

Recent Updates for the Structural Conjugate Heat Transfer Solver in LS-DYNA

Thomas Klöppel

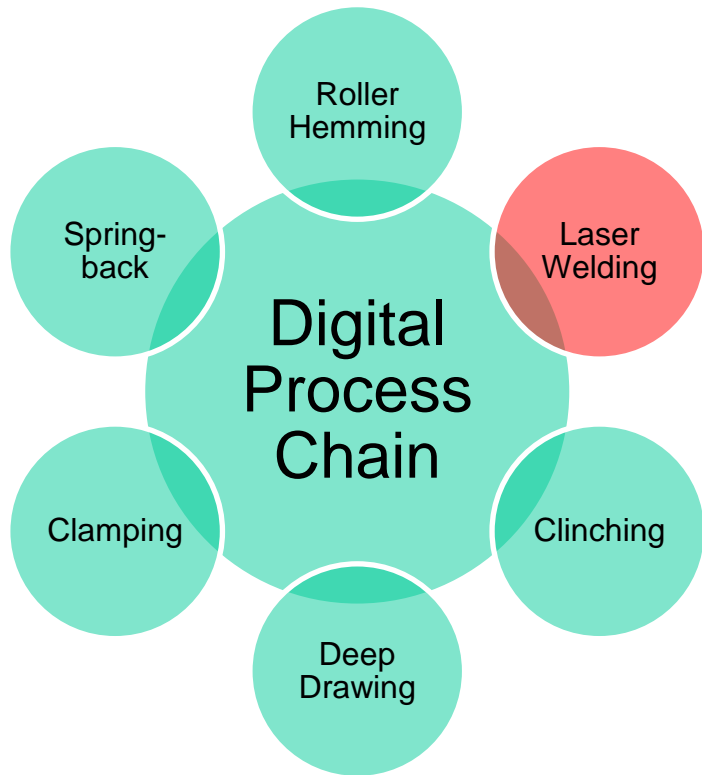
DYNAmore GmbH



14th German LS-DYNA Forum

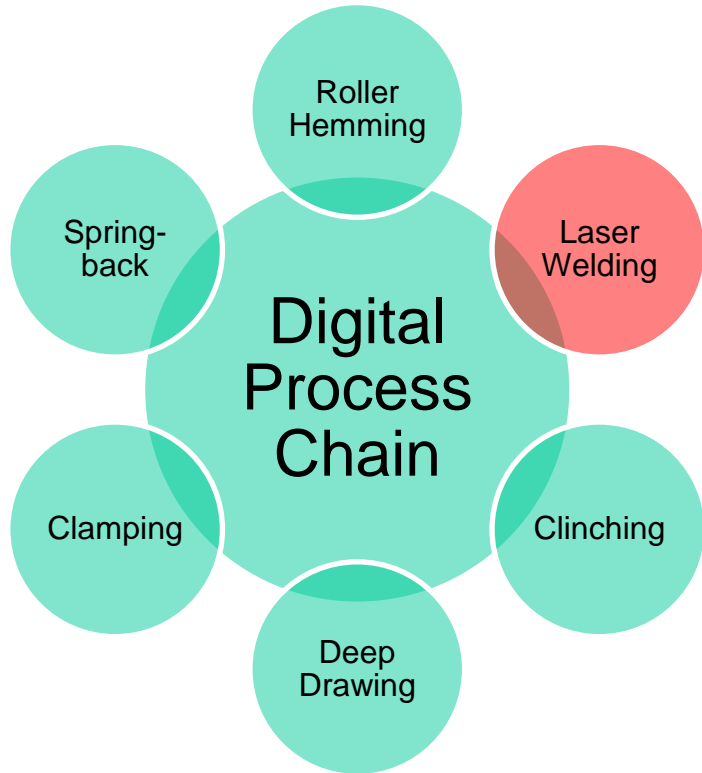
Bamberg, Oct. 10-12, 2016

Motivation – process chain in manufacturing



- 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 and heat treatment stages particularly important
 - Locally very high temperature gradients
 - Large distortions
 - Changes in the microstructure of the material in the heat affected zone

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 data 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!

CONTENT

- Motivation
- Flexible heat source definition
- Material formulation to capture evolution of micro-structure
- New contact options in LS-DYNA
- Remarks on Simulation Strategies
- Conclusion and Outlook

CONTENT

- Motivation

- Flexible heat source definition
 - *BOUNDARY_THERMAL_WELD
 - *BOUNDARY_THERMAL_WELD_TRAJECTORY

- Material formulation to capture evolution of micro-structure

- New contact options in LS-DYNA

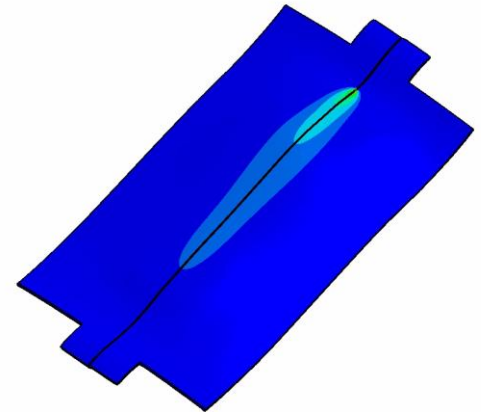
- Remarks on Simulation Strategies

- Conclusion and Outlook

*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
 - Structure solver necessary
 - Weld path definition not straight-forward for curve geometries
 - How to compensate for part deformation due to welding itself?
- Only applicable to solid parts
- Incremental heating may lead to severe element distortion



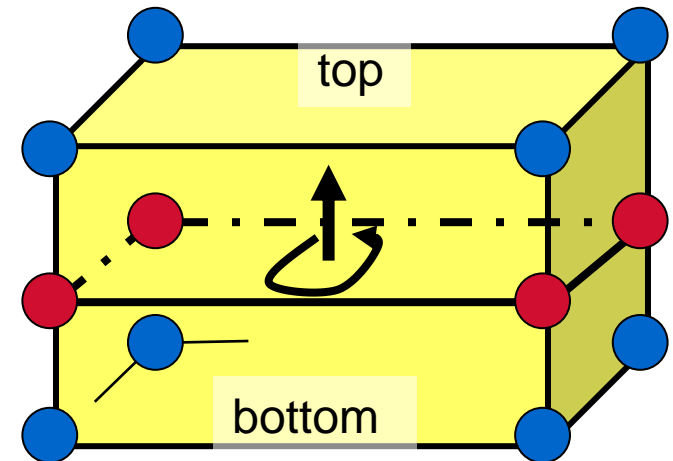
Need a more flexible and easier to use boundary condition for welding!

