Powering Innovation That Drives Human Advancement

New LS-DYNA keyword *LOAD_EXTERNAL_VARIABLE and its application to case-hardening

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Motivation:

- Certain manufacturing process steps (for example heat treatment) are diffusion-type processes that have to be simulated in LS-DYNA to close the process chain
  - Translate problem into equivalent temperature diffusion problem
    - Not possible to simulate a temperature dependent diffusion processes
    - How to consider the results in a thermal-mechanical coupled simulation?

- Transfer of nodal field data from a previous simulation
  - *INITIAL_HISTORY_NODES
    - Only for initialization and, thus, field cannot change over time
    - Not applicable to thermal simulations

New nodal loading condition *LOAD_EXTERNAL_VARIABLE

How can we define external field data?

*LOAD_EXTERNAL_VARIABLE – Input

	1	2	3	4	5	6	7	8
Card 1	**VID**	**DBAS**	**DSCA**	**DLCID**	NMP	NTMP		
Card 2	IMP	PID	PTYP					
Card 3	ITMP	TPID	TPTYP					
Card 4	ID	IDTYP	BAS	SCA	LCID			
Card 4.1 (IDTYP=3)	FILENAME							

- Any external variable can be referenced by its id **VID**
- Default values for all nodes not referenced otherwise in the keyword
  - Value $\tilde{\alpha}$ is defined as $\tilde{\alpha} = \tilde{\alpha}_B + \tilde{\alpha}_S \times \tilde{f}(t)$
  - Input of base value **DBAS** ($\tilde{\alpha}_B$), scaling value **DSCA** ($\tilde{\alpha}_S$) and load curve **DLCID** ($\tilde{f}(t)$)

*LOAD_EXTERNAL_VARIABLE – Reference to material data

	1	2	3	4	5	6	7	8
Card 1	VID	DBAS	DSCA	DLCID	**NMP**	NTMP		
Card 2	**IMP**	**PID**	**PTYP**					
Card 3	ITMP	TPID	TPTYP					
Card 4	ID	IDTYP	BAS	SCA	LCID			
Card 4.1 (IDTYP=3)	FILENAME							

- Structure material behavior is modified based on the local external variable value
  - Card 2 is repeated **NMP** times
  - Material property index **IMP** defines the material property of part (**PTYP**=1) or part set (**PTYP**=2) with ID **PID** that is affected
  - Depending on **IMP** and base material, the external variable either serves as scaling factor (SF) or as independent variable for a load curve (LC) / table (TAB) evaluation

*LOAD_EXTERNAL_VARIABLE – Reference to material data

- Material property index table

IMP	*MAT_106		*MAT_251		*MAT_254	
1	**LCE**	LC	**E**	SF	**JMAKACC**	LC
2	**LCPR**	LC	**LCSS**	TAB(3d,4d)		
3	**LCSIGY**	LC	**LCSS**	TAB(4d)		
4	**LCR**	LC				
5	**LCX**	LC				
6	**LCALPH**	LC				
7	**LCC**	LC				
8	**LCP**	LC				
9	**LCFAIL**	LC				

$$x_b = x_{eq}(T)(x_a + x_b)\left(1 - e^{-\left(\frac{t}{\beta(\alpha)\cdot\tau(T)}\right)^{n(T)}}\right)$$

*LOAD_EXTERNAL_VARIABLE – Reference to material data

	1	2	3	4	5	6	7	8
Card 1	VID	DBAS	DSCA	DLCID	NMP	**NTMP**		
Card 2	IMP	PID	PTYP					
Card 3	**ITMP**	**TPID**	**TPTYP**					
Card 4	ID	IDTYP	BAS	SCA	LCID			
Card 4.1 (IDTYP=3)	FILENAME							

- Thermal material behavior is modified based on the local external variable value
  - Card 3 is repeated **NTMP** times
  - Material property index **ITMP** defines the material property of part (**TPTYP**=1) or part set (**TPTYP**=2) with ID **TPID** that is affected
  - External variable serves as independent variable for a load curve evaluation

*LOAD_EXTERNAL_VARIABLE – Reference to material data

- Material property index table

IMP	*MAT_T08	*MAT_T10
1	LCC	LCC
2	LCK1	LCK
3	LCK2	
4	LCK3	

*LOAD_EXTERNAL_VARIABLE – Tabulated definition

	1	2	3	4	5	6	7	8
Card 1	VID	DBAS	DSCA	DLCID	NMP	NTMP		
Card 2	IMP	PID	PTYP					
Card 3	ITMP	TPID	TPTYP					
Card 4	**ID**	**IDTYP**	**BAS**	**SCA**	**LCID**			
Card 4.1 (IDTYP=3)	FILENAME							

- Node (**IDTYP**=1) or Node Set (**IDTYP**=2) cards
  - Value α is defined as $\alpha = \alpha_B + \alpha_S \times f(t)$
  - Input of base value **BAS** (α_B), scaling value **SCA** (α_S) and load curve **LCID** ($f(t)$)
  - Card 4.1 is not read in that case
  - Card 4 can be repeated as often as necessary

*LOAD_EXTERNAL_VARIABLE – Binary definition

	1	2	3	4	5	6	7	8
Card 1	VID	DBAS	DSCA	DLCID	NMP	NTMP		
Card 2	IMP	PID	PTYP					
Card 3	ITMP	TPID	TPTYP					
Card 4	ID	**IDTYP**	BAS	SCA	LCID			
Card 4.1 (IDTYP=3)	**FILENAME**							

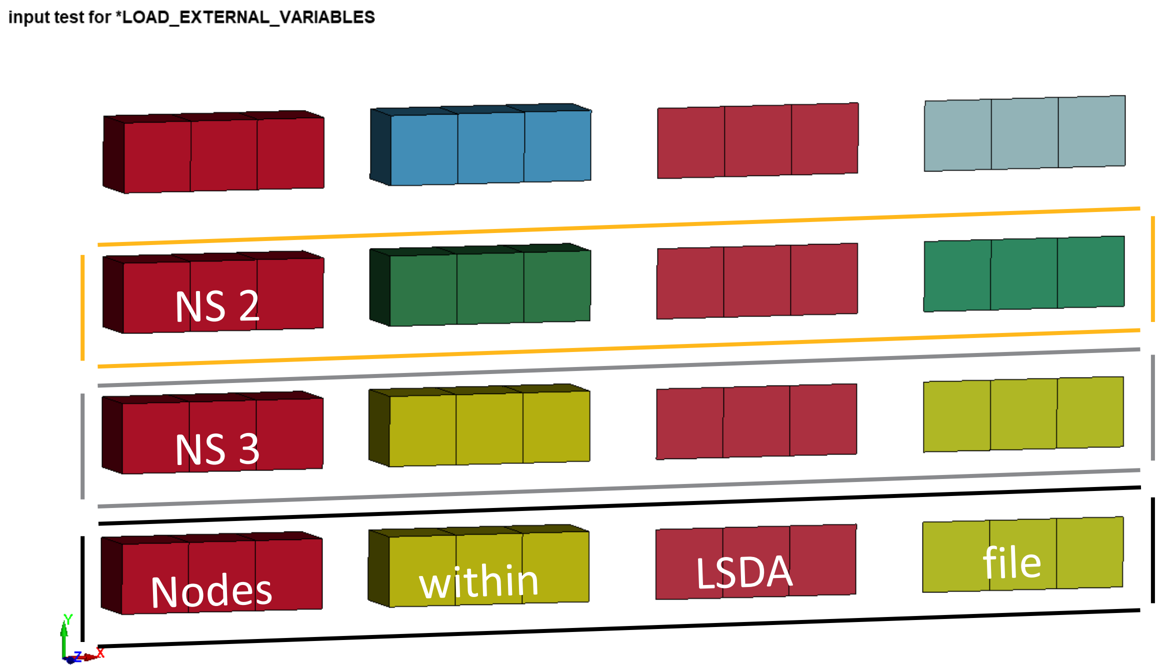
- LSDA option (**IDTYP**=3)
  - All other parameters in Card 4 are ignored
  - **FILENAME** refers to a LSDA file containing the information of the TPRINT section of the binout database file
  - Temperature data in the file will be interpreted as external variable data

