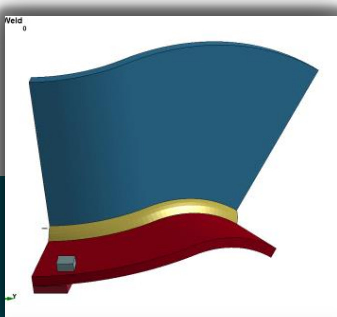
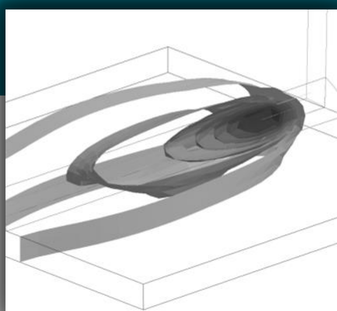


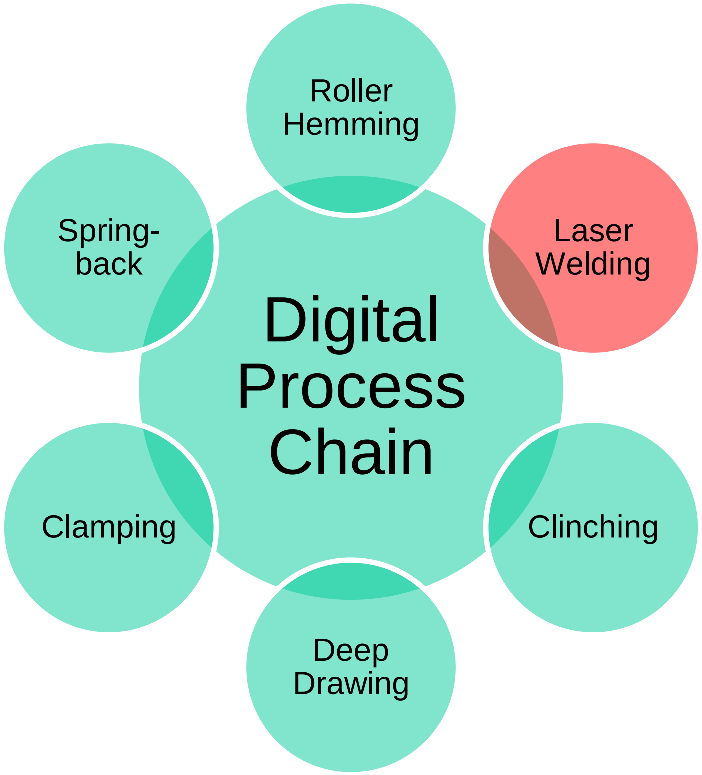


Neue Funktionalitäten in LS-DYNA für die Simulation von Schweißprozessen und Wärmebehandlung

Dr. Thomas Klöppel
DYNAmore GmbH
Stuttgart

Infotag Schweißen und Wärmebehandlung
17. Oktober 2017, Aachen

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!

CONTENT

- Motivation
- Flexible heat source definition
- Material formulations for welding simulations
- New contact options in LS-DYNA
- Conclusion

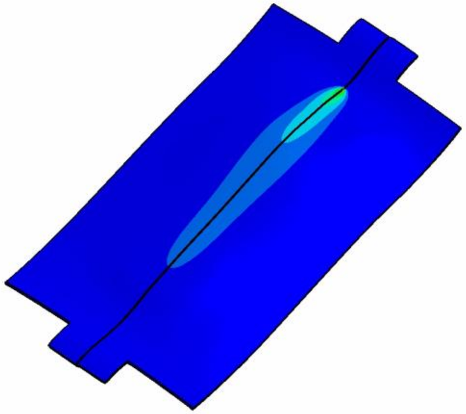
CONTENT

- Motivation
- Flexible heat source definition
  - *BOUNDARY_THERMAL_WELD
  - *BOUNDARY_THERMAL_WELD_TRAJECTORY
- Material formulations for welding simulations
- New contact options in LS-DYNA
- Conclusion

*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 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 thermal 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
- possibility to define 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

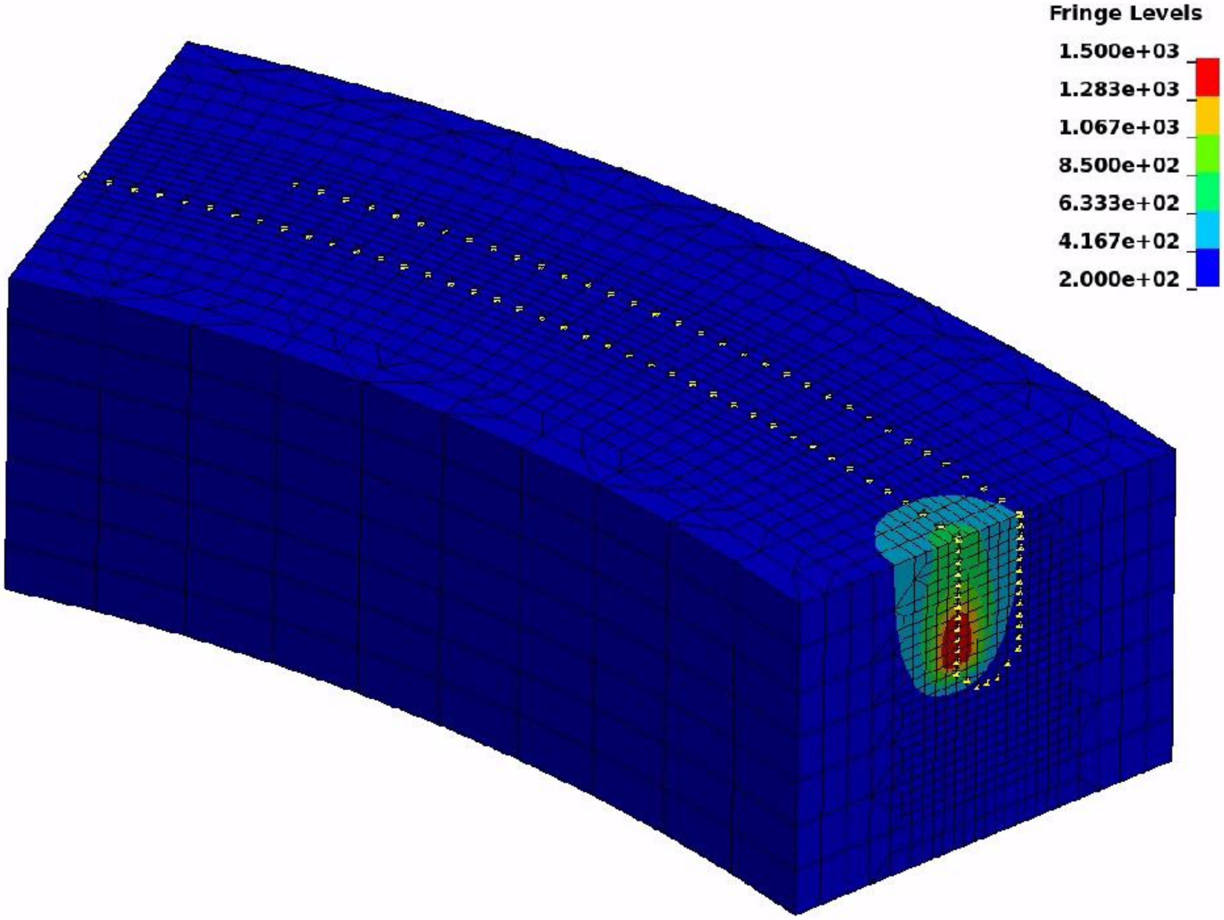
*BOUNDARY_THERMAL_WELD_TRAJECTORY

	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
- NCYC: number of sub-cycling steps