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



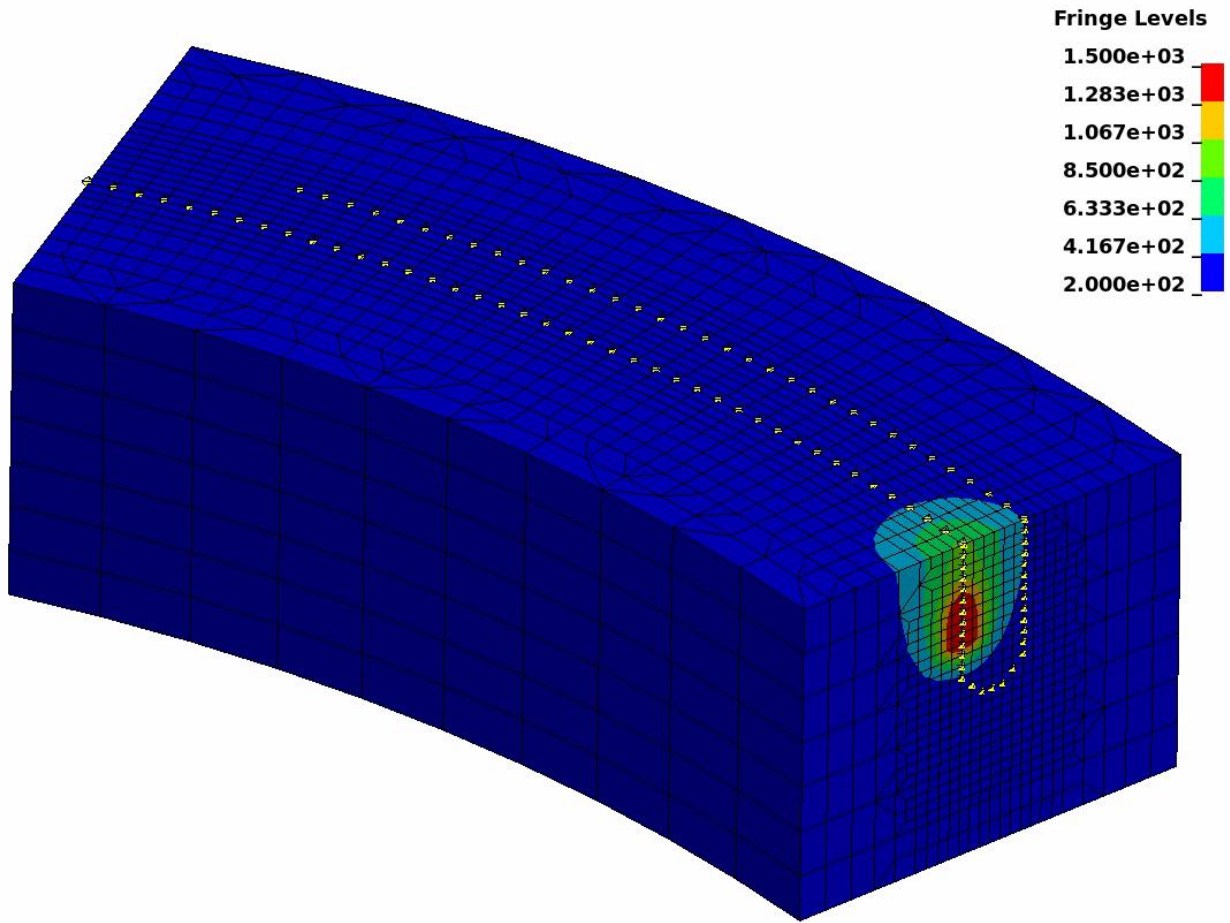
*BOUNDARY_THERMAL_WELD_TRAJECTORY

	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

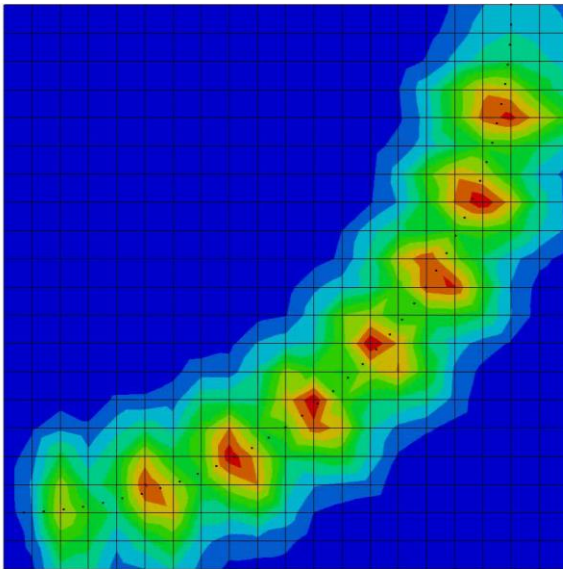
■ Example: Trajectory definition



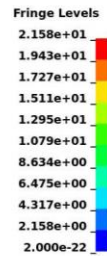
*BOUNDARY_THERMAL_WELD_TRAJECTORY

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

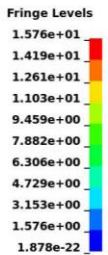
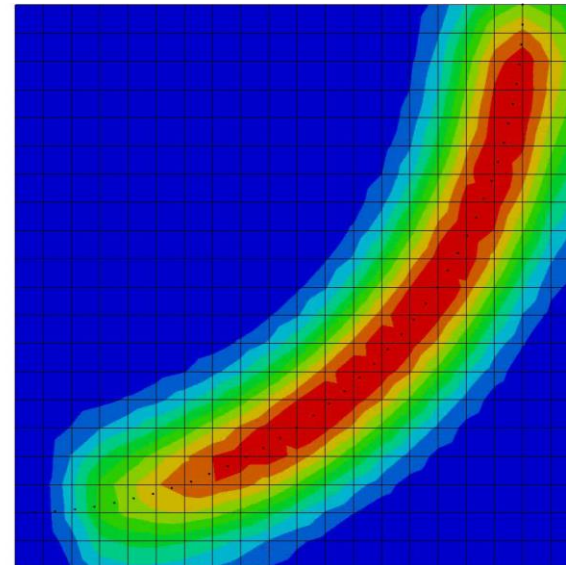
■ NCYC: number of sub-cycling steps



