DYNAmore Express Webinar

Transferring Phase Transformation Data from *MAT_244 to *MAT_254

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Agenda

- Motivation
- Introduction to *MAT_244 / *MAT_UHS_STEEL
- Introduction to *MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE
- Parameter identification for phase evolution in *MAT_254 based on *MAT_244
- Summary

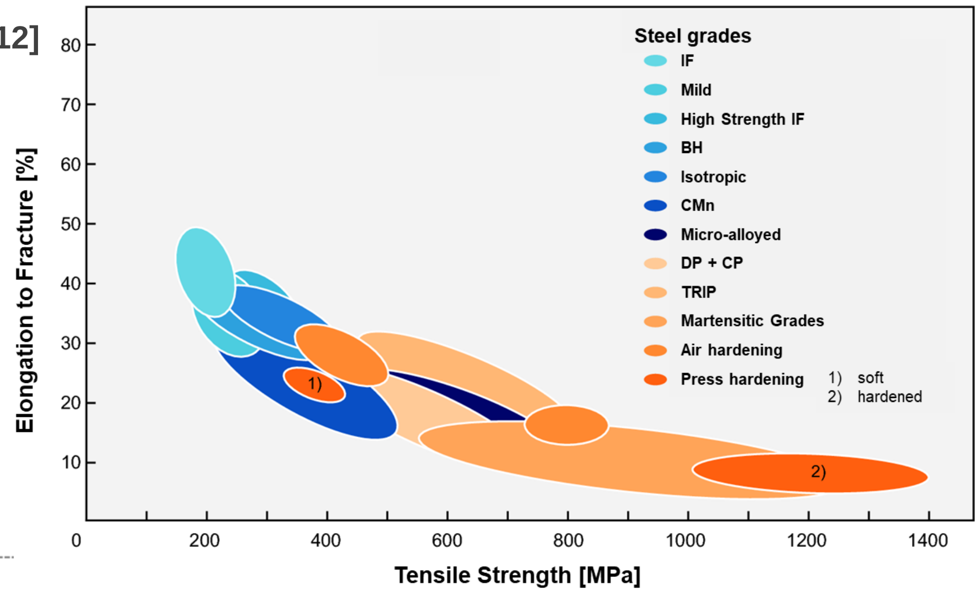
Motivation I: Steel Grades

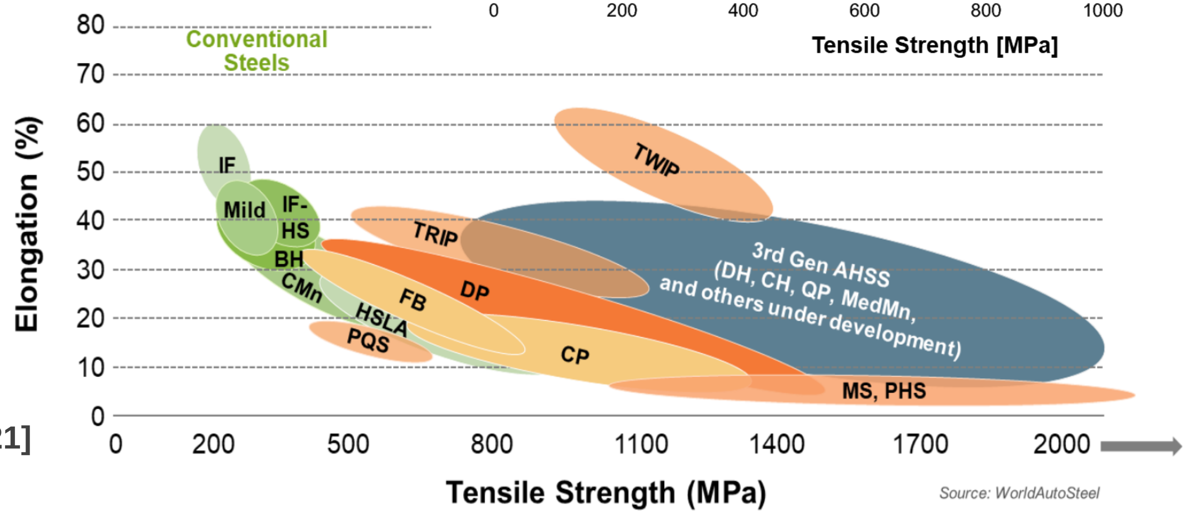
- Goal: benefit from the advanced characteristics of UHS steels

- Properties of the product are process dependent (mainly of cooling rate)

- Relatively well-known and well-controlled environment

[source: Hochholdinger 2012]



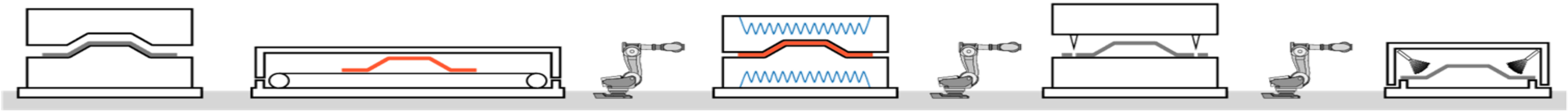


[source: WorldAutoSteel 2021]

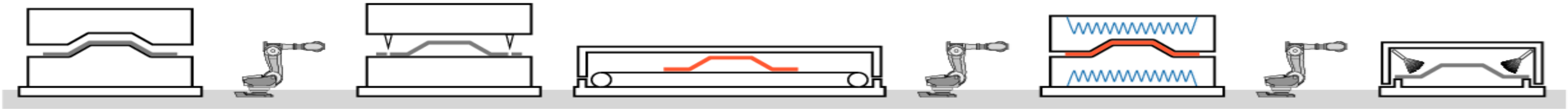
Motivation I: Press-Hardening Processes for Steel

[source: Hochholdinger 2012]

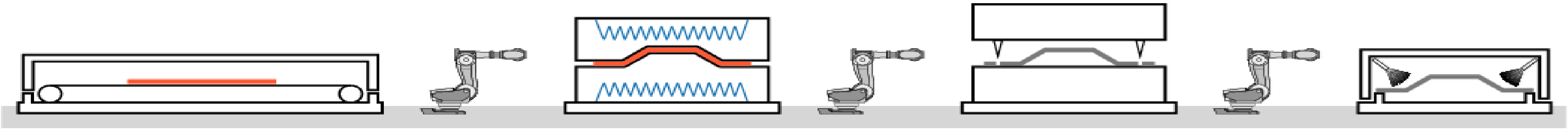
- Indirect press-hardening



- Indirect press-hardening (phs-ultraform)



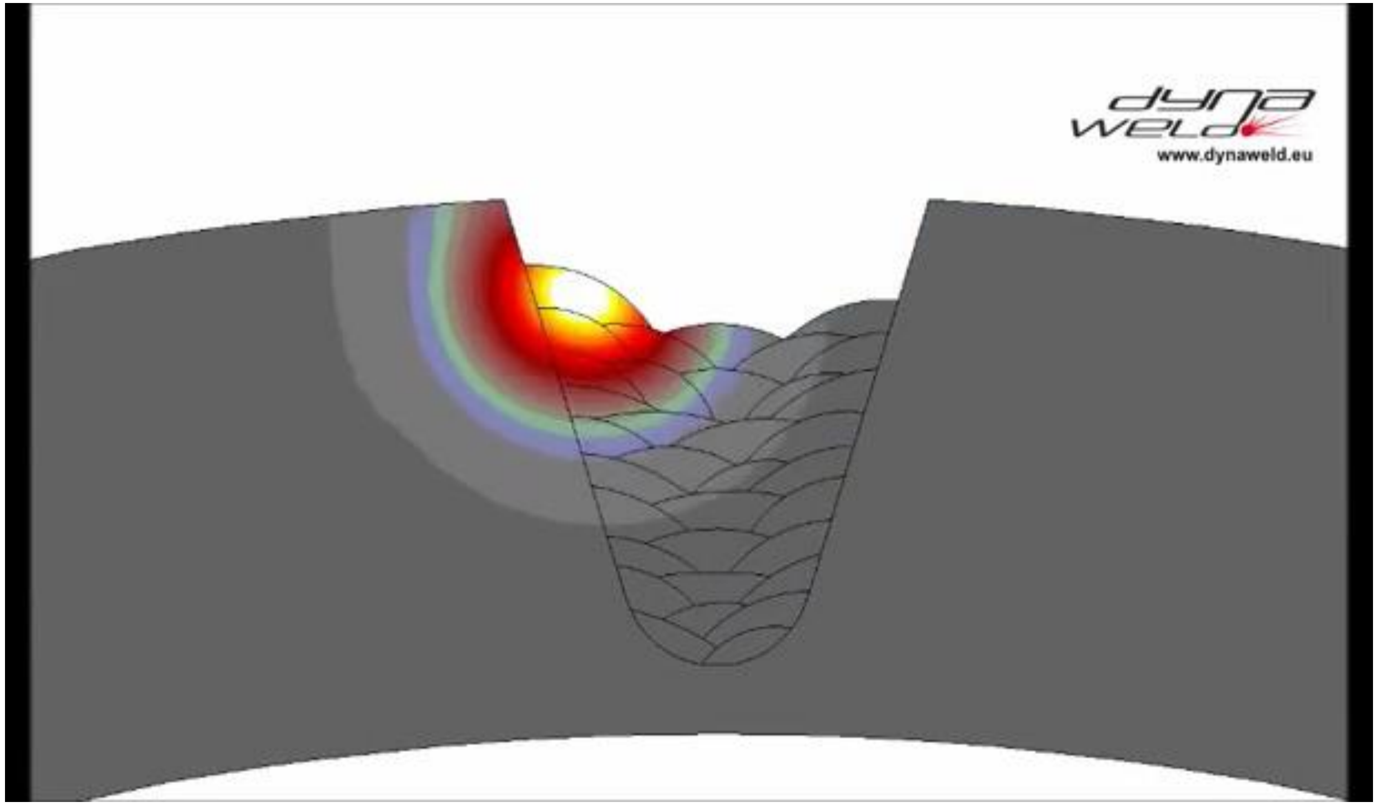
- Direct press-hardening



Motivation II: Welding procedures

[source: www.dynaweld.info]

- Process characteristics
  - Extremely rapid heating
  - Cooling due to convection and radiation to environment
  - Cooling due to heat flux within the part
- “Un-controlled” phase transformations
- Possibly multiple reheating