*BOUNDARY_THERMAL_WELD_TRAJECTORY

- Example: Trajectory definition

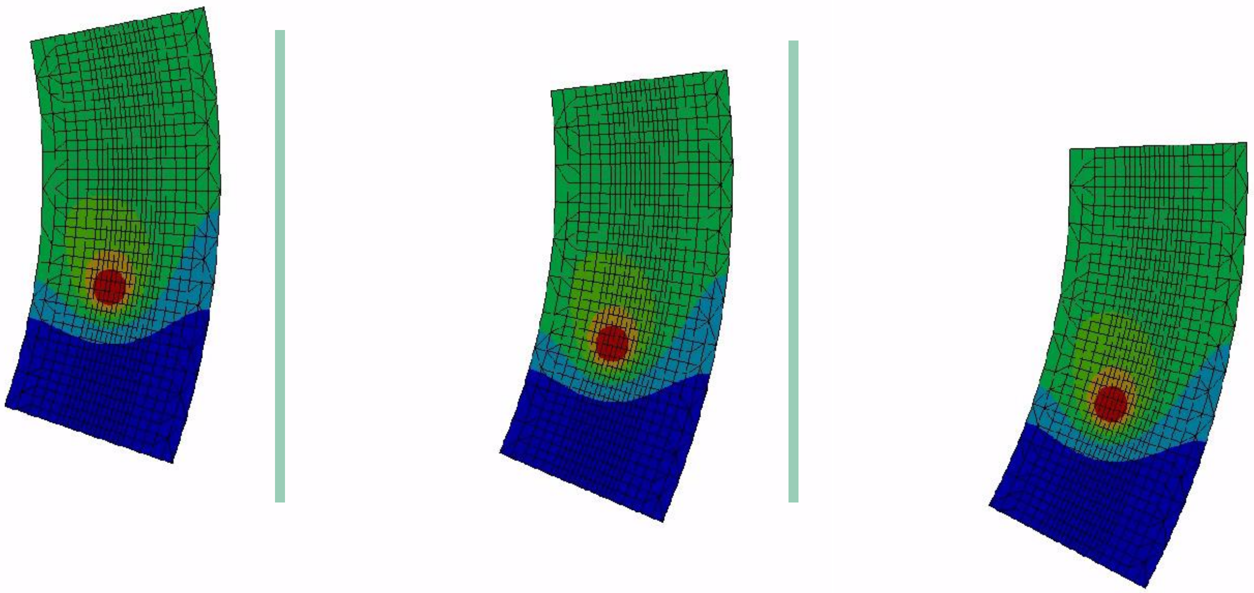


*BOUNDARY_THERMAL_WELD_TRAJECTORY

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

- RELVEL: Use relative or absolute velocities in coupled simulations

RELVEL=1



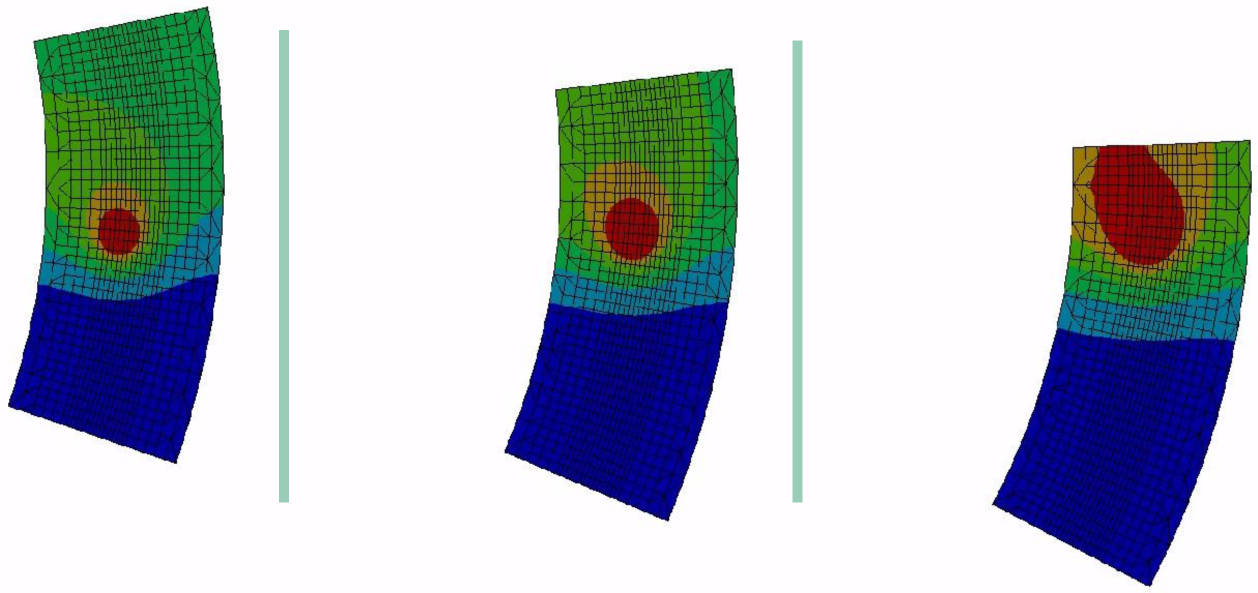
Increasing rotational speed

*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



Increasing rotational speed

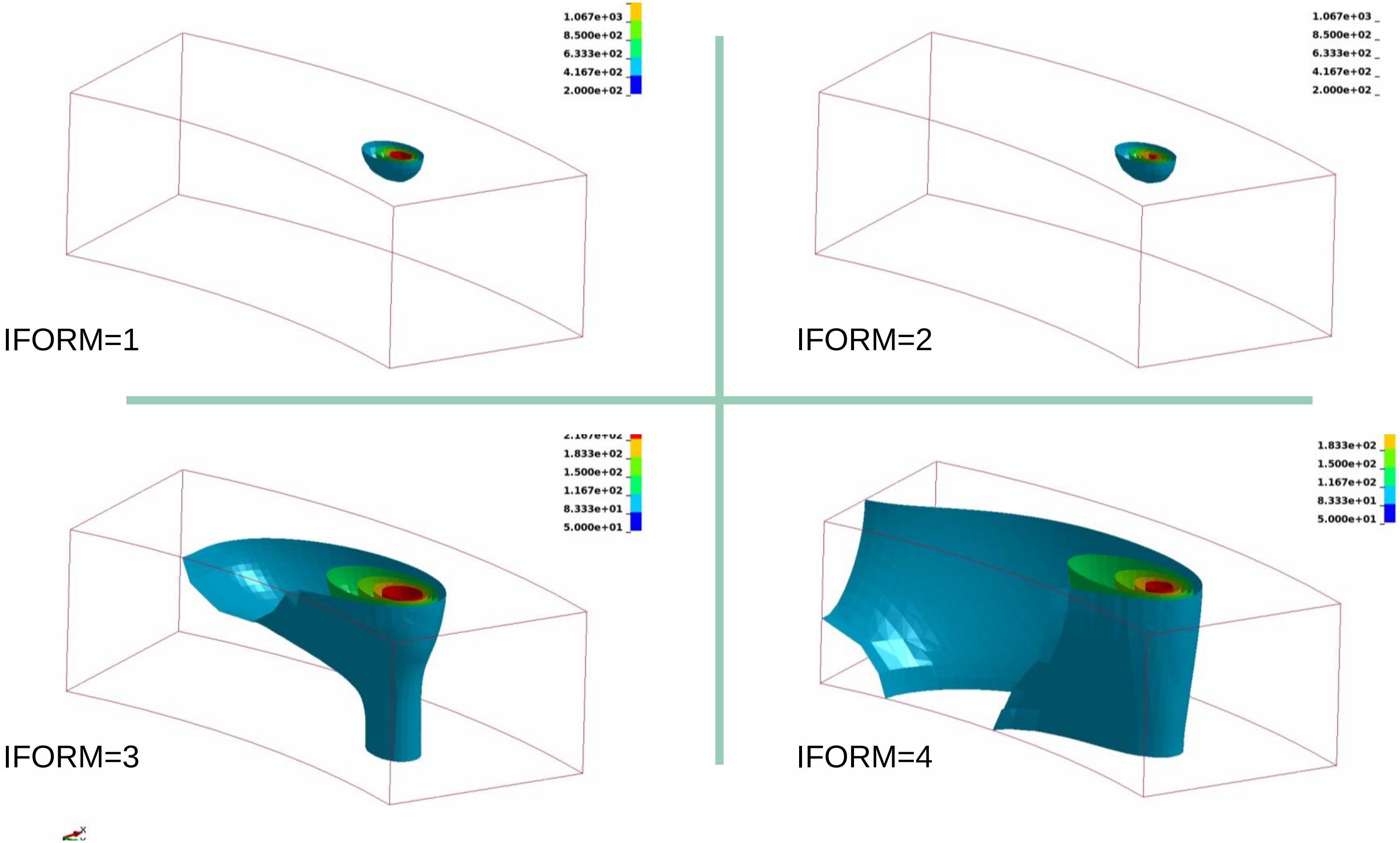
*BOUNDARY_THERMAL_WELD_TRAJECTORY

	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
  - EQ.5. user-defined (*DEFINE_FUNCTION)

- P*x*: Parameters for weld pool geometry

