applicable to solid parts



Modelling a moving heat source

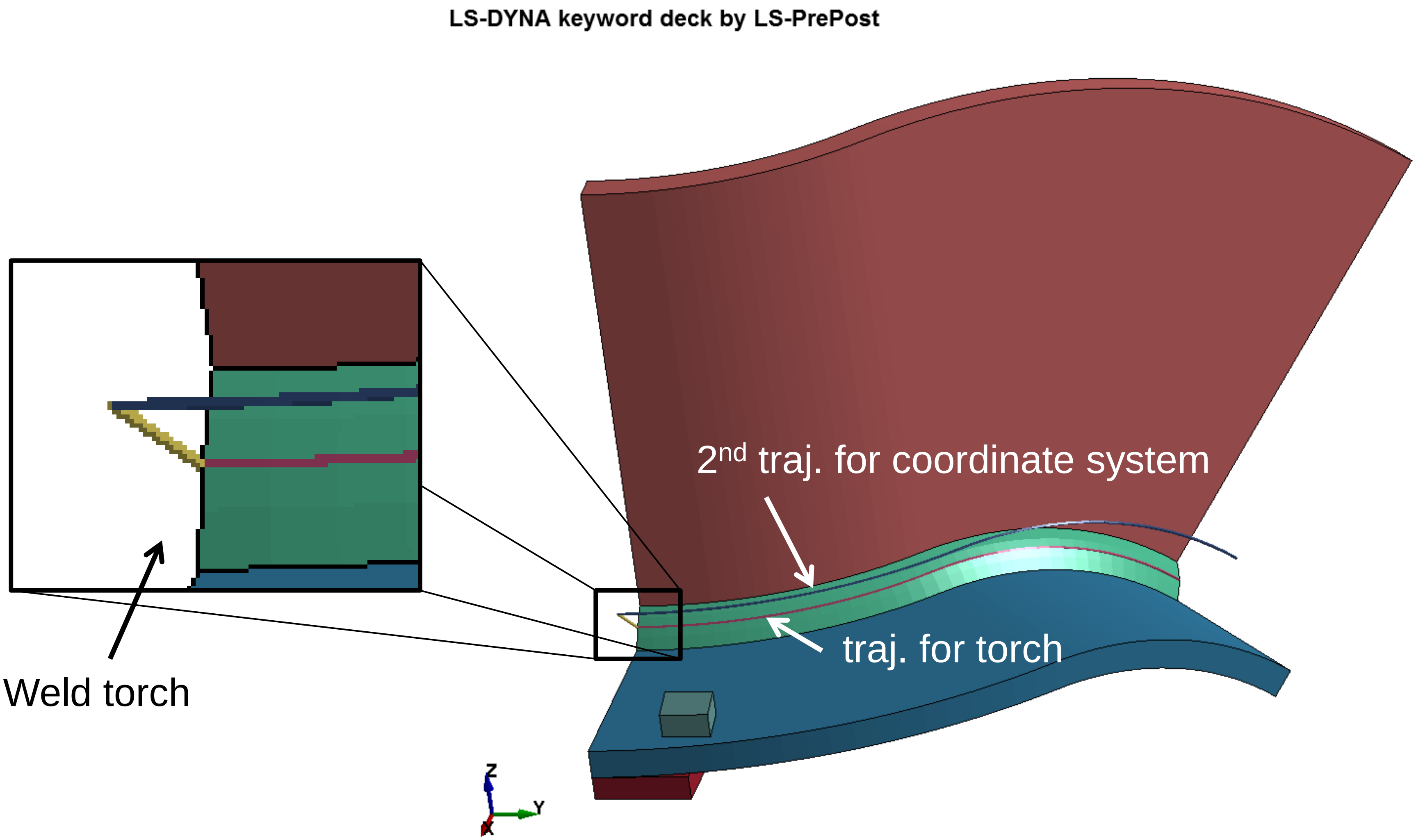
- Useful keyword: *CONTACT_GUIDED_CABLE

	1	2	3	4	5	6	7	8
Card 1	NSID	PID	CMULT	WBLCID	CBLCID	TBLCID		

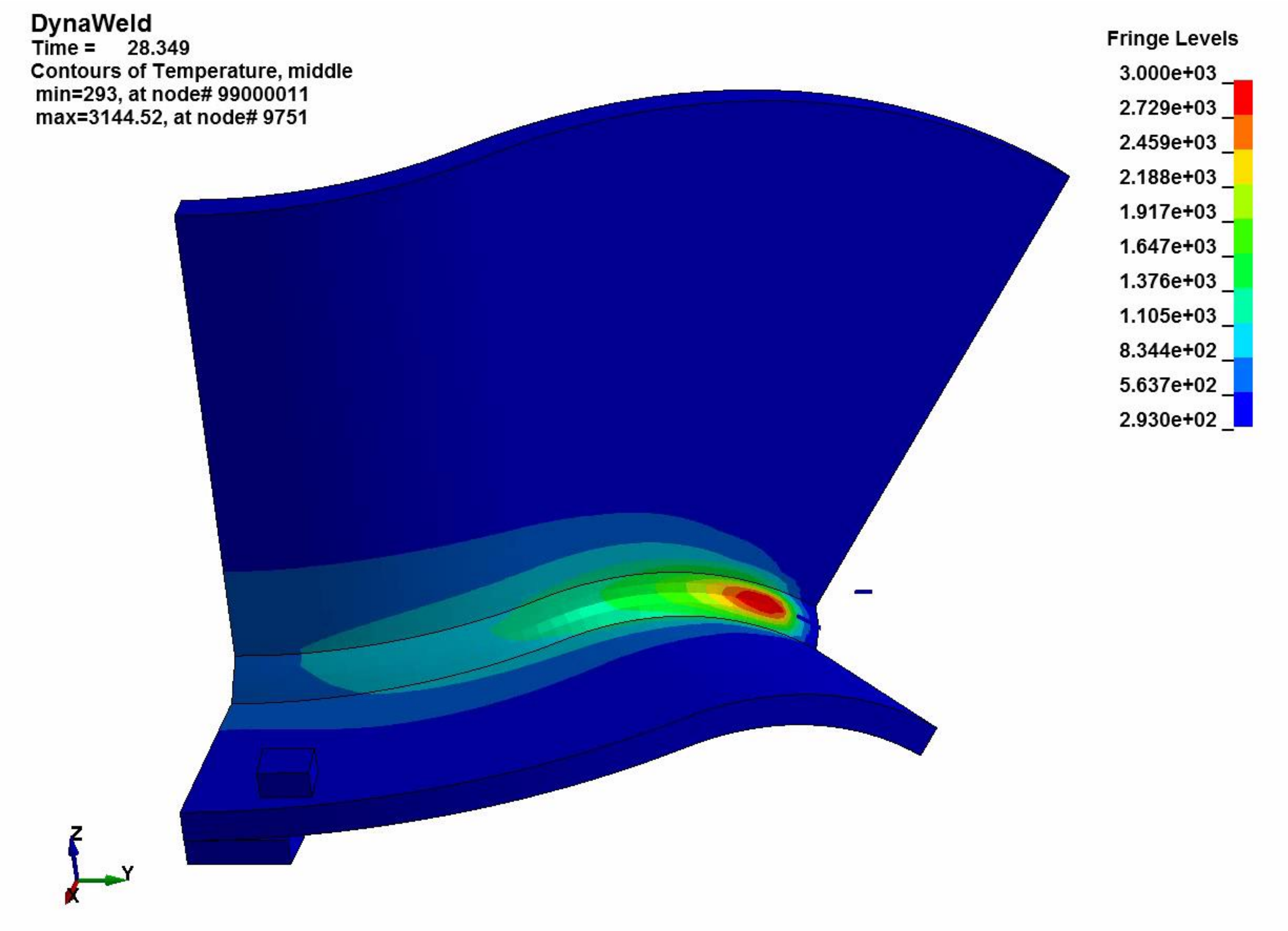
  - It forces beams in PID onto the trajectory defined by nodes in NSID

- Possible solution
  - Select a trajectory on the weld seam
  - Define contact between this trajectory and a beam B1 (N1 and N2)
  - Define a second trajectory and a beam B2 (N3 and N4) following it in a prescribed manner
  - Welding torch aiming directions from N3 to N1 (*BOUNDARY_THERMAL_WELD)
  - Define local coordinate system N1,N2,N3
  - Use *BOUNDARY_PRESCRIBED_MOTION_RIGID_LOCAL to move heat source

Movement of the heat source - example



Movement of the heat source - example



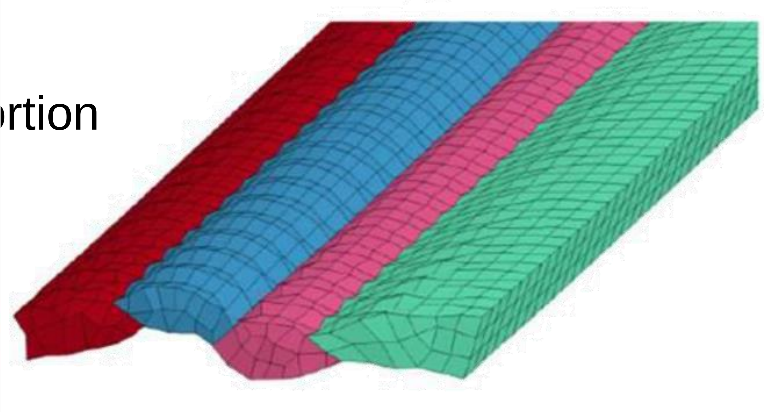
*BOUNDARY_THERMAL_WELD - Summary

- Only Goldak-type equivalent heat source available

- Weld source motion possible, follows motion of node NID
  - Structure solver necessary
  - Weld path definition not straight-forward for curve geometries
  - Compensation for part deformation requires complex pre-processing

- The incremental heating leads to element distortion when the used timestep is too large.

- No heat entry to shell elements



Need a more flexible and easier to use boundary condition for welding!

A new heat source - approach

- Move the heat source motion to a new keyword.

- The heat source follows a node path (*SET_NODE) with a prescribed velocity
  - No need to include the mechanical solver
  - In case of coupled simulations the weld path is continuously updated

- Automatically compute weld aiming direction based on surface normal

- Provide a list of pre-defined equivalent heat sources

- Use “sub-timestep” for integration of heat source for smooth temperature fields

- Implementation for solid and thermal thick shells

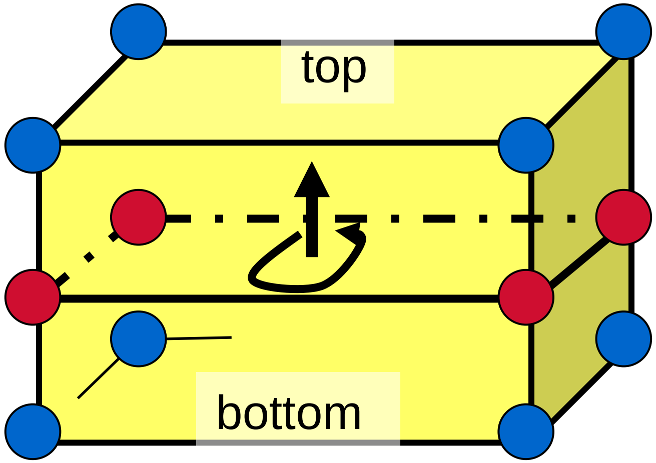
Interlude – thermal thick shell in LS-DYNA

- LS-DYNA features a twelve node thermal thick shell element formulation
  - Bi-linear shape functions in-plane
  - Quadratic approximation in thickness direction

- User only specifies the standard four node shell element
  - LS-DYNA automatically generates top and bottom virtual nodes, using right hand rule
  - Activated with TSHELL=1 on *CONTROL_SHELL

- Top/bottom surfaces can be addressed in thermal boundary conditions

- Different temperature values at different locations transferred to the mechanical solver



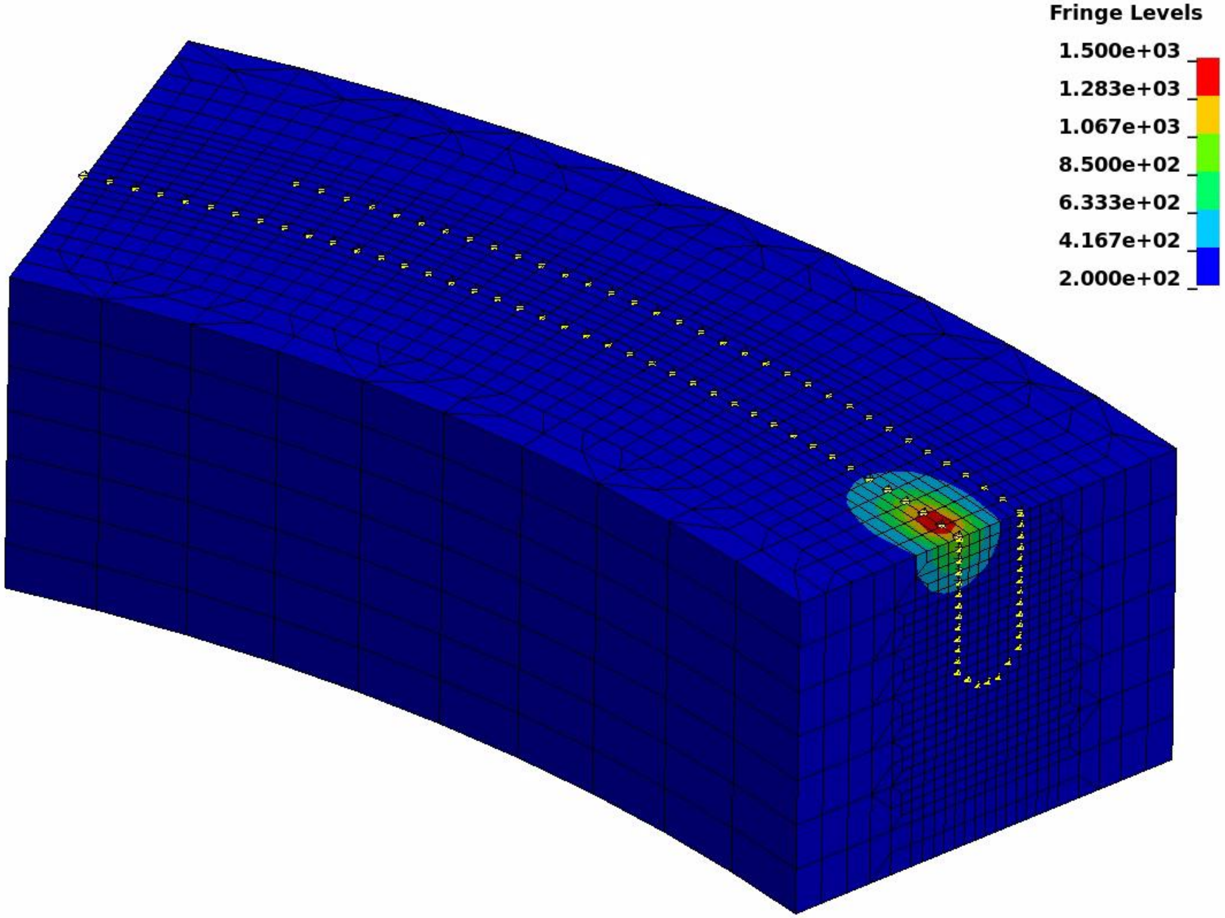
*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NSID1	VEL1	SID2	VEL2	NCYC	RELVEL
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8
Opt.	Tx	Ty	Tz					