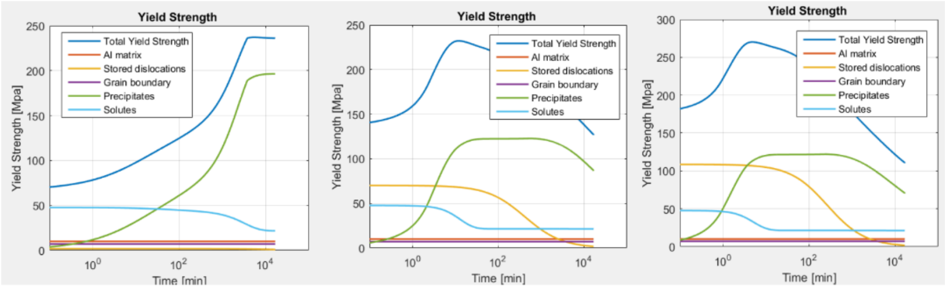


Motivation III: Bake Hardening Effect for Aluminium

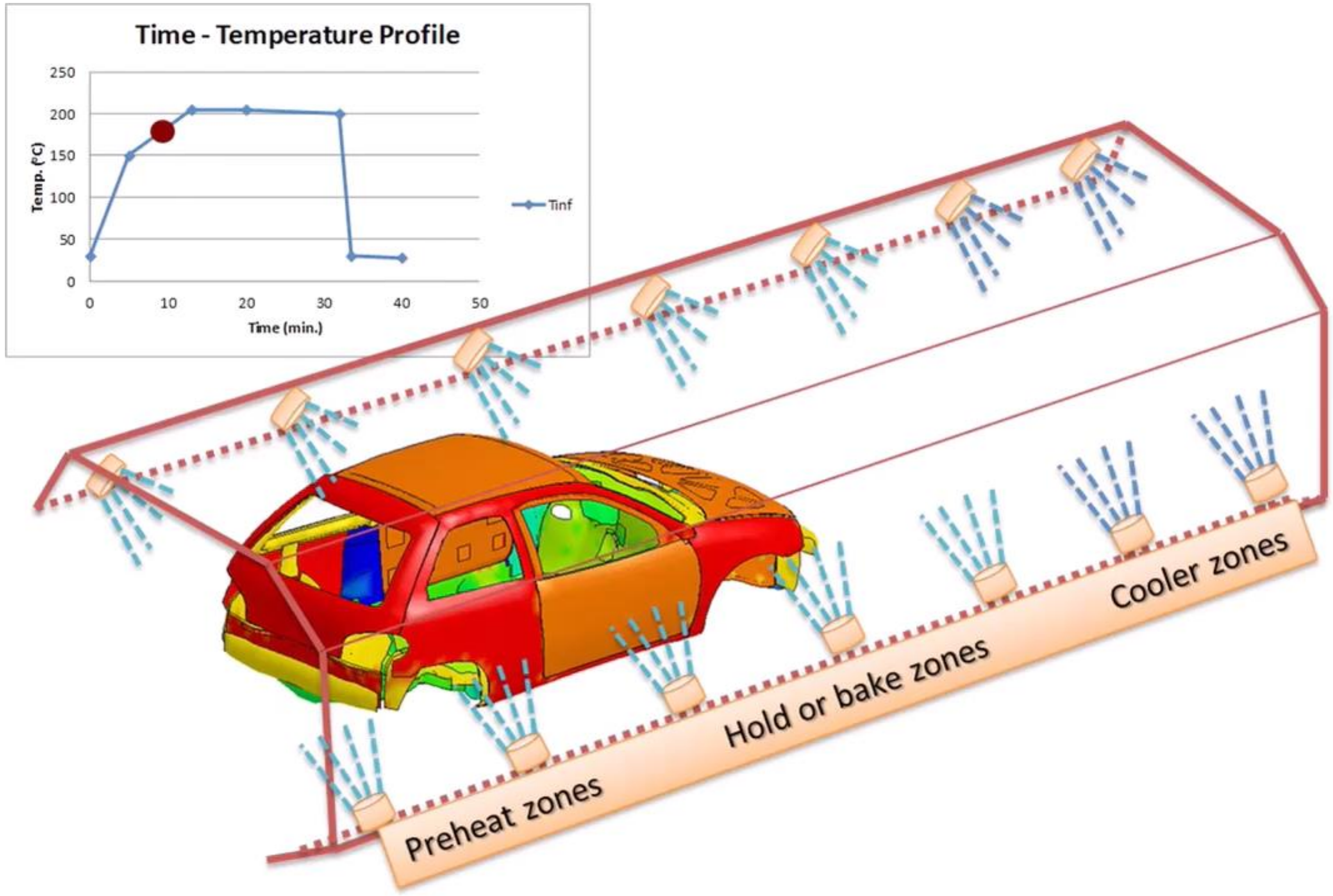
- "Heat treatment" process in paint shop
  - Assembled car body driven through oven
  - Different temperature zones
  - Shadowing of certain parts

- Spatially and temporally varying temperature profiles

- Locally distributed material properties



Jurendic et al: "FE Implementation of AA6xxx Series Aluminium Pre-Strain Dependent Strengthening Response During Paint Bake", 11. European LS-Dyna Conference 2017, Salzburg



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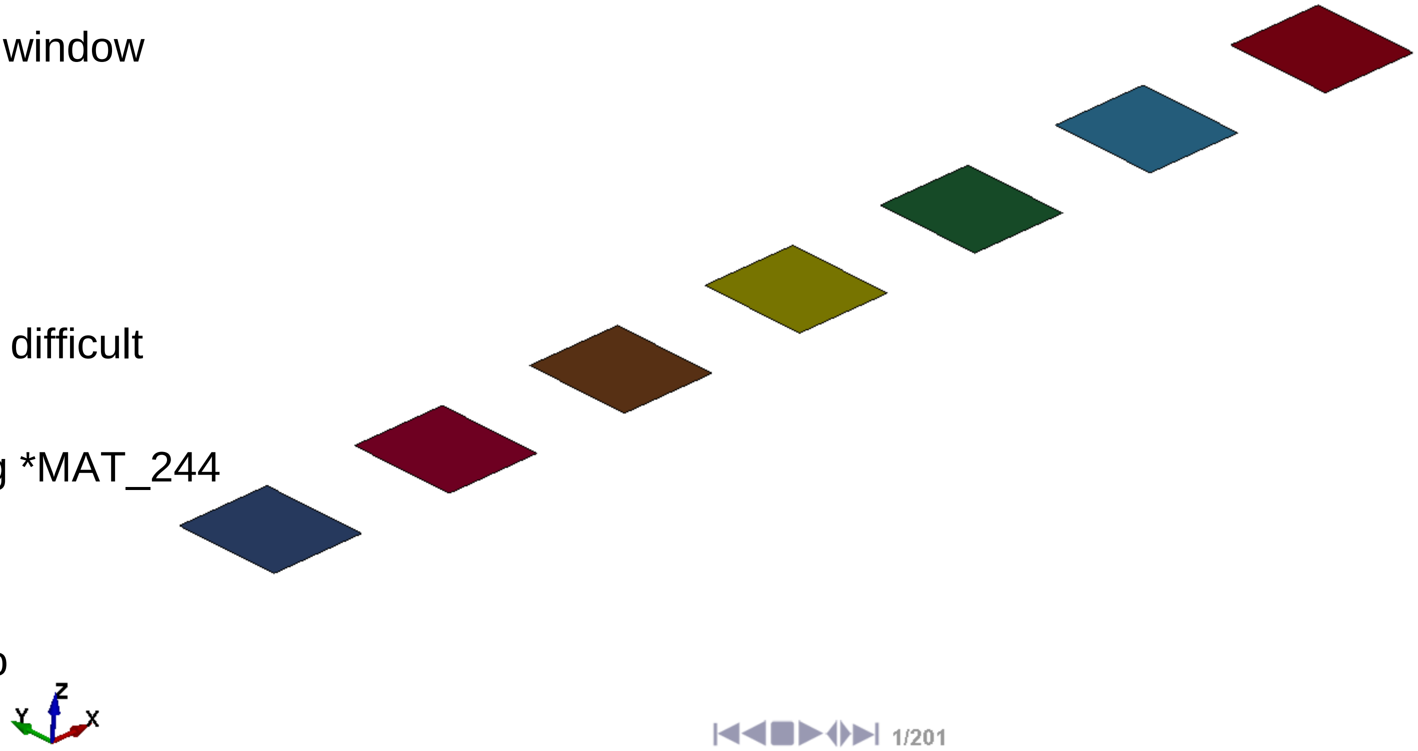
Example: Austenite decomposition during quenching of 22MnB5

- Numerical experiment setup:
  - 14 elements quenched from 1500K to different holding temperatures T
  - Calculated with *MAT_244 with initial 100% austenite
  - Seven elements in ferrite formation window
  - Seven elements in pearlite formation window

- For this webinar:
  - We know, what we want to describe
  - Depending on the problem, in can be difficult to identify what has to be described
  - Virtual experiments based on existing *MAT_244 replaces real world experiments
  - „What, if we have the data?“-scenario



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Agenda

- Motivation

- Introduction to *MAT_244 / *MAT_UHS_STEEL
  - Overview
  - Phase transformation algorithms
  - “Experimental” results

- Introduction to *MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

- Parameter identification for phase evolution in *MAT_254 based on *MAT_244

- Summary

*MAT_UHS_STEEL / *MAT_244 – Overview

- Tailored for hot stamping / press hardening processes
- Accounts for austenite decomposition into ferrite, pearlite, bainite, and martensite as well as re-austenitization

- Mechanical features:
  - Elasto-plastic material with a von-Mises plasticity model
  - Temperature and strain-rate effects
  - Transformation induced strains and plasticity
  - Thermal expansion
- Any mechanical quantity α is determined by a rule of mixtures based on the current phase fractions x_i and the quantity α_i of phase i:

$$\alpha = \sum_{i=1}^{5} x_i \alpha_i$$

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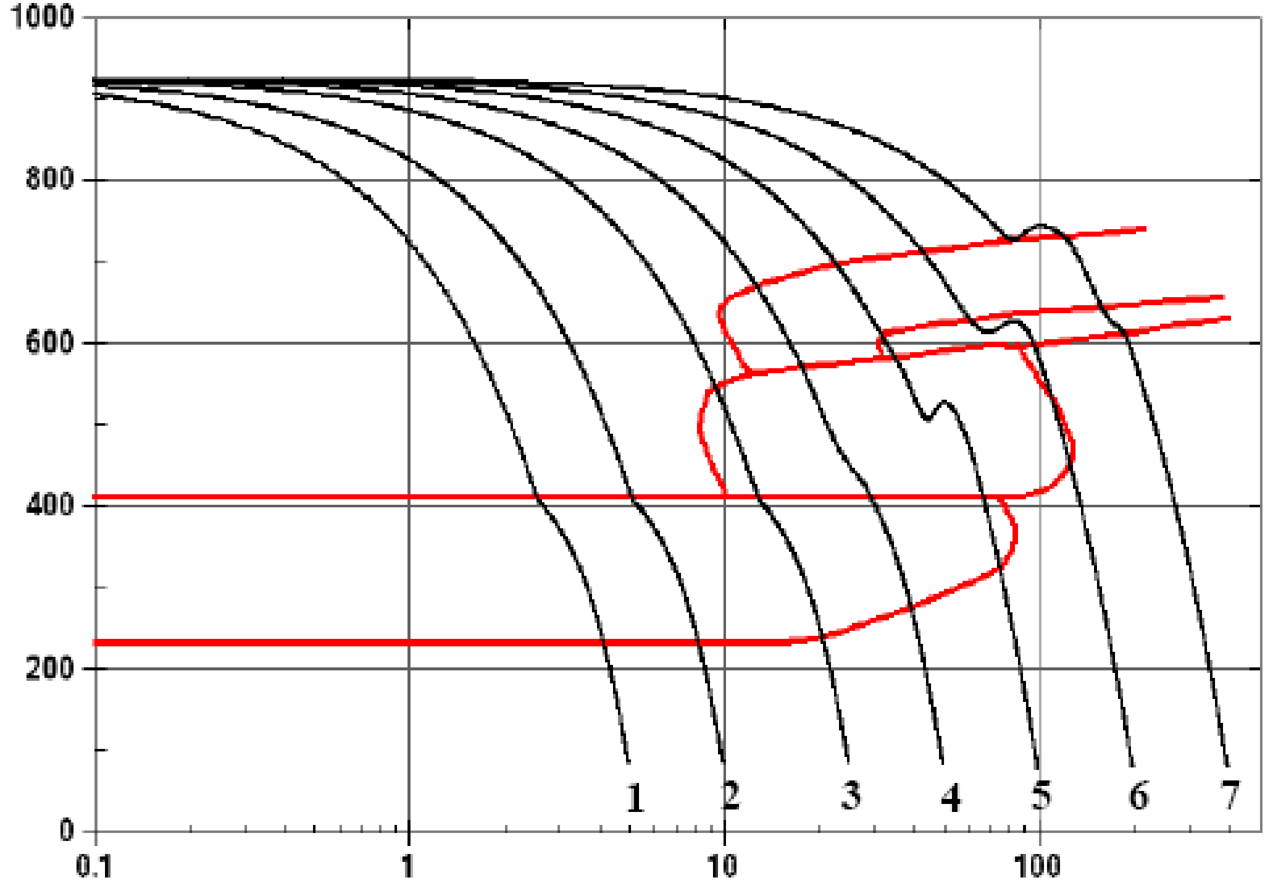
*MAT_UHS_STEEL / *MAT_244 – Overview

- User input:
  - Alloying elements in mass percent
    B, C, Co, Mo, Cr, Ni, V, W, Cu, P, Al, As, Ti
  - Latent heats for phase change reaction
  - Activation energy for phase transformation
  - Initial grain size
  - Yield curves for each phase
  - Coefficients of thermal expansion

- Material output
  - Current phase fraction of ferrite, pearlite, bainite and martensite
  - Computed Vickers hardness
  - Resulting yield strength



recalculated CCT diagramm

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*MAT_UHS_STEEL / *MAT_244 – Phase transformation

- Implemented model is based on the work of P. Åkerström
- Start temperatures in K are determined based on the alloying elements
- Data is reported to d3hsp and message file
- Start temperatures can also be given as user input
  - Load curve input for different temperatures in heating and cooling

```
------- MAT_UHS_STEEL PHASE INFO -------
MAT_UHS on part number           =                1
Ferrite start temperature        =    1110.29508501582
Pearlite start temperature       =    994.889440000000
Bainite start temperature        =    847.909400000000
Martensite start temperature     =    685.323300000000
Heat algorithm is: OFF
The Ferrite phase is:     ON
The Pearlite phase is:    ON
The Bainite phase is:     ON
The Martensite phase is: ON
---------------------------------------
```


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*MAT_UHS_STEEL / *MAT_244 – Phase transformation

- Model by Kirkaldy & Venugopalan and by Watt for diffusion-controlled phase change from austenite to bainite, ferrite and pearlite
  - Rate equation to calculate the decomposition of austenite

$$\frac{dX_i}{dt} = F_G \cdot F_{T,i} \cdot F_{X_i} \cdot F_{C,i}\,, \qquad i = 2,3,4$$

where F_G: grain size; $F_{T,i}$: temperature; F_{X_i}: current phase concentration; $F_{C,i}$: chemical composition

  - $F_G = 2^{0.5(G-1)}$
  - $F_{T,i} = \left(T_{st,i} - T\right)^{n_i} \exp\left(-\frac{Q_i}{RT}\right)$
  - $F_{X_i} = \frac{X_i^{\frac{2}{3}(1-X_i)} \cdot (1 - X_i)^{\frac{2}{3}X_i}}{\exp\left(C_{r,i} X_i^2\right)}$

  - Ghost fractions:

$$X_i = \frac{x_i}{x_{eq,i}}$$

x_i: true phase fractions have to sum up to 1.0

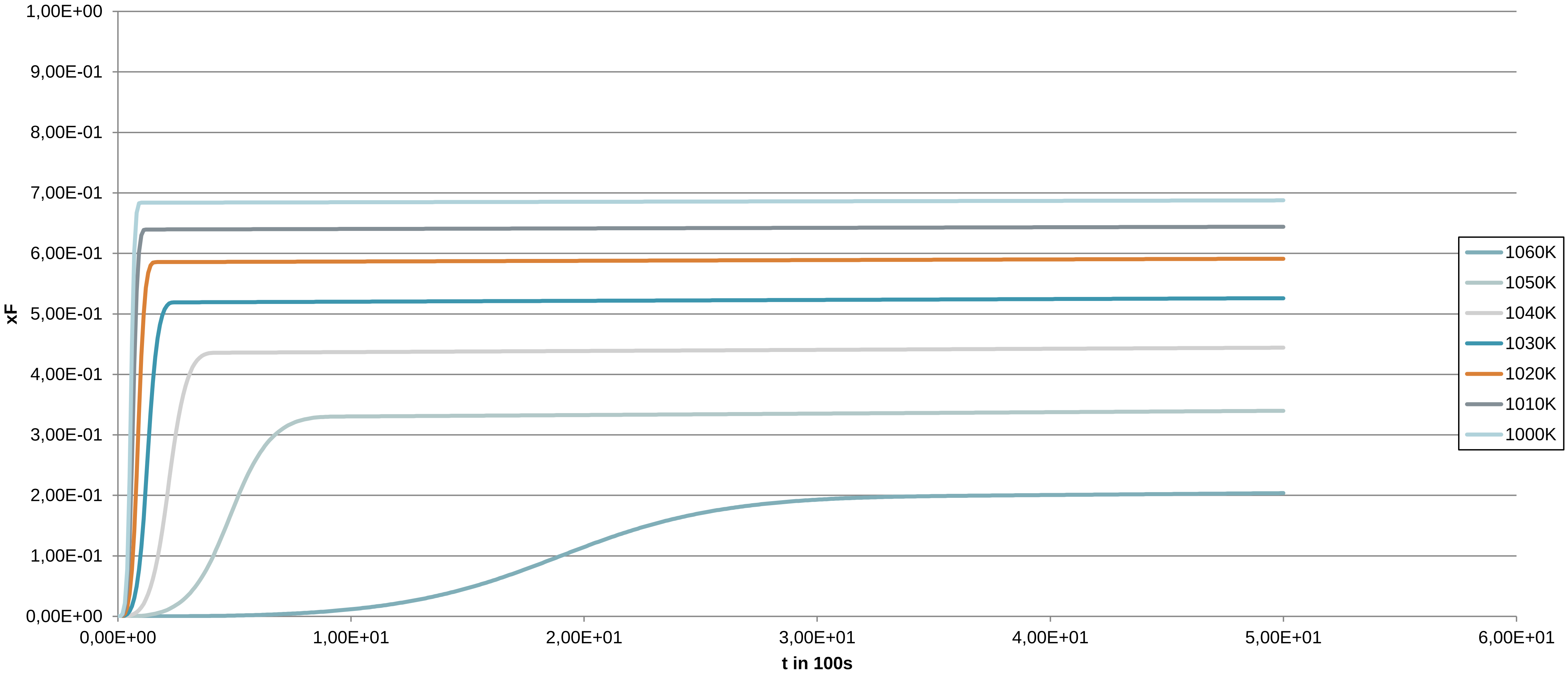
- Martensite formation follows empirical equation by Koistinen & Marburger
  - Diffusionless phase transformation

$$x_5 = F_{T,5}$$

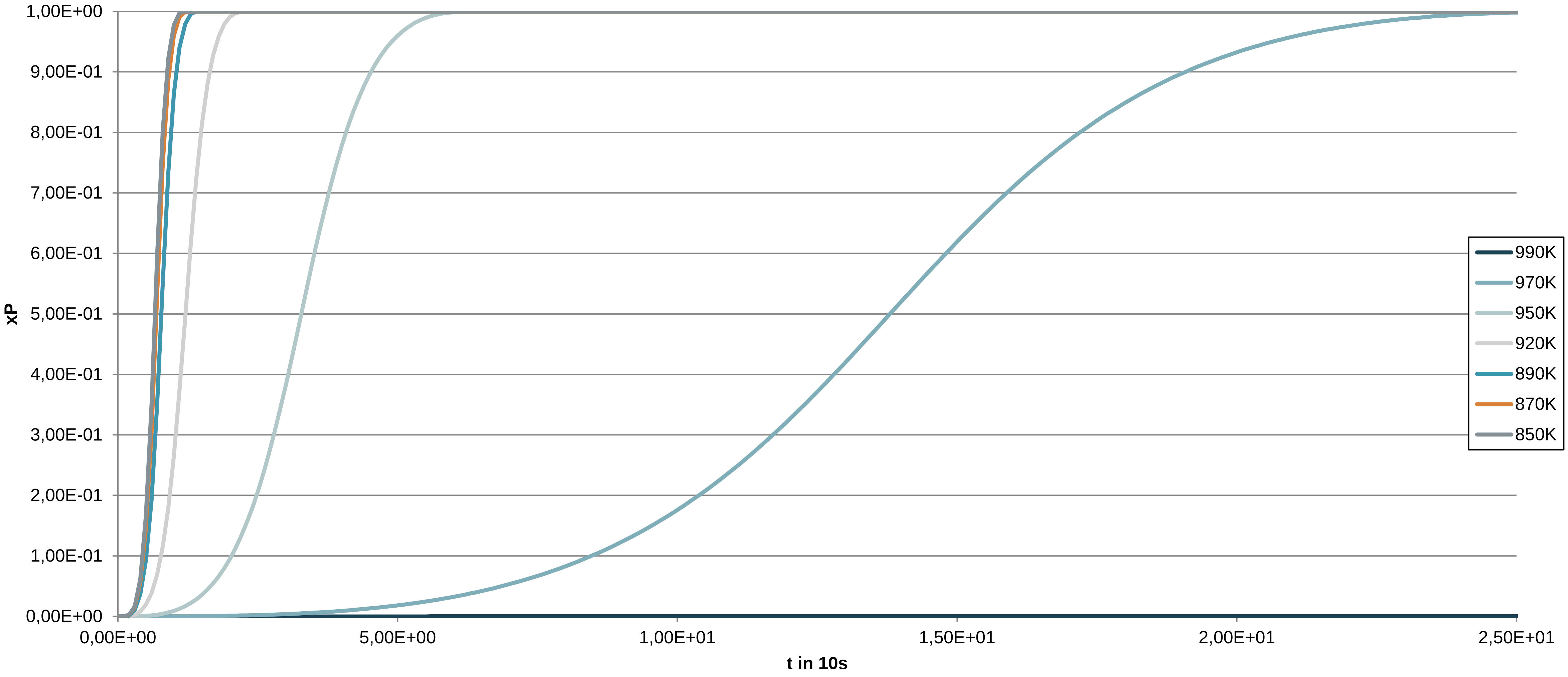
$F_{T,5}$: temperature

  - $F_{T,5} = x_1\left(1 - \exp\left(-\alpha\left(T_{st,5} - T\right)\right)\right)$

*MAT_UHS_STEEL / *MAT_244 – “experimental” ferrite concentration



*MAT_UHS_STEEL / *MAT_244 – “experimental” pearlite concentration



*MAT_UHS_STEEL / *MAT_244 – Limitations

- Process limitations
  - Tailored for hot stamping / press hardening processes
  - Basic welding functionality with a ghosting approach has been added
  - Only limited capability for phase transformations during heating phases
  - No methodology for tempering available

- Material limitations
  - Restriction to five phases
  - Only feasible for 22MnB5:
    - Heuristic formulas for start and end temperatures of phase transformation
    - Empirical equations for the phase transformation parameters

Agenda

- Motivation
- Introduction to *MAT_244 / *MAT_UHS_STEEL
- Introduction to *MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE
  - Overview of basic and elaborate properties
  - Phase change model
    - Data structure of input
    - JMAK
- Application of *MAT_254 on phase evolution in 22MnB5 steel grade
- Summary

*MAT_254 – Overview

- Up to 24 individual phases (= 552 possible phase change scenarios)
- Phase changes in heating, cooling or in a temperature window
- User can choose from a list of phase change models for each scenario

- Basic mechanical features:
  - Elasto-plastic material with a von-Mises plasticity model
  - Temperature and strain-rate effects
  - Transformation induced strains and plasticity
  - Thermal expansion
- Any mechanical quantity α is determined by a rule of mixtures based on the current phase fractions x_i and the quantity α_i of phase i:

$$\alpha = \sum_{i=1}^{24} x_i \alpha_i$$

*MAT_254 – Overview

- Elaborate features:
  - Latent heat algorithm
  - Calculation and output of NXH additional pre-defined post-processing histories, controlled by parameter POSTV
    - Accumulated thermal strain
    - Accumulated strain tensor
    - Plastic strain tensor
    - Equivalent strain
  - Calculation and output of NUSHIS additional user-defined histories
    - Refers to *DEFINE_FUNCTION keyword
    - Possible input: time, user-defined histories, phase concentrations, temperature, peak temperature, temperature rate, stress state, plastic strain data
  - Enhanced annealing option by evolution equation for plastic strain depending on time and temperature

History Variable #	Description
1 → N	Phase concentrations
N+1	Maximum temperature
N+2	Cooling rate
N+3	Yield stress
N+4	Young’s modulus
N+5	Grain size
N+6	Indicator of plastic behavior
N+7 → N+6+NUSHIS	User defined history variables
N+7+NUSHIS	Current temperature
N+8+NUHIS → N+7+NUHIS+NXH	Post-process history data as described in the preceding table
N+8+NUHIS+NXH → 2N+7+NUHIS+NXH	Plastic strains of microstructure

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*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 2a	XASTR	XAEND	XAPAR1	XAPAR2	XAPAR3		CTEANN	
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5	PTTAB6	PTTAB7	PTTAB8
Card 5	PTEPS	TRIP	PTLAT	POSTV	NUSHIS	GRAI	T1PHAS	T2PHAS
Card 5a	FUNUSH1	FUNUSH2	FUNUSH3	FUNUSH4	FUNUSH5	FUNUSH6	FUNUSH7	FUNUSH8
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

- Very general material implementation to capture micro-structure evolution
- Implementation available for solids and shells as well as for explicit and implicit

*MAT_254 – Phase transformation

	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	PTTAB6	PTTAB7	PTTAB8

- Microstructural phase evolution
  - Parametrization to be given in a matrix-like structure
  - Transformation can be restricted to subset of the theoretically possible phase transformation
  - Matrix input (*DEFINE_TABLE_2D/3D) for
    - Phase transformation law (2D)
    - Start and end temperatures (2D)
    - Transformation constants (2D)

from phase \ to phase	1	2	3	…	n
1		$data_{12}$	$data_{13}$	…	$data_{1n}$
2	$data_{21}$		$data_{23}$	…	$data_{2n}$
3	$data_{31}$	$data_{32}$		…	$data_{3n}$
…	⋮	⋮	⋮		⋮
n	$data_{n1}$	$data_{n2}$	$data_{n3}$	…	

*MAT_254 – Phase transformation

	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	PTTAB6	PTTAB7	PTTAB8

- Microstructural phase evolution
  - Parametrization to be given in a matrix-like structure
  - Transformation can be restricted to subset of the theoretically possible phase transformation
  - Matrix input (*DEFINE_TABLE_2D/3D) for
    - Phase transformation law (2D)
    - Start and end temperatures (2D)
    - Transformation constants (2D)
    - Temperature (rate) dependent parameters (3D)
    - …

from phase \ to phase	1	2	3	…	n
1		LC_{12}	LC_{13}	…	LC_{1n}
2	LC_{21}		LC_{23}	…	LC_{2n}
3	LC_{31}	LC_{32}		…	LC_{3n}
⋮	⋮	⋮	⋮		⋮
n	LC_{n1}	LC_{n2}	LC_{n3}	…	

*MAT_254 – Phase transformation

	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	PTTAB6	PTTAB7	PTTAB8

- Available phase transformation laws
  1) Koistinen-Marburger
  2) Generalized Johnson-Mehl-Avrami-Kolmogorov (JMAK)
  3) Åkerström (cooling, *MAT_244)
  4) Oddy (heating, *MAT_244)
  5) Recovery model, part I (heating, Ti-6Al-4V)
  6) Recovery model, part II (heating, Ti-6Al-4V)
  7) Parabolic growth, part I (heating, Ti-6Al-4V)
  8) Parabolic growth, part II (heating, Ti-6Al-4V)
  9) Incomplete Koistinen-Marburger (cooling, Ti-6Al-4V)

from phase \ to phase	1	2	3	…	n
1		law_{12}	law_{13}	…	law_{1n}
2	law_{21}		law_{23}	…	law_{2n}
3	law_{31}	law_{32}		…	law_{3n}
…	⋮	⋮	⋮		⋮
n	law_{n1}	law_{n2}	law_{n3}	…	

*MAT_254 – Phase transformation

	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	PTTAB6	PTTAB7	PTTAB8

- Available phase transformation laws
  1) Koistinen-Marburger
  2) Generalized Johnson-Mehl-Avrami-Kolmogorov (JMAK)
  3) Åkerström (only cooling, *MAT_244)
  4) Oddy (only heating, *MAT_244)
- Sign of entry defines usage in cooling or heating

- Example: 22MnB5…
  - … reproducing *MAT_244

from phase \ to phase	1 Austenite	2 Ferrite	3 Pearlite	4 Bainite	5 Martensite
1		3	3	3	1
2	-4				
3	-4				
4	-4				
5	-4				

*MAT_254 – Phase transformation

	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	PTTAB6	PTTAB7	PTTAB8

- Available phase transformation laws
  1) Koistinen-Marburger
  2) Generalized Johnson-Mehl-Avrami-Kolmogorov (JMAK)
  3) Åkerström (only cooling, *MAT_244)
  4) Oddy (only heating, *MAT_244)
- Sign of entry defines usage in cooling or heating

- Example: 22MnB5…
  - … reproducing *MAT_244
  - … best practice

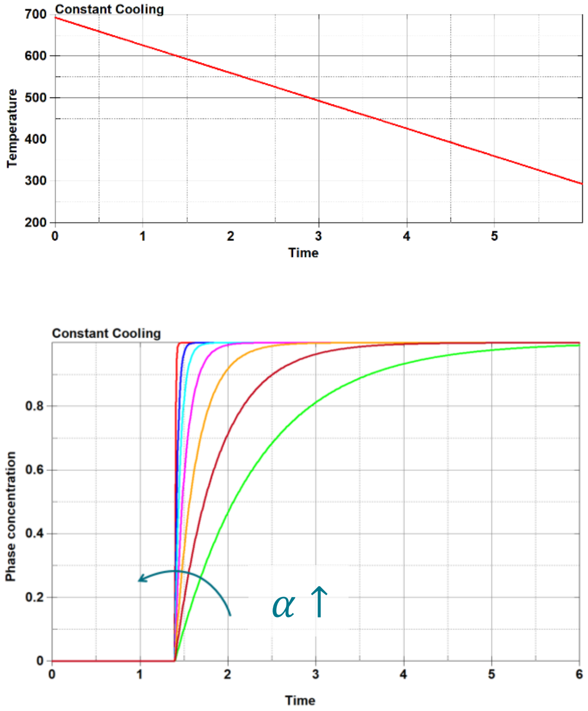
from phase \ to phase	1	2	3	4	5
1		2	2	2	1
2	-2				
3	-2				
4	-2				
5	-2				
	Austenite	Ferrite	Pearlite	Bainite	Martensite

*MAT_254 – Phase transformation

	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	PTTAB6	PTTAB7	PTTAB8

- Koistinen-Marburger:
  - Diffusionless process

$$x_b = x_a\left(1 - e^{-\alpha|T_{\text{start}} - T|}\right)$$



- Parameter:
  - PTX1: α

*MAT_254 – Phase transformation

	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**	**PTTAB6**	**PTTAB7**	**PTTAB8**

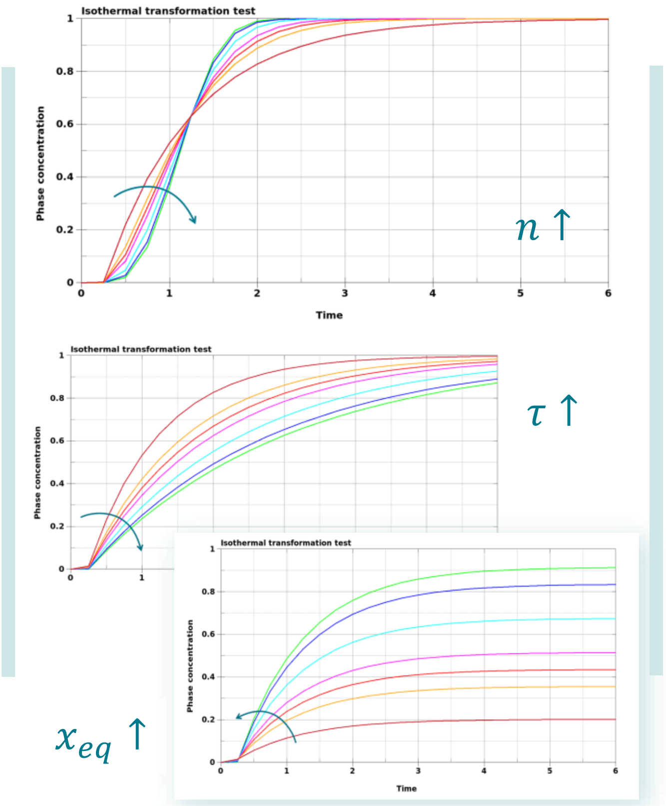
- Johnson-Mehl-Avrami-Kolmogorov (JMAK):
  - Integral form (incomplete, isothermal case)

$$x_b = x_{eq}(T)(x_a + x_b)\left(1 - e^{-\left(\frac{t}{\tau(T,\varepsilon^p)}\right)^{n(T)}}\right)$$

  - Evolution equation:

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

$$k_{ab} = \frac{x_{eq}(T)}{\tau(T,\varepsilon^p)} f(\dot{T}), k'_{ab} = \frac{1.0 - x_{eq}(T)}{\tau(T,\varepsilon^p)} f'(\dot{T}),$$
$$\tau(T,\varepsilon^p) = \tau^0(T) \cdot \alpha(\varepsilon^p)$$



- Parameter:
  - PTTAB1: $n(T)$
  - PTTAB2: $x_{eq}(T)$
  - PTTAB3: $\tau^0(T)$
  - PTTAB4: $f(\dot{T})$
  - PTTAB5: $f'(\dot{T})$
  - PTTAB6: $\alpha(\varepsilon^p)$

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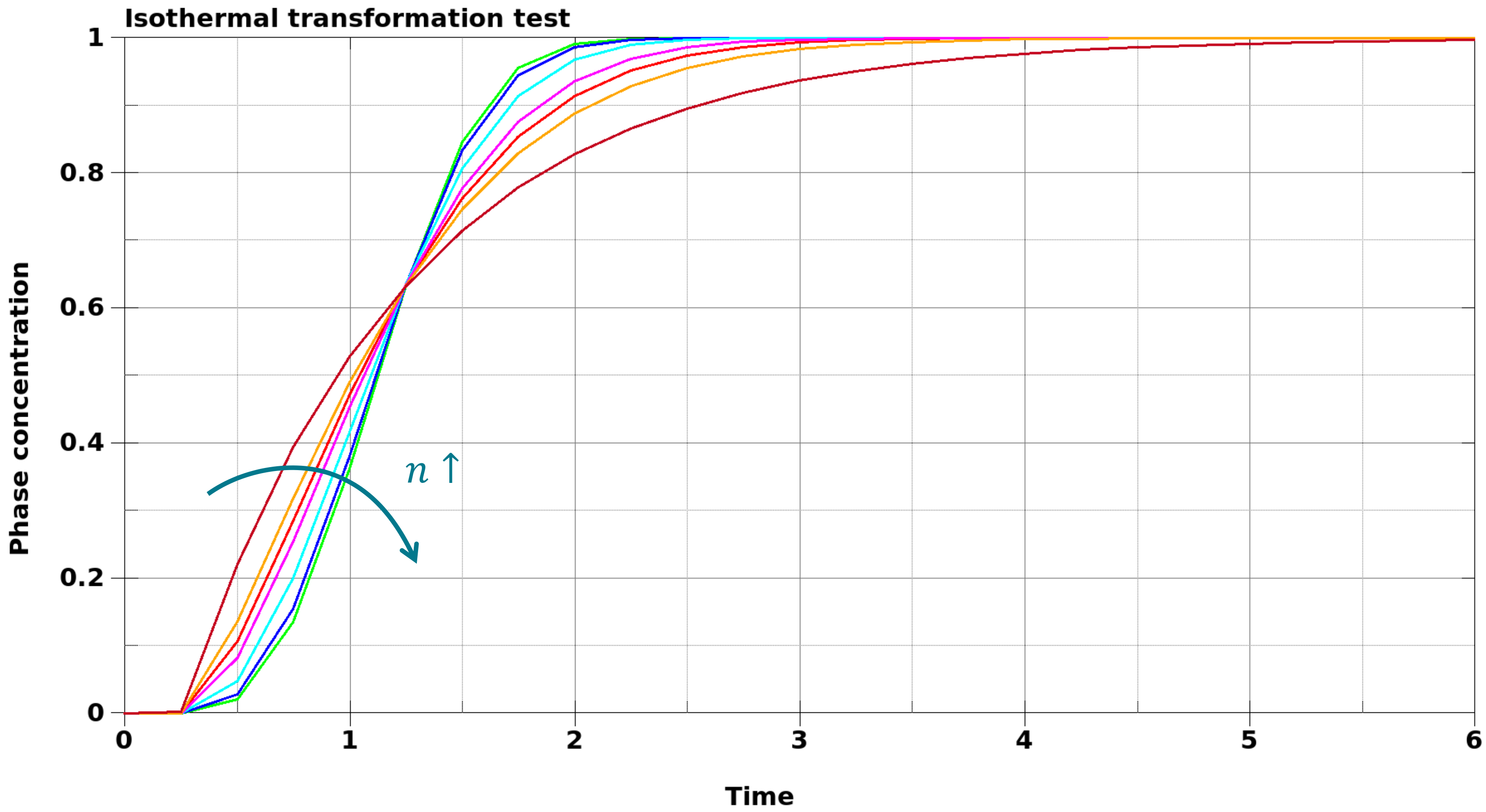
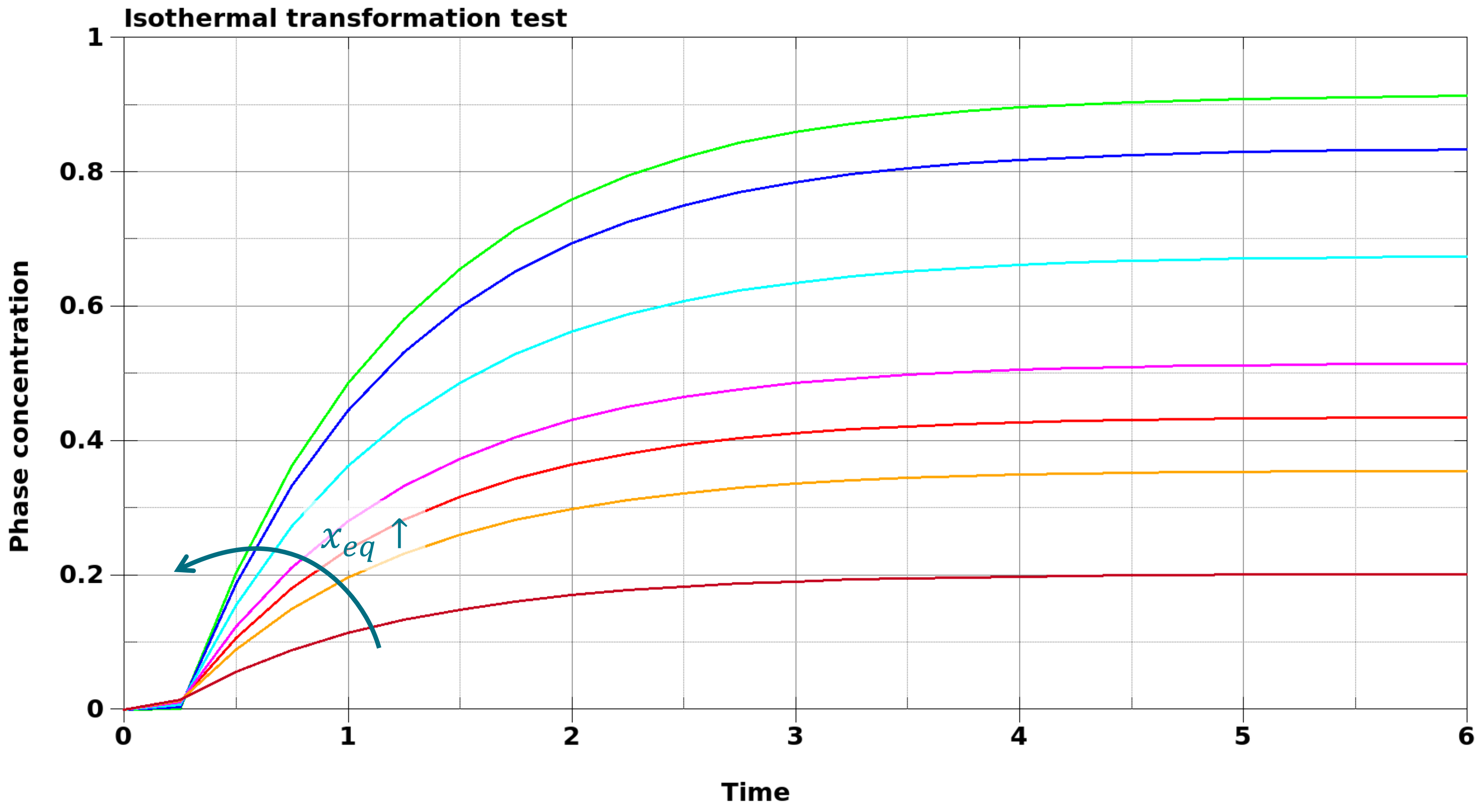
*MAT_254 – Phase transformation validation

- Influence of parameter $n(T)$ on isothermal transformation



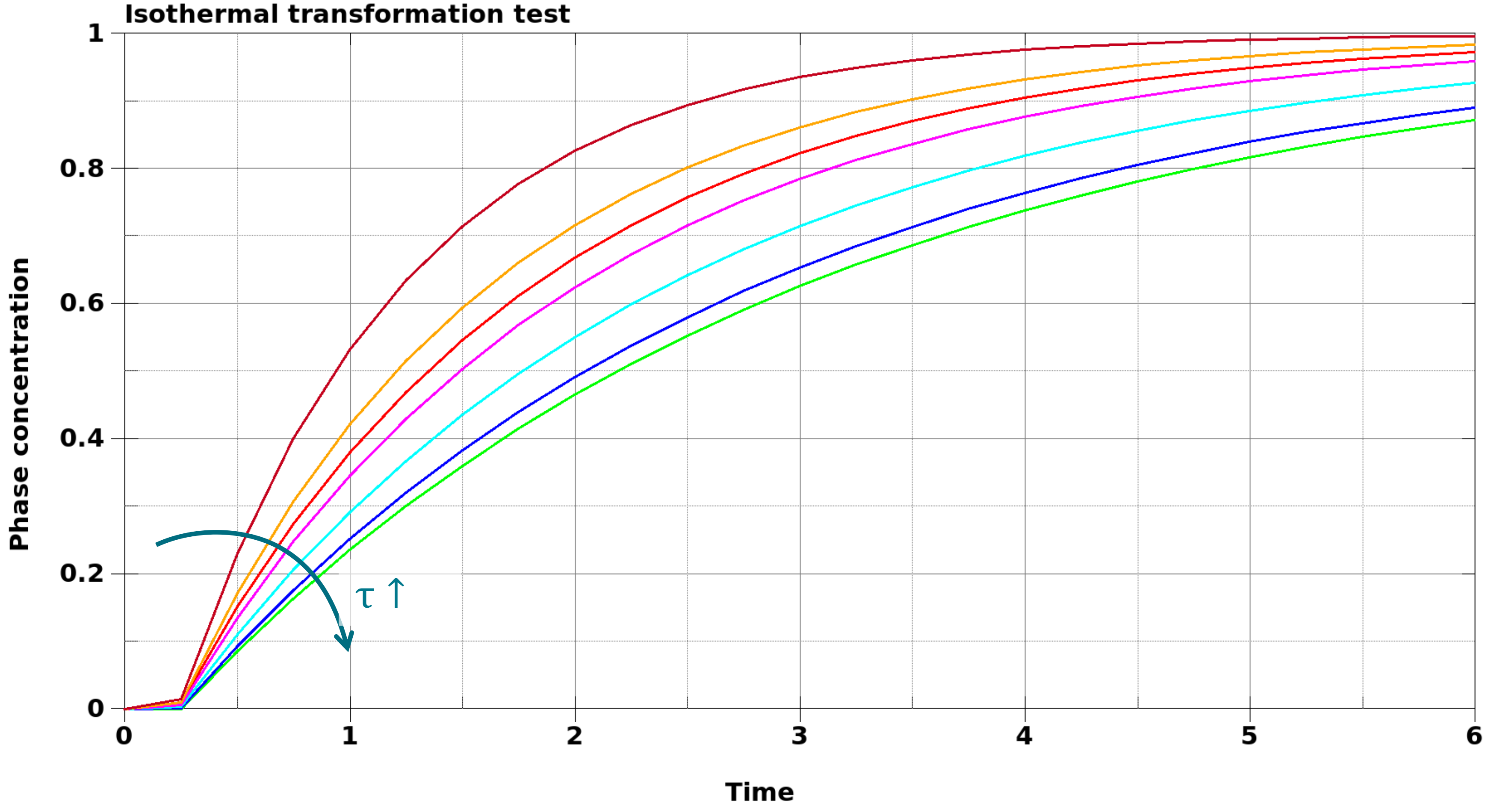
*MAT_254 – Phase transformation validation

- Influence of parameter $x_{eq}(T)$ on isothermal transformation



*MAT_254 – Phase transformation validation

- Influence of parameter $\tau(T)$ on isothermal transformation



Agenda

- Motivation

- Introduction to *MAT_244 / *MAT_UHS_STEEL

- Introduction to *MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

- Parameter identification for phase evolution in *MAT_254 based on *MAT_244
  - $x_{eq}(T)$
  - Overview on direct approach and graphical approach
  - $n(T)$ and $\tau(T)$ with the direct approach
  - $n(T)$ and $\tau(T)$ with the graphical approach

- Summary

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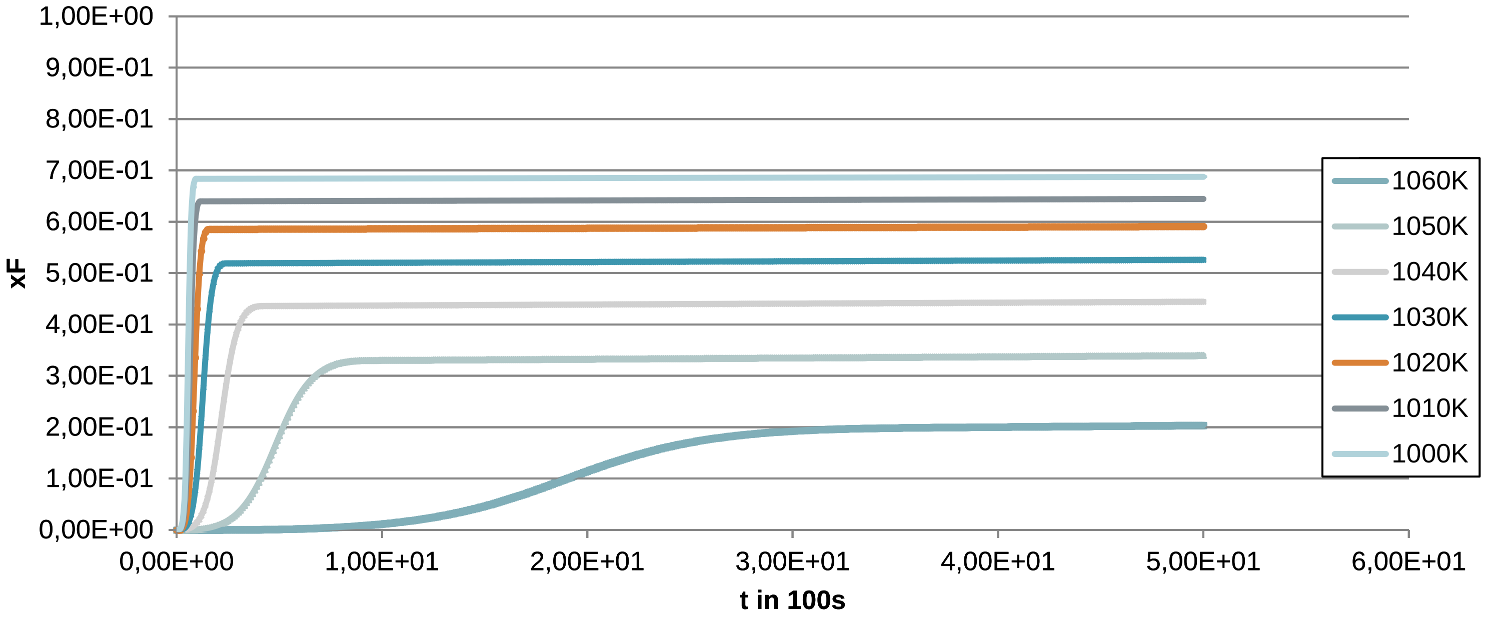
JMAK-Approach for two phases a and b – austenite and ferrite

- $x_{eq}(T)$



T	$x_{eq}(T)$
1060	0.204
1050	0.340
1040	0.444
1030	0.526
1020	0.591
1010	0.644
1000	0.688

- Physical experiments to get these results are usually difficult

Overview on direct approach and graphical approach

- Integral form of JMAK

$$x_b = x_{eq}(T)\left(x_a^0 + x_b^0\right)\left(1 - e^{-\left(\frac{t}{\tau(T)}\right)^{n(T)}}\right)$$

- Rearanged for “relative reaction coordinate”

$$\left[\frac{P(T,t)-P_{Min}}{P_{Max}-P_{Min}} =\right] \phi = \frac{x_b}{x_{eq}(T)\left(x_a^0+x_b^0\right)} = 1 - e^{-\left(\frac{t}{\tau(T)}\right)^{n(T)}}$$

- Linear Equation:

$$\lambda = \ln\left(\ln\left(\frac{1}{1-\phi}\right)\right) = n(T)\ \ln\left(\frac{t}{\tau(T)}\right)$$

- For a given temperature, two parameters are unknown: $n(T)$ and $\tau(T)$. With two points, $[t_1, \lambda_1]$ and $[t_2, \lambda_2]$, two equations can be rearrangend:
  - $\lambda_1 = n(T)\ \ln\left(\frac{t_1}{\tau(T)}\right)$ and $\lambda_2 = n(T)\ \ln\left(\frac{t_2}{\tau(T)}\right)$
  - $n(T) = \frac{\lambda_1-\lambda_2}{\ln\left({t_1}/{t_2}\right)}$ and $\tau(T) = e^{\left(\frac{\lambda_1 \ln(t_2)-\lambda_2 \ln(t_1)}{\lambda_1-\lambda_2}\right)}$

- Use of $k(T)$ as $\left(\frac{1}{\tau(T)}\right)^{n(T)}$
- Linear Equation:

$$\lambda = \ln\left(\ln\left(\frac{1}{1-\phi}\right)\right) = \ln\left(k(T)\right) + n(T)\ln(t)$$

- Plot λ vs. $\ln(t)$ for different temperatures
- Get $n(T)$ as slope, $\ln\left(k(T)\right)$ as intersection
- $k(T)$ often is described with an Arrhenius approach: $k(T) = k_0 e^{-\frac{Q}{RT}}$

Direct approach for ferrite

- $\lambda = \ln\left(\ln\left(\frac{1}{1-\phi}\right)\right)$

- Choosen values
  - $\phi_1 \sim 0.1 \ (\lambda_1 = -2.25)$
  - $\phi_2 \sim 0.9 \ (\lambda_2 = \ 0.83)$

- PTSTART, PTEND based on *MAT_244

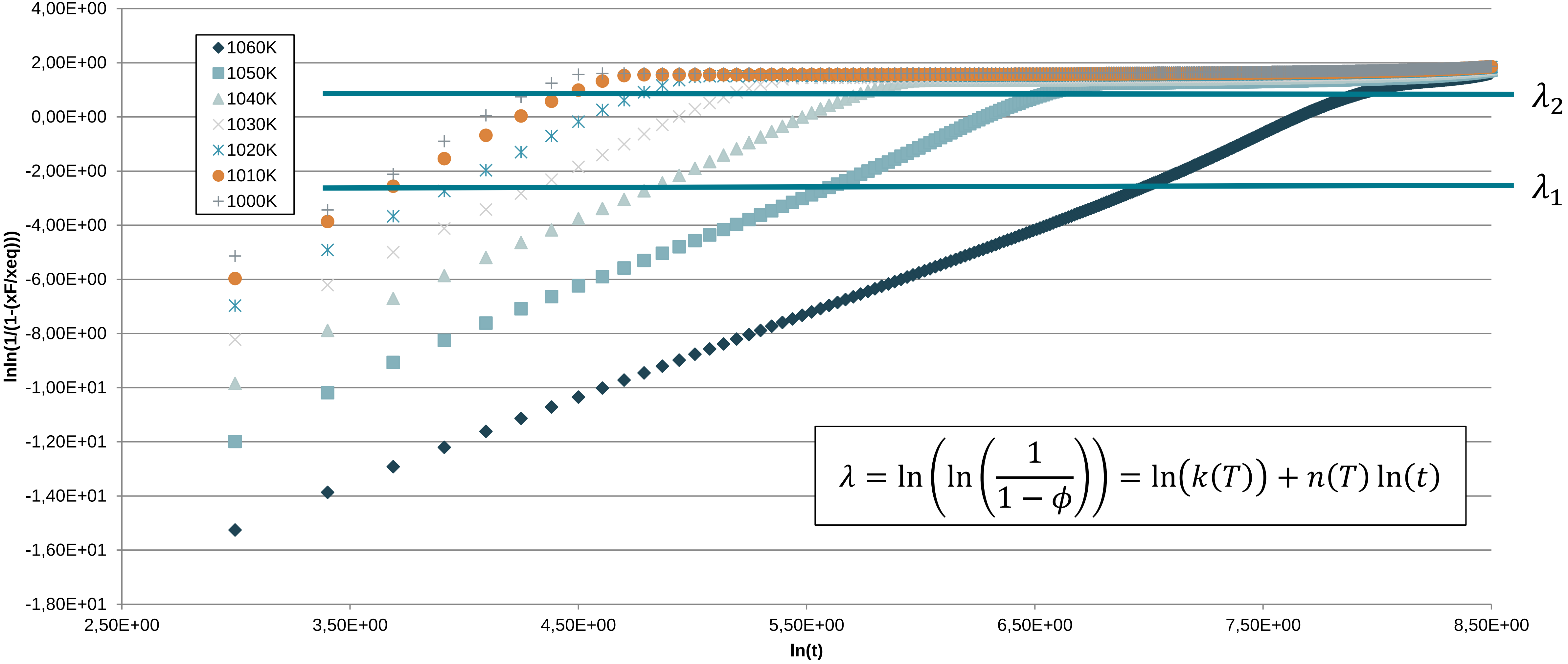
```
START TEMPERATURES
    Ferrite     start temperature        = 1.06987E+03
    Pearlite    start temperature        = 9.94744E+02
```

$$n(T) = \frac{\lambda_1 - \lambda_2}{\ln\left({t_1}/{t_2}\right)}$$

$$\tau(T) = e^{\left(\frac{\lambda_1 \ln(t_2) - \lambda_2 \ln(t_1)}{\lambda_1 - \lambda_2}\right)}$$

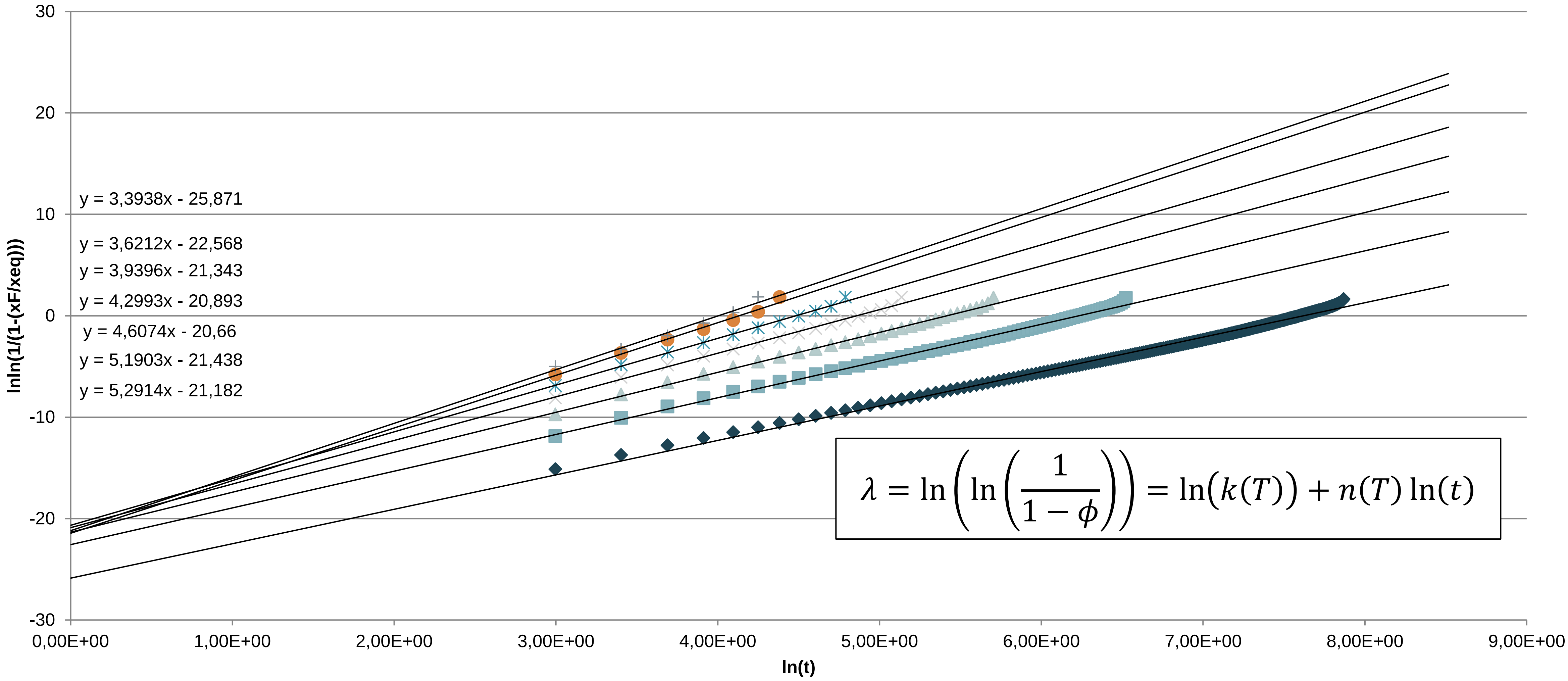
T	λ_1	t_1	λ_2	t_2	$n(T)$	$\tau(T)$	$x_{eq}(T)$
1060	-2.22	1190	0.87	2780	3.65	2187	0.204
1050	-2.23	300	0.85	700	3.64	553	0.340
1040	-2.11	140	0.86	310	3.80	247	0.444
1030	-2.31	80	0.90	180	3.96	143	0.526
1020	-2.74	50	0.91	120	4.17	96	0.591
1010	-2.55	40	0.99	90	4.37	71	0.644
1000	-2.12	40	0.74	70	5.11	60	0.688

Graphical approach for ferrite



$$\lambda = \ln\left(\ln\left(\frac{1}{1-\phi}\right)\right) = \ln\big(k(T)\big) + n(T)\ln(t)$$

Graphical approach for ferrite – detail



$$\lambda = \ln\left(\ln\left(\frac{1}{1-\phi}\right)\right) = \ln\big(k(T)\big) + n(T)\ln(t)$$

Graphical approach for ferrite

- $\lambda = \ln\left(\ln\left(\frac{1}{1-\phi}\right)\right)$

- Calculate relaxation time based on:
  - $\tau(T) = k(T)^{-\left(\frac{1}{n(T)}\right)}$

- PTSTART, PTEND based on *MAT_244

```
START TEMPERATURES
          Ferrite      start temperature          = 1.06987E+03
          Pearlite     start temperature          = 9.94744E+02
```

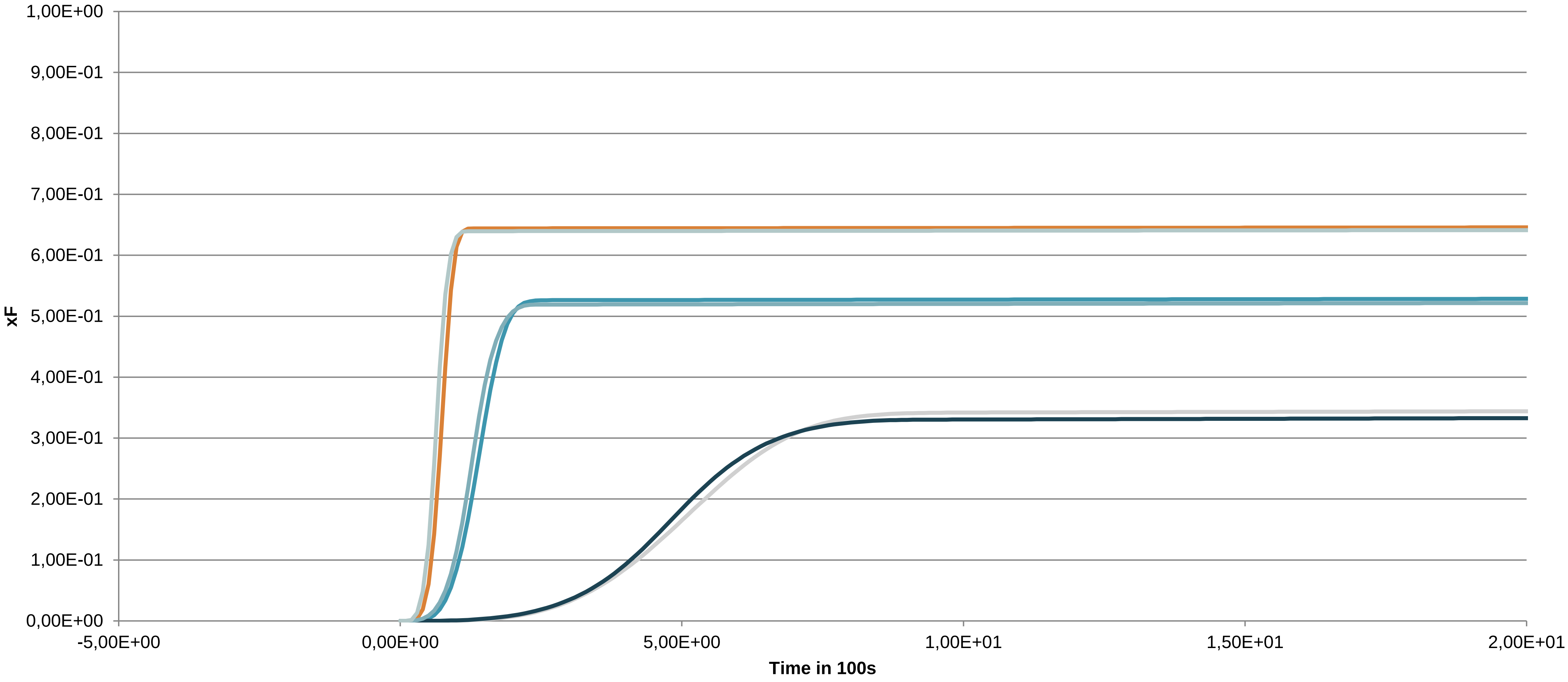
T	$\ln(k(T))$	$\tau(T)$	$n(T)$	$x_{eq}(T)$
1060	-25.871	2062	3.39	0.204
1050	-22.568	509	3.62	0.340
1040	-21.343	228	3.93	0.444
1030	-20.893	130	4.29	0.526
1020	-20.660	89	4.60	0.591
1010	-21.438	62	5.19	0.644
1000	-21.182	54	5.29	0.688

Comparison between direct and graphical approach

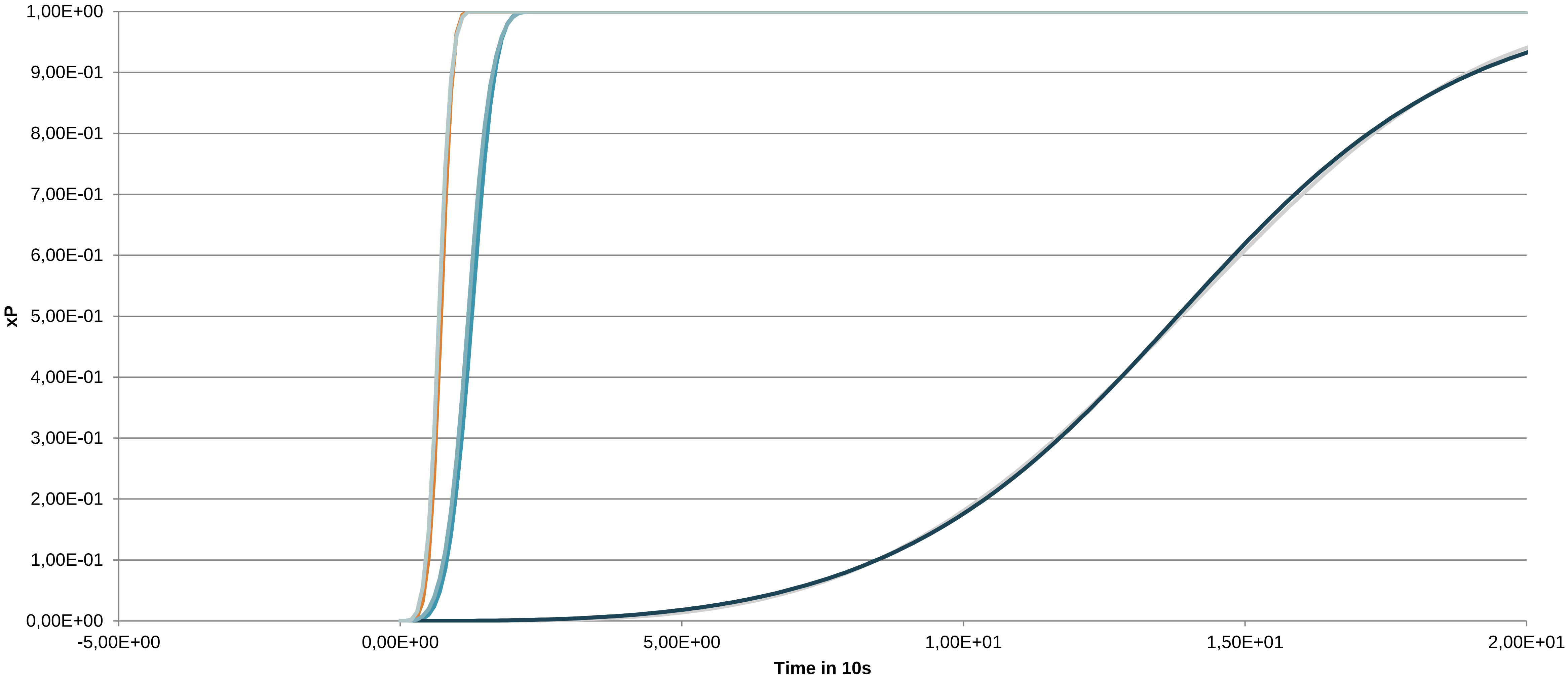
- Similar parameters

T	$x_{eq}(T)$	$n(T)$		$\tau(T)$	
		Direct	Graph	Direct	Graph
1060	0.204	3.65	3.39	2187	2062
1050	0.340	3.64	3.62	553	509
1040	0.444	3.80	3.93	247	228
1030	0.526	3.96	4.29	143	130
1020	0.591	4.17	4.60	96	89
1010	0.644	4.37	5.19	71	62
1000	0.688	5.11	5.29	60	54

Comparison between virtual experiment (244) and JMAK (254) – ferrite



Comparison between virtual experiment (244) and JMAK (254) – pearlite



Agenda

- Motivation
- Introduction to *MAT_244 / *MAT_UHS_STEEL
- Introduction to *MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE
- Parameter identification for phase evolution in *MAT_254 based on *MAT_244
- Summary

Summary

- Introduced *MAT_244 / *MAT_UHS_STEEL
  - Tailored for hot stamping / press hardening processes
  - Accounts for austenite decomposition into ferrite, pearlite, bainite, and martensite as well as re-austenitization
  - As input only chemical compostion of the alloy and mechanical properties needed
  - Restricted applicability in terms of materials and processes

- Discussed *MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE
  - Phase transformations between up to 24 phases can be accounted for in a very flexible
    - User can choose from a list of pre-defined phase transformation models
    - Tabular input of transformation data
  - Elaborated features to describe the mechanical properties accurately
  - Applicable to a wide range of materials (e.g. steels, titanium, aluminum) and to various processes (e.g. press hardening, hot forming, welding, heat treatment)

Summary

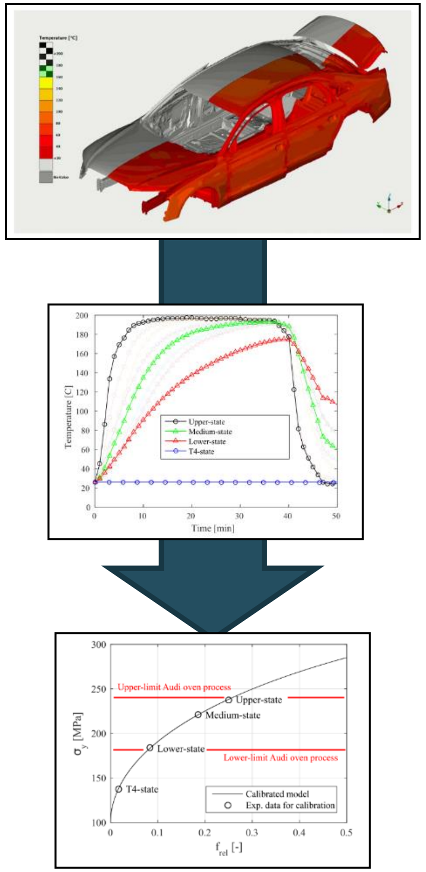
- Discussed a “blueprint” how to identify parameters for phase transformation
  - Calculation of “relative reaction coordinate” according to test data
  - Creation of balance lines enables trivial parameter identification …
  - … and a quality check for the chosen modelling approach!
  - Application on the austenite decomposition to ferrite of 22MnB5

- Further discussion on:
  - Which phases or pseudo-phases to take into account
  - Resulting mechanical properties (yield strength, …)
  - Application on other processes and materials

from phase \ to phase	1 (Austenite)	2 (Ferrite)	3 (Pearlite)	4 (Bainite)	5 (Martensite)
1		2	2	2	1
2	-2				
3	-2				
4	-2				
5	-2				

Summary

- Degree of Hardening for EN AW 6xxx described with a JMAK-based phenomenological approach



BAKE-HARDENING MODEL DEVELOPMENT

MODEL FOR THE RELATIVE VOLUME FRACTION OF PRECIPITATES

- Based on the Avrami equation
- Using isokinetic assumption an ordinary differential equation can be defined for the growth rate of relative volume fraction of precipitates
- Solving the rate equation gives the relative volume fraction of precipitates for a given thermal history

Avrami equation

$$\frac{f - f_0}{f_{\mathrm{eq}} - f_0} = 1 - \exp\left(-\left(\frac{t}{\tau}\right)^n\right)$$

$f_{rel} = \frac{f}{f_{eq}} = Rel. vol. fraction\ precipitates$

$f_{rel0} = \frac{f_0}{f_{eq}} = Rel.\ vol.\ frac.\ prec.\ at\ start$

$Q = Activation\ energy\ for\ diffusion$

$R = Universal\ gas\ constant$

$n = Avrami\ exponent$

$t_0 = Time\ constant$

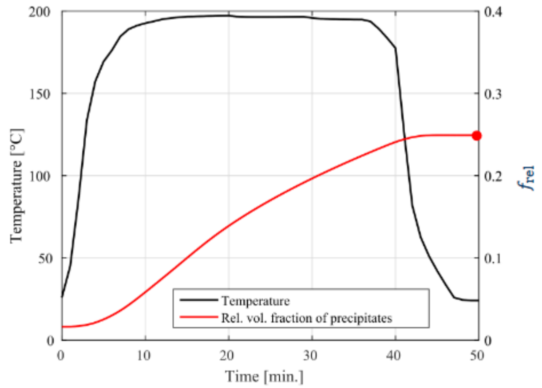
Isokinetic assumption

Rate equation

$$\frac{\mathrm{d}f_{\mathrm{rel}}}{\mathrm{d}t} = (1 - f_{\mathrm{rel}})\frac{n}{\tau}\left(ln\left(\frac{1 - f_{\mathrm{rel0}}}{1 - f_{\mathrm{rel}}}\right)\right)^{\frac{n-1}{n}}$$

$$\tau(T) = t_0 exp\left(\frac{Q}{RT}\right)$$

4 unknown parameters



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