temperature field, NCYC = 1,
Peak temperature = 21.6



temperature field, NCYC = 10
Peak temperature = 15.8

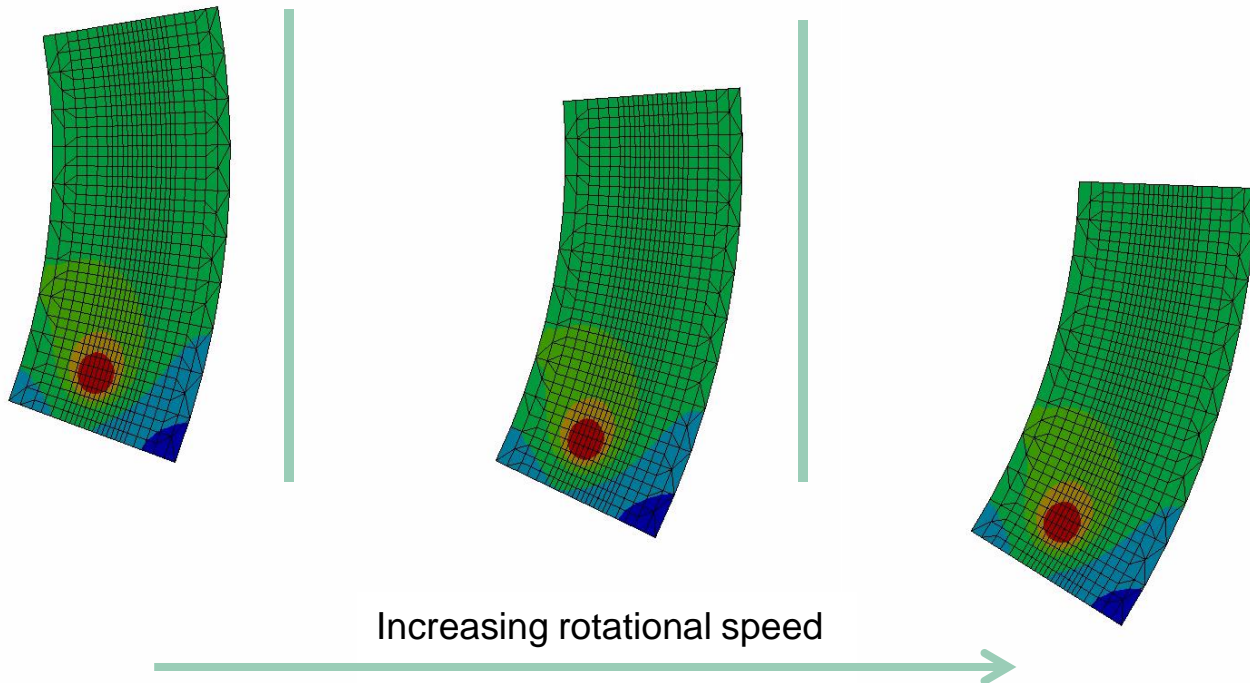


*BOUNDARY_THERMAL_WELD_TRAJECTORY

	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

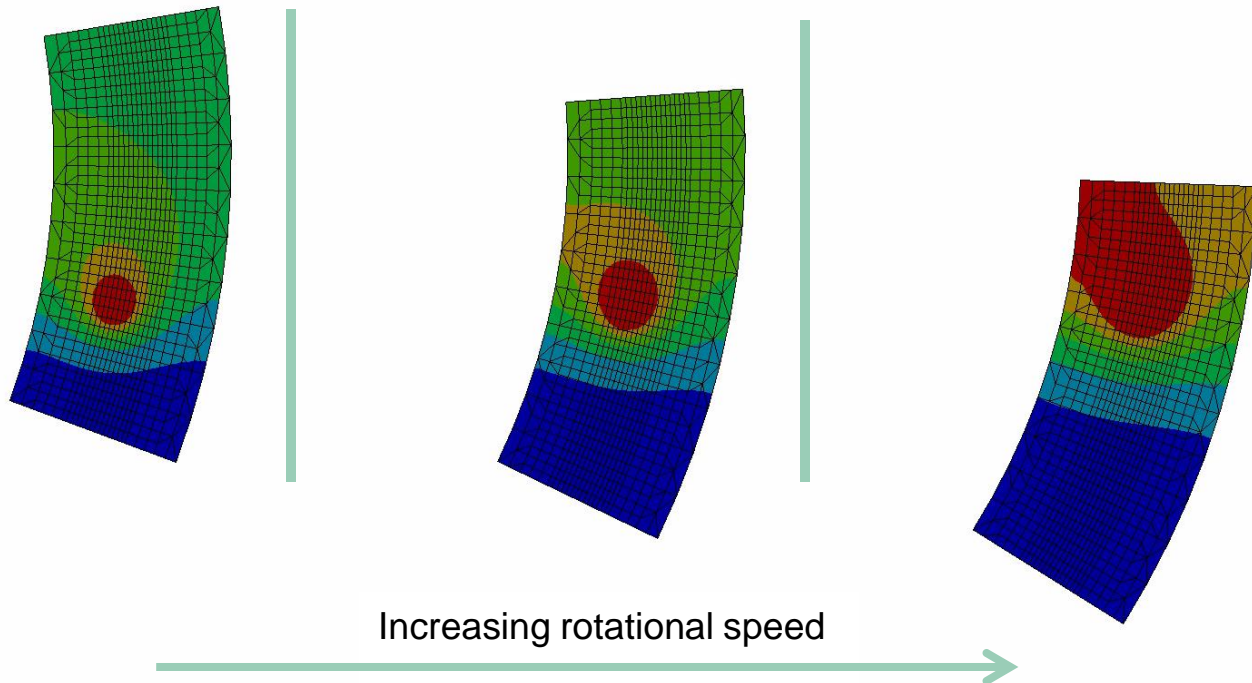


*BOUNDARY_THERMAL_WELD_TRAJECTORY

	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

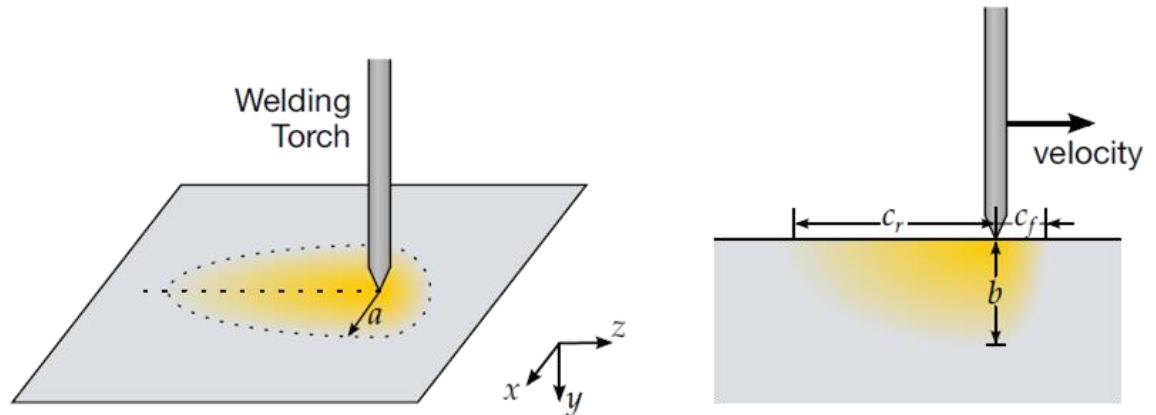
- Px: Parameters for weld pool geometry

*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



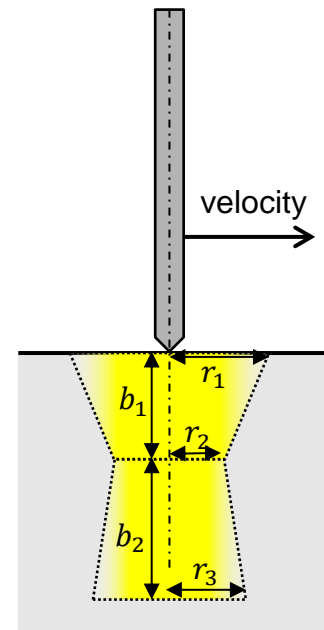
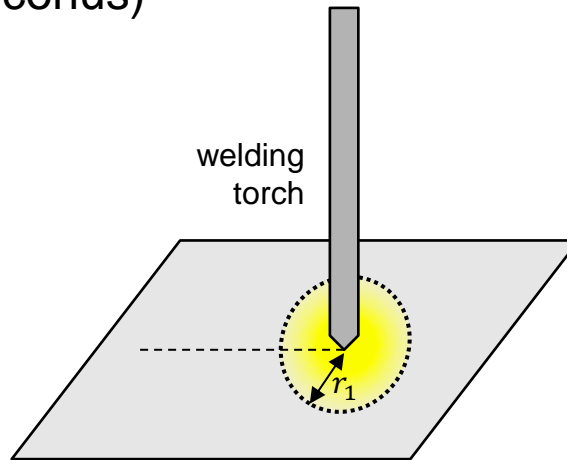
$$q = \frac{2n\sqrt{n}FQ}{\pi\sqrt{\pi}abc} \exp\left(\frac{-nx^2}{a^2}\right) \exp\left(\frac{-ny^2}{b^2}\right) \exp\left(\frac{-nz^2}{c^2}\right)$$

*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=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

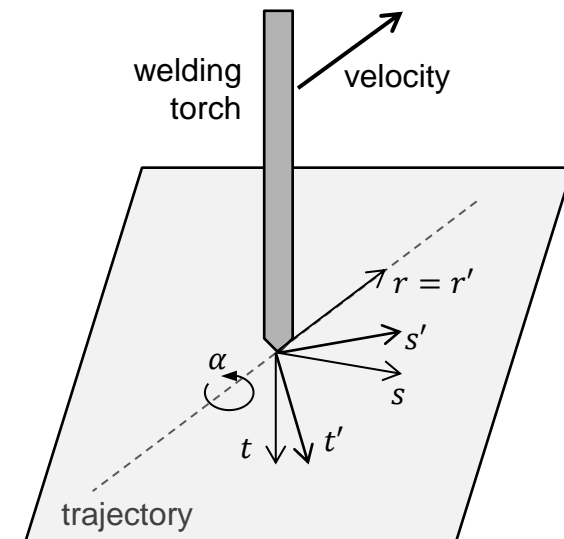
	1	2	3	4	5	6	7	8
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	

- **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: $0.05 \times (\text{weld source depth})$

*BOUNDARY_THERMAL_WELD_TRAJECTORY

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

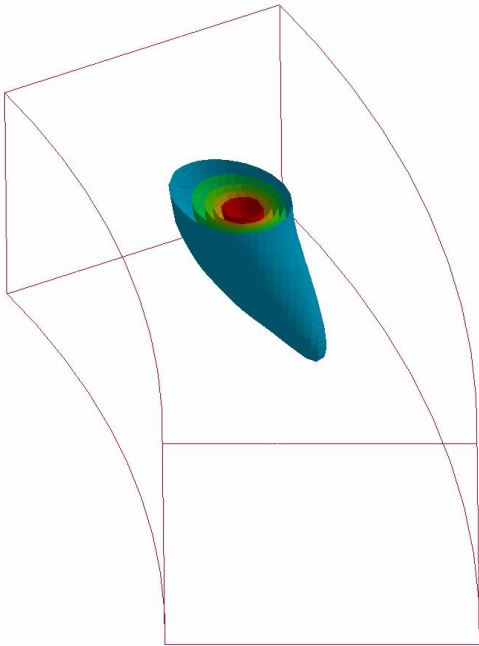
- LCROT: load curve defining the rotation (α in degree) of weld source around the trajectory as function of time.
- LCMOV: load curve for offset of weld source in depth (t') after rotation as function of time
- LCLAT: load curve for lateral offset (s') after rotation as function of time



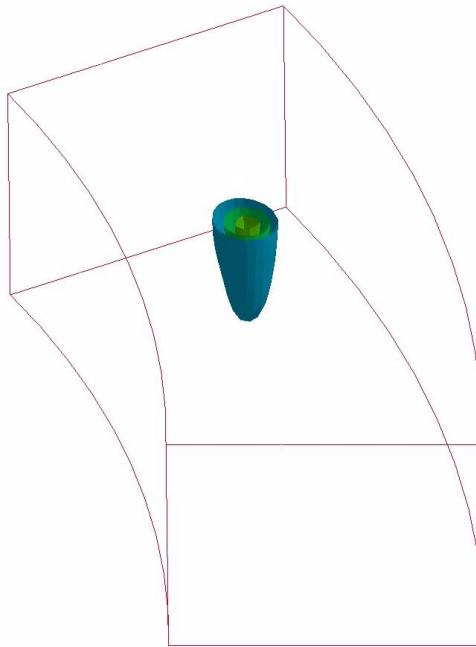
*BOUNDARY_THERMAL_WELD_TRAJECTORY

■ Example: Influence of oscillations for...