- NSID1: Node set ID defining the trajectory
- VEL1: Velocity of weld source on trajectory
  - LT.0: |VEL1| is load curve ID for velocity vs. time
- SID2: Second set ID for weld beam direction
  - GT.0: S2ID is node set ID, beam is aimed from these reference nodes to trajectory
  - EQ.0: beam aiming direction is (Tx, Ty, Tz)
  - LT.0: SID2 is segment set ID, weld source is orthogonal to the segments
- VEL2: Velocity of reference point for SID2.GT.0

*BOUNDARY_THERMAL_WELD_TRAJECTORY

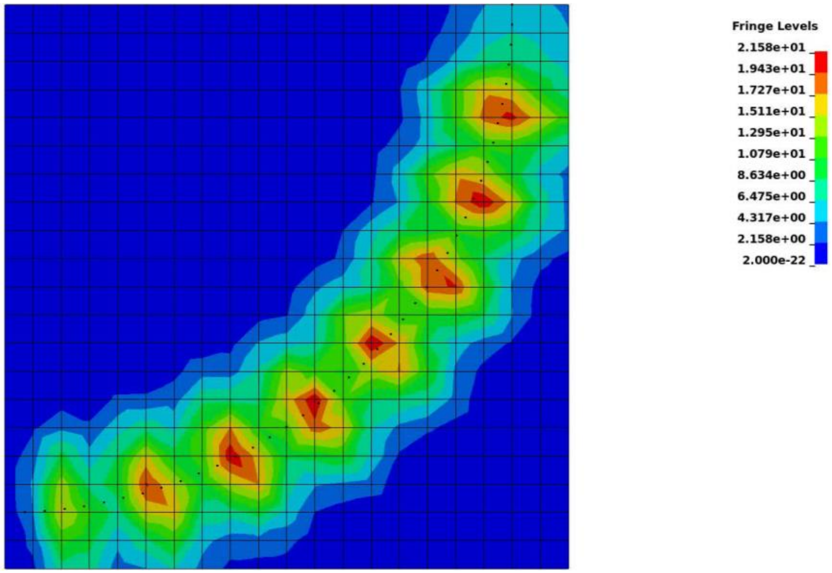
- Example: Trajectory definition



*BOUNDARY_THERMAL_WELD_TRAJECTORY

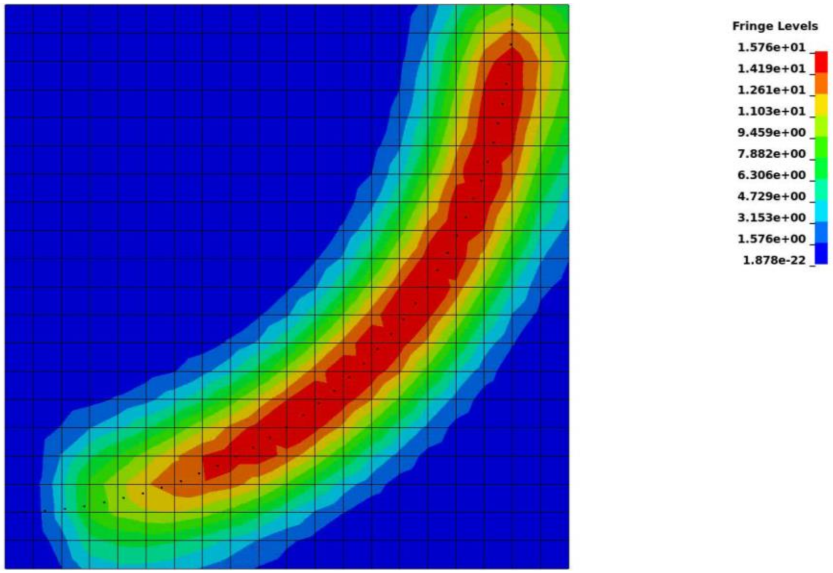
	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NSID1	VEL1	SID2	VEL2	NCYC	RELVEL

- NCYC: number of sub-cycling steps



temperature field, NCYC = 1

temperature field, NCYC = 10

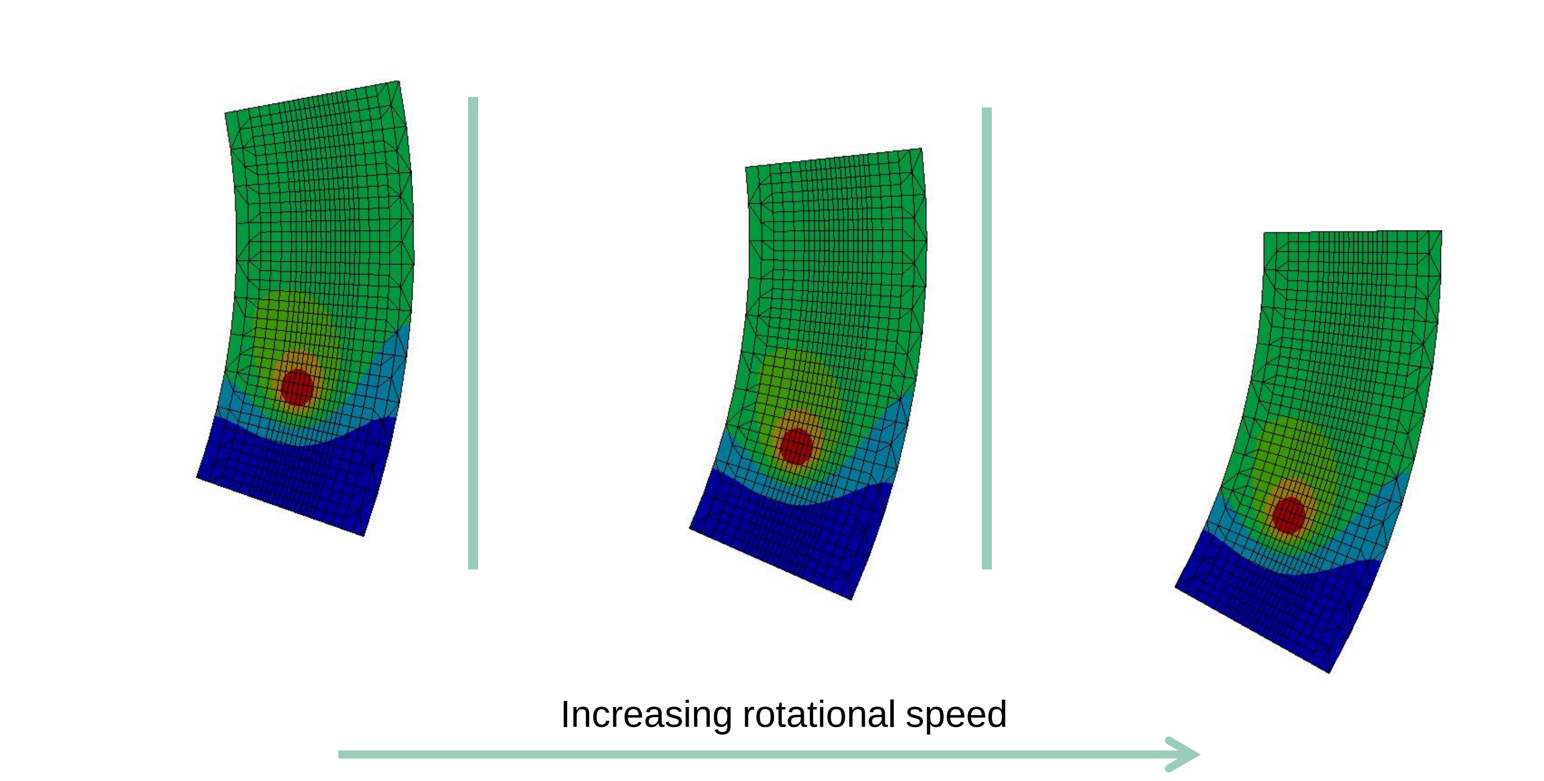


*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NSID1	VEL1	SID2	VEL2	NCYC	RELVEL

- RELVEL: Use relative or absolute velocities in coupled simulations

RELVEL=1



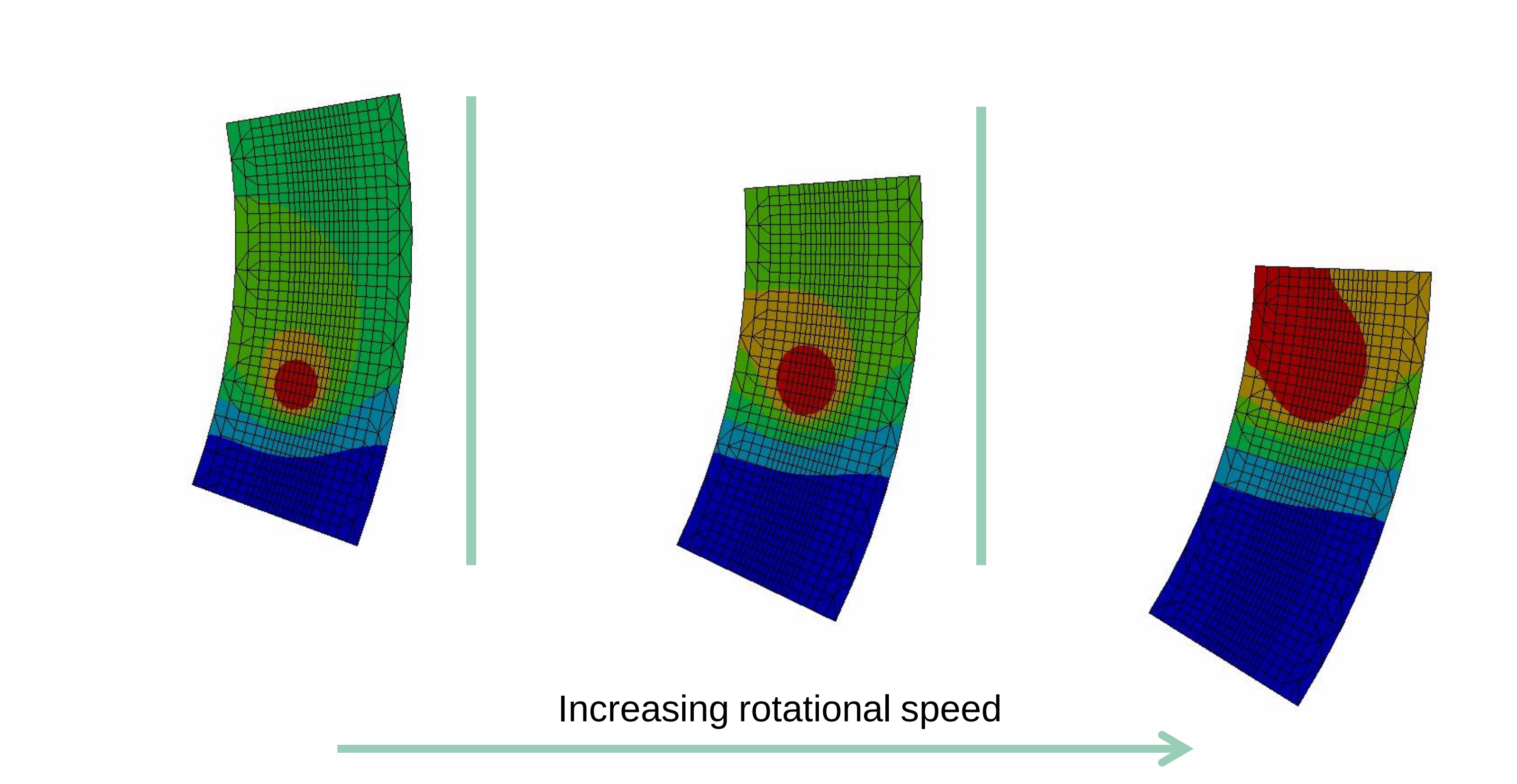
Increasing rotational speed

*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NSID1	VEL1	SID2	VEL2	NCYC	RELVEL

- RELVEL: Use relative or absolute velocities in coupled simulations

RELVEL=0



*BOUNDARY_THERMAL_WELD_TRAJECTORY

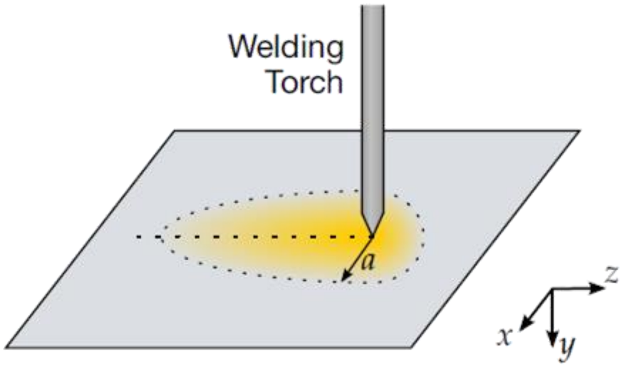
	1	2	3	4	5	6	7	8
Card 2	`IFORM`	`LCID`	`Q`	`LCROT`	`LCMOV`	`LCLAT`	`DISC`	
Card 3	`P1`	`P2`	`P3`	`P4`	`P5`	`P6`	`P7`	`P8`

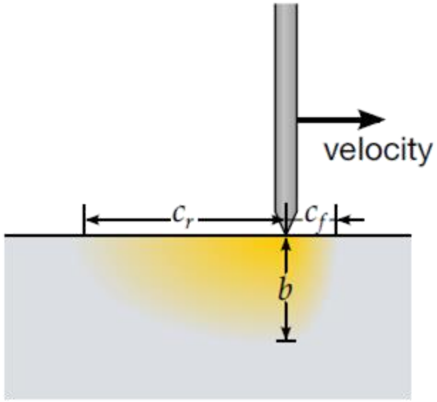
- IFORM: Geometry for energy rate density distribution
  - EQ.1. Goldak-type heat source (double ellipsoidal heat source with Gaussian density distribution)
  - EQ.2. double ellipsoidal heat source with constant density
  - EQ.3. double conical heat source with constant density
  - EQ.4. conical heat source
- P*x*: Parameters for weld pool geometry