Validation Examples

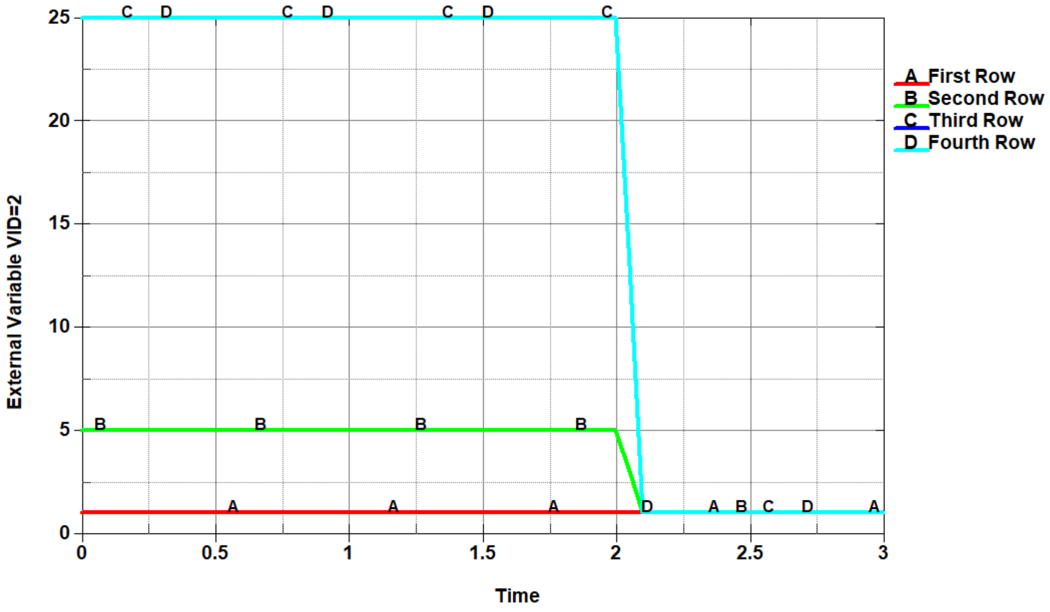
Is the new information correctly processed?