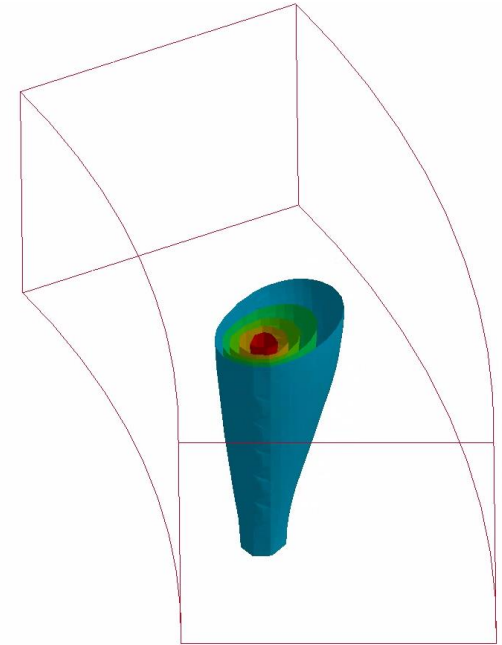
...LCROT



... LCMOV

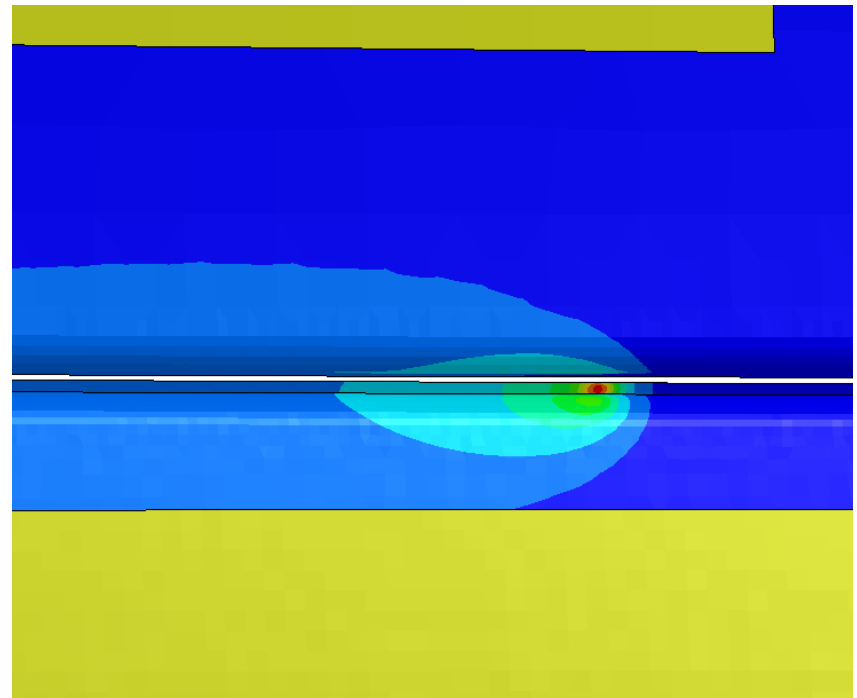
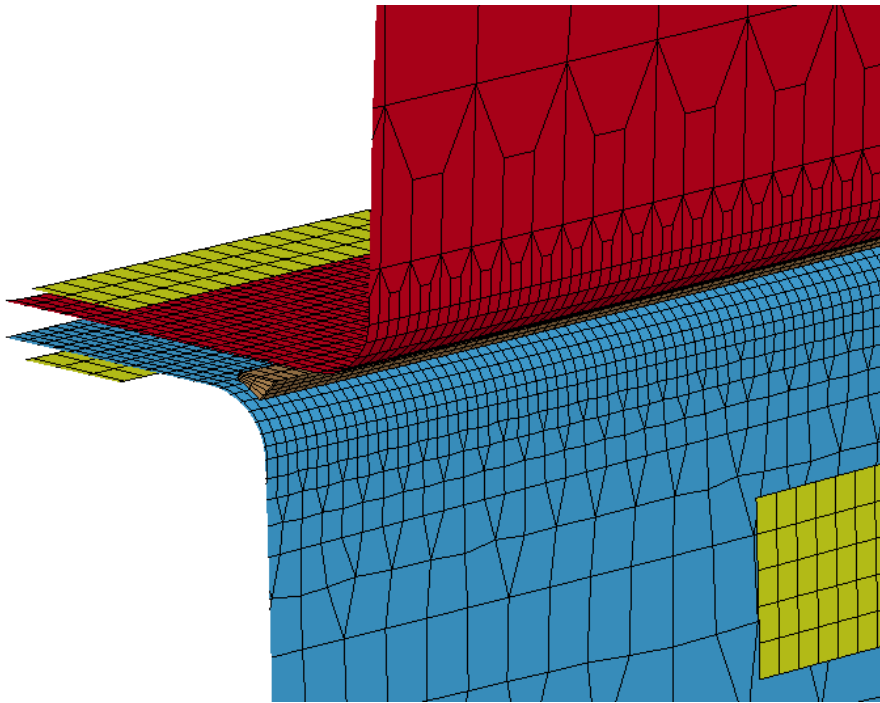


... LCLAT



Industrial examples

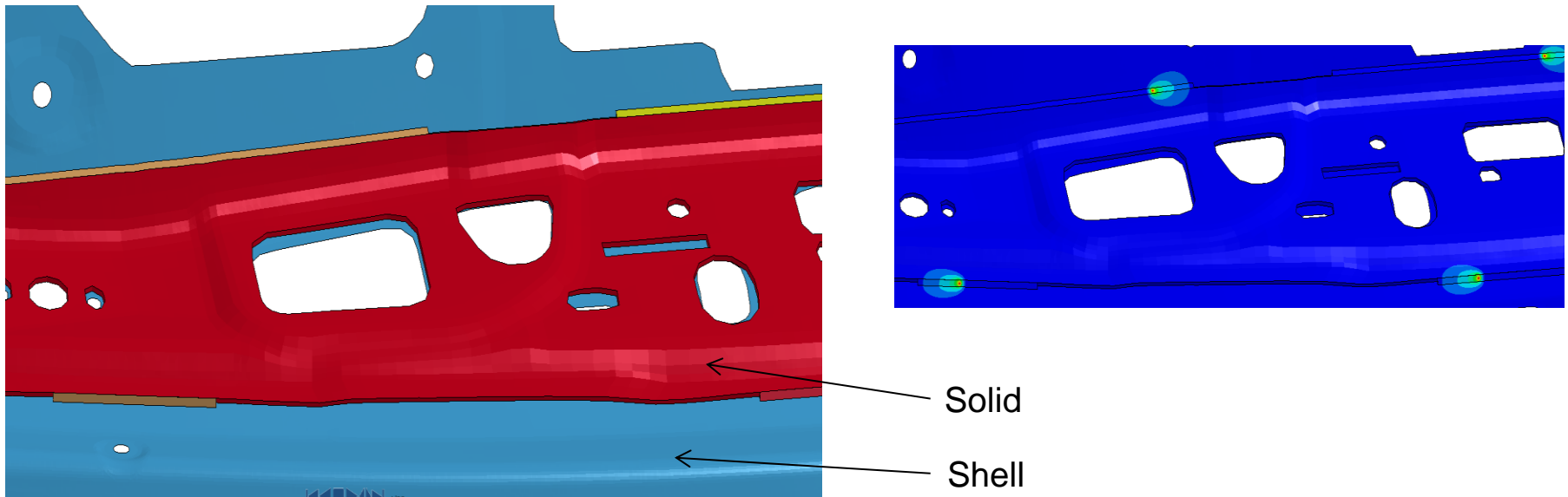
- Forming and clamping usually done with shell structures
- Additional filler discretized with solids



- 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

- Flexible heat source definition

- Material formulation to capture evolution of micro-structure
 - *MAT_UHS_STEEL / *MAT_244
 - *MAT_GENERALIZED_PHASECHANGE / *MAT_254

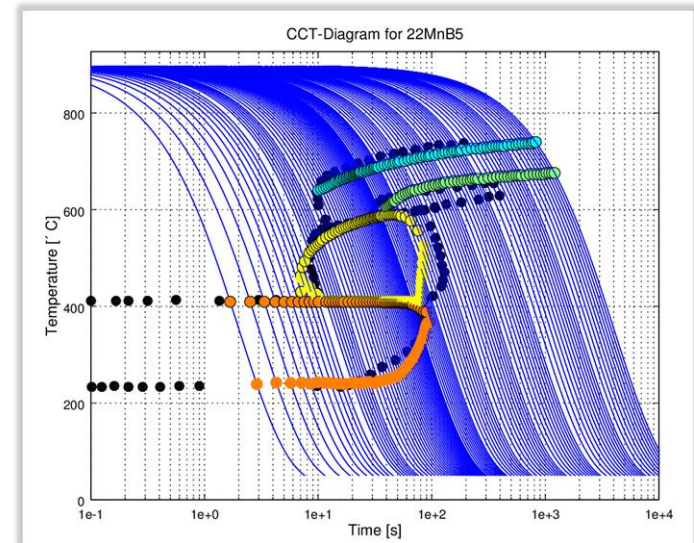
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Status Quo: *MAT_UHS_STEEL/*MAT_244

- 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
 - 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!

*MAT_254

- Implementation of *MAT_GENERALZE_PHASE_CHANGE for shells and solids

- 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 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:

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

- 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:

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

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

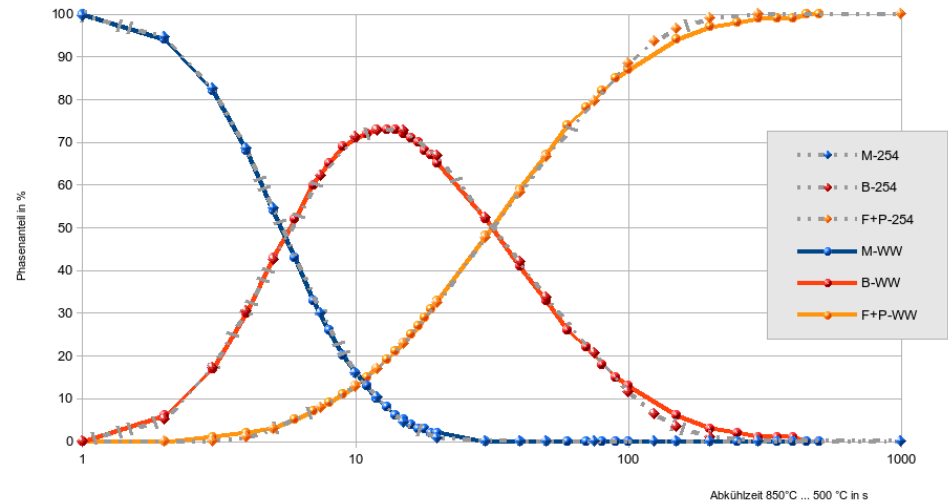
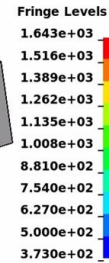
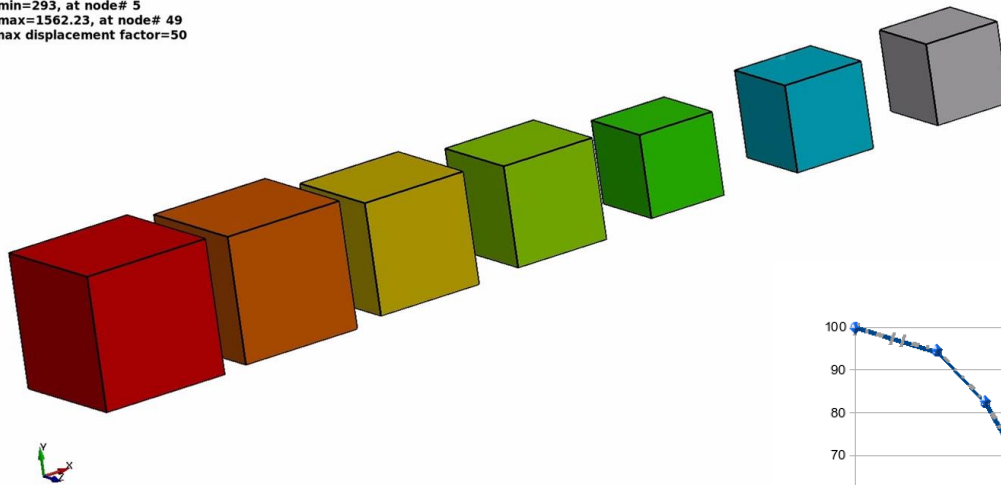
■ Parameter:

- 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

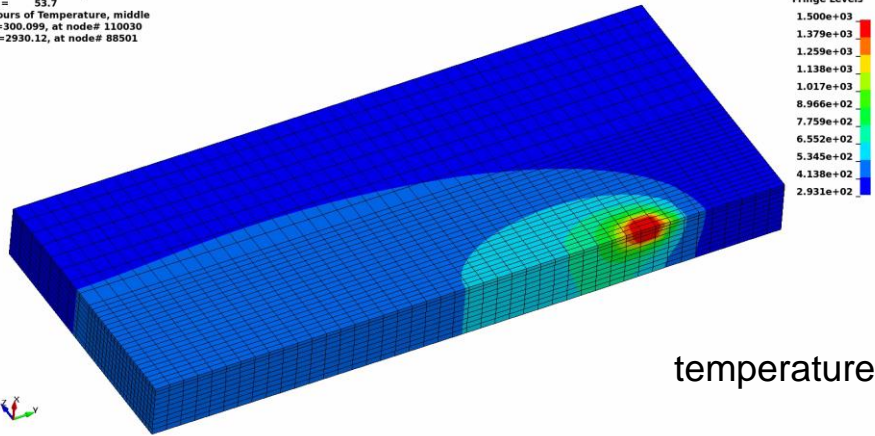
Gefügeumwandlungstest 1.0 - 10.0
 Time = 16.6
 Contours of Temperature
 min=293, at node# 5
 max=1562.23, at node# 49
 max displacement factor=50



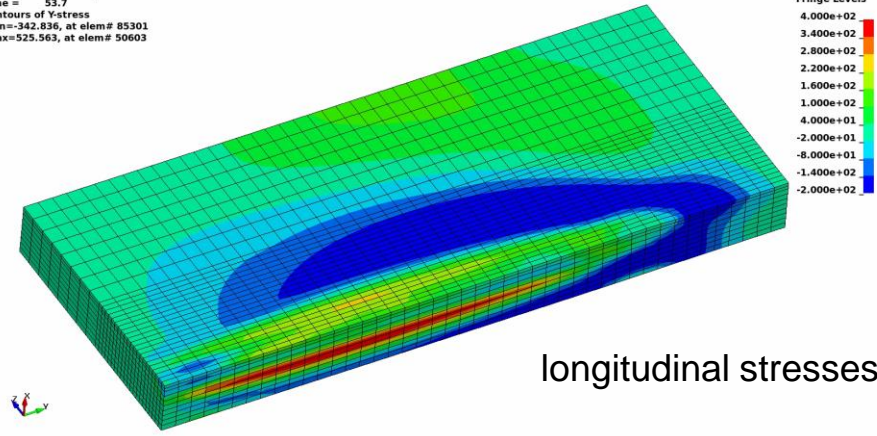
Residual stresses

■ Nitschke-Pagel test

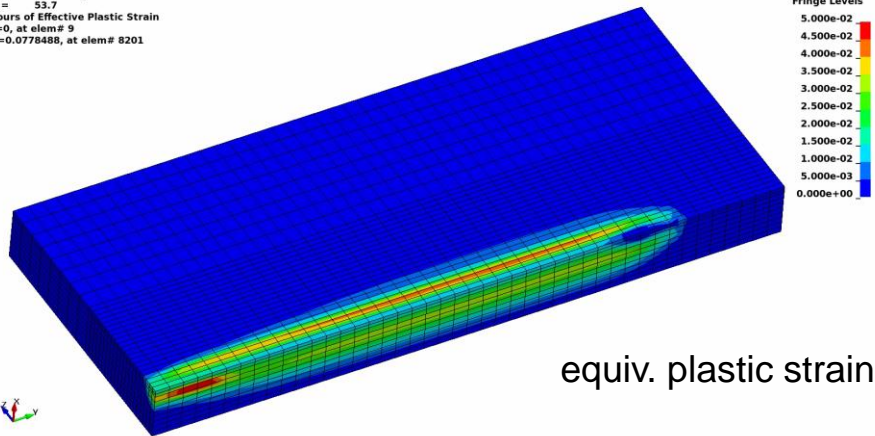
LS-DYNA user input
Time = 53.7
Contours of Temperature, middle
min=300.099, at node# 110030
max=2930.12, at node# 88501



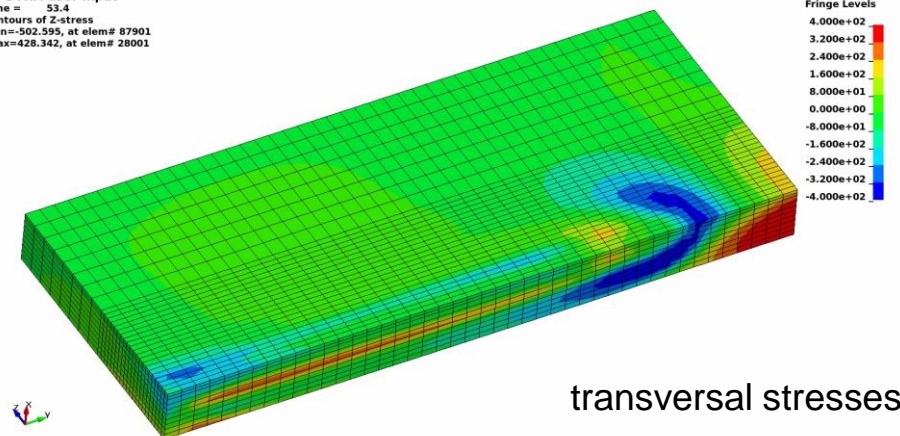
LS-DYNA user input
Time = 53.7
Contours of Y-stress
min=-342.836, at elem# 85301
max=525.563, at elem# 50603



LS-DYNA user input
Time = 53.7
Contours of Effective Plastic Strain
min=0, at elem# 9
max=0.0778488, at elem# 8201



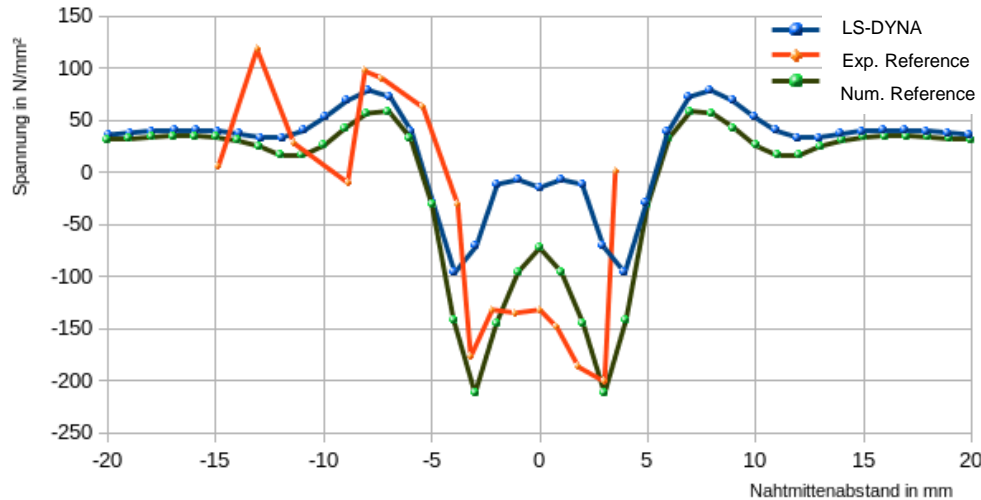
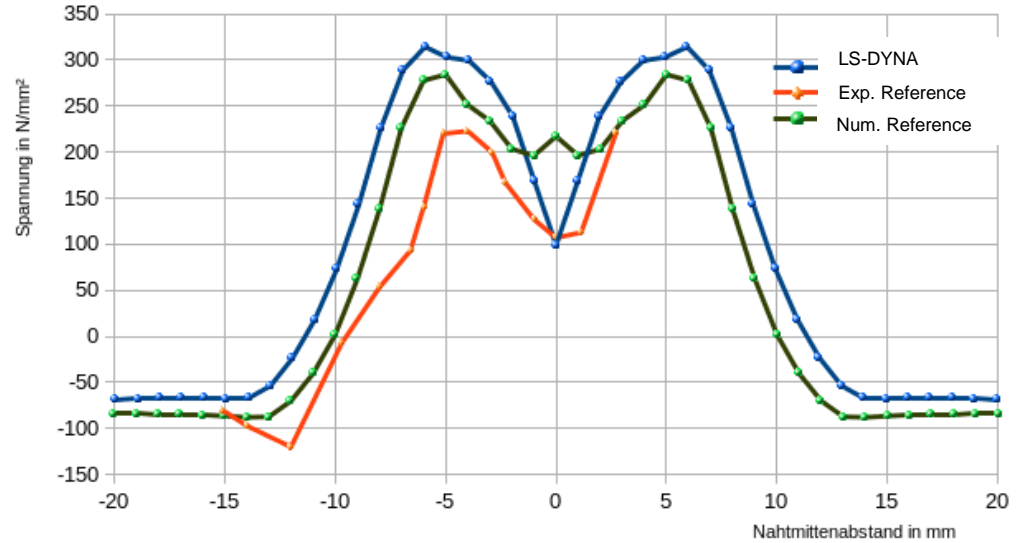
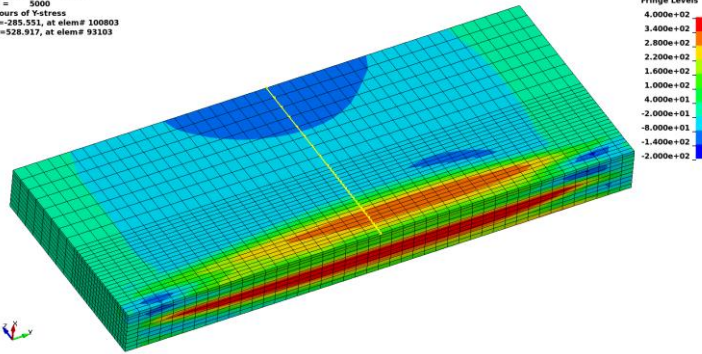
LS-DYNA user input
Time = 53.4
Contours of Z-stress
min=-502.595, at elem# 87901
max=428.342, at elem# 28001