*BOUNDARY_THERMAL_WELD_TRAJECTORY



*BOUNDARY_THERMAL_WELD_TRAJECTORY

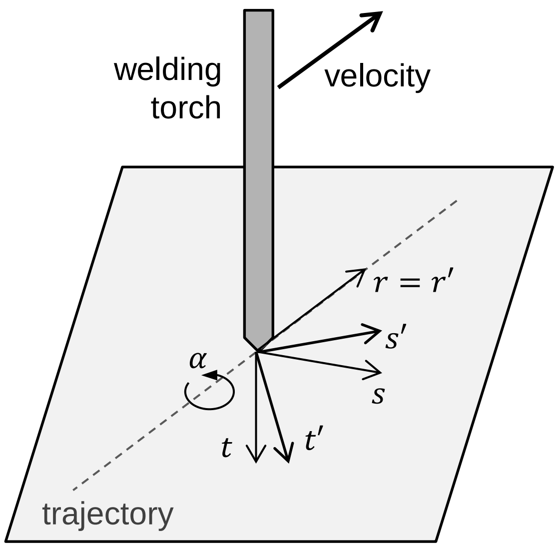
	1	2	3	4	5	6	7	8
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	

- 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

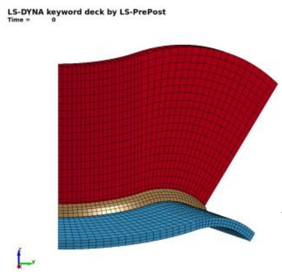
	1	2	3	4	5	6	7	8
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	

- 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

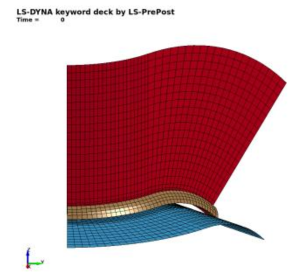


Test example

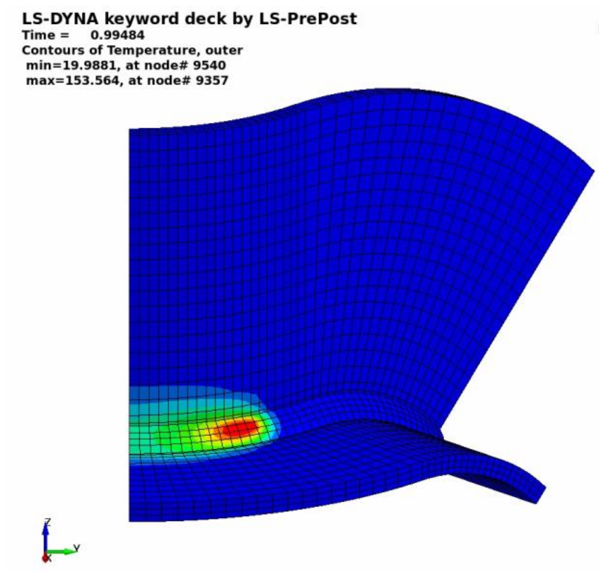
- New Keyword is applicable to thermal thick shells / mixed discretizations
- Three-dimensional curved T-Joint, thermal-only analysis