Validation – Model and External Variable Definition

- Model

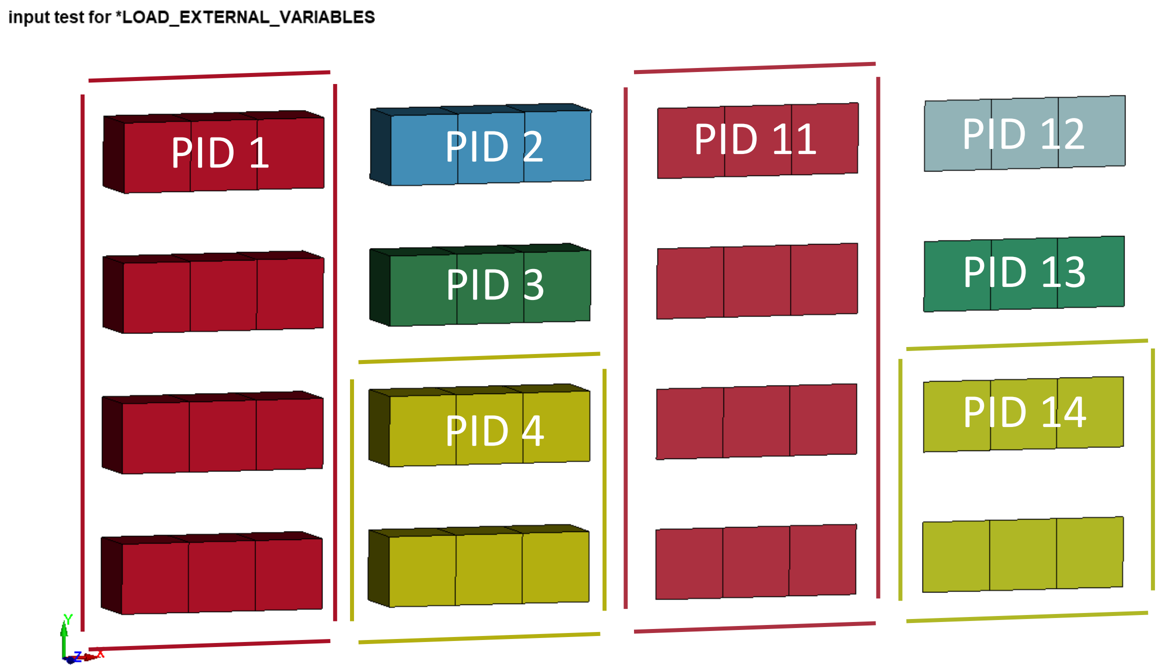


- External variable VID=2



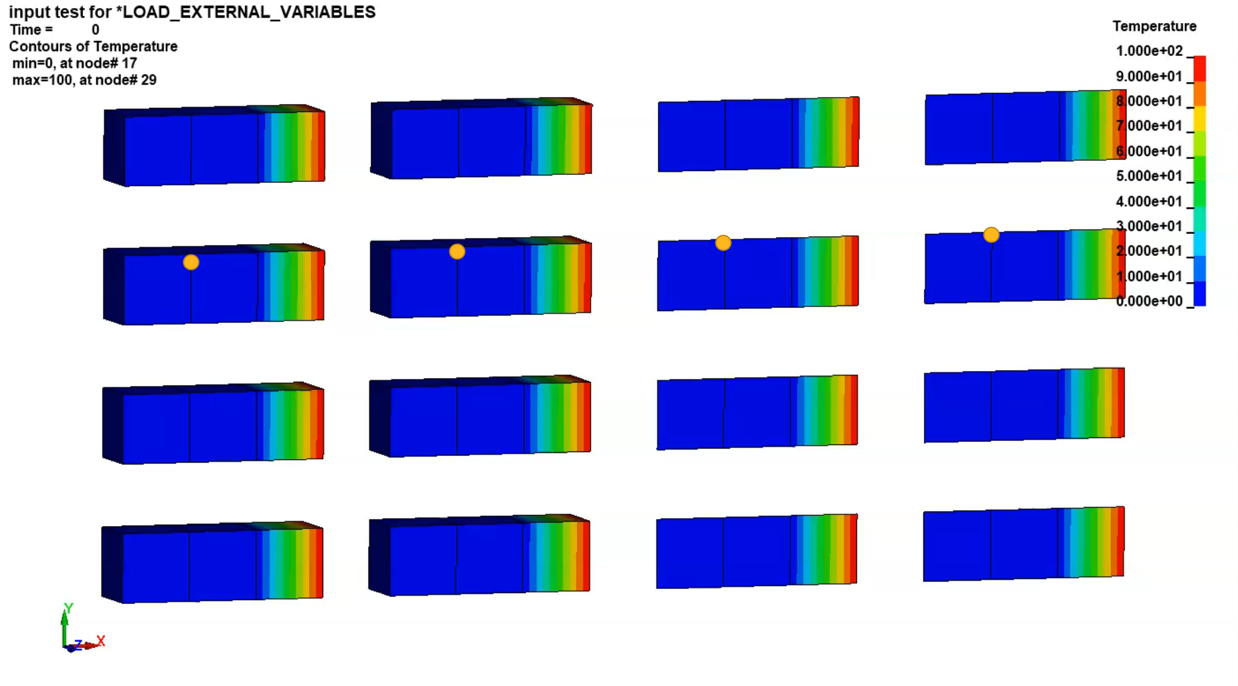
Validation in thermal solver

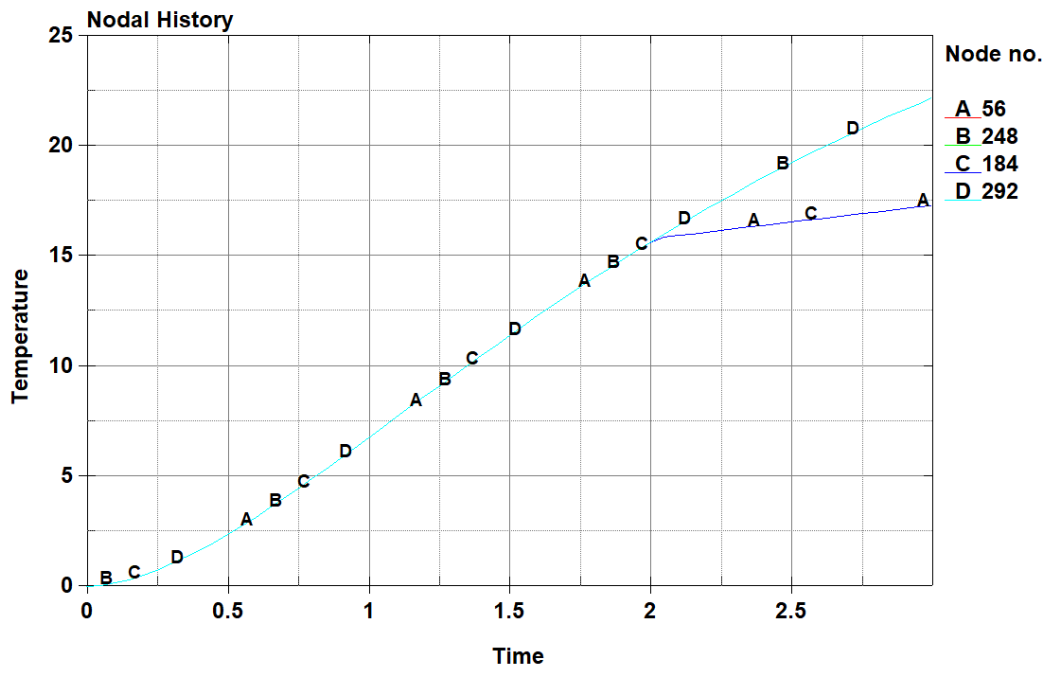
- Model



- Constant heat capacity everywhere
- Parts 1 and 11 use the same *MAT_T10
  - Conductivity equals value of VID 2
- Parts 2, 3, 4, 12, 13, 14 use *MAT_T01
  - Parts 2, 12: TC=1.0
  - Parts 3, 13: TC=5.0
  - Parts 4, 14: TC=25.0
- Conditions:
  - T=100 on the right of each block
  - T=0 on the left of each block
  - Zero initial temperature for free nodes