Residual stresses

Nitschke-Pagel test

LS-DYNA user input
Time = 3000
Contours of Fstress
min=-285.531, at elem# 100803
max=528.917, at elem# 93103



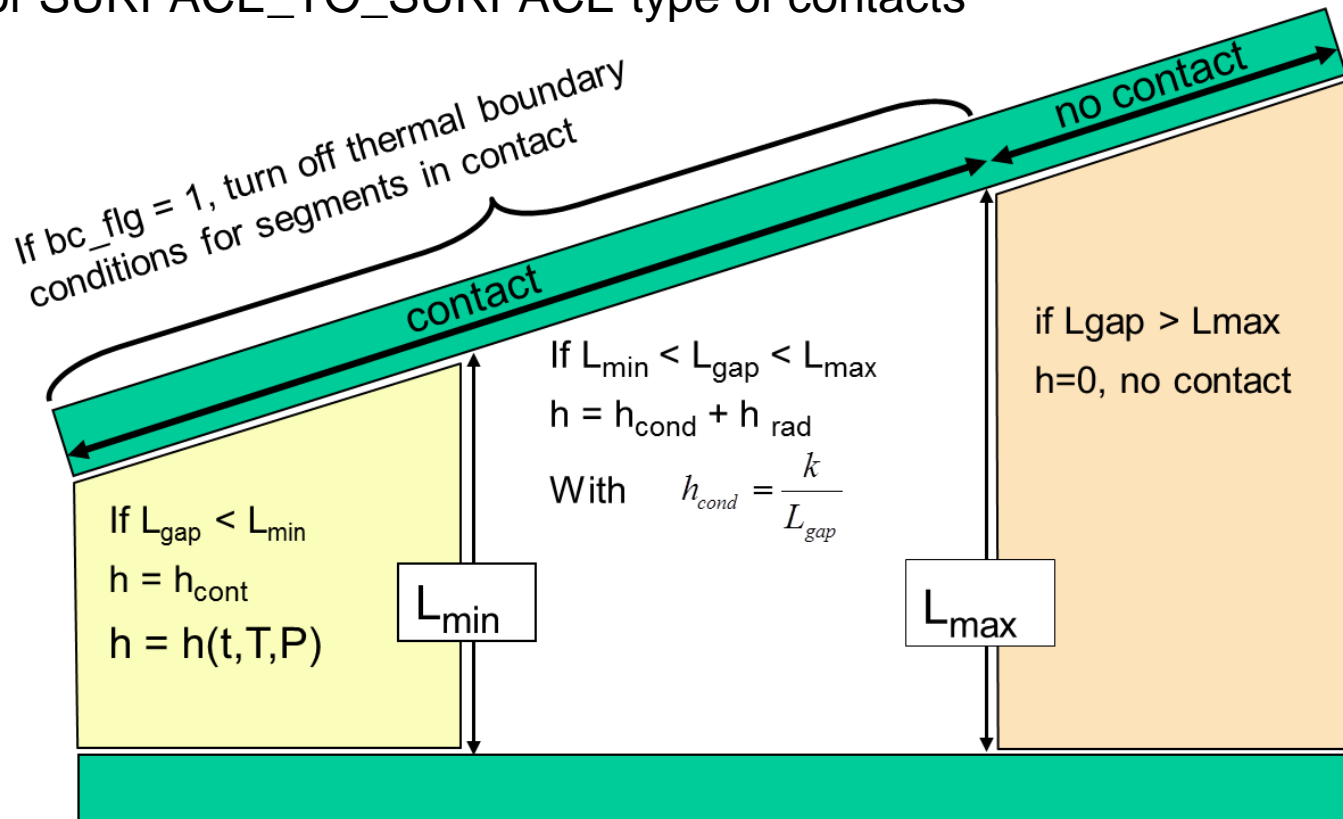
CONTENT

- Motivation
- Flexible heat source definition
- Material formulation to capture evolution of micro-structure
- New contact options in LS-DYNA
 - Temperature activated tied contact
 - Thermal shell edge contact
- Remarks on Simulation Strategies
- Conclusion and Outlook

Status Quo: *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



Welding without filler elements

- Important for laser welding
- Ghosting approach, which has been implemented in LS-DYNA in some material formulations no longer feasible
- 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 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

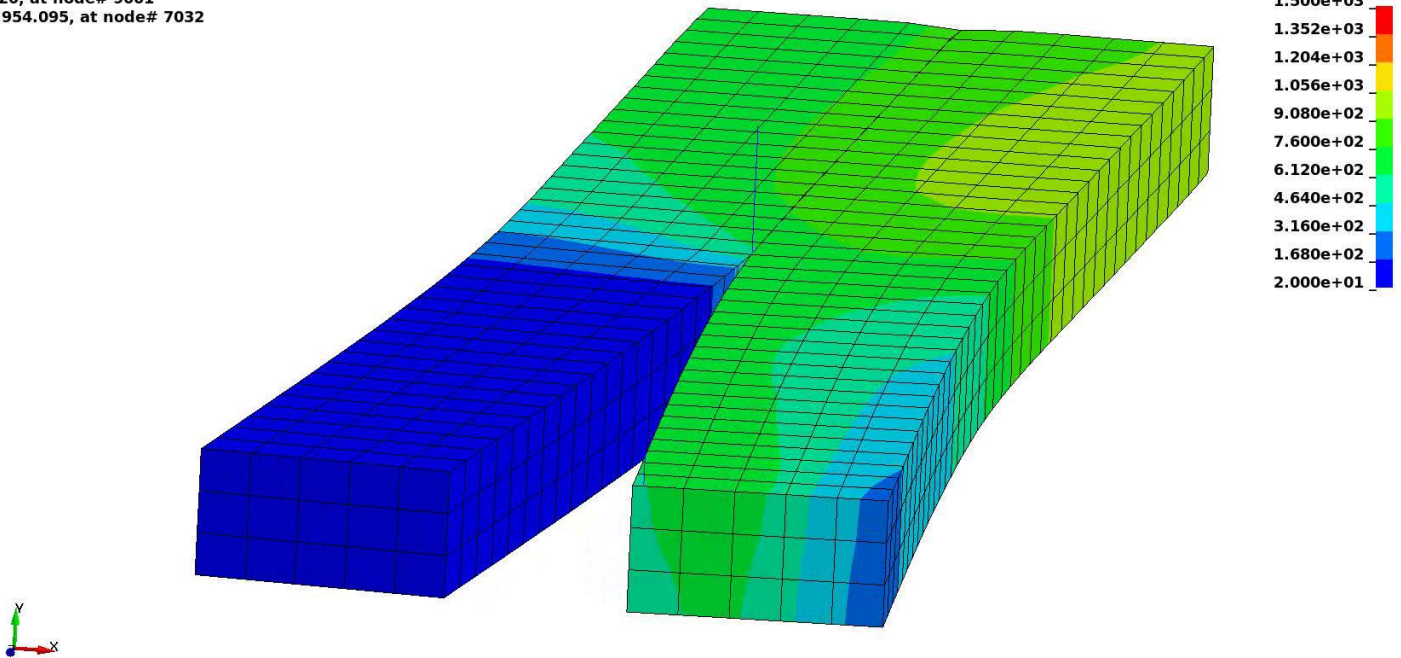
- Card5 is standard for THERMAL option
 - H0: Heat transfer coefficient for unwelded regions

*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

welding_contact_automatic_tied_weld_thermal.k
Contours of Temperature
min=20, at node# 9001
max=954.095, at node# 7032