*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8

- For IFORM=1 (Goldak)
  - P1: a
  - P2: b
  - P3: c_f
  - P4: c_r
  - P5: F_f
  - P6: F_r
  - P7: n



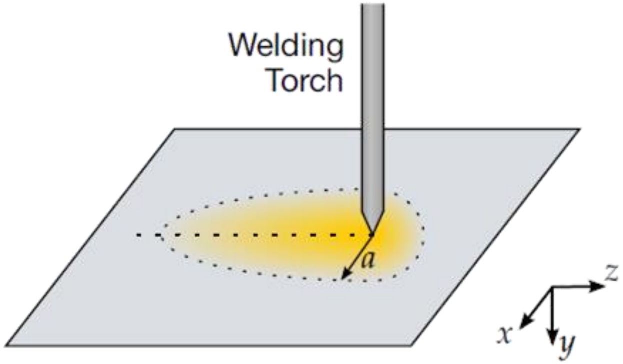


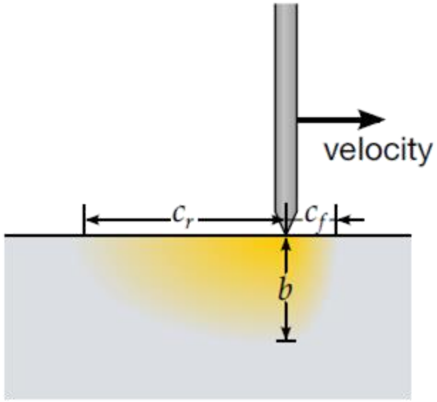
$$q = \frac{2n\sqrt{n}FQ}{\pi\sqrt{\pi}abc} \exp\left(\frac{-nx^2}{a^2}\right) \exp\left(\frac{-ny^2}{b^2}\right) \exp\left(\frac{-nz^2}{c^2}\right)$$

*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8

- For IFORM=2 (double ellipsoid)
  - P1: a
  - P2: b
  - P3: c_f
  - P4: c_r
  - P5: F_f
  - P6: F_r



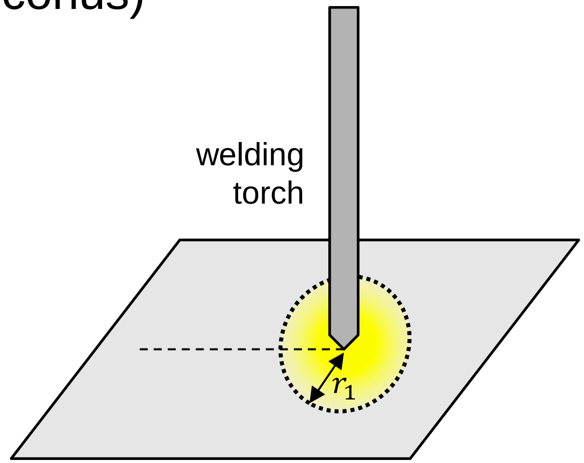


$$q = \frac{3FQ}{2\pi abc}$$

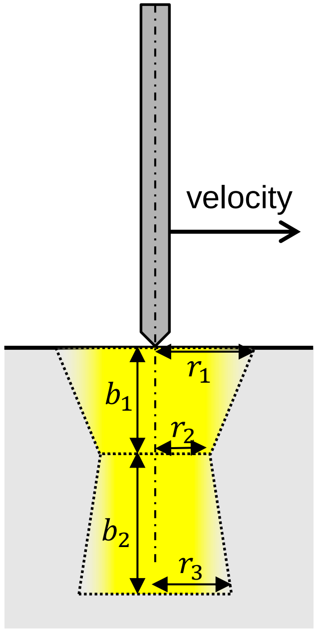
*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8

- For IFORM=3 (double conus)
  - P1: r_1
  - P2: r_2
  - P3: r_3
  - P4: b_1
  - P5: b_2
  - P6: F_1
  - P7: F_2



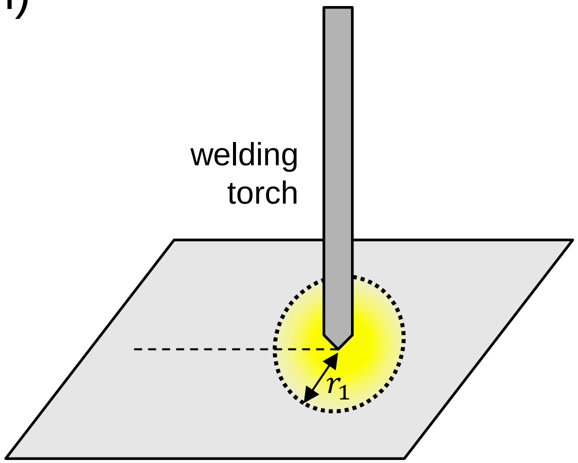
$$q = \frac{3FQ}{2\pi b(R^2 + r^2 + Rr)}$$

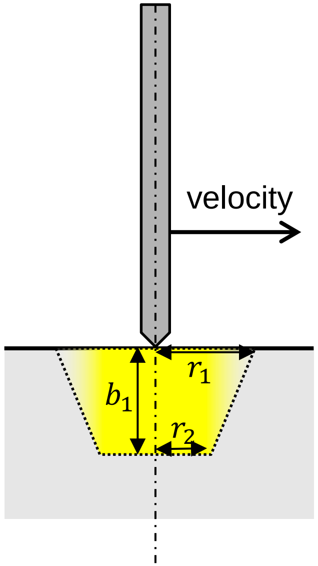


*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8

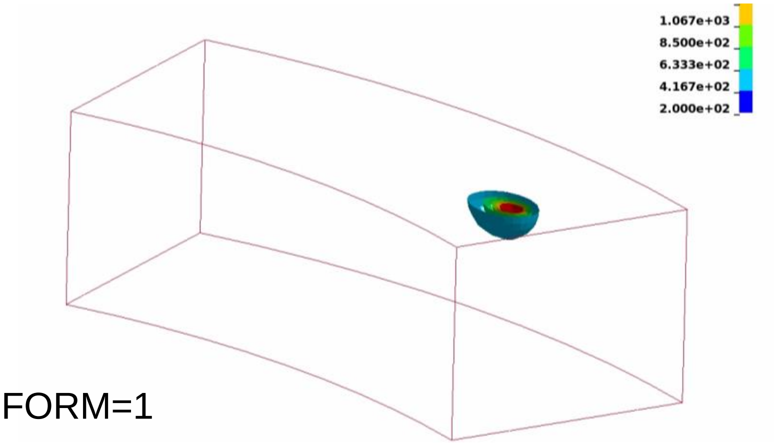
- For IFORM=4 (frustrum)
  - P1: r_1
  - P2: r_2
  - P3: b_1



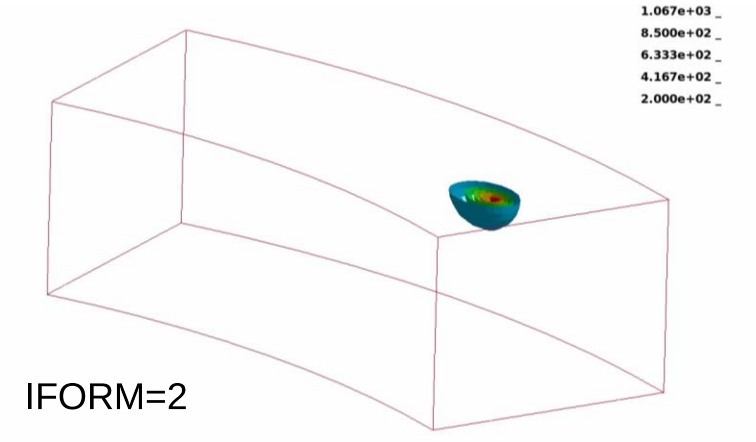


$$q = \frac{3Q}{\pi b(R^2 + r^2 + Rr)}$$

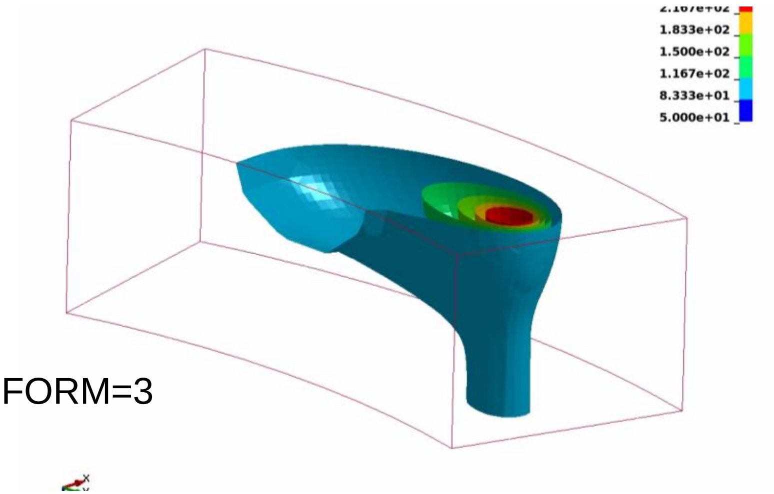
*BOUNDARY_THERMAL_WELD_TRAJECTORY



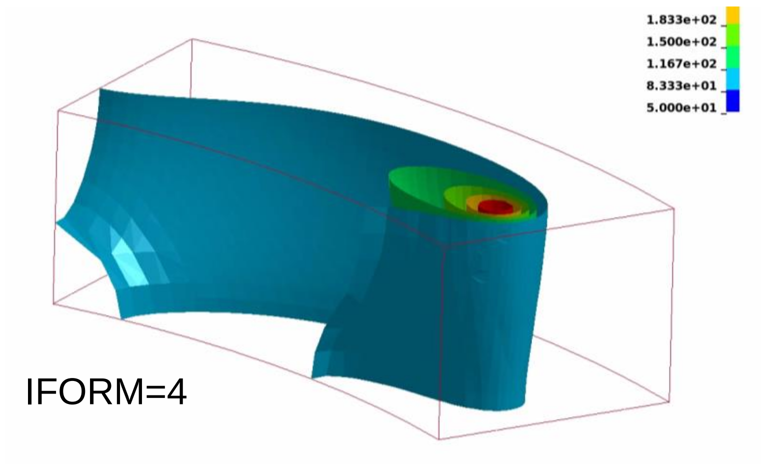
IFORM=1



IFORM=2



IFORM=3



IFORM=4

*BOUNDARY_THERMAL_WELD_TRAJECTORY

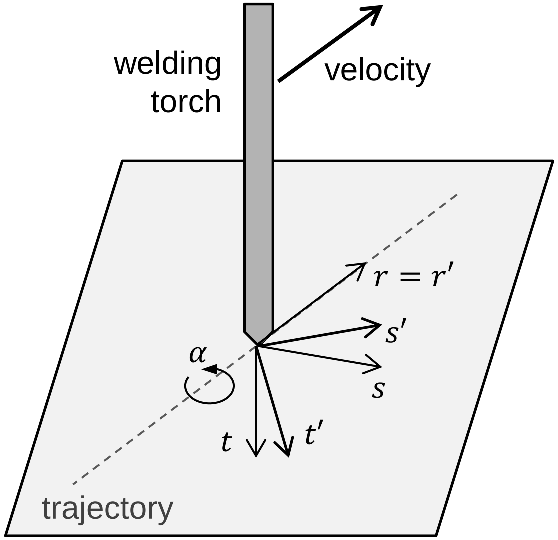
	1	2	3	4	5	6	7	8
Card 2	`IFORM`	`LCID`	`Q`	`LCROT`	`LCMOV`	`LCLAT`	`DISC`	

- LCID: Load curve ID for weld energy input rate vs. time
  - EQ.0: use constant multiplier value Q
- Q: Curve multiplier for weld energy input
  - LT.0: use multiplier value |Q| and accurate integration of heat
- DISC: Resolution for accurate integration. Edge length for cubic integration cells
  - Default: 0.05*(weld source depth)

*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	

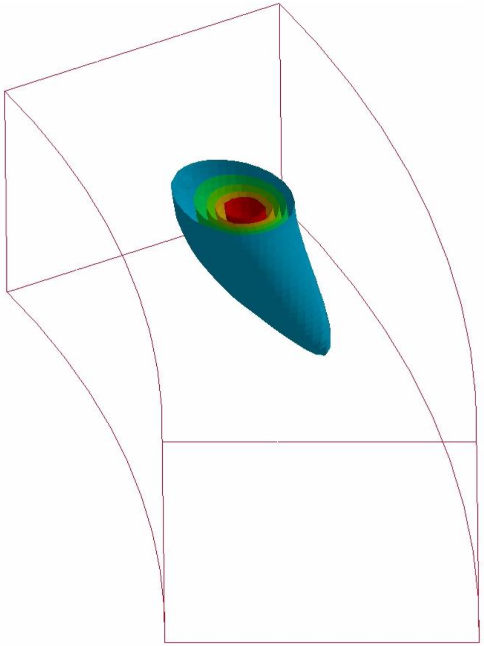
- LCROT: load curve defining the rotation (α in degree) of weld source around the trajectory as function of time.
- LCMOV: load curve for offset of weld source in depth (t') after rotation as funtion of time
- LCLAT: load curve for lateral offset (s') after rotation as function of time

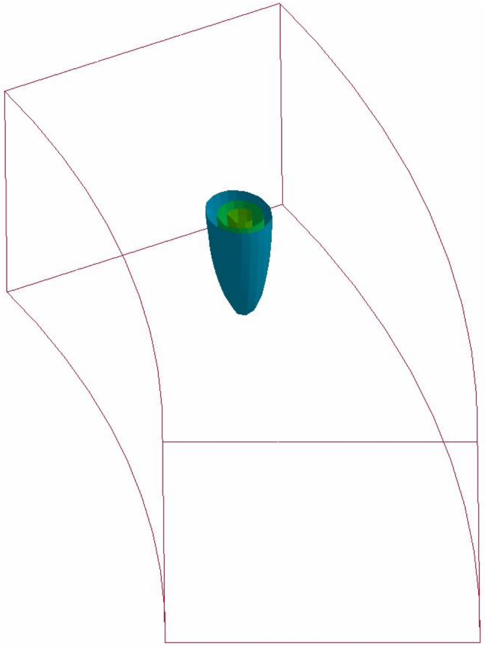


*BOUNDARY_THERMAL_WELD_TRAJECTORY

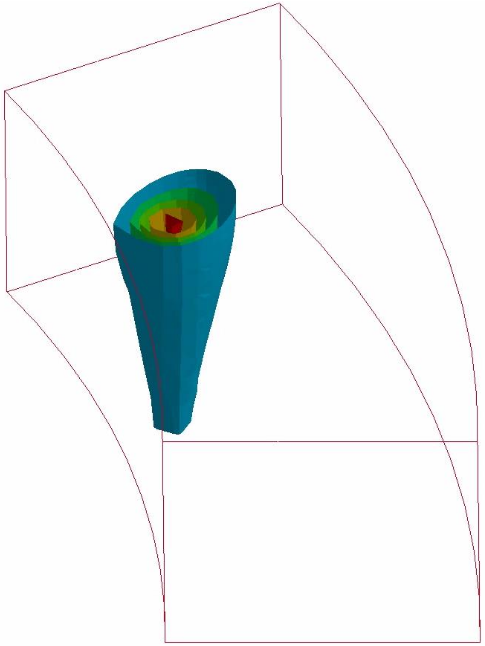
- Example: Influence of oscillations for…