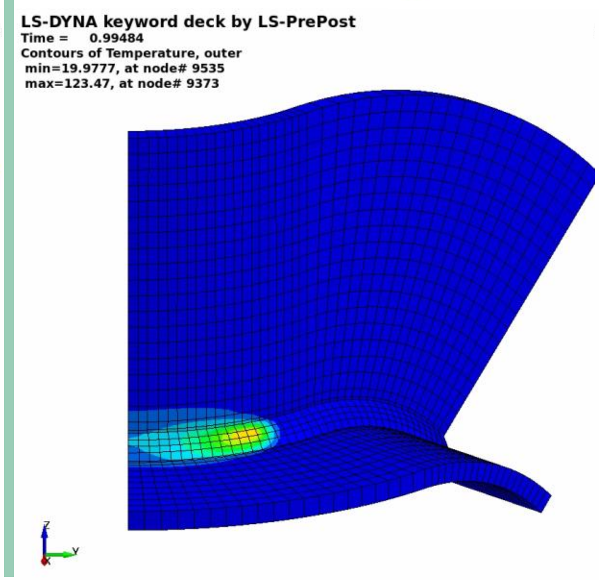
Solids



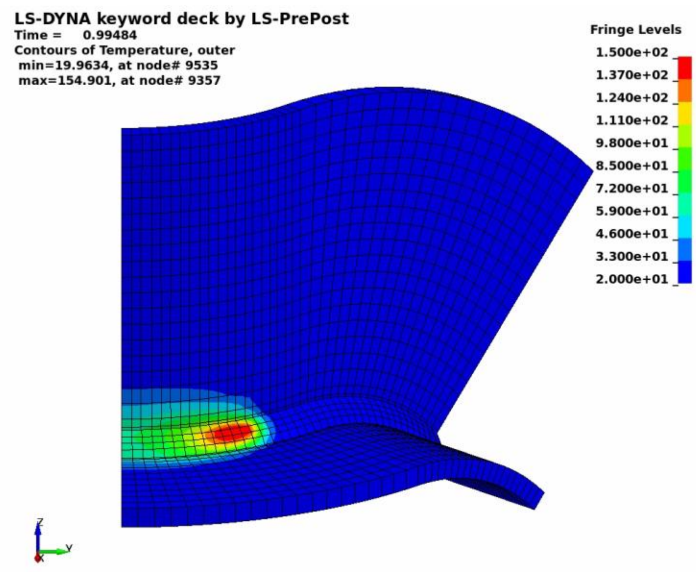
Solids and shells



BC on all solids



BC on solids only



BC on solids and shells

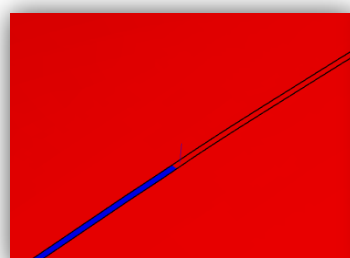
CONTENT

- Motivation
- Flexible heat source definition
- Material formulations for welding simulations
  - *MAT_THERMAL_CWM / *MAT_T07
  - *MAT_CWM / *MAT_270
  - *MAT_UHS_STEEL / *MAT_244
  - *MAT_GENERALIZED_PHASECHANGE / *MAT_254
- New contact options in LS-DYNA
- Conclusion

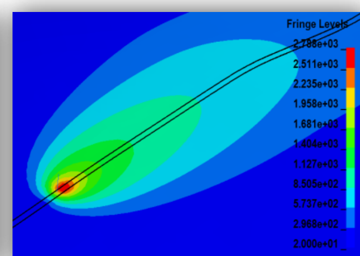
*MAT_THERMAL_CWM / *MAT_T07

	1	2	3	4	5	6	7	8
Card 1	TMID	TRO	TGRLC	TGRMULT	HDEAD	TDEAD		
Card 2	LCHC	LCTC	TLSTART	TLEND	TISTART	TIEND	HGHOST	TGHOST

- Material has birth time TISTART and TIEND
- Before birth, HDEAD and TDEAD are used
- After birth, material is in a “Ghost” state until activated between TLSTART and TLEND
- All input for activated material is temperature dependent
- TGR stands for thermal generation rate



activation

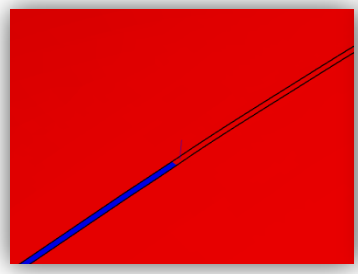


temperatures

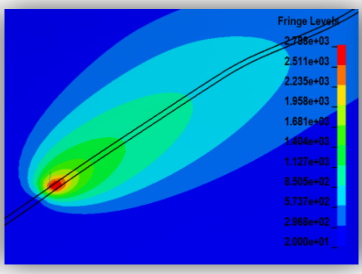
*MAT_CWM / *MAT_270

- Material had 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
    - Von-Mises plasticity with mixed isotropic/kinematic hardening
    - Thermal expansion

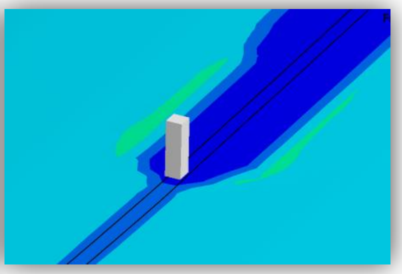
- Anneal at specific temperature



activation



temperatures



annealing

*MAT_CWM / *MAT_270

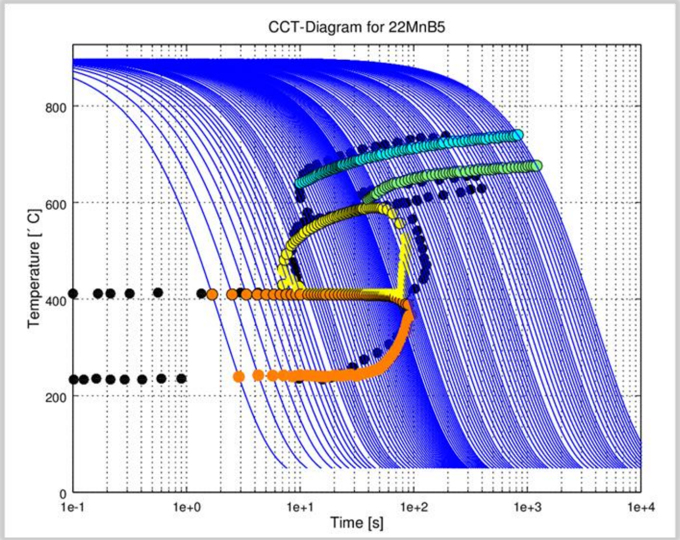
	1	2	3	4	5	6	7	8
Card 1	MID	RO	LCEM	LCPR	LCSY	LCHR	LCAT	BETA
Card 2	TASTART	TAEND	TLSTART	TLEND	EGHOST	PGHOST	AGHOST	
Opt.	T2PHASE	T1PHASE						

- Card1 contains properties for activated material
- TASTART and TAEND define range for annealing (linear process)
- TLSTART and TLEND define range for activation
- EGHOST, PGHOST and AGHOST are properties for ghost material
- T2PHASE and T1PHASE define temperature range for which the cooling rate is evaluated and stored in HISV11

***MAT_270 is well-suited to predict residual distortions but does not account for micro-structure evolution**

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 / *MAT_GENERALZE_PHASE_CHANGE