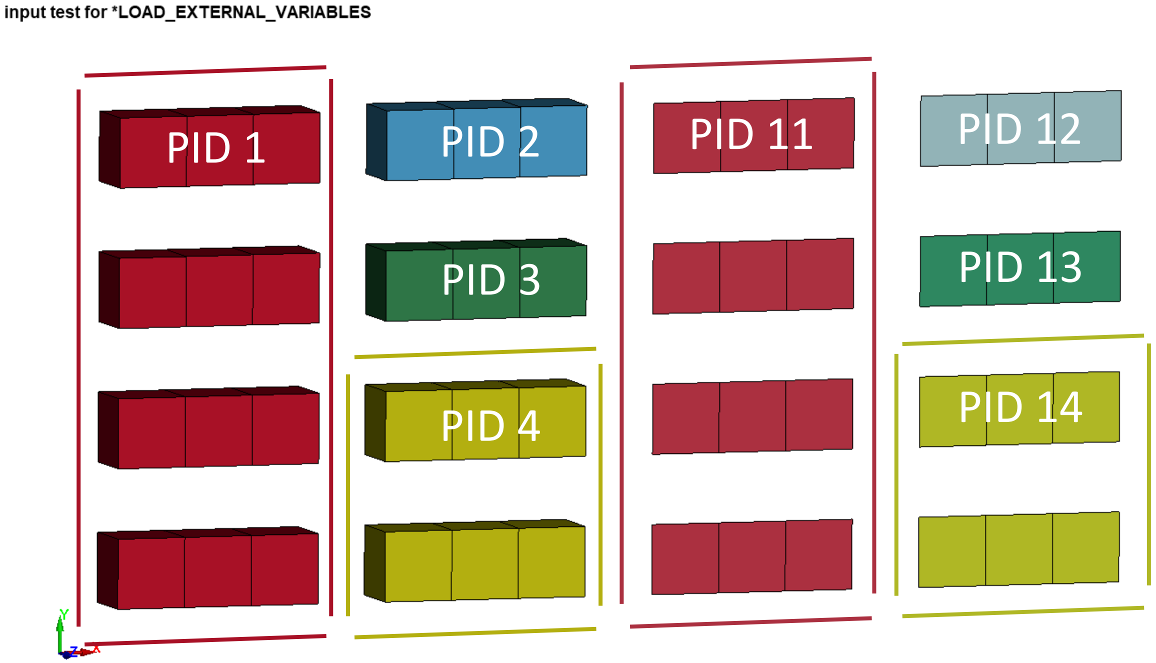
Validation in thermal solver



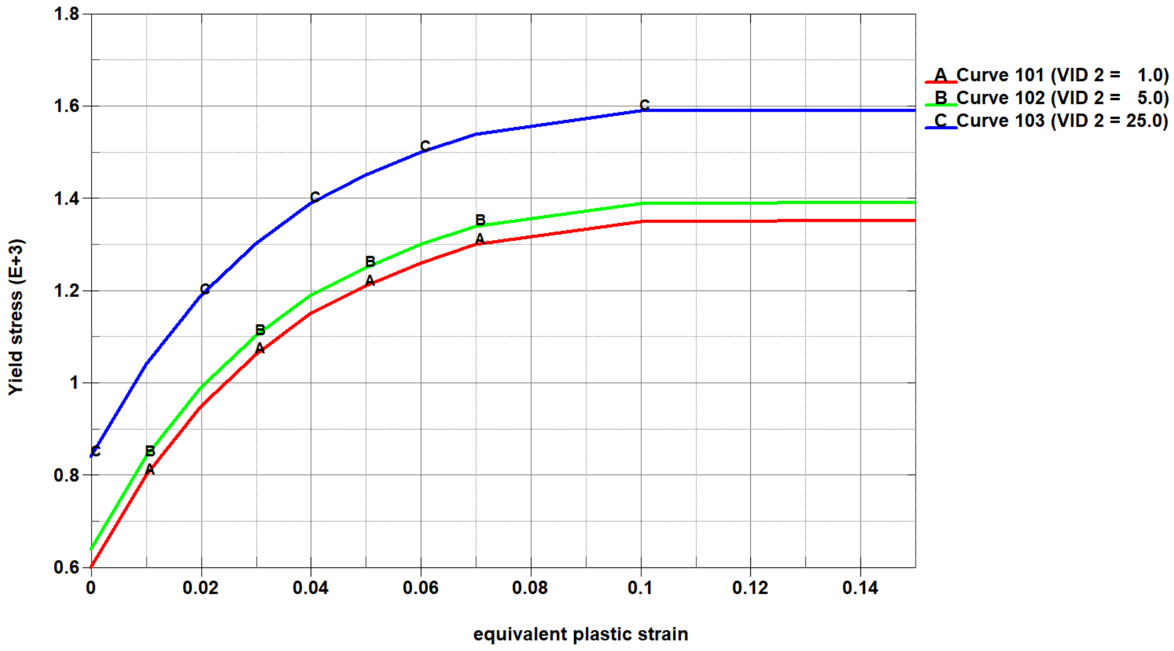


Validation in mechanical solver: *MAT_251

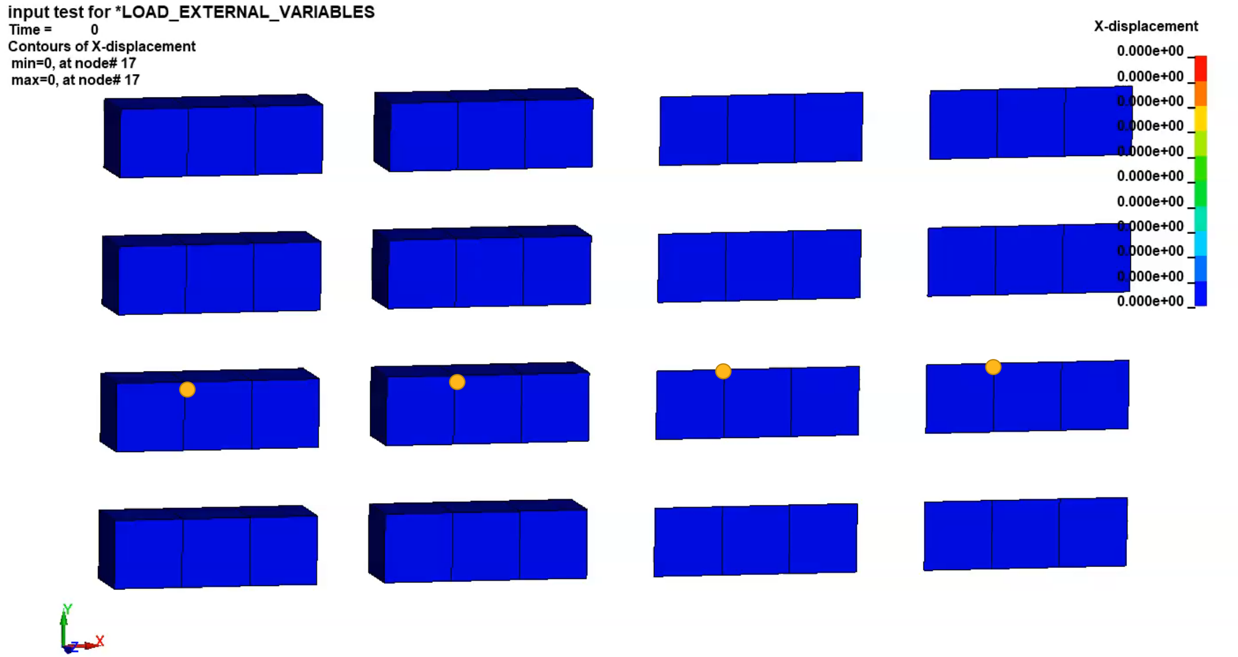
- Model

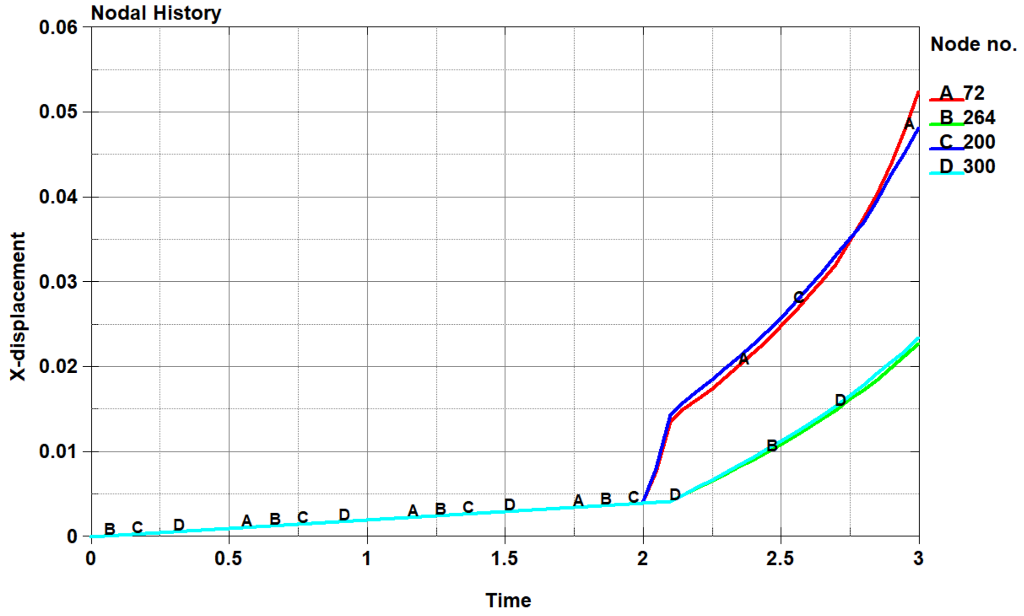


- Constant, identical material parameters except for yield stress
- Parts 1 and 11 use the same *MAT_251
  - Yield stress is a function of VID 2 (3d table)