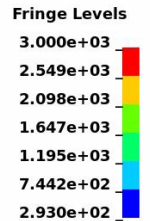
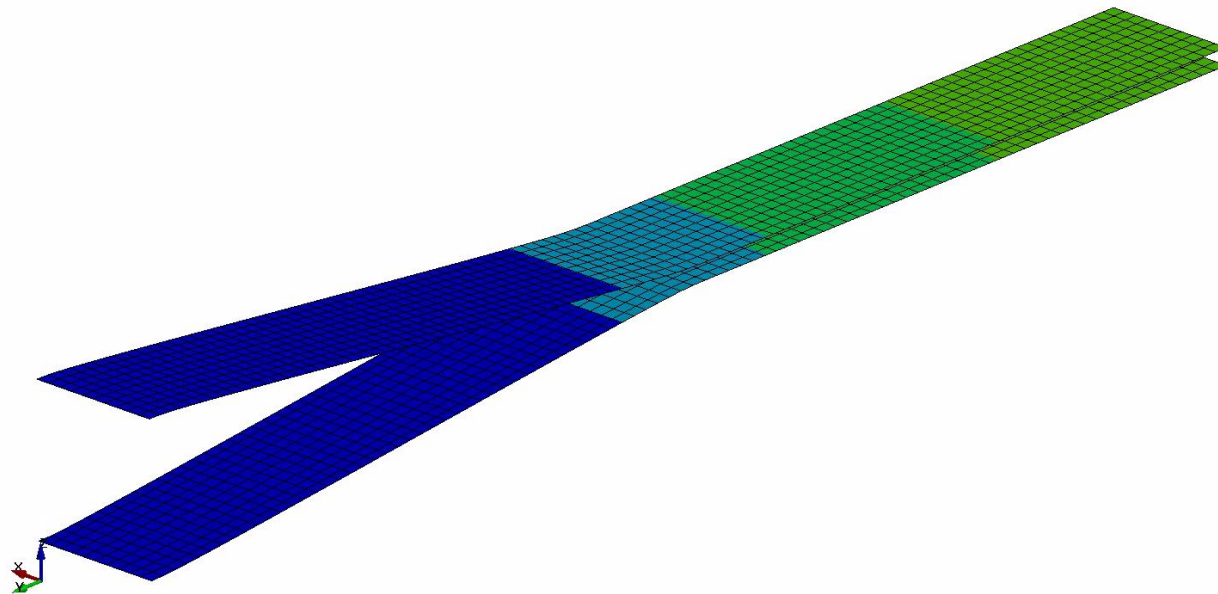


*CONTACT__AUTOMATIC_SURFACE_TO_SURFACE__TIED_WELD_THERMAL

■ Example: laser welding

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

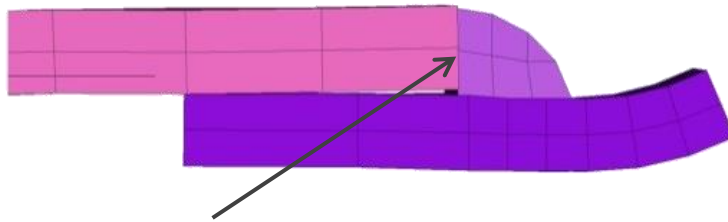
Time = 10



Thermal edge contact

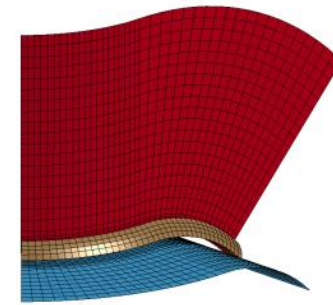
	1	2	3	4	5	6	7	8
Card	K	Hrad	H0	LMIN	LMAX	CHLM	BC_FLAG	ALGO

- 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**

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

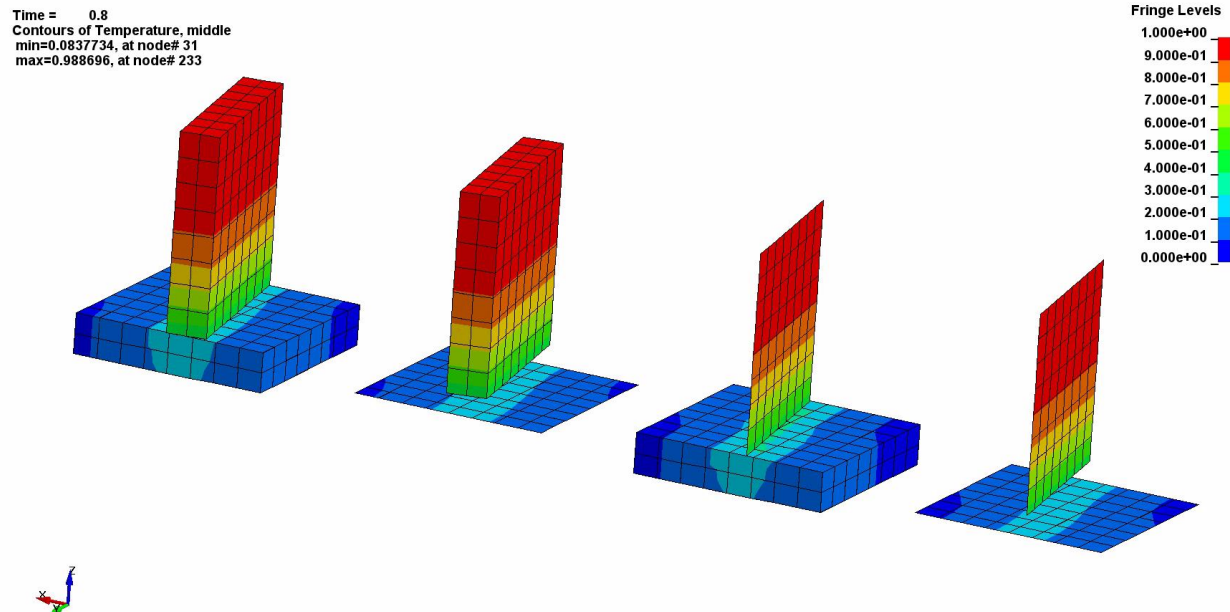


T-Joint with shells

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

Thermal edge contact – Example

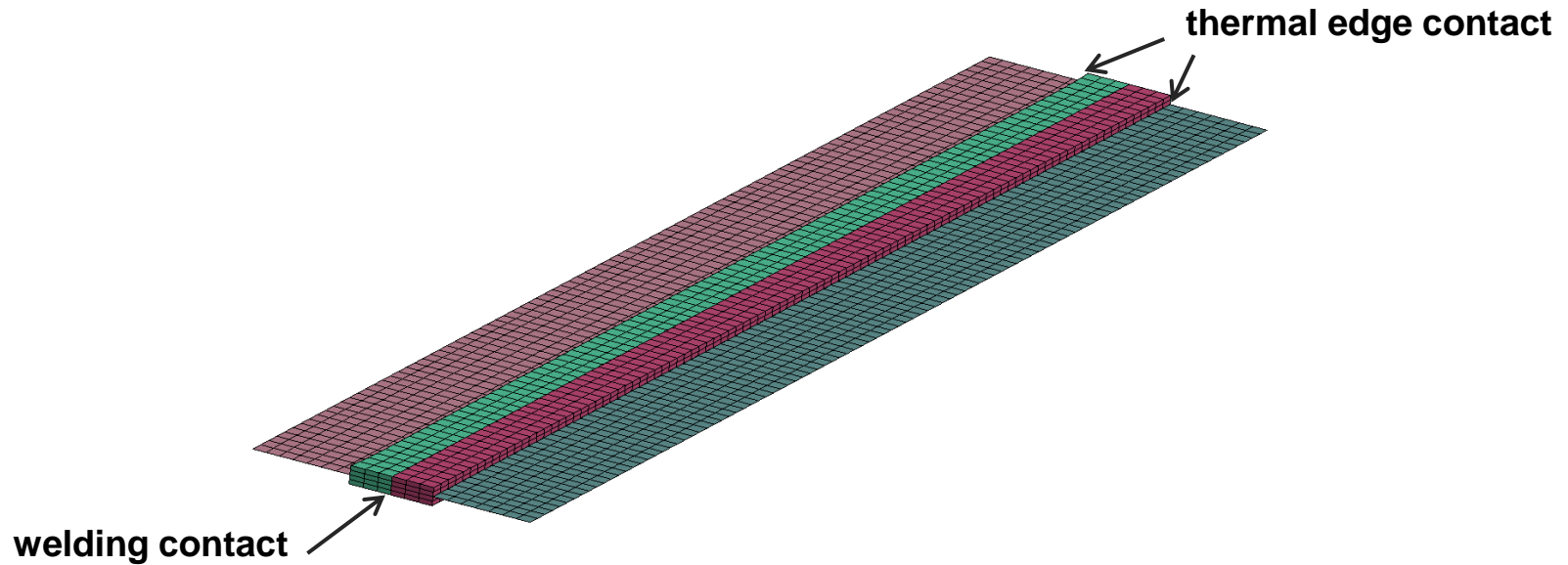
- Thermal only-analysis of heat transfer across a rotated T-joint
- Two-way contact
- Comparison of different discretization approaches for both parts (solid to shell, solid to shell, shell to solid, shell to shell)