- Very general material implementation to capture micro-structure evolution in hot forming, welding and heat treatment
- Implementation available for solid and shell elements and for explicit and implicit simulations

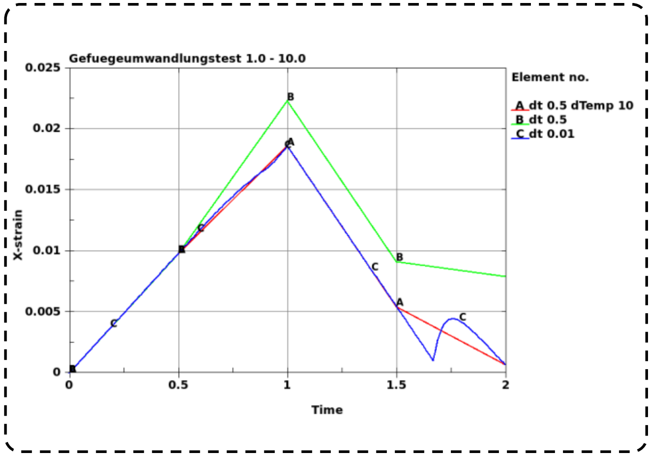
- Microstructural phase evolution:
  - Up to 24 individual phases can be accounted for
  - List of generic phase change mechanisms (Leblond, JMAK, Koistinen-Marburger,…) for each possible phase change in heating and cooling
  - Parameters for transformation law are directly given in tables
- Additional features:
  - Strain rate dependent thermo-elasto-plastic properties defined for individual phases
  - Transformation induced plasticity and strains and latent heat
  - User-defined history variables as functions of current state of the material using DEFINE_FUNCTION keyword (e.g. for hardness, damage estimation, …)

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 1	MID	RHO	N	E	PR	MIX	MIXR	
Card 2	TASTART	TAEND	TABCTE				DTEMP	
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5			
Card 5	PTEPS	TRIP			NUSHIS	GRAI	T1PHAS	T2PHAS
Card 6	FUNUSH1	FUNUSH2	FUNUSH3	FUNUSH4	FUNUSH5	FUNUSH6	FUNUSH7	FUNUSH8
Card 7	LCY1	LCY2	LCY3	LCY4	LCY5	LCY6	LCY7	LCY8
Card 8	LCY9	LCY10	LCY11	LCY12	LCY13	LCY14	LCY15	LCY16
Card 9	LCY17	LCY18	LCY19	LCY20	LCY21	LCY22	LCY23	LCY24

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 1	MID	RHO	N	E	PR	MIX	MIXR	
Card 2	TASTART	TAEND	TABCTE				DTEMP	
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5			
Card 5	PTEPS	TRIP			NUSHIS	GRAI	T1PHAS	T2PHAS
Card 6	FUNUSH1	FUNUSH2	FUNUSH3	FUNUSH4	FUNUSH5	FUNUSH6	FUNUSH7	FUNUSH8
Card 7	LCY1	LCY2	LCY3	LCY4	LCY5	LCY6	LCY7	LCY8
Card 8	LCY9	LCY10	LCY11	LCY12	LCY13	LCY14	LCY15	LCY16
Card 9	LCY17	LCY18	LCY19	LCY20	LCY21	LCY22	LCY23	LCY24



- Selected mechanical features
  - temperature dependent elastic properties
  - yield stress (van Mises) temperature and strain rate dependent
  - transformation induced strains and transformation induced plasticity
  - reset of plastic strains in a certain temperature range
  - sub-cycling on integration point level to deal with large temperature rates

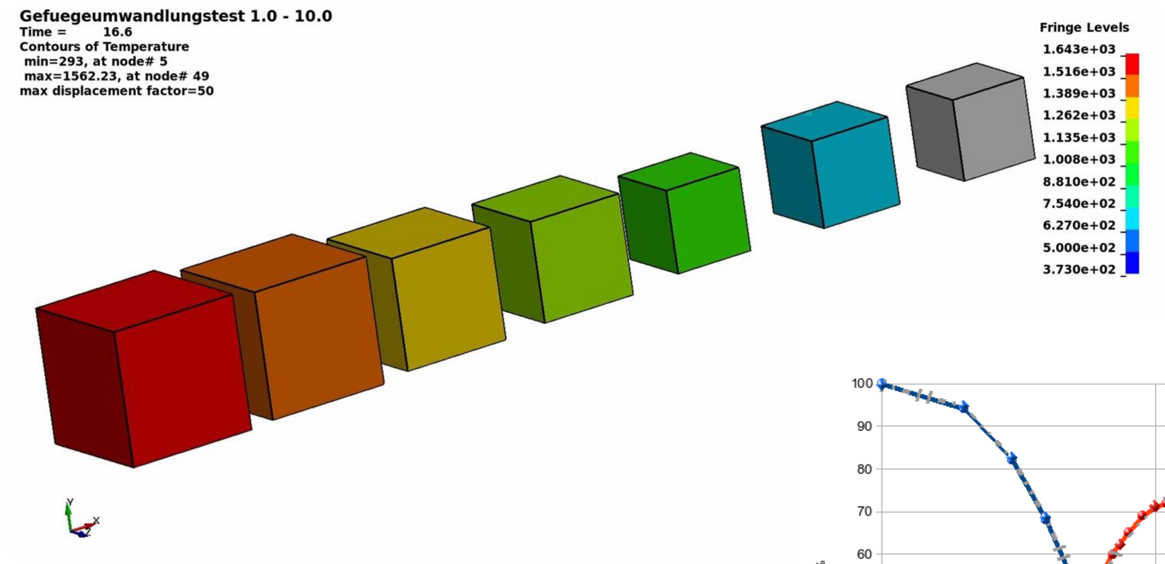
*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

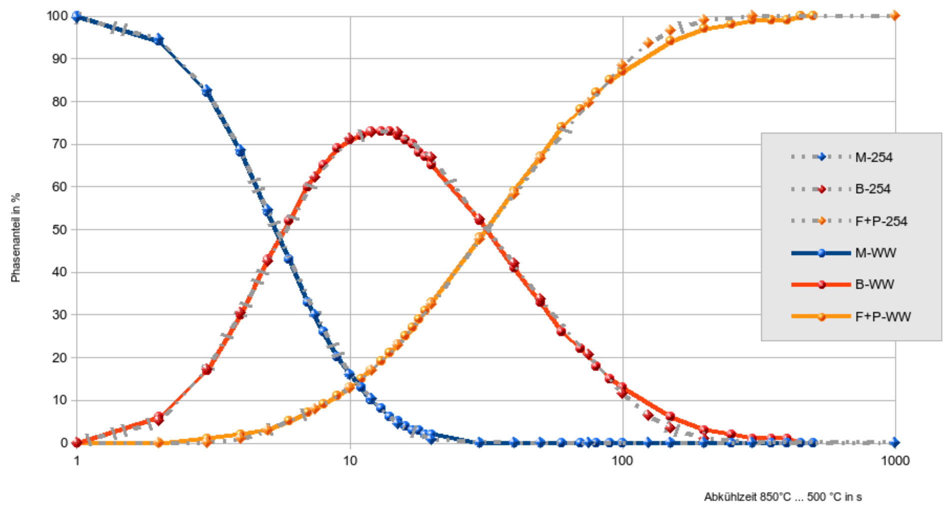
	1	2	3	4	5	6	7	8
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5			