…LCROT





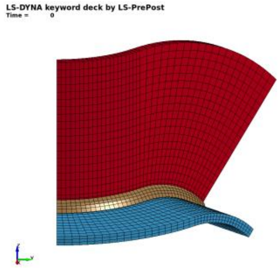
… LCMOV



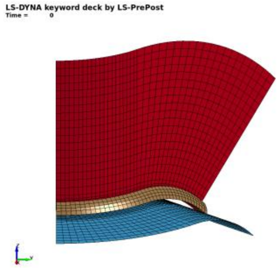
… LCLAT

Example 1

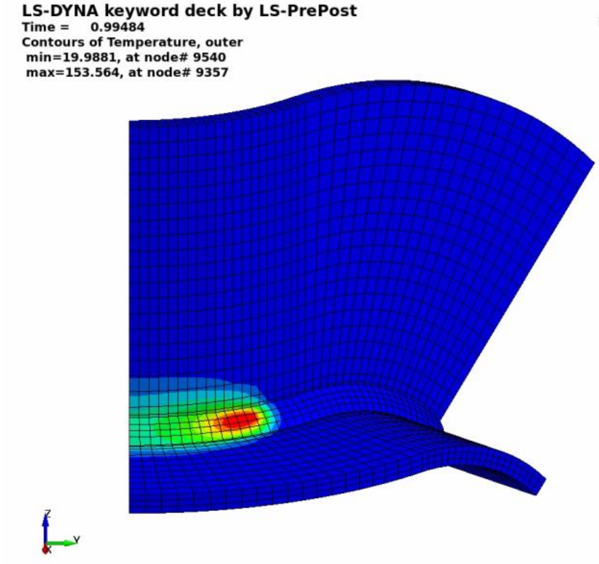
- New Keyword is applicable to thermal thick shells / mixed discretizations
- Three-dimensional curved T-Joint, thermal-only analysis


LS-DYNA keyword deck by LS-PrePost
Time = 0

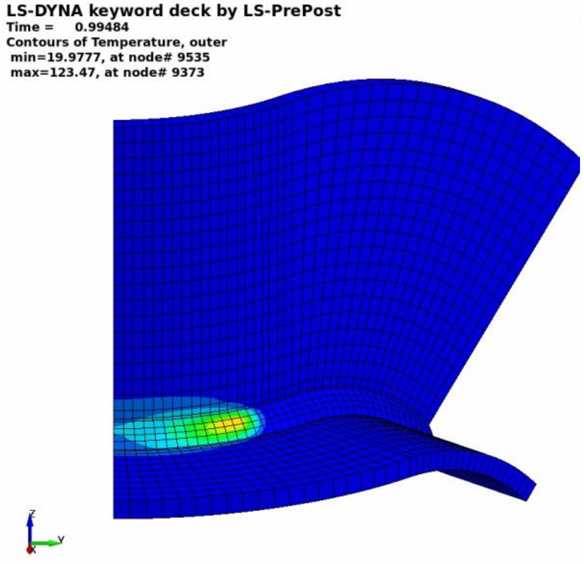
Solids


LS-DYNA keyword deck by LS-PrePost
Time = 0

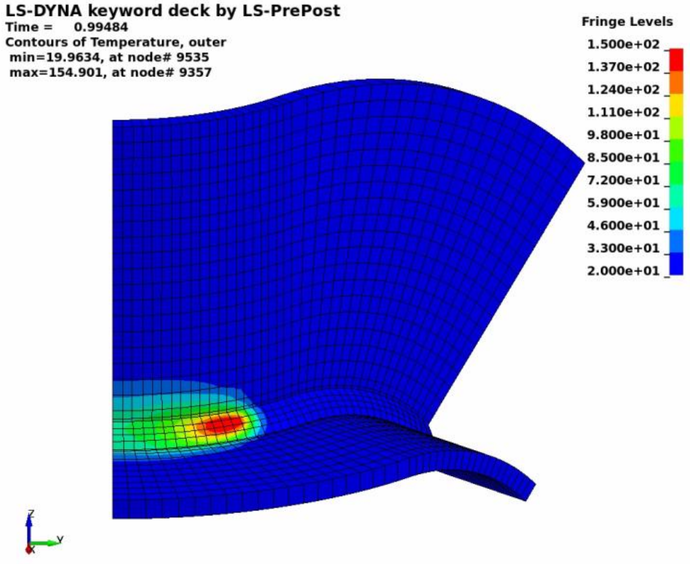
Solids and shells


LS-DYNA keyword deck by LS-PrePost
Time = 0.99484
Contours of Temperature, outer
min=19.9881, at node# 9540
max=153.564, at node# 9357

BC on all solids


LS-DYNA keyword deck by LS-PrePost
Time = 0.99484
Contours of Temperature, outer
min=19.9777, at node# 9535
max=123.47, at node# 9373

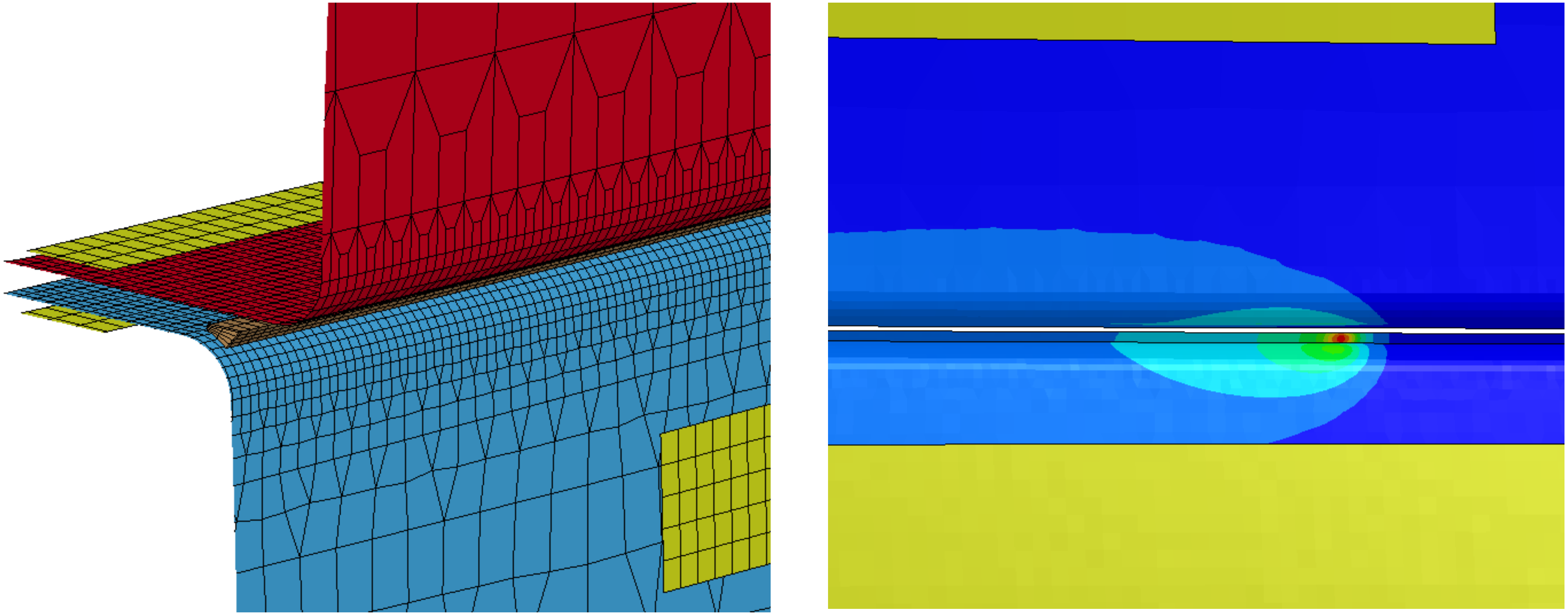
BC on solids only


LS-DYNA keyword deck by LS-PrePost
Time = 0.99484
Contours of Temperature, outer
min=19.9634, at node# 9535
max=154.901, at node# 9357

BC on solids and shells

Industrial examples

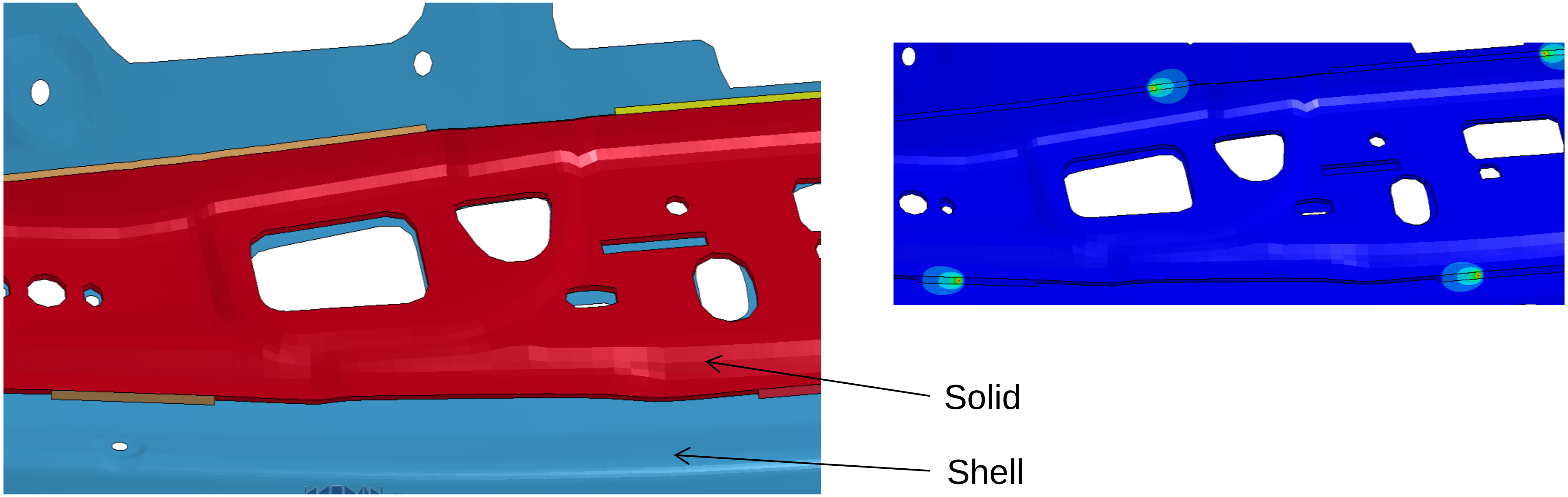
- Forming and clamping usually done with shell structures
- Additional filler discretized with solids



- Very smooth temperature distribution across discretization boundaries

Industrial examples

- Welding simulation can be used to investigate optimal welding strategy
  - Different welding orders one weld seam at a time
  - Simultaneous welding of multiple weld seam

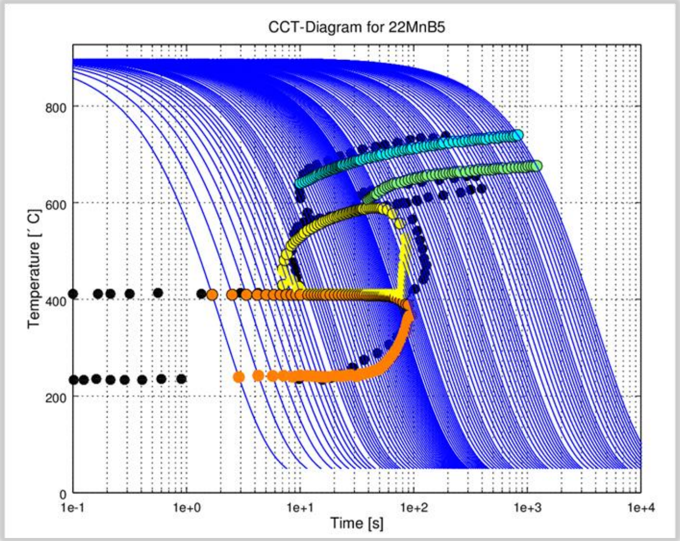


CONTENT

- Motivation
- *BOUNDARY_THERMAL_WELD_TRAJECTORY
- *MAT_GENERALIZED_PHASECHANGE / *MAT_254
- New contact options in LS-DYNA
- Remarks on Simulation Strategies

*MAT_UHS_STEEL/*MAT_244 - Basis

- 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



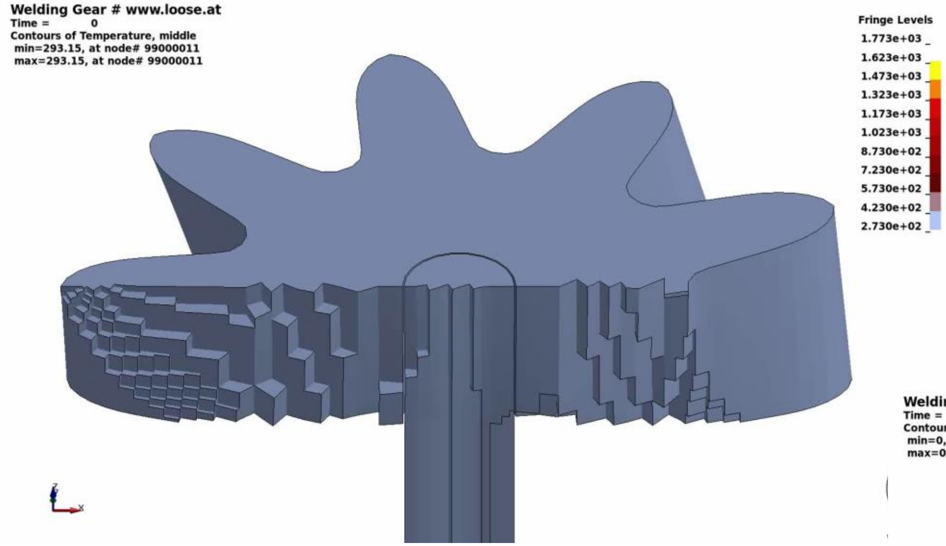
- Added:
  - Transformation induced strains
  - Welding functionality
  - Different transformation start temperatures for heating and for cooling

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

Heuristic formulas connecting chemistry with mechanics fail otherwise!