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

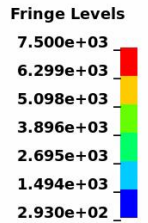
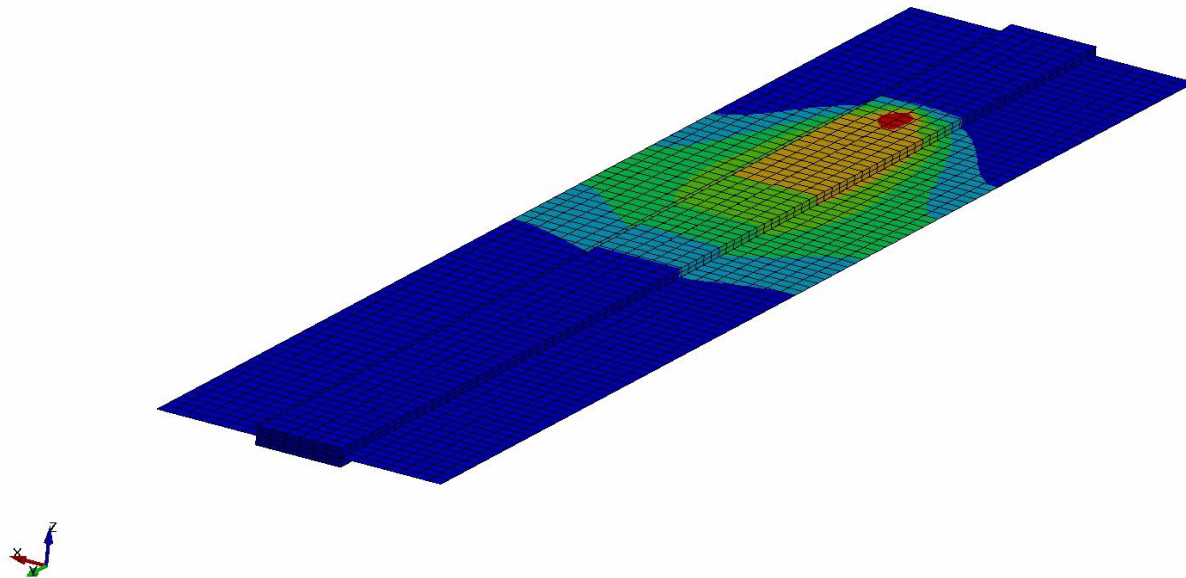




Thermal edge contact + welding contact - Example

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

Time = 3

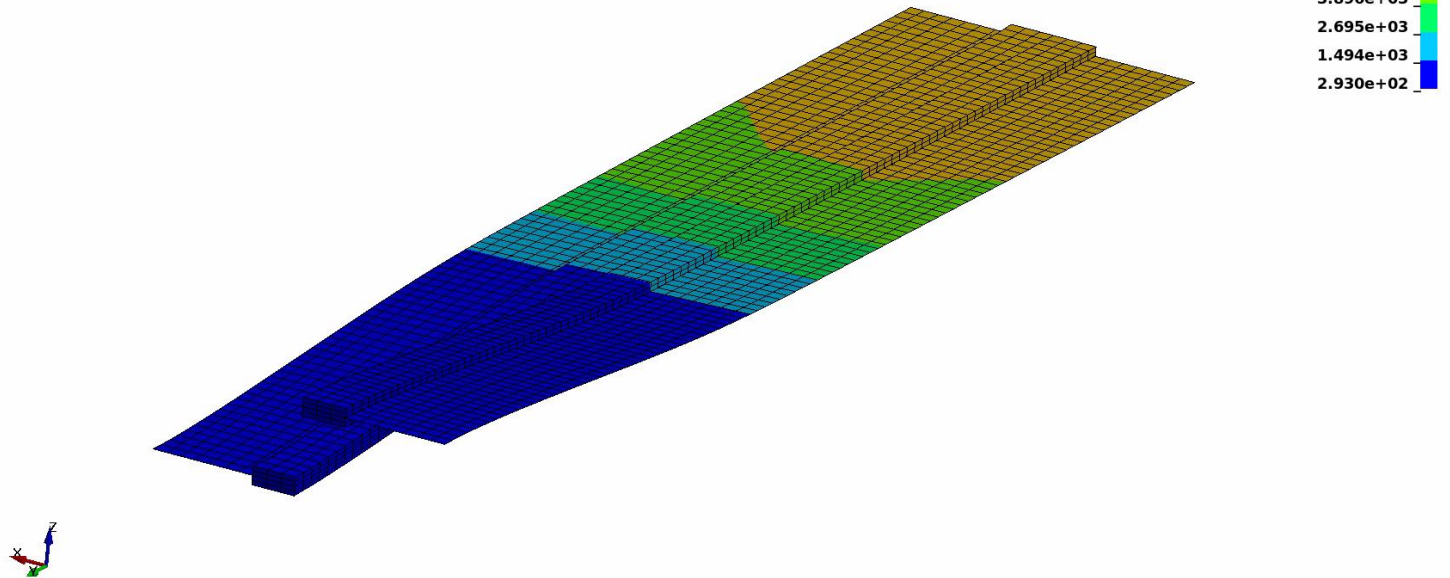




Thermal edge contact + welding contact - Example

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

Time = 7.6292



CONTENT

- Motivation
- Flexible heat source definition
- Material formulation to capture evolution of micro-structure
- New contact options in LS-DYNA
- Remarks on Simulation Strategies
- Conclusion and Outlook

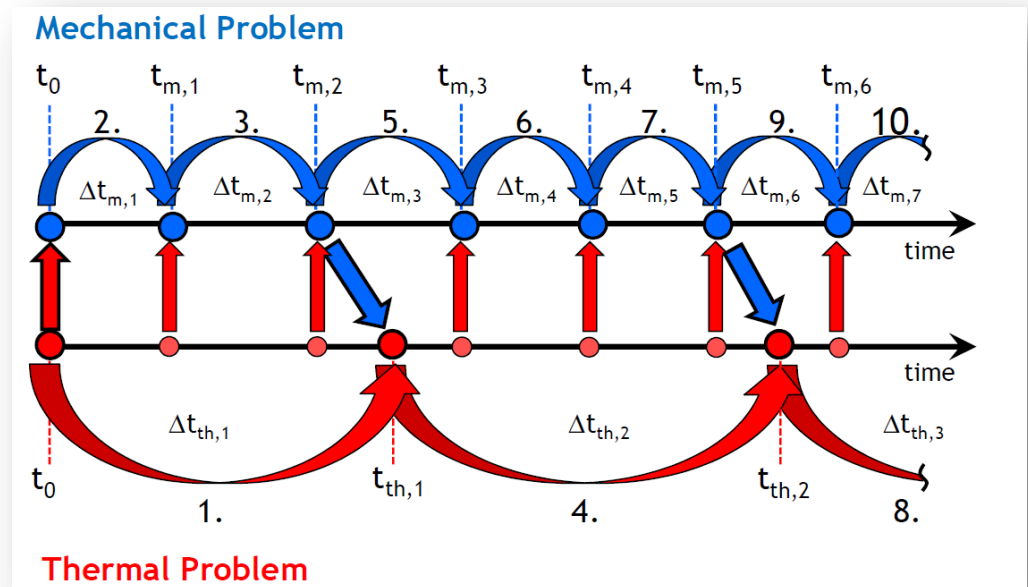
Remarks on Simulation Strategies

■ 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



CONTENT

- Motivation
- Flexible heat source definition
- Material formulation to capture evolution of micro-structure
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Conclusion

■ *BOUNDARY_THERMAL_WELD_TRAJECTORY

- Realistic description of the heat source for all fusion welding processes and local heat treatment
- Easy and flexible input also for curved and deforming structures
- Readily applicable as tool in the virtual process chain even with mixed discretizations

■ *MAT_GENERALIZED_PHASECHANGE

- General material formulation accounting for microstructure evolution
- Very flexible input structure
- Valid description for a wide range of steel alloys

■ New contact formulations

- Welding contact for solids and shell, featuring a switch from sliding to tied contact activated by the temperature
- Edge contact for heat transfer between shell edges and surfaces

Outlook

- ***BOUNDARY_THERMAL_WELD_TRAJECTORY**
 - Implementing new equivalent heat sources

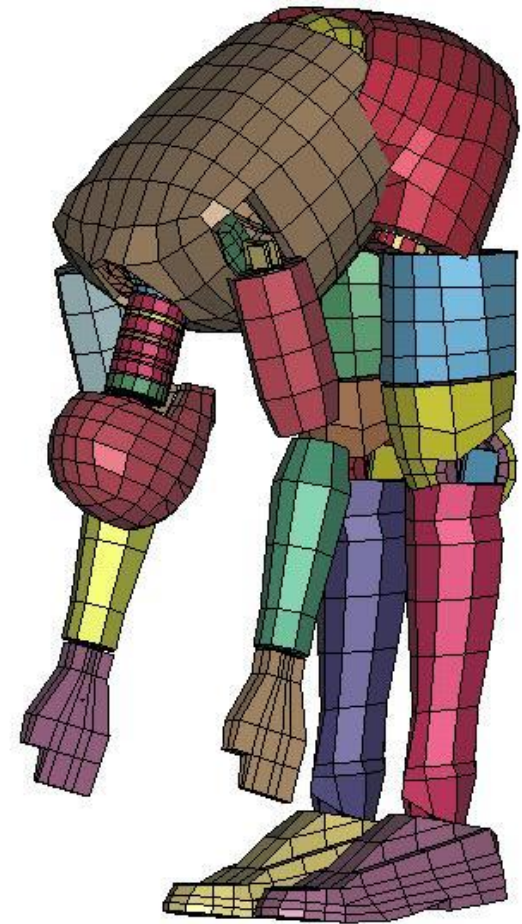
- ***MAT_GENERALIZED_PHASECHANGE**
 - Add more features like damage and failure
 - Extend formulation for Aluminum alloys

- **Contacts**
 - Implement new features for MPP contact types

- **Composite thick shell formulation**
 - Consider stacking sequence defined by ***PART_COMPOSITE_TSHELL**

- ...

Thank you
for your attention!



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