

# ***MICROSTRUCTURE EVOLUTION DURING HOT ROLLING***

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# The PhD project



- SANDVIK (SMT) is working on improvement of the automated hot rolling process which is based on models from ABB.
- Models are used to predict the variables in rolling mills.
- The task is to identify existing models and improve those that need improvement, and replace those which have better alternatives with help of MIKRAB Toolbox.

# Intentions for the project



- Modeling the Hot rolling process to determine optimum rolling schedules
- Modeling the annealing process
- Optimization of recrystallization and annealing
- Achieving a final microstructure with just one special type of carbide and less or no other types of carbides
- Fine grain size in final microstructure
- Homogeneous material properties due to homogeneous microstructure in all bands
- Reasonable tolerance in thickness and flatness

# Individual Study Plan (ISP)

- Literature survey on microstructure evolution in hot working
- Learning the “MIKRAB Toolbox” by G. Engberg and model the hot deformation of 13C26
- Run a gap analysis between Toolbox and logged process data from the rolling mill
- Publish first technical paper from the results[2015]
- PhD courses (60-90 hp) [2014-2016]
  - Scientific writing , Applied Thermodynamics and kinetics, computational techniques in material science, and Phase transformation

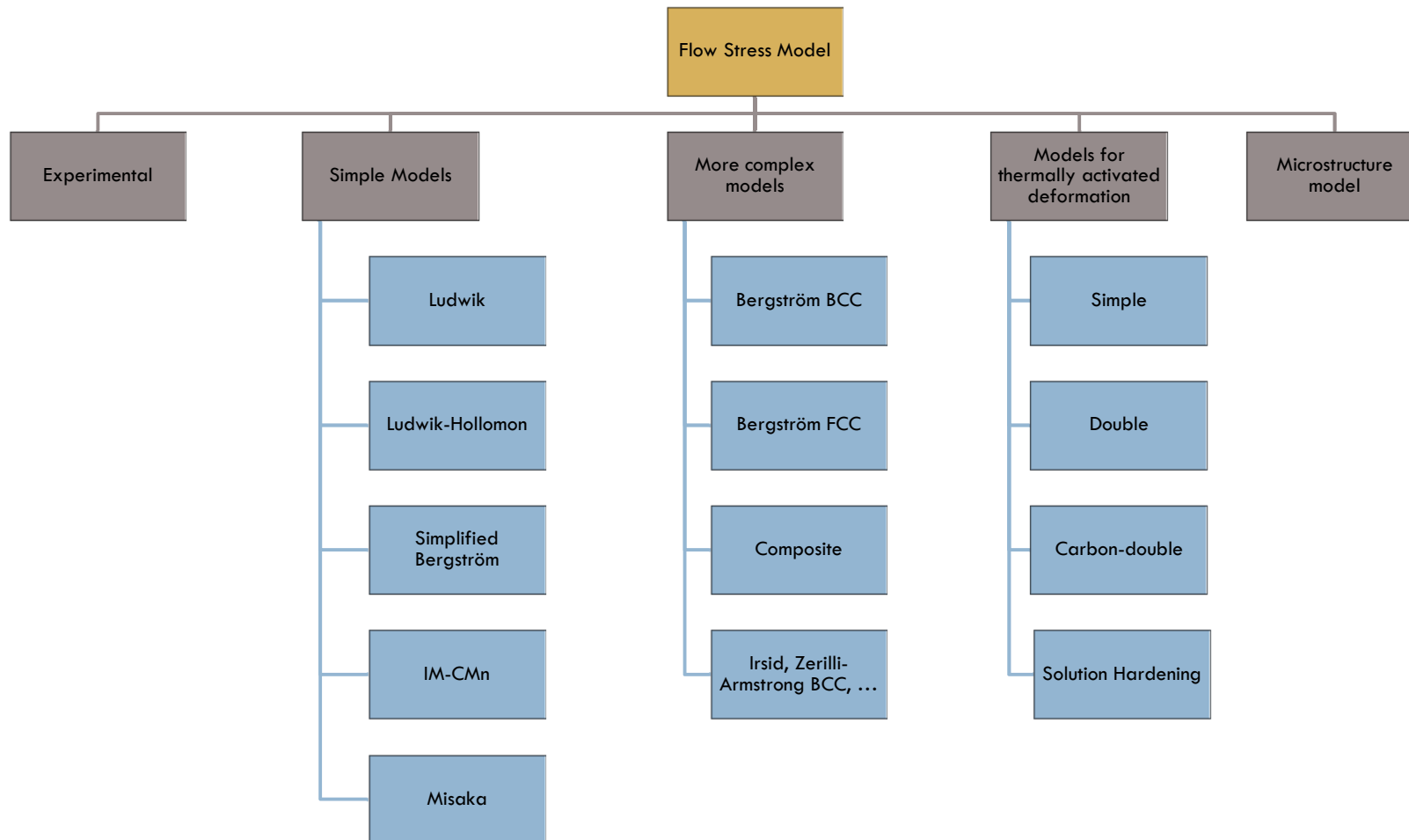
# MIKRAB Toolbox



To make a applicable tool for predicting and controlling material development during a metal working process it is necessary to:

- Know the material properties
- Have a good process model (In 2002 created by Professor Göran Engberg using MATLAB)

# MIKRAB Toolbox

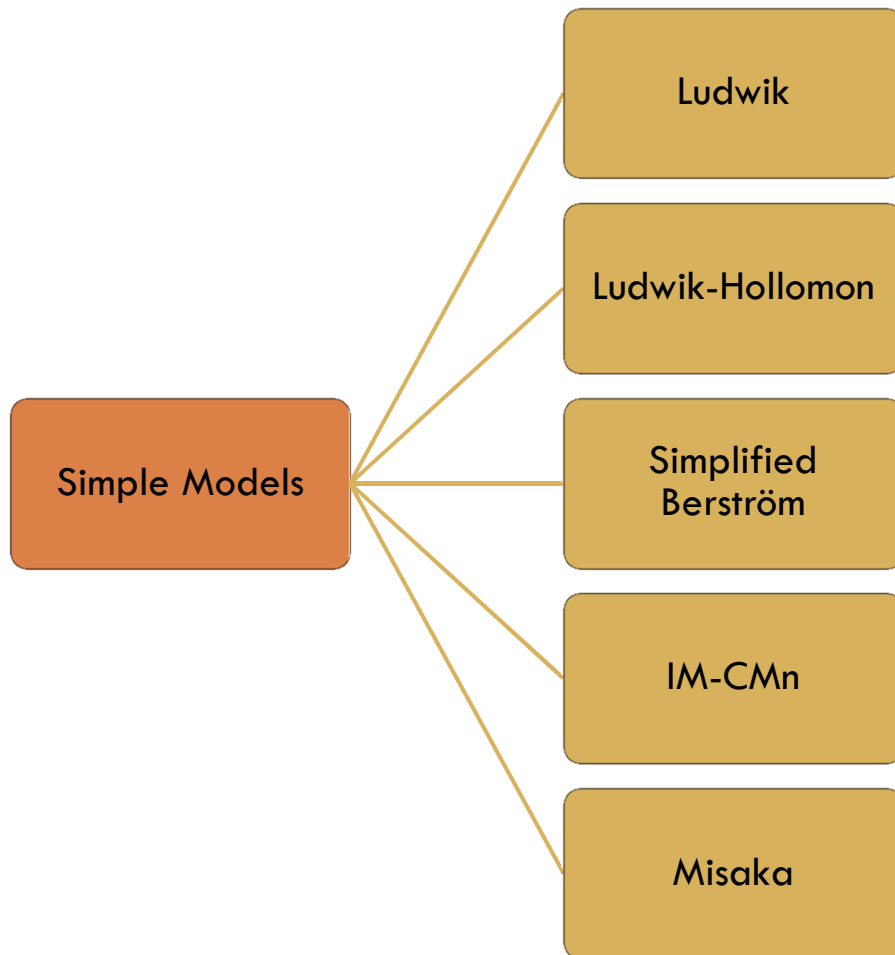


# Experimental



- By using this model, linear interpolation of given experimental data will be used.

# Simple models





# Simple models

- In order to describe a larger strain interval two models can be used simultaneously, using minimum value at each strain

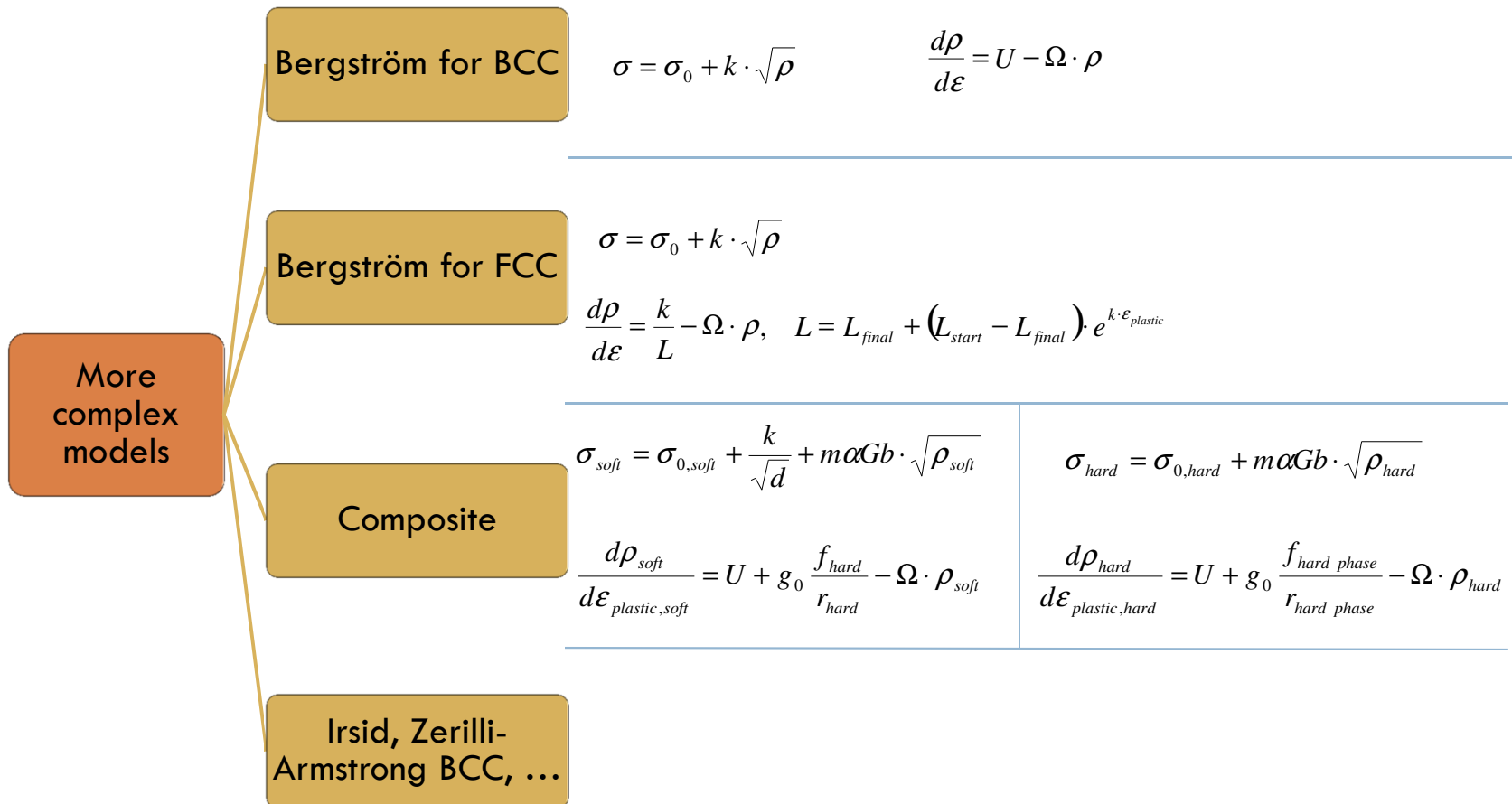
- Ludwik 
$$\sigma = \sigma_0 + k \cdot \sqrt{\epsilon_{plastic}}$$

- Ludwik-Hollomon 
$$\sigma = \sigma_0 + k \cdot \epsilon_{plastic}^n \cdot \epsilon^m$$

- Simplified Bergström for BCC 
$$\sigma = \sigma_0 + k \cdot \sqrt{1 - e^{-\Omega \epsilon_{plastic}}}$$

The initial dislocation density is neglected in this simplified version.

# Dislocation evolution models (Complex models)