Example

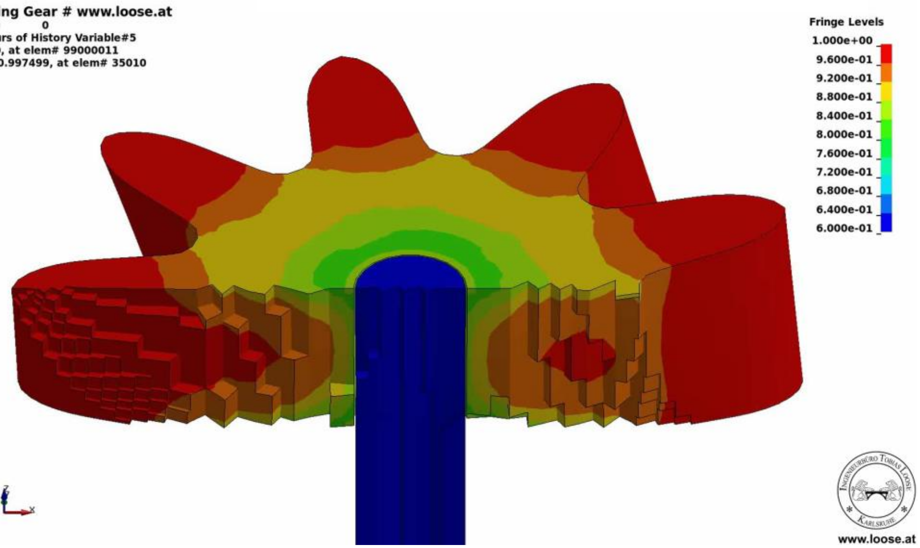
- A gear is heated, quenched, welded to a joint



Welding Gear # www.loose.at
Time = 0
Contours of Temperature, middle
min=293.15, at node# 99000011
max=293.15, at node# 99000011

Temperature field

Martensite concentration



Welding Gear # www.loose.at
Time = 0
Contours of History Variable#5
min=0, at elem# 99000011
max=0.997499, at elem# 35010

*MAT_254

- Started the implementation of *MAT_GENERALZE_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 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 1	MID	RHO	N	E	PR	MIX	MIXR	BETA
Card 2	TASTART	TAEND	TABCTE				DTEMP	TIME
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5			
Card 5	PTEPS	TRIP				GRAI		
Card 6	LCY1	LCY2	LCY3	LCY4	LCY5	LCY6	LCY7	LCY8
Card 7	LCY9	LCY10	LCY11	LCY12	LCY13	LCY14	LCY15	LCY16
Card 8	LCY17	LCY18	LCY19	LCY20	LCY21	LCY22	LCY23	LCY24

- Special welding card not needed. Liquid filler can be accounted for by an additional phase
- Damage and failure modelling, latent heat, grain growth modelling yet to be implemented

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 1	MID	RHO	N	E	PR	MIX	MIXR	BETA

- N: Number of phases in microstructure
- E: Young’s modulus
  - LT.0: |E| is load curve ID/table ID for E vs. temperature (vs. phase)
- PR: Poissons’s ratio
  - LT.0: |E| is load curve ID/table ID for PR vs. temperature (vs. phase)
- MIX: Load curve ID for initial phase concentrations
- MIXR: LC / TAB ID for mixing rule (temperature dependent)

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

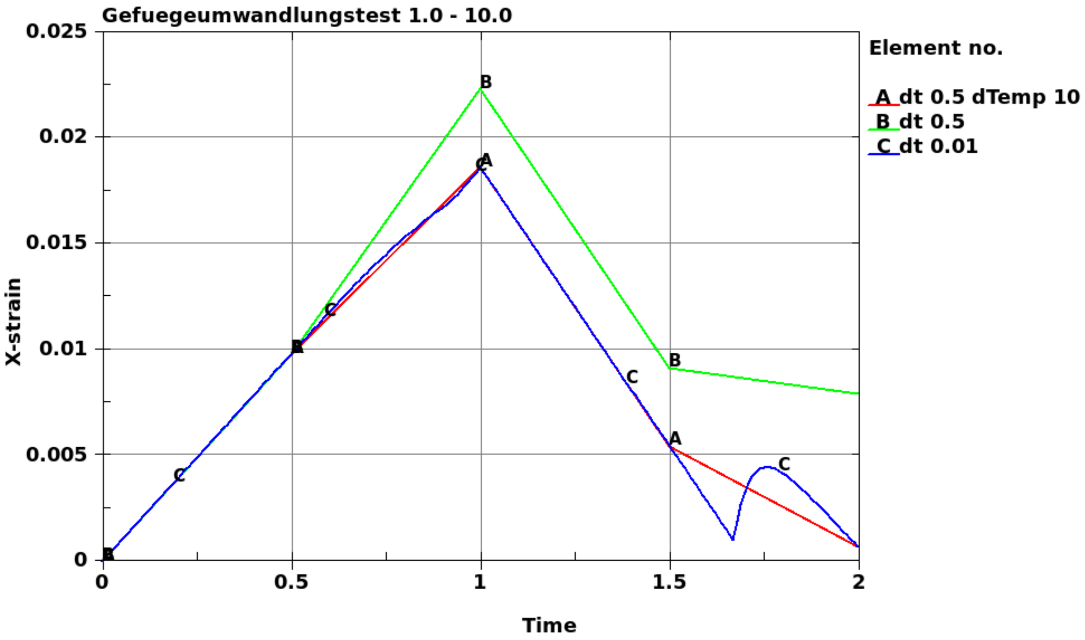
	1	2	3	4	5	6	7	8
Card 2	TASTART	TAEND	TABCTE				DTEMP	TIME

- TASTART: Reset of history variables start temperature
- TAEND: Reset of history variables end temperature

- TABCTE: coefficient of thermal expansion (CTE)
  - LT.0: |TABCTE| is load curve ID/table ID for CTE vs. temperature (vs. phase)
- DTEMP: Maximum temperature variation within a time step
  - If temperature increase exceeds DTEMP, sub time steps locally on integration point level are used
  - Important for rapid heating and cooling scenarios to resolve non-linearities

Effect of DTEMP

- Rapid heating and cooling of a single element
- Non-linear strains as transformation induced strains and the coefficient of thermal expansion depend on the temperature



- Results for small time steps can be reproduced if DTEMP is sufficiently small

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	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			

- PTLAW: Table ID containing phase transformation laws
  - If law ID.GT.0: used for cooling
  - If law ID.LT.0: used for heating
  - |LAW ID|:
    - EQ.1: Koistinen-Marburger
    - EQ.2: JMAK
    - EQ.3: Kirkaldy (only cooling)
    - EQ.4: Oddy (only heating)
- PTSTR: Table ID containing start temperatures
- PTEND: Table ID containing end temperature
- PTX*i*: *i*-th scalar parameter (2D table input)
- PTTAB*i*: *i*-th temperature dependent parameter (3D table input)

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	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			

- Koistinen Marburger
  - Evolution equation:

$$x_b = x_a\left(1.0 - e^{-\alpha(T_{start}-T)}\right)$$

  - Parameter:
    - PTX1: α

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	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			

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

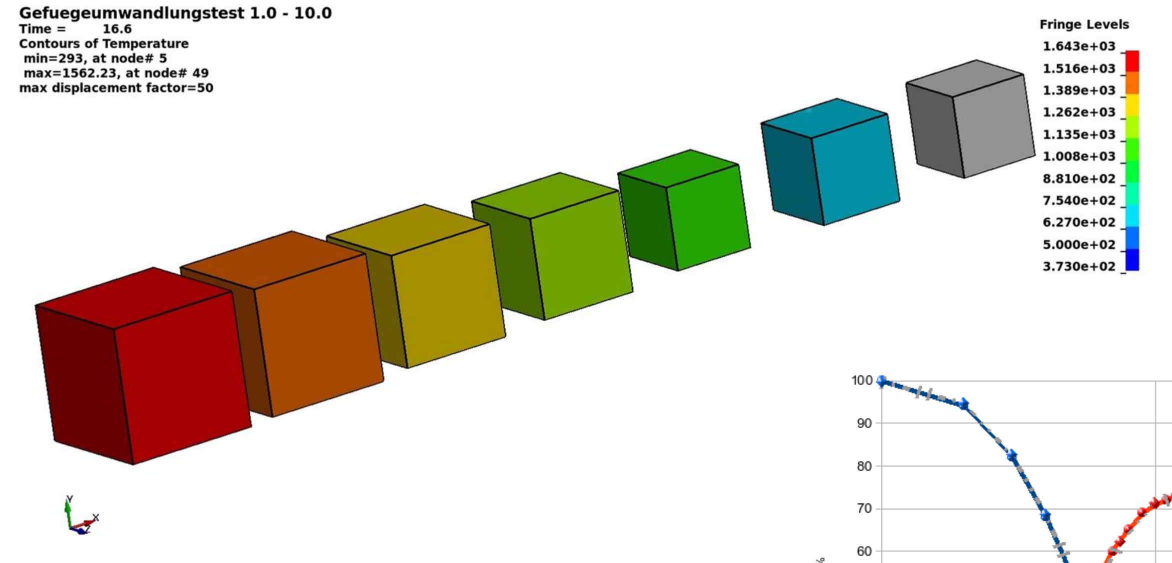
$$\frac{dx_b}{dt} = n(T)(k_{ab}x_a - k'_{ab}x_b)\left(\ln\left(\frac{k_{ab}(x_a + x_b)}{k_{ab}x_a - k'_{ab}x_b}\right)\right)^{\frac{n(T)-1.0}{n(T)}}$$

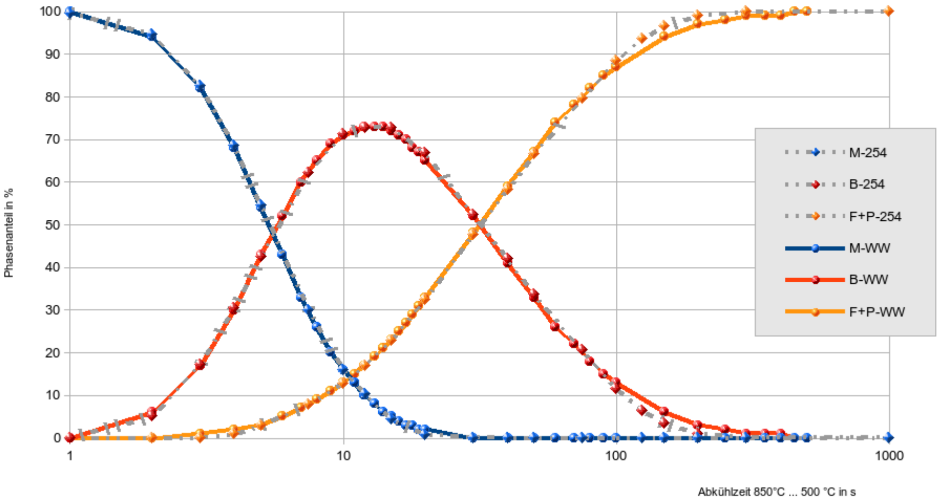
$$k_{ab} = \frac{x_{eq}(T)}{\tau(T)} f(\dot{T}), k'_{ab} = \frac{1.0 - x_{eq}(T)}{\tau(T)} f'(\dot{T})$$

  - Parameter:
    - PTTAB1: $n(T)$
    - PTTAB2: $x_{eq}(T)$
    - PTTAB3: $\tau(T)$
    - PTTAB4: $f(\dot{T})$
    - PTTAB5: $f'(\dot{T})$

*MAT_254 with JMAK

- First example: Phase change test for steel S420





*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	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			

- Kirkaldy (equivalent to *MAT_244):
  - Evolution equation:

$$\frac{dX_b}{dt} = 2^{0.5(G-1)} f(C)(T_{start} - T)^{n_T} D(T) \frac{X_b^{n_1(1.0-X_b)}(1.0 - X_b)^{n_2 X_b}}{\mathrm{Y}(X_b)}, x_b = X_b x_{eq}(T)$$

  - Parameter:
    - PTX1: $f(C)$
    - PTX2: n_T
    - PTX3: n_1
    - PTX4: n_2
    - PTTAB1: $\mathrm{D}(T)$
    - PTTAB2: $\mathrm{Y}(X_b)$
    - PTTAB3: $x_{eq}(T)$

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	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			

- Oddy (equivalent to *MAT_244):
  - Evolution equation:

$$\frac{dx_b}{dt} = n \cdot \frac{x_a}{c_1(T - T_{start})^{-c_2}} \cdot \left(\ln\left(\frac{(x_a + x_b)}{x_a}\right)\right)^{\frac{n-1.0}{n}}$$

  - Parameter:
    - PTX1: n
    - PTX2: c_1
    - PTX3: c_2

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

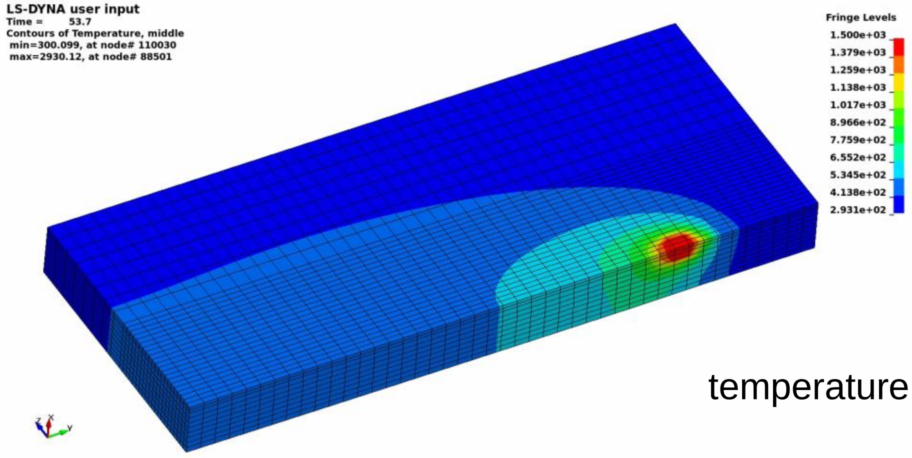
	1	2	3	4	5	6	7	8
Card 5	PTEPS	TRIP				GRAI		
Card 6	LCY1	LCY2	LCY3	LCY4	LCY5	LCY6	LCY7	LCY8
Card 7	LCY9	LCY10	LCY11	LCY12	LCY13	LCY14	LCY15	LCY16
Card 8	LCY17	LCY18	LCY19	LCY20	LCY21	LCY22	LCY23	LCY24