- 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 with JMAK

- First example: Phase change test for steel S420





*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

Card 5	PTEPS	TRIP			NUSHIS	GRAI	T1PHAS	T2PHAS
Card 6	FUNUSH1	FUNUSH2	FUNUSH3	FUNUSH4	FUNUSH5	FUNUSH6	FUNUSH7	FUNUSH8

- NUHIS: Number of user defined history variables
- FUNUSH*i*: Function ID
- T1PHAS: lower temperature limit for cooling rate computation
- T2PHAS: upper temperature limit for cooling rate computation

- User defined histories:
  - written as additional histories for output
  - can be defined as function of other history data
    time, temp, temp rate, stresses, phase mixture, plastic strains, …

CONTENT

- Motivation
- Flexible heat source definition
- Material formulations for welding simulations
- New contact options in LS-DYNA
  - Temperature activated tied contact
  - Thermal shell edge contact
- Conclusion

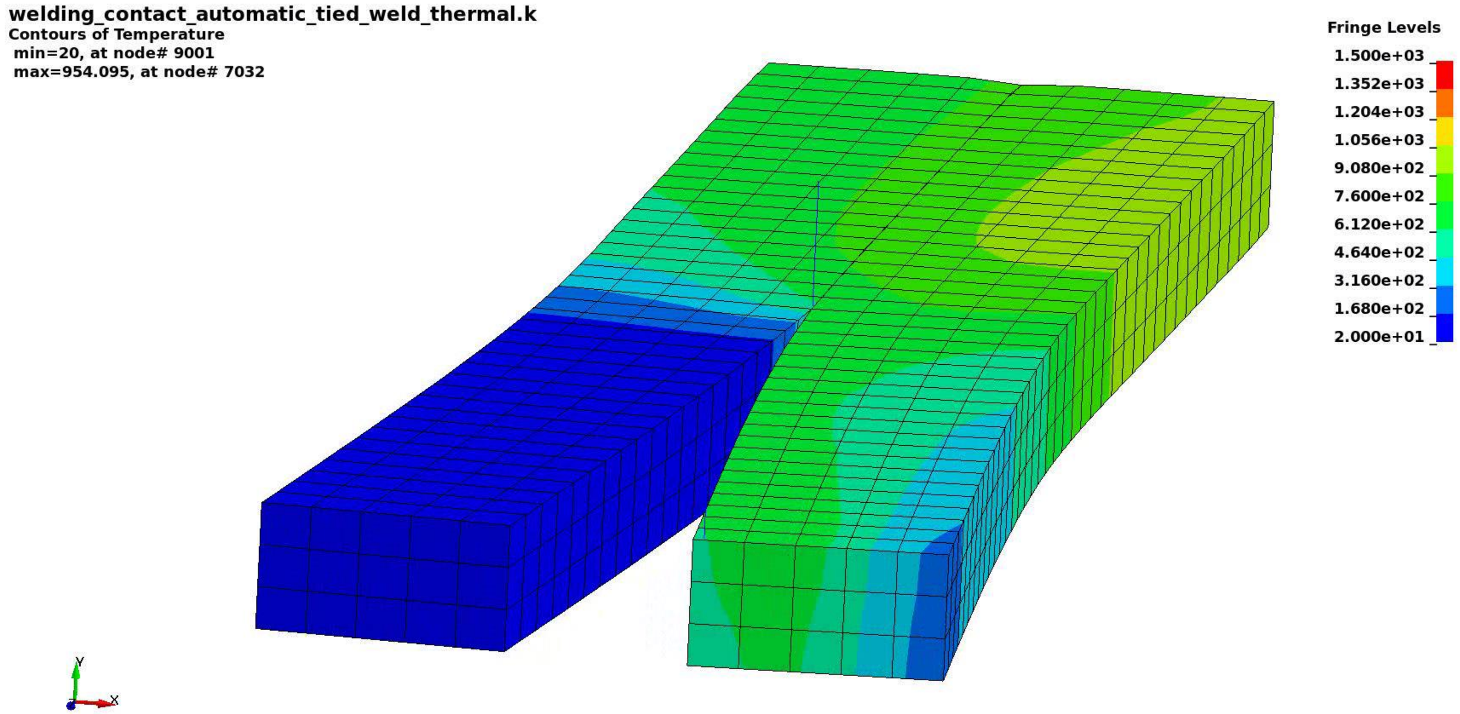
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL

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

- Contact that can locally switch from a sliding to a tied formulation
- 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
- MORTAR version also available and recommended

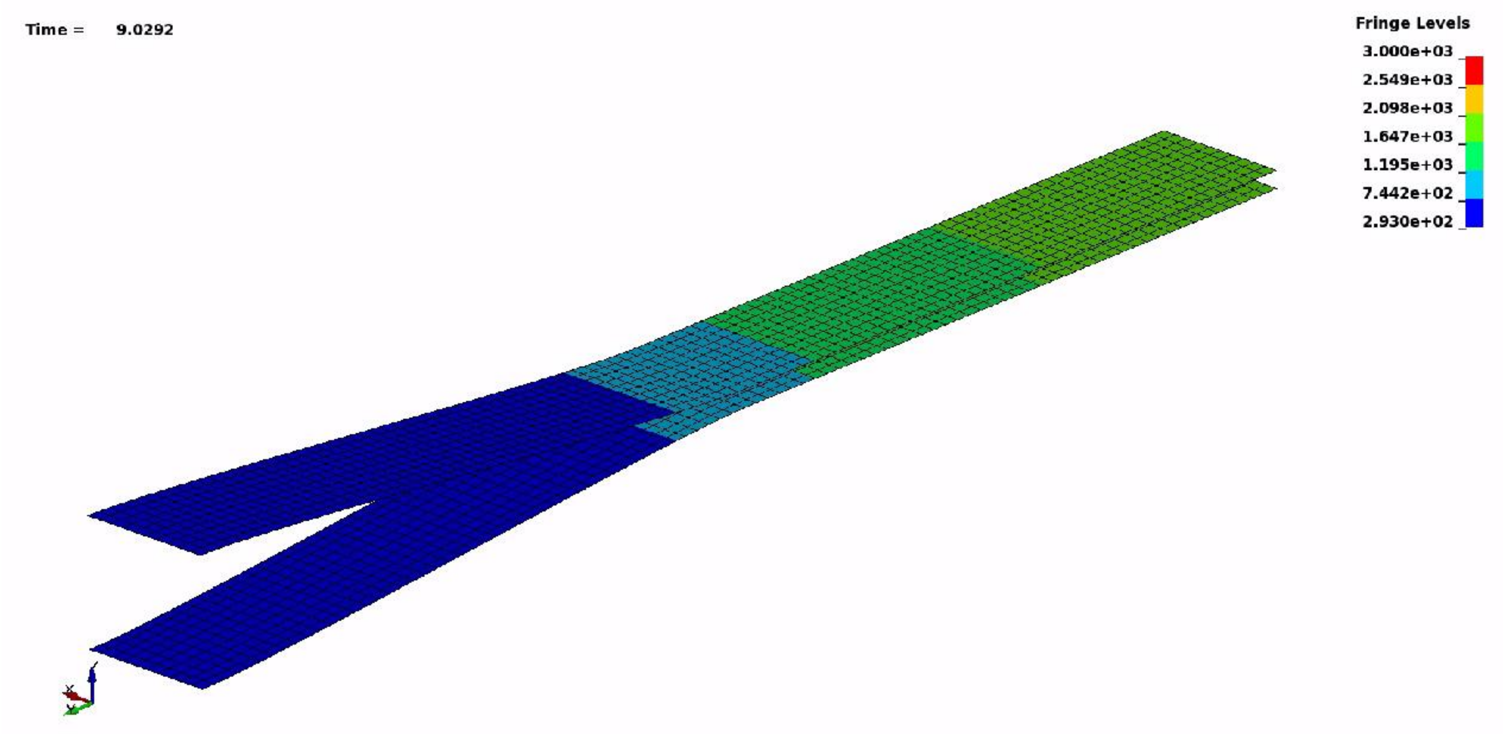
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL

- 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

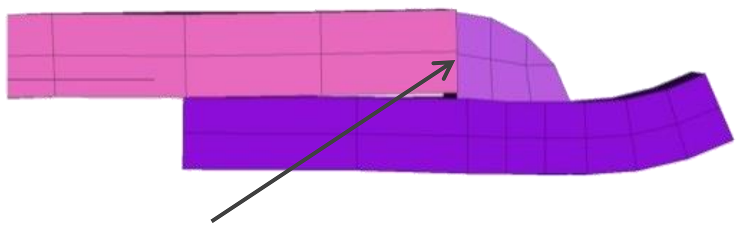
- Example: laser welding
  - During welding the sheets are allowed to move
  - A very high heat conductivity in the contact area is assumed



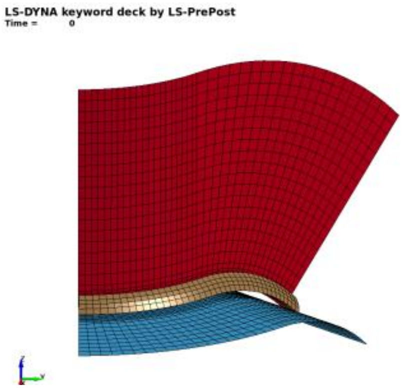
Thermal edge contact

	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

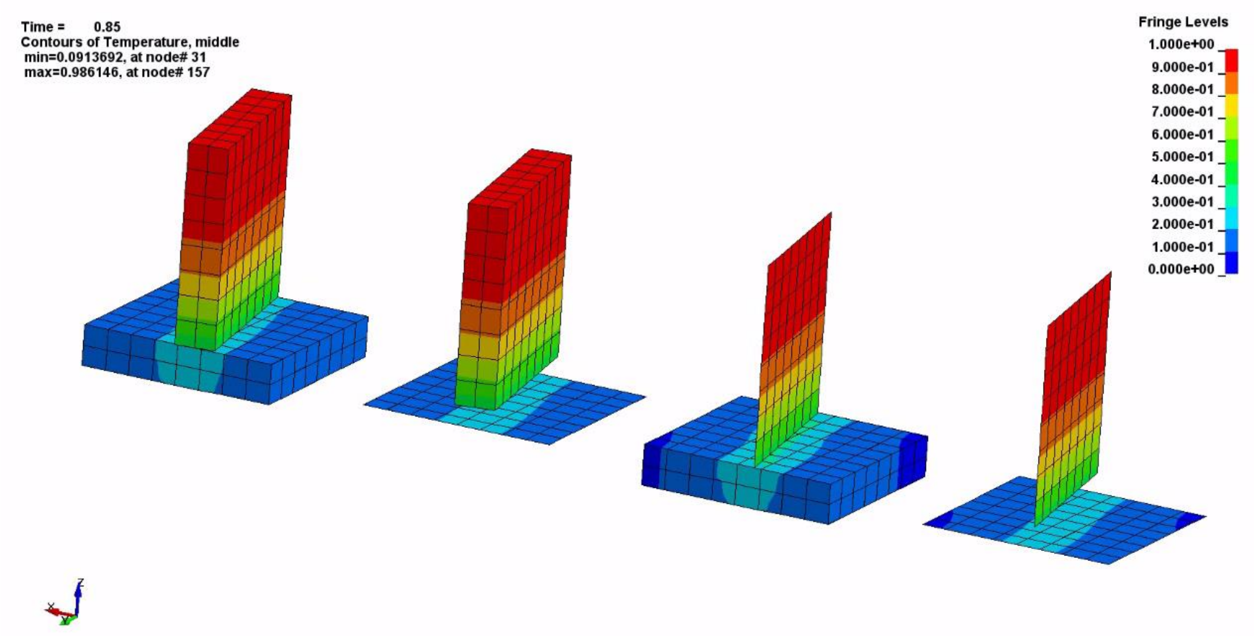


T-Joint with shells

- Activated for ALGO.eq.2 or 3 (one way)
- Can be used in a variety of contact types in SMP and MPP