Validation in mechanical solver: *MAT_251



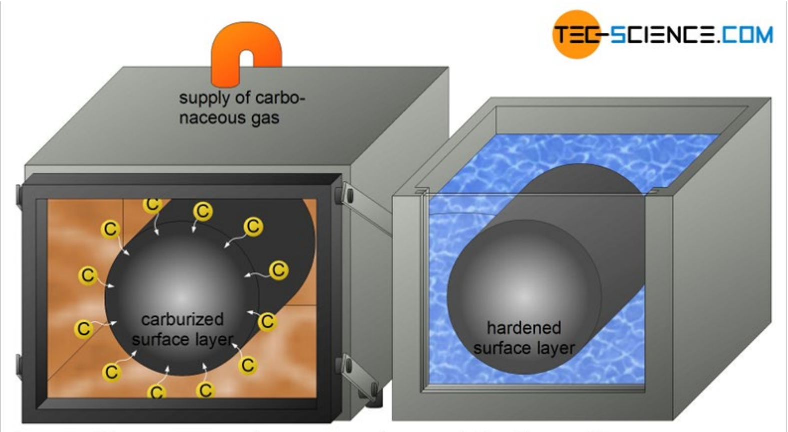


Case Hardening Example

Is approach useful for a more realistic scenario?

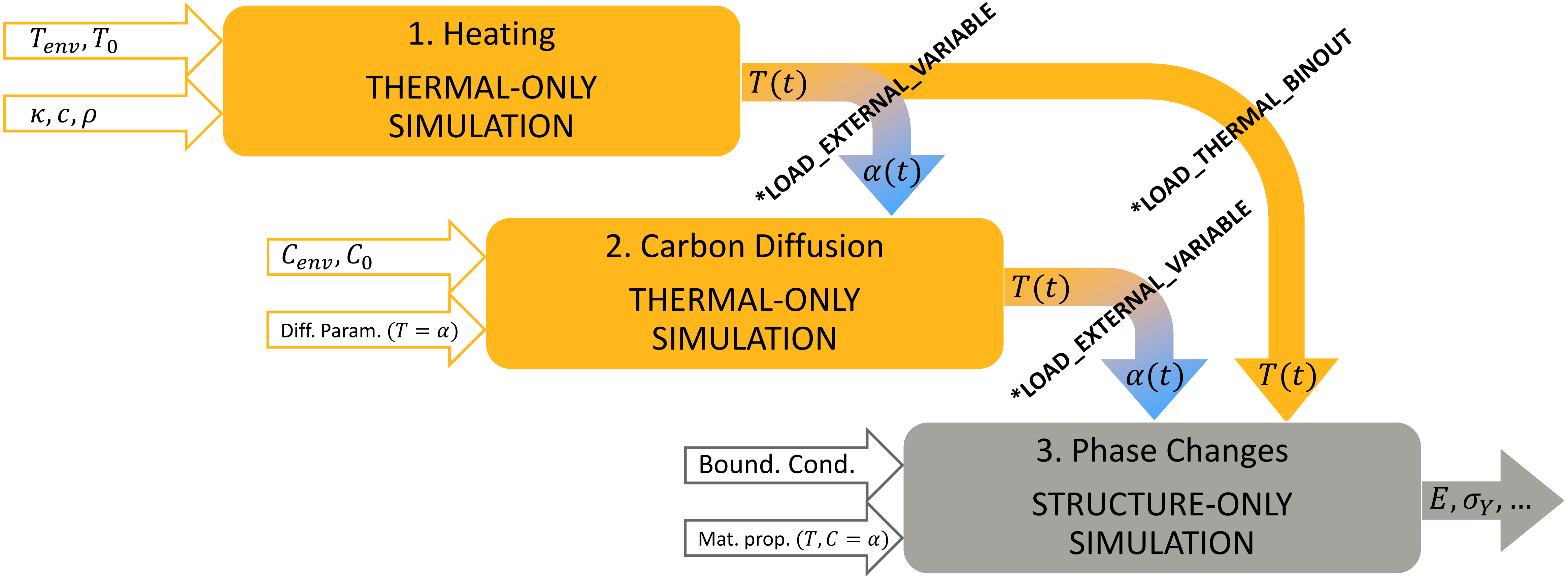
Carburization and Direct Hardening - Process

- Heating of a steel specimen in an oven with a carbonaceous environment
  - Austenitization in the material
  - Diffusion of carbon into the material (temperature dependent)
- Quenching of the specimen
  - Diffusion process of carbon stops
  - Austenite decomposition
    - Carbon concentration in the material slows down diffusion control phase changes
    - Carbon concentration locally improves martensite formation

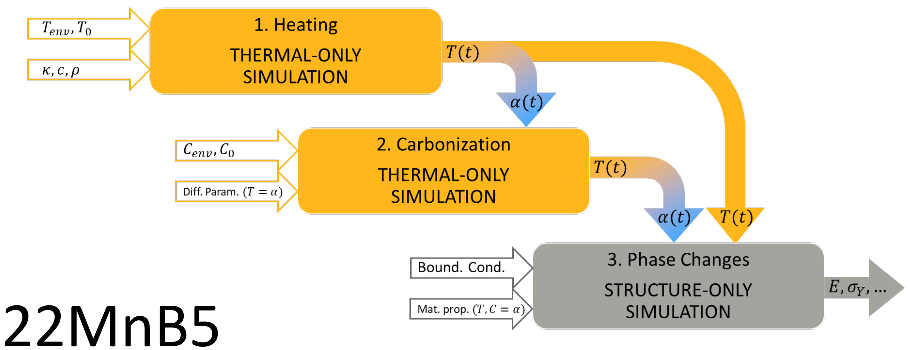


https://www.tec-science.com/material-science/heat-treatment-steel/surface-hardening-case-hardening/