- PTEPS: Table ID for transformation induced strains
- TRIP: Flag for transformation induced plasticity (active for TRIP.gt.0)
- GRAIN: Initial grain size

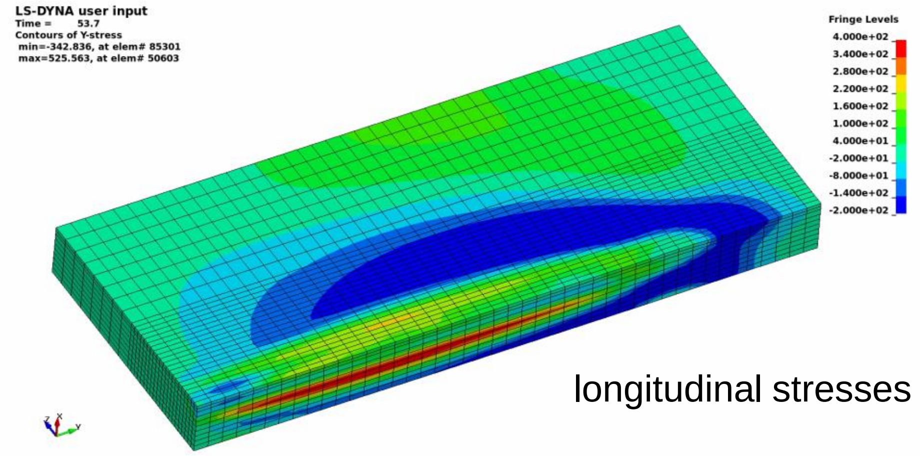
- LCY*xy:* Load curve or table ID for yield stress vs. equivalent plastic strain (vs. strain rate vs. temperature)

Residual stresses

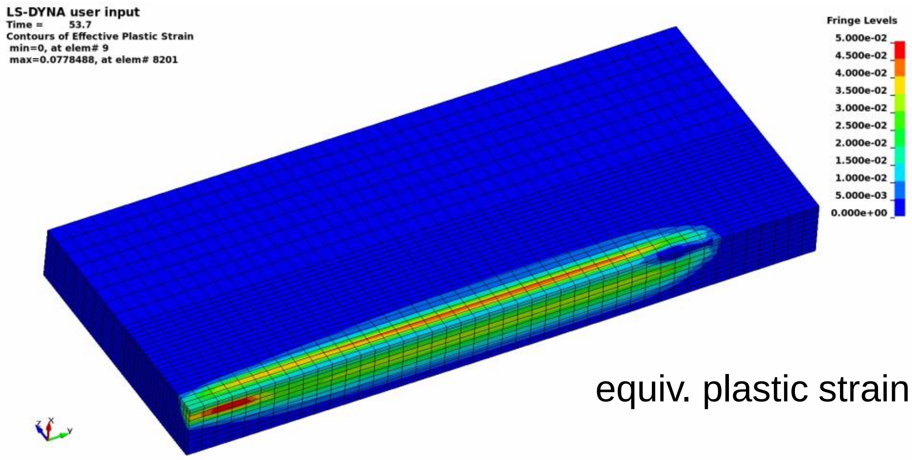
- Nitschke-Pagel test



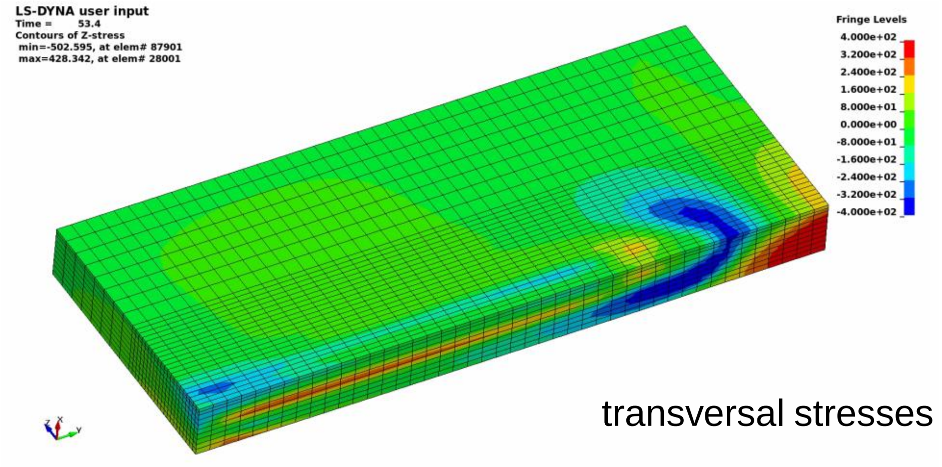
temperature



longitudinal stresses



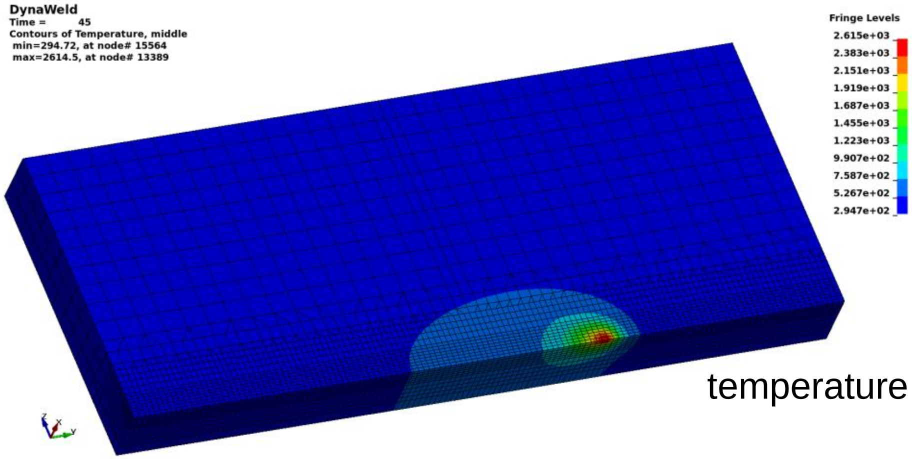
equiv. plastic strain



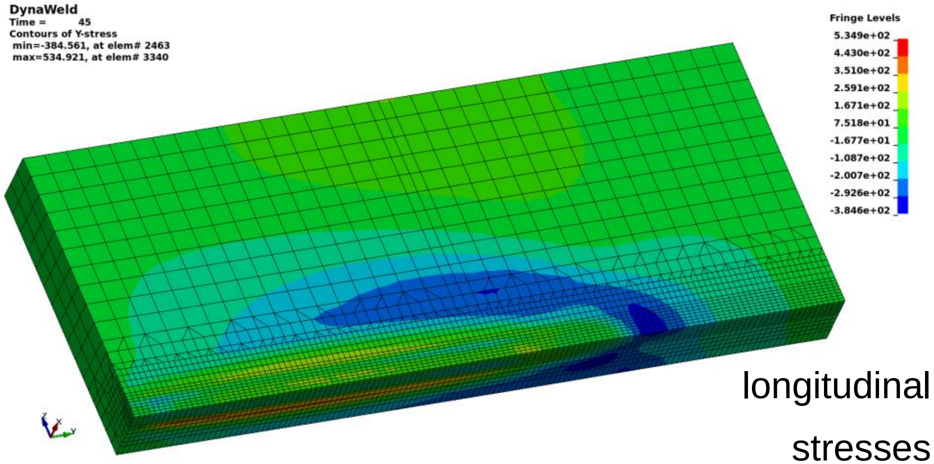
transversal stresses

Residual stresses

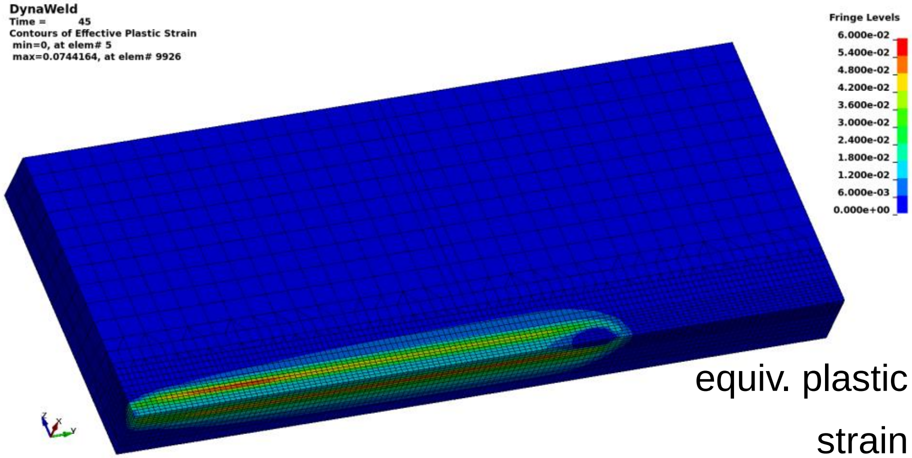
- Nitschke-Pagel test



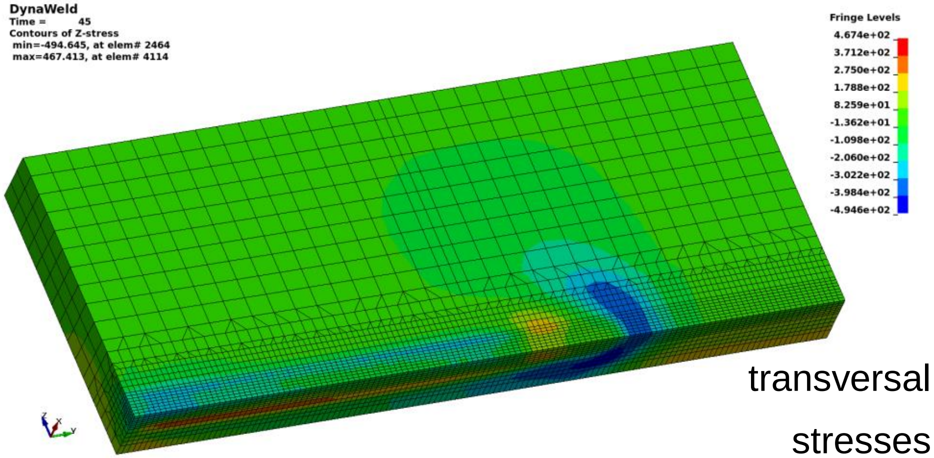
temperature



longitudinal stresses



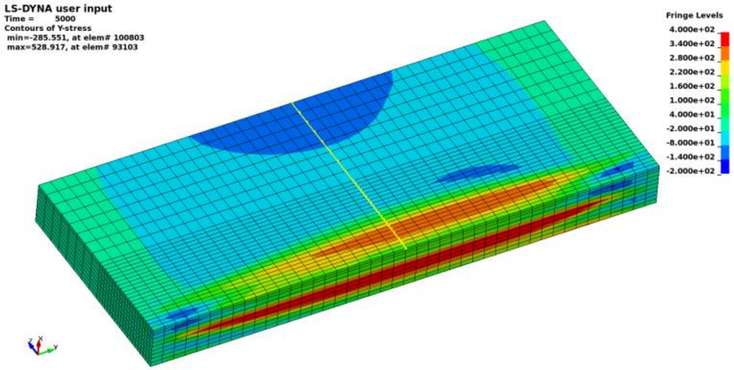
equiv. plastic strain

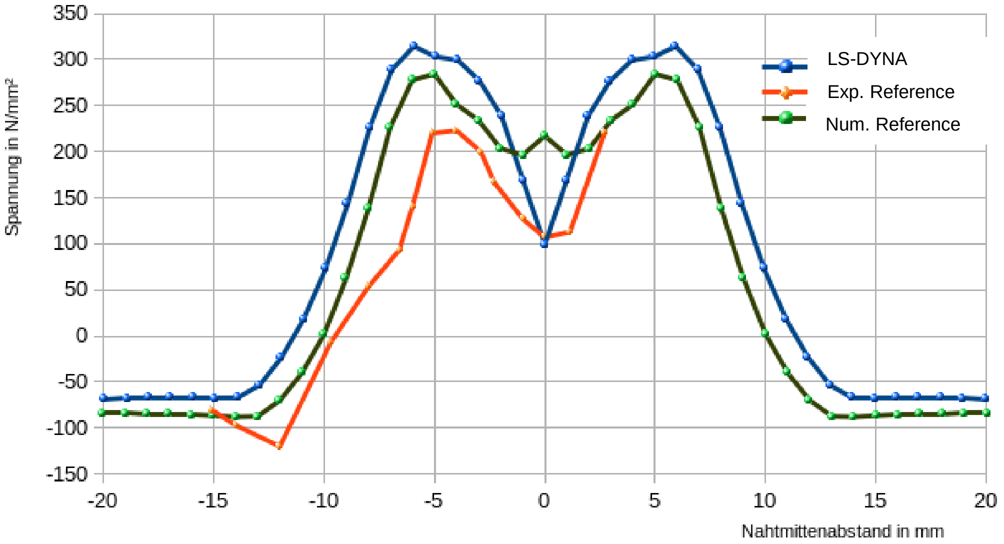


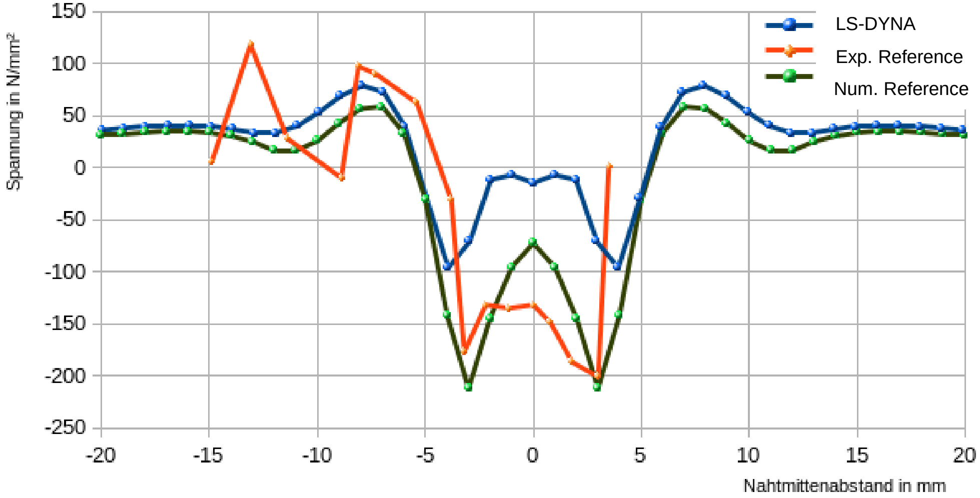
transversal stresses

Residual stresses

- Nitschke-Pagel test







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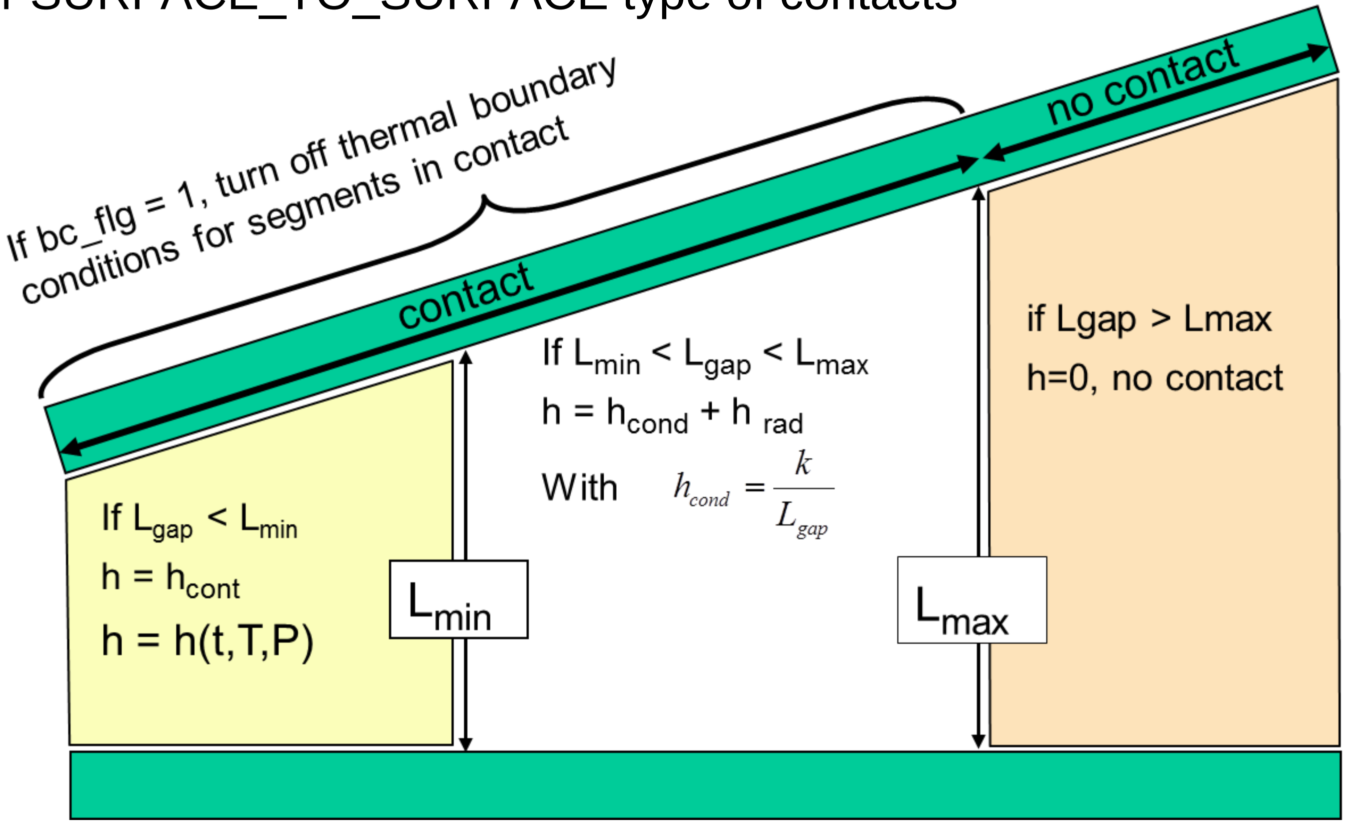
*CONTACT_OPTION_THERMAL

	1	2	3	4	5	6	7	8
Card	K	Hrad	H0	LMIN	LMAX	CHLM	BC_FLAG	ALGO

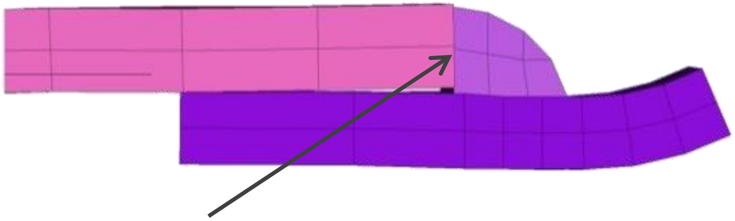
- Works for SURFACE_TO_SURFACE type of contacts



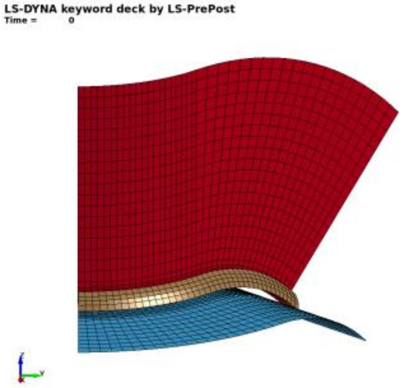
Contacts in LS-DYNA – necessary enhancements

- Welding without adding material (laser welding)
  - Ghosting approach, which has been implemented in LS-DYNA in some material formulations no longer feasible
  - Significant sliding of parts before welding

- Edge contact
  - Certain scenarios require to consider heat transfer across the edge of a shell into a surface



Coupling of a sheet metal to a weld seam



T-Joint with shells

Welding without filler elements

- 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 in SMP (share memory parallel), MPP versions to follow

*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL

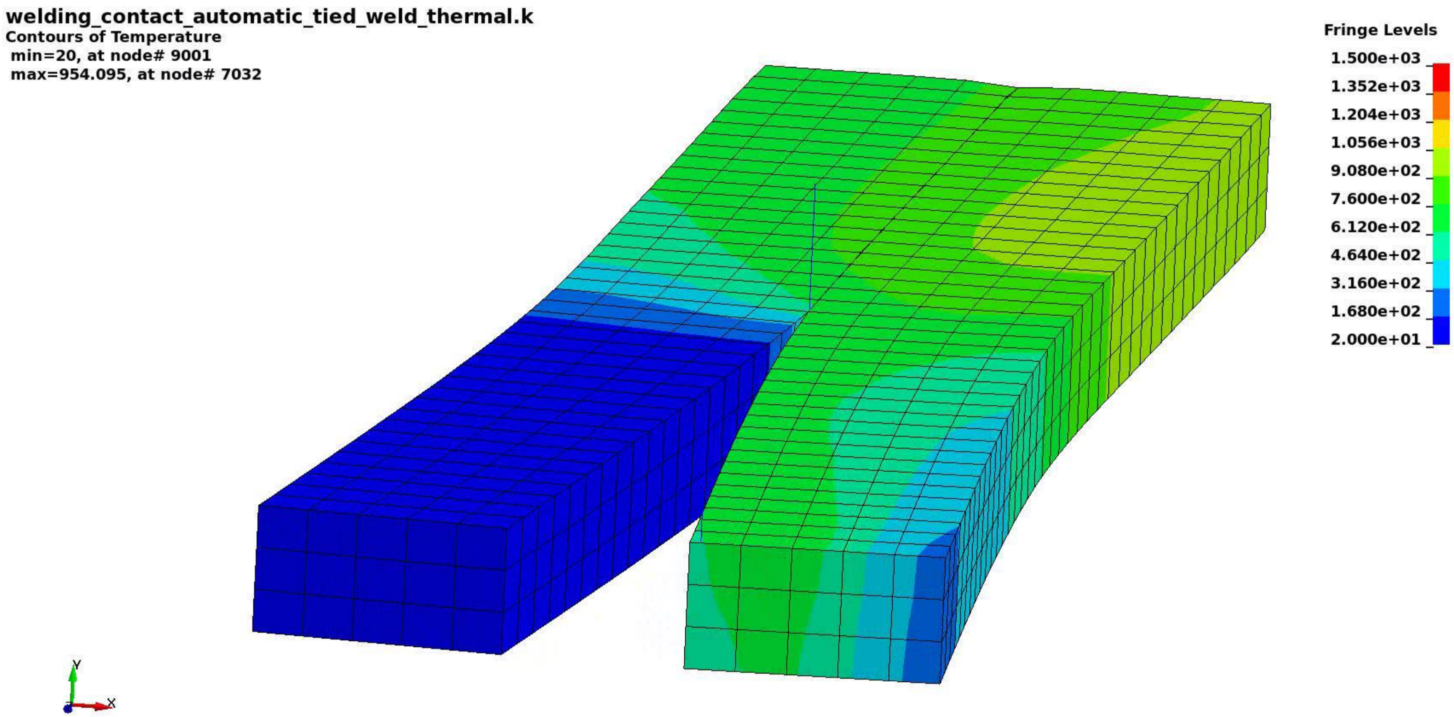
	1	2	3	4	5	6	7	8
Card 4	**TEMP**	**CLOSE**	**HWELD**					
Card 5	K	Hrad	**H0**	LMIN	LMAX	CHLM	BC_FLAG	ALGO

- Card4 is read if TIED_WELD is set
  - TEMP: Welding temperature
  - CLOSE: maximum contact gap for which tying is considered
  - HWELD: Heat transfer coefficient for welded regions

- Card5 is standard for THERMAL option
  - H0: Heat transfer coefficient for unwelded regions

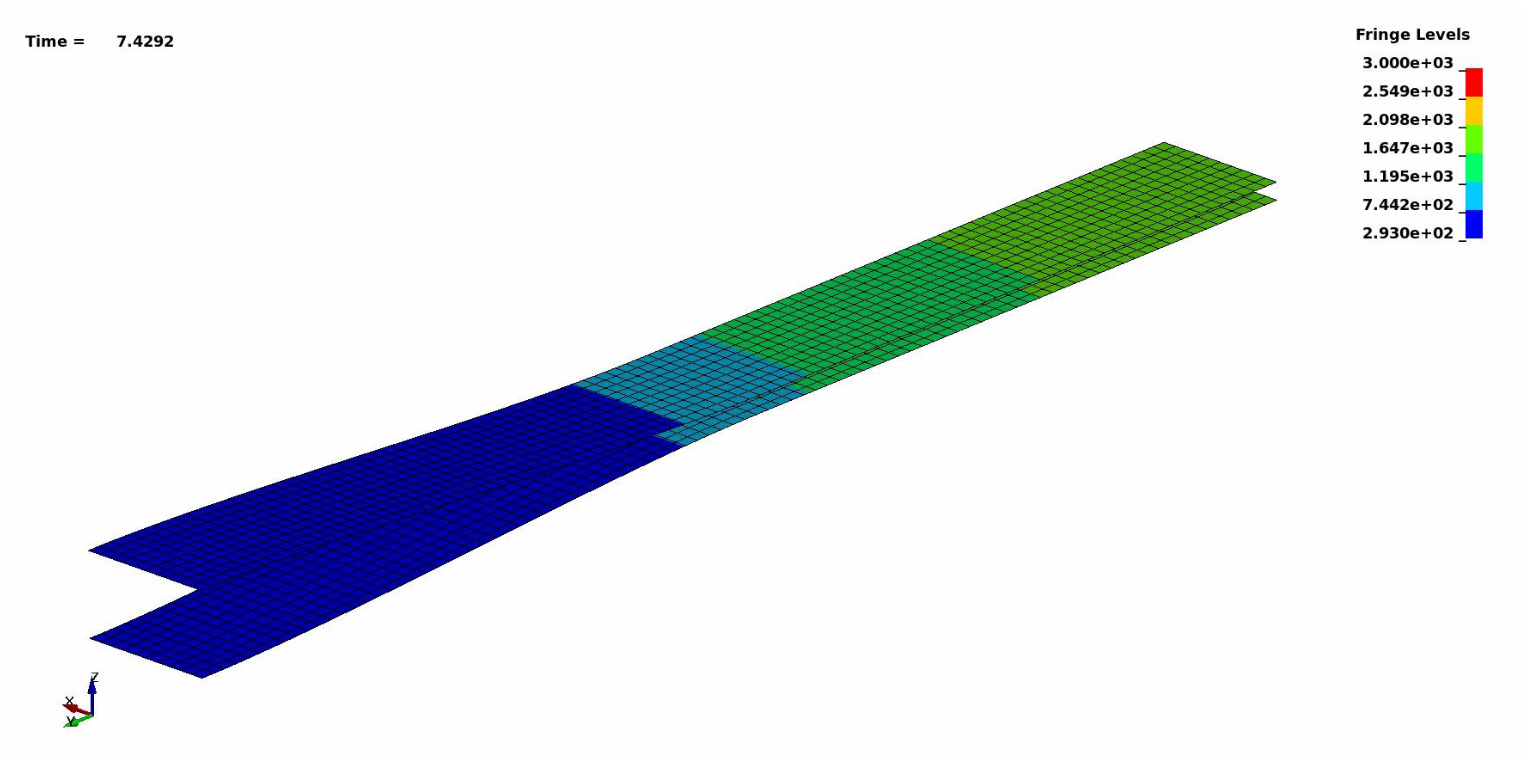
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL

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



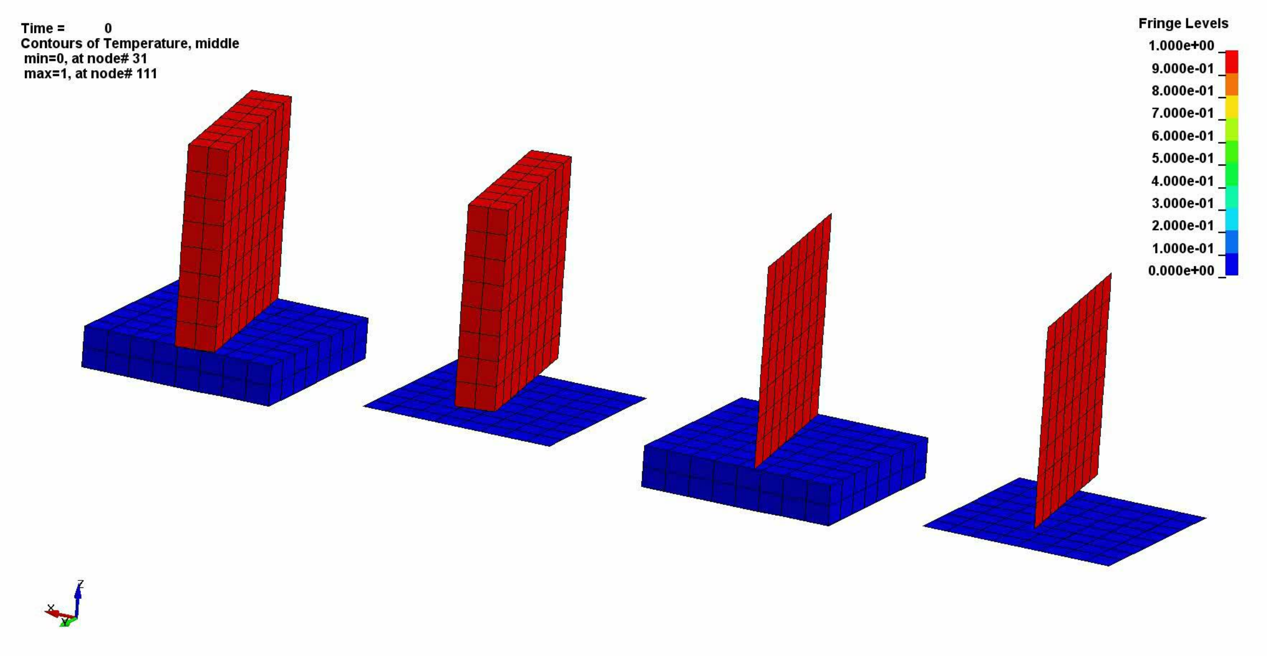
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL

- Example: laser welding
  - During welding the sheets are allowed to move
  - A very high heat conductivity in the contact area is assumed



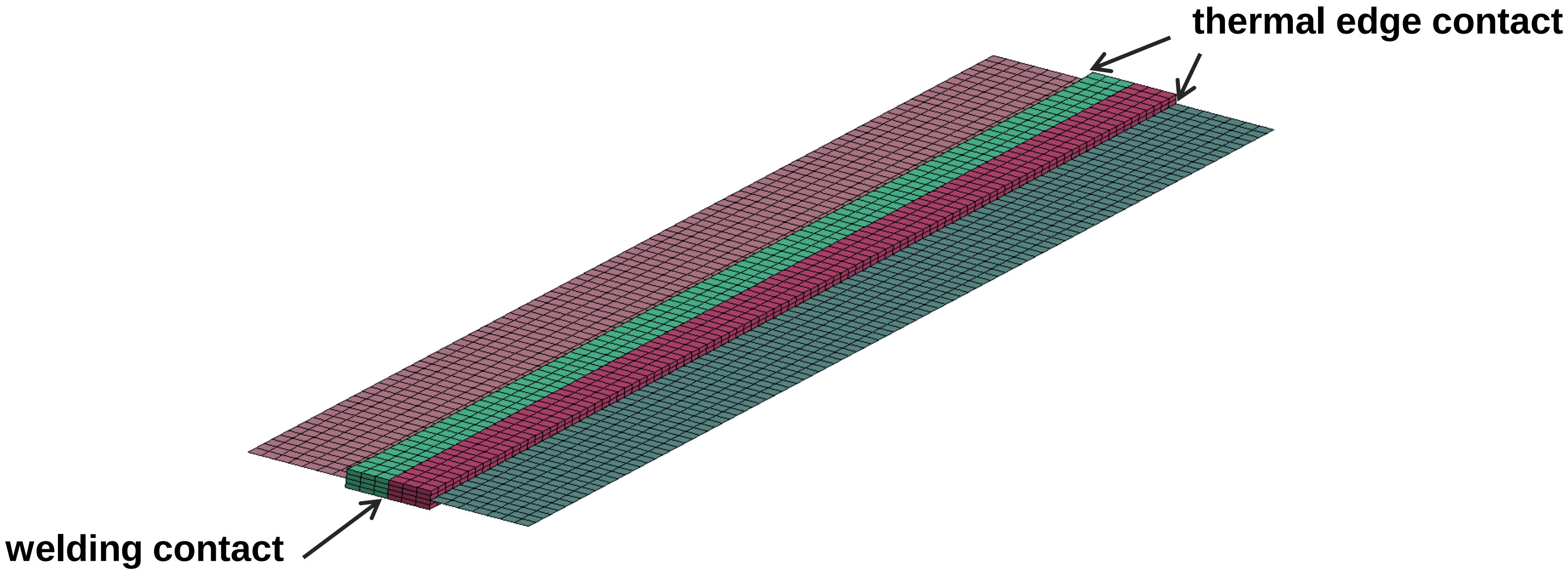
Thermal edge contact

- Activated for ALGO.eq.2 or 3 (one way)
- Can be used in a variety of contact types
  - SURFACE_TO_SURFACE, NODES_TO_SURFACE
  - SPOTWELD
  - TIED_SHELL_EDGE_TO_SOLID, TIED_SHELL_EDGE_TO_SURFACE



Thermal edge contact + welding contact

- Example:
  - Laser welding of a butt weld of a shell structure
  - Welded area discretized with solids
  - Shell elements tied to the solid elements



Thermal edge contact + welding contact

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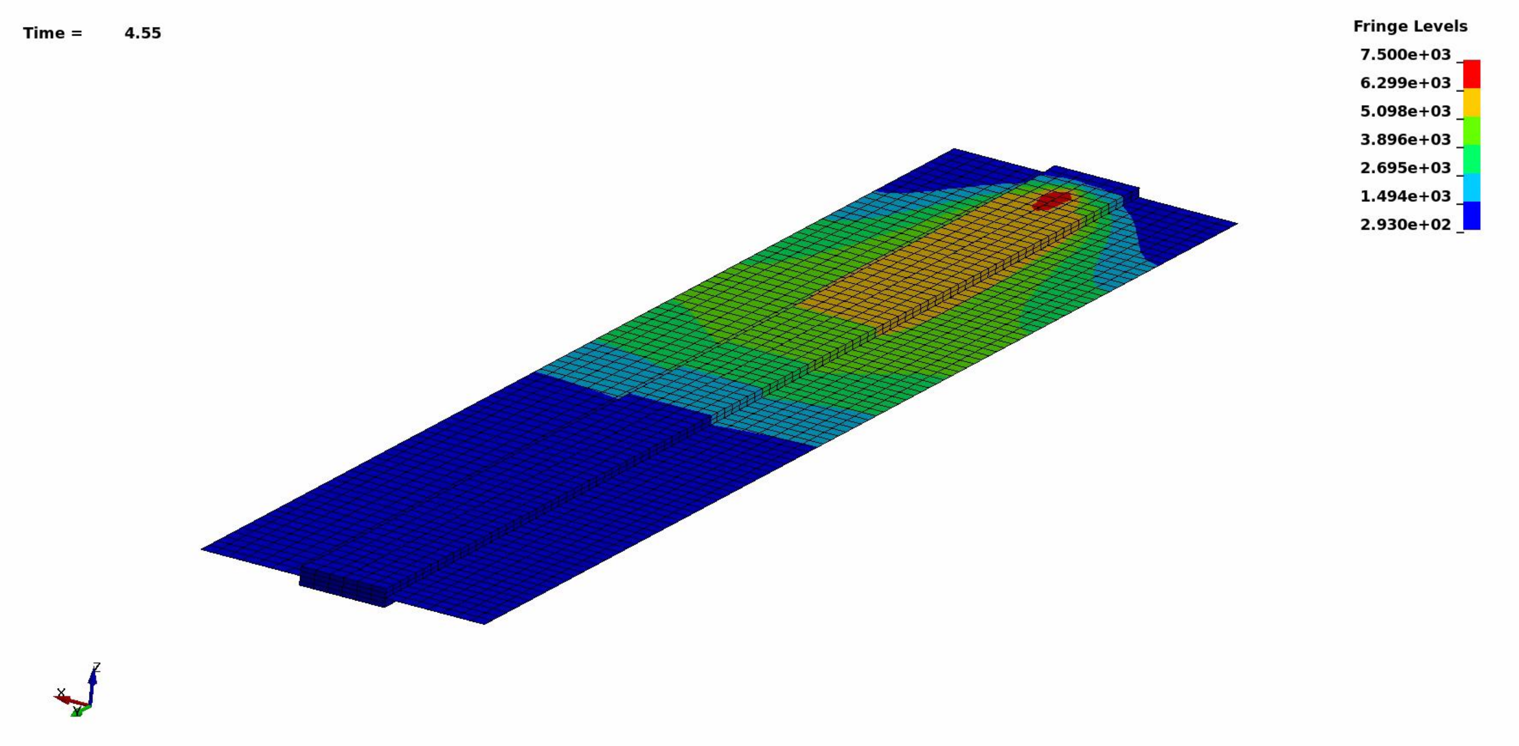

Thermal edge contact + welding contact

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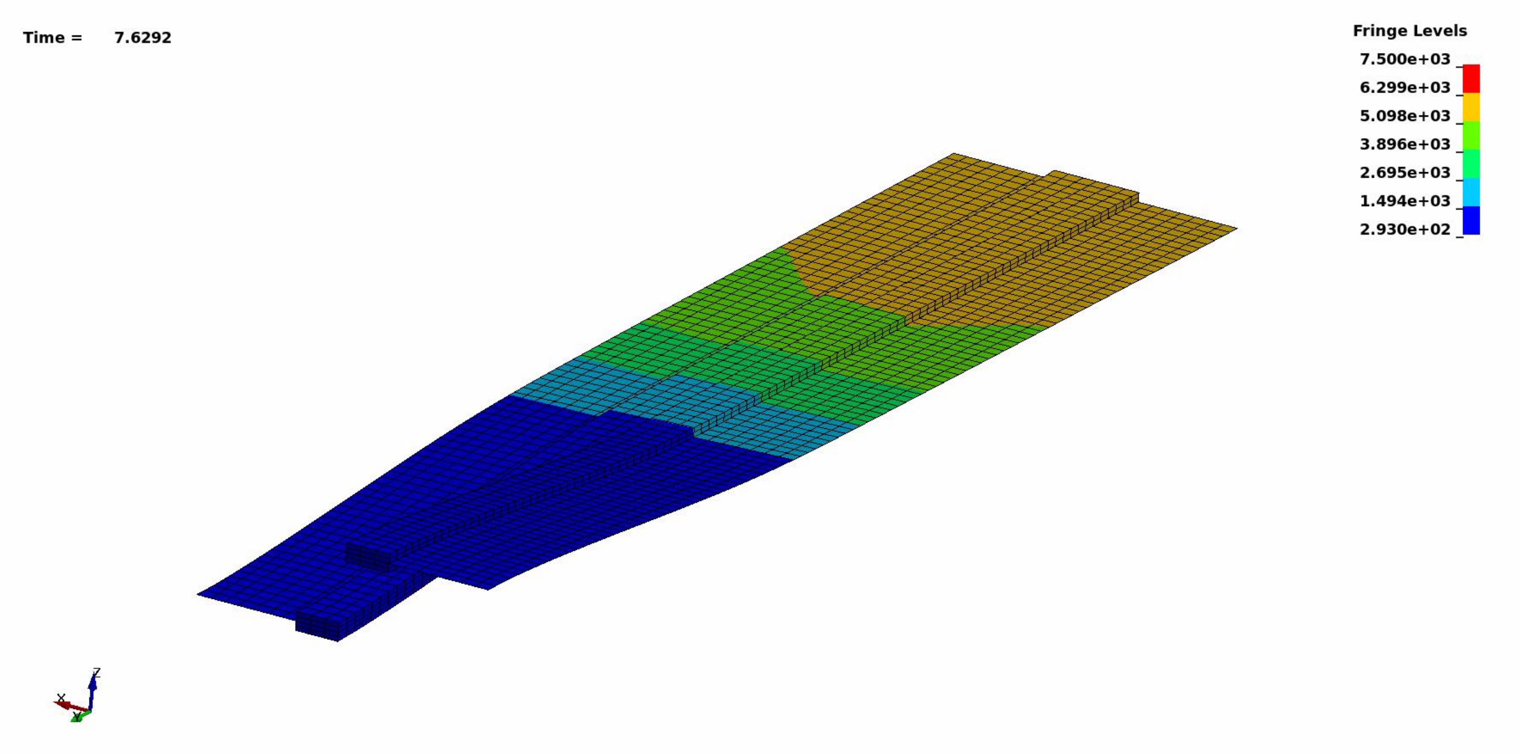

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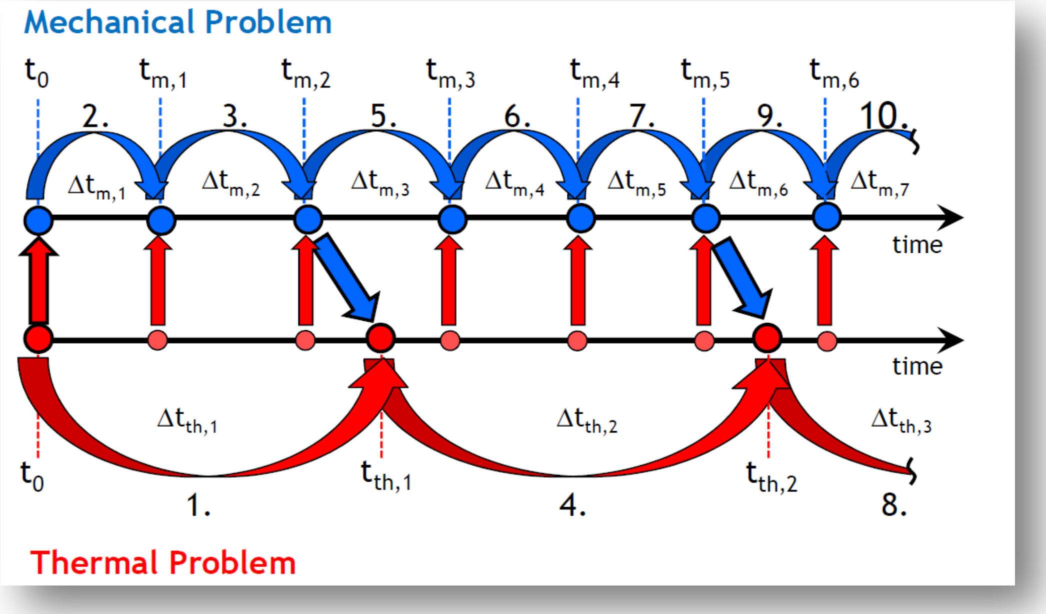
Remarks on Simulation Strategies

- Coupled thermo-mechanical analysis
  - Default strategy in LS-DYNA
  - Staggered approach



- De-coupled approach
  - Run thermal problem first
  - Use results of thermal run as boundary condition *LOAD_THERMAL_D3PLOT
  - Yields the same results, if output frequency of the thermal run is sufficiently high
  - Might be easier in terms of boundary conditions for the thermal run
  - Allows to easily test variations of the mechanical model
  - Re-implementation to accept thermal thick shell results

Thank you!