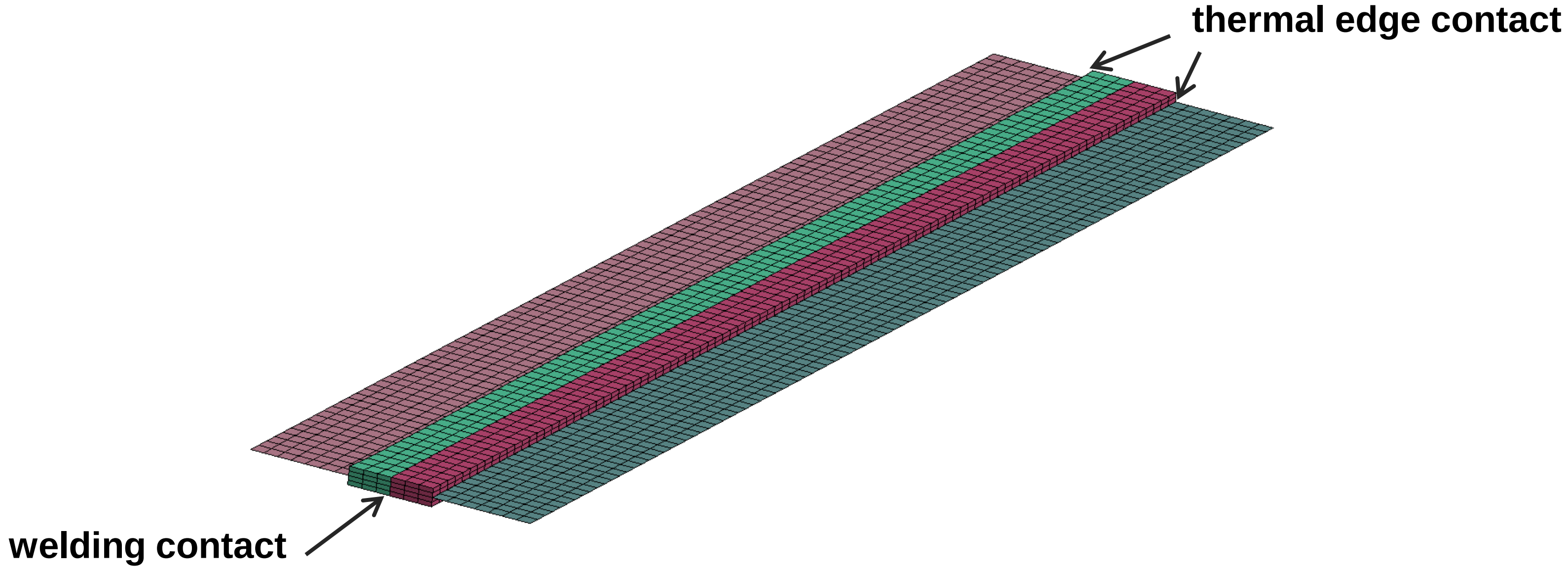
Thermal edge contact – Example

- 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
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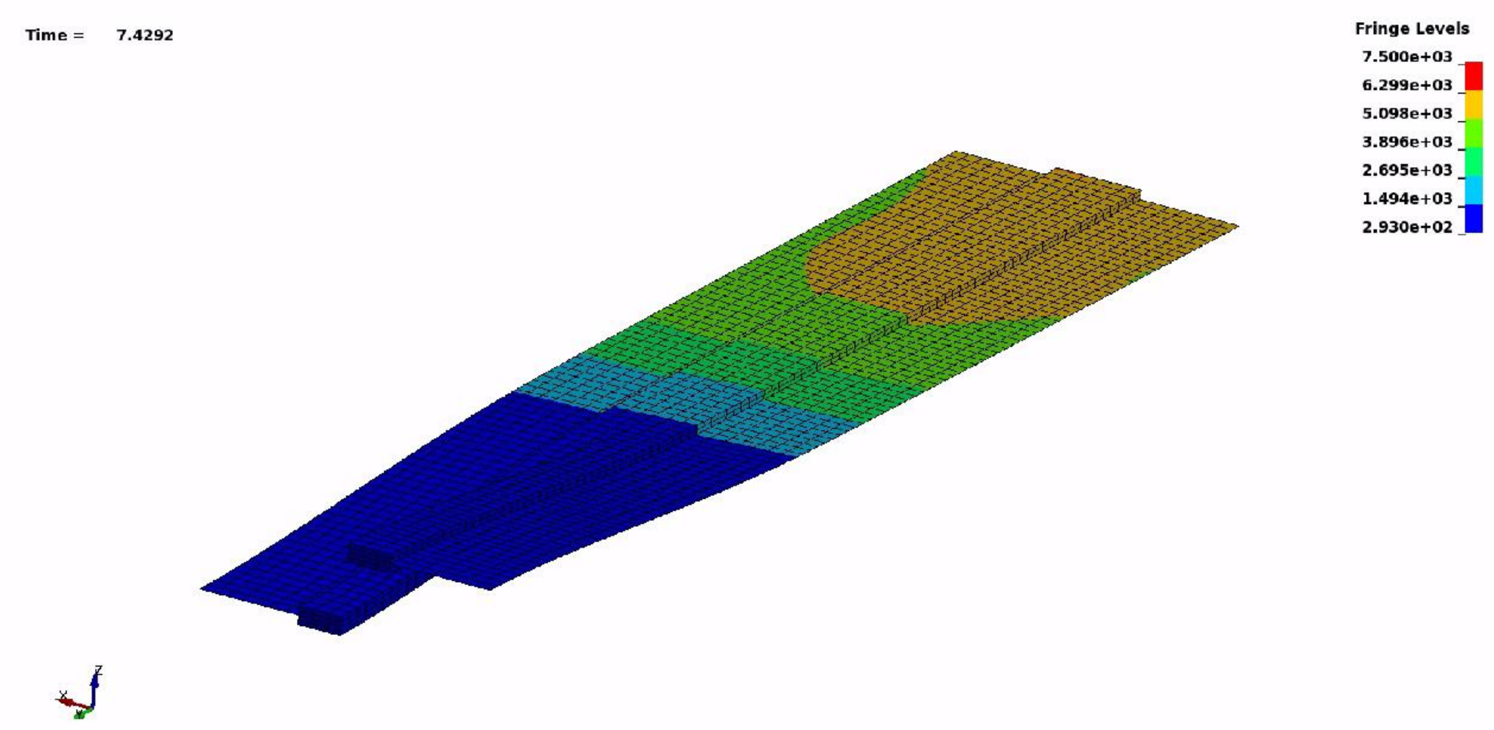
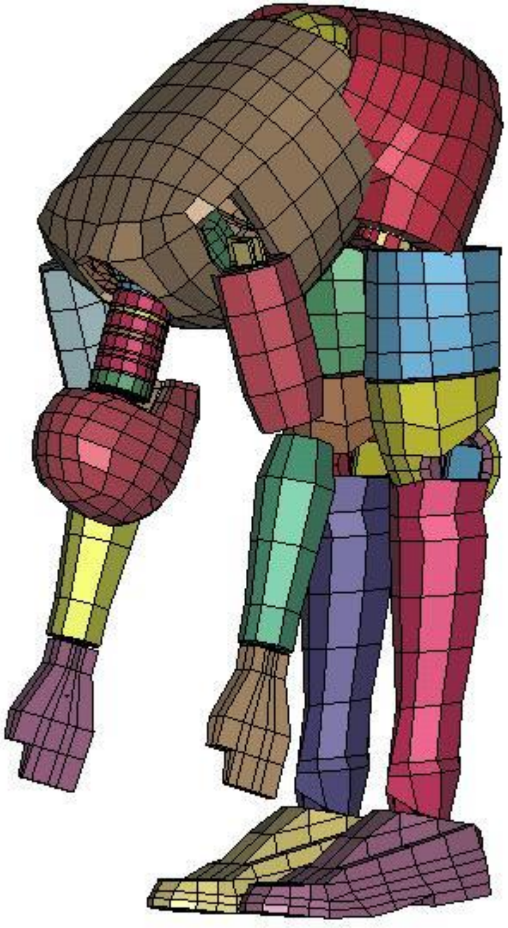


CONTENT

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

Thank you
for your attention!



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