Carburization Heat Treatment – Numerical Model

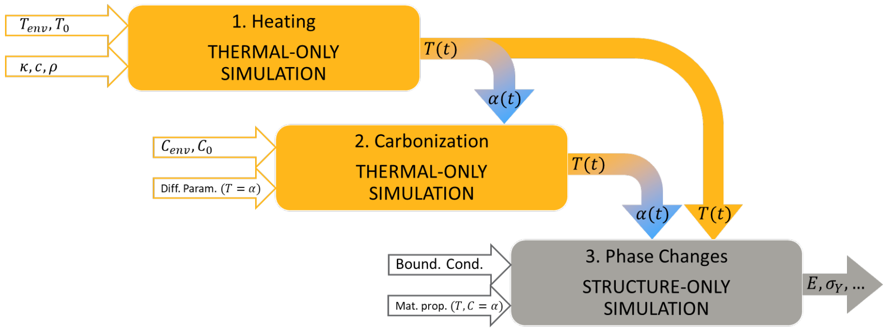


Carburization – Remarks on the Simulation

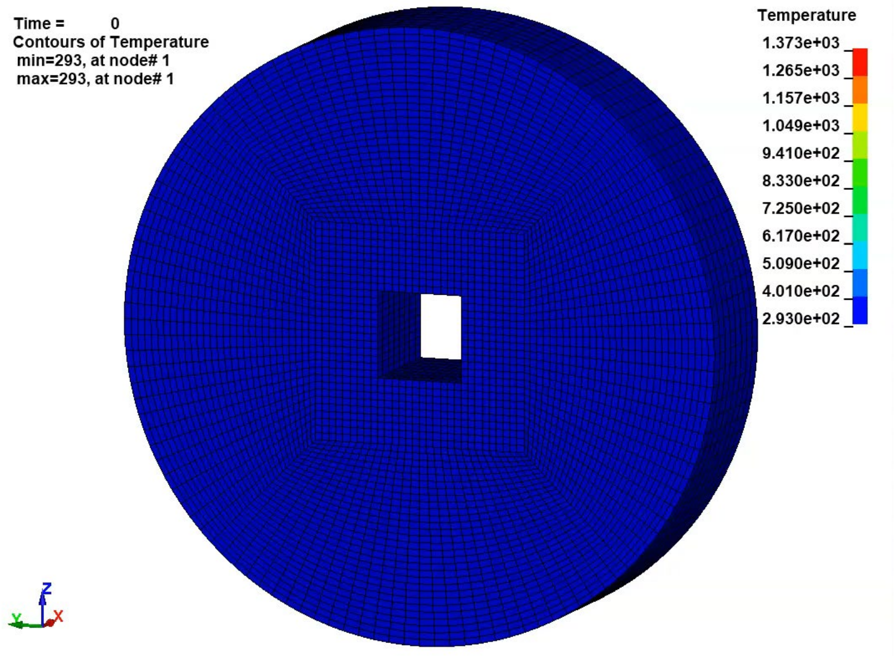


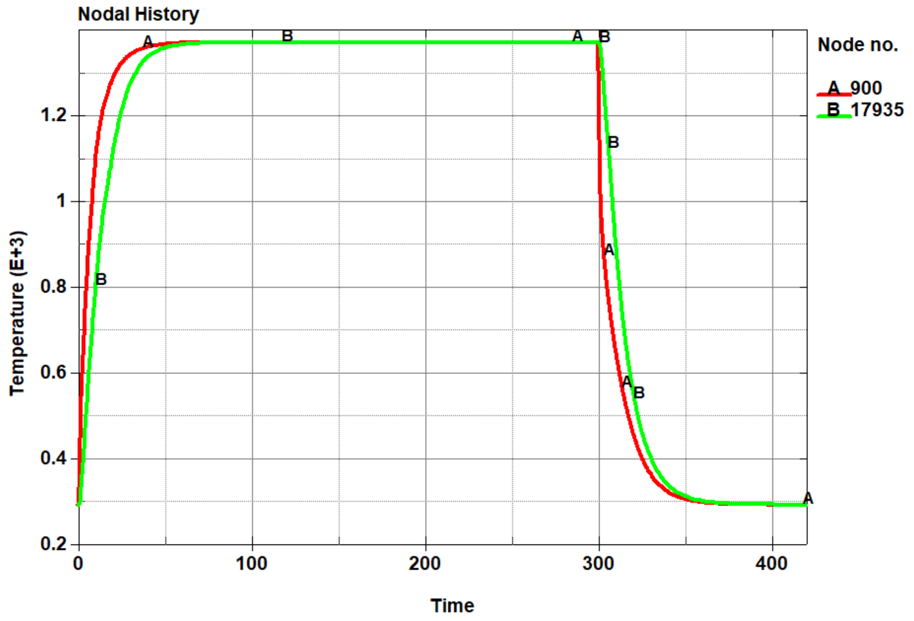
- Use generic data for the carbon diffusion parameters
- Modify material data (*MAT_254) that is available for a 22MnB5
  - Steel grade is usually not used for case-hardening
  - Change some phase transition parameter to better resemble a case-hardening steel
  - Introduce dependency on carbon content by generic load curve to demonstrate the possibilities of the new concept

Carburization – Numerical Results

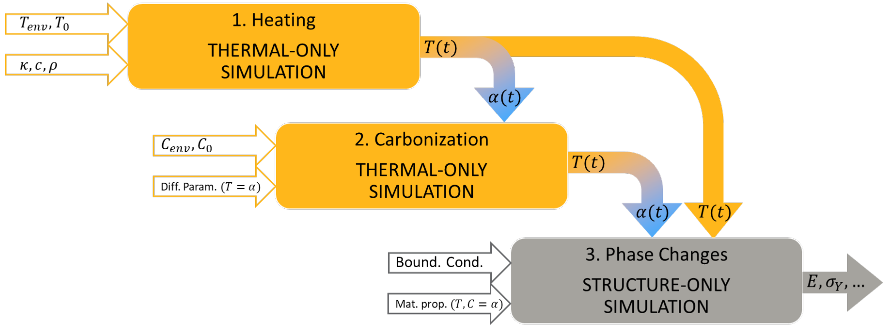


- 1. Heating
  - $T_{oven} = 1373K, t_{oven} = 300s,$
    $T_{quench} = 293K, t_{quench} = 120s$
  - Results:

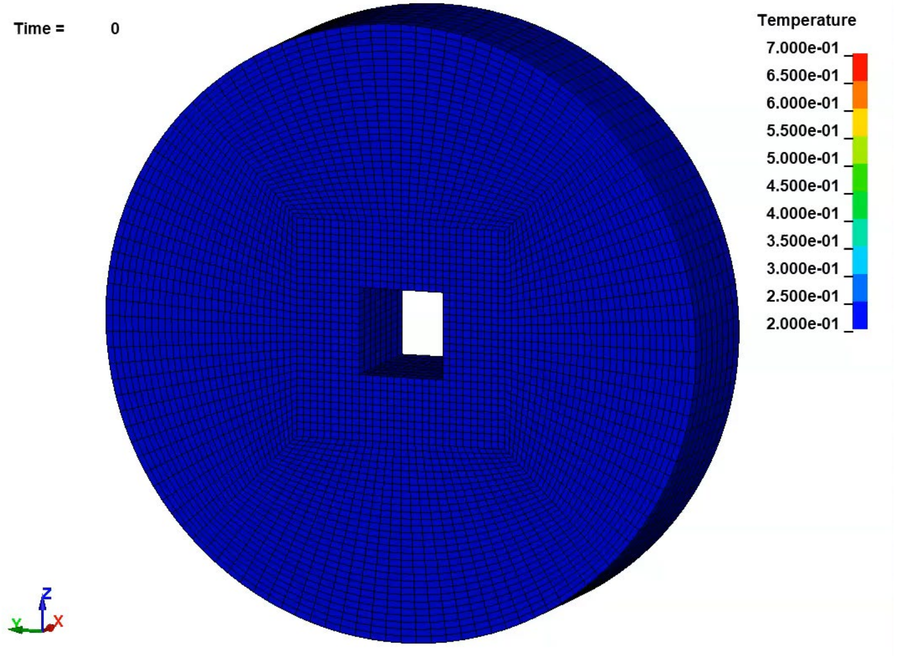


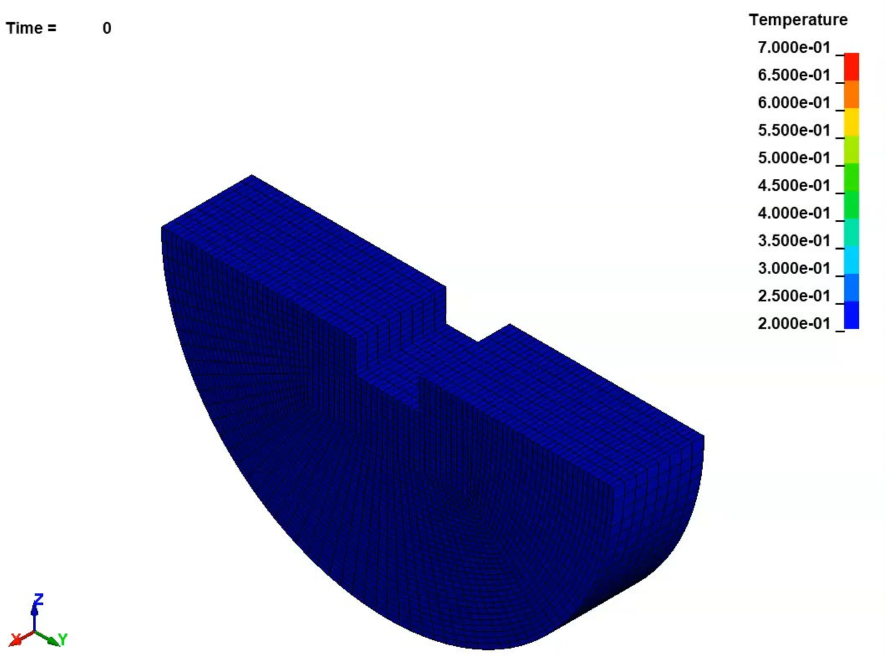


Heat treatment of a tensile specimen



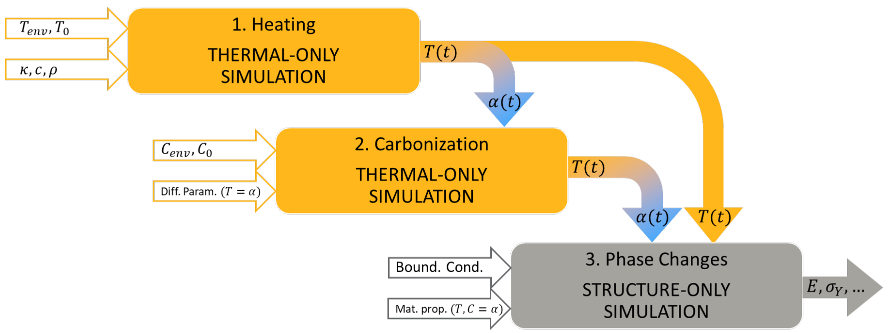
- 2. Carburization
  - $C_{oven} = 0.7, C_0 = 0.2$
  - Results:

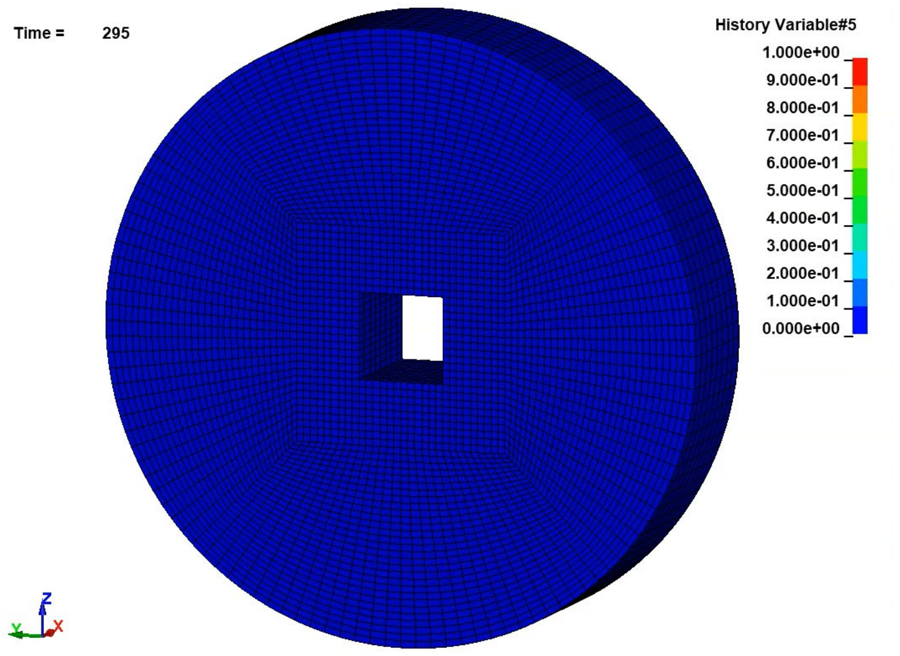


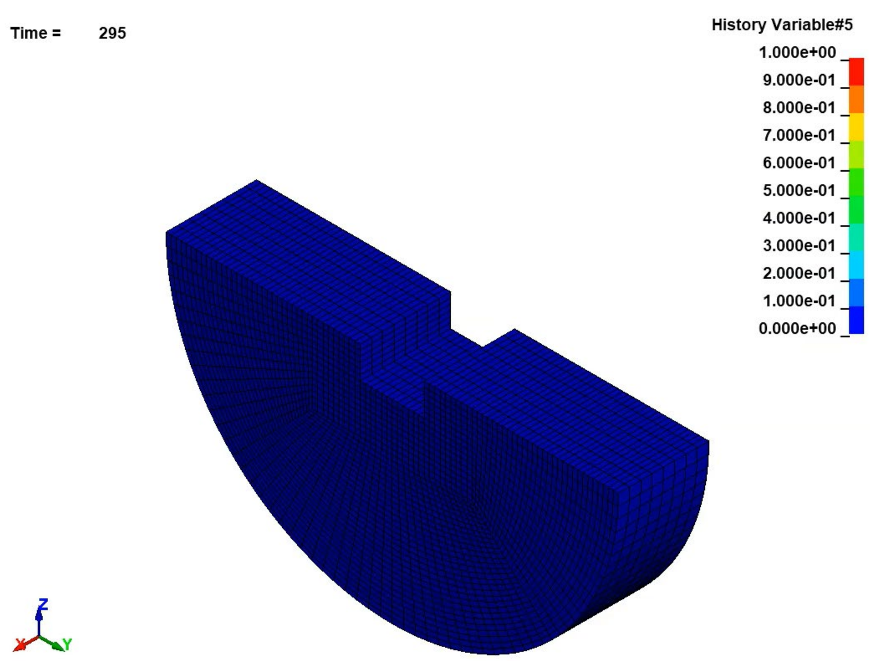


Heat treatment of a tensile specimen

- 3. Phase Change (modified UHS parameters)
  - Resulting martensite distribution

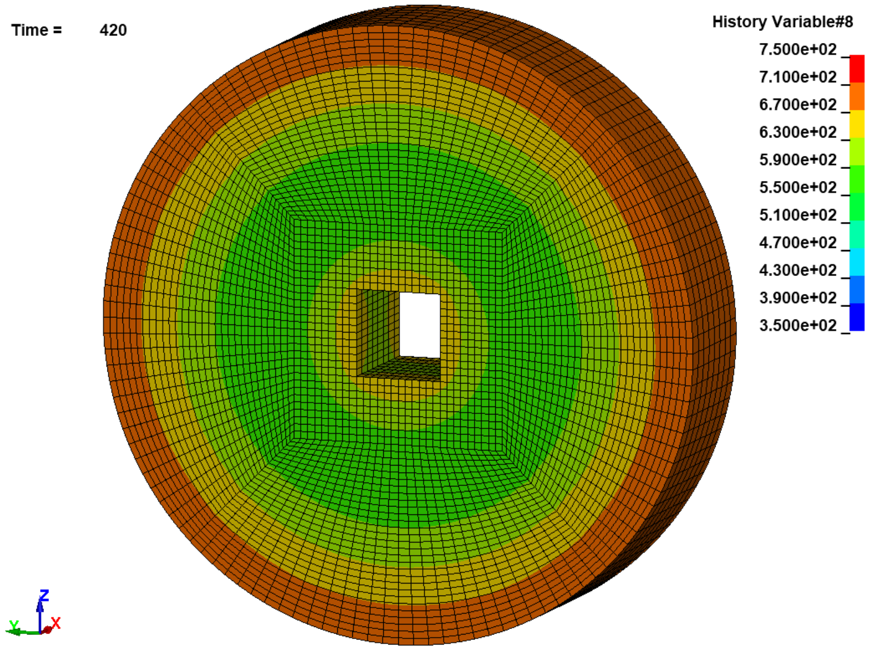


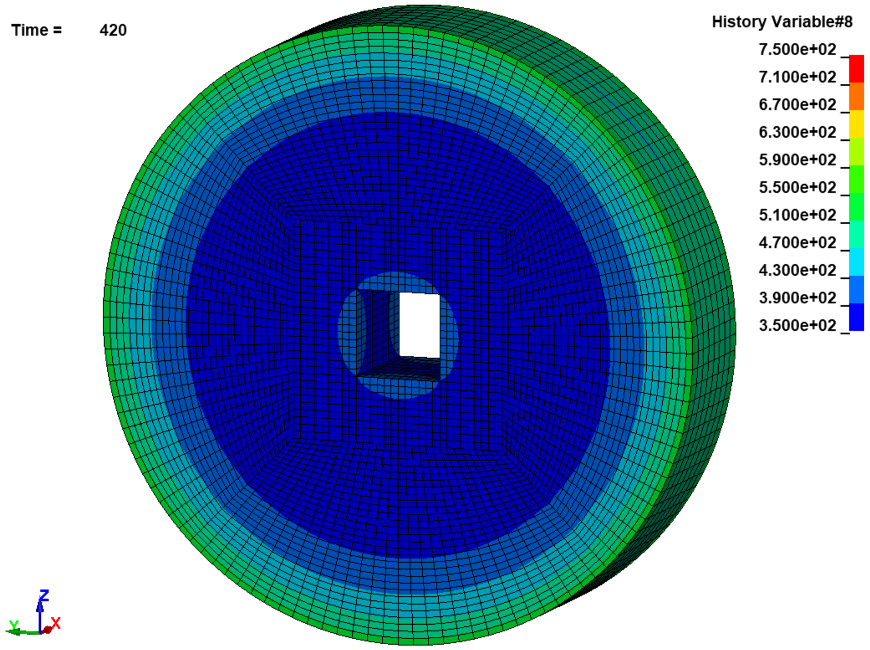




Heat treatment of a tensile specimen

- Comparison to base model ($C = C_0 = 0.2$)
  - Yield stress distribution





Conclusion and Outlook

Conclusion and Outlook

- Presented new concept of external variables in LS-DYNA for locally and temporally varying direct definition of data
- Data can be used to modify thermal (*MAT_T10), structural (*MAT_106, *MAT_251) and phase change parameters (*MAT_254)
- New keyword *MAT_ADD_EXTVAR_EXPANSION to connect material expansion to external field
- Demonstrated the capabilities of the approach with a simplified case-hardening example

- In future, we will extend the functionality to further material models, boundary conditions and damage (*MAT_ADD_GISSMO)

Ansys

*LOAD_EXTERNAL_VARIABLE

- Input example

```
*LOAD_EXTERNAL_VARIABLE
$      VID      DBAS      DSCA      DLCID          NMP       NTMP
         2       0.0       1.0        105            2          1
$      IMP       PID      PTYP
         3         1         0
         5         1         0
$     ITMP      TPID     TPTYP
         1        11         1
$       ID     IDTYP       BAS       SCA       LCID
        11         2       0.0       1.0        101
        12         2       0.0       1.0        102
                   3
res1.binout
                   3
res2.binout
         1         1       0.0       1.0        100
         3         1       2.5       1.0        100
```

- Translation:

External variable 2

- Influences the mechanical properties with index 3 and 5 of part 1
- Modifies thermal property with index 1 for part set 11
- Follows curve 101 and 102 for node sets 11 and 12, respectively
- Interprets nodal temperature results from two files
- Follows curve 100 for nodes 1 and 3, using an offset for the latter
- Uses load curve 105 for all other nodes

Material expansion due to an external variable

*MAT_ADD_EXTVAR_EXPANSION

	1	2	3	4	5	6	7	8
Card 1	PID	LCID	MULT	LCIDY	MULTY	LCIDZ	MULTZ	IDEV

- New keyword to add expansion property to an (arbitrary) material model in part **PID**
- Isotropic or orthotropic expansion based on an external variable α with id **IDEV**
  - Expansion strain rate proportional with rate $\dot{\alpha}$ of the external variable
  - Expansion coefficient $\gamma(\alpha)$ itself can be a function of the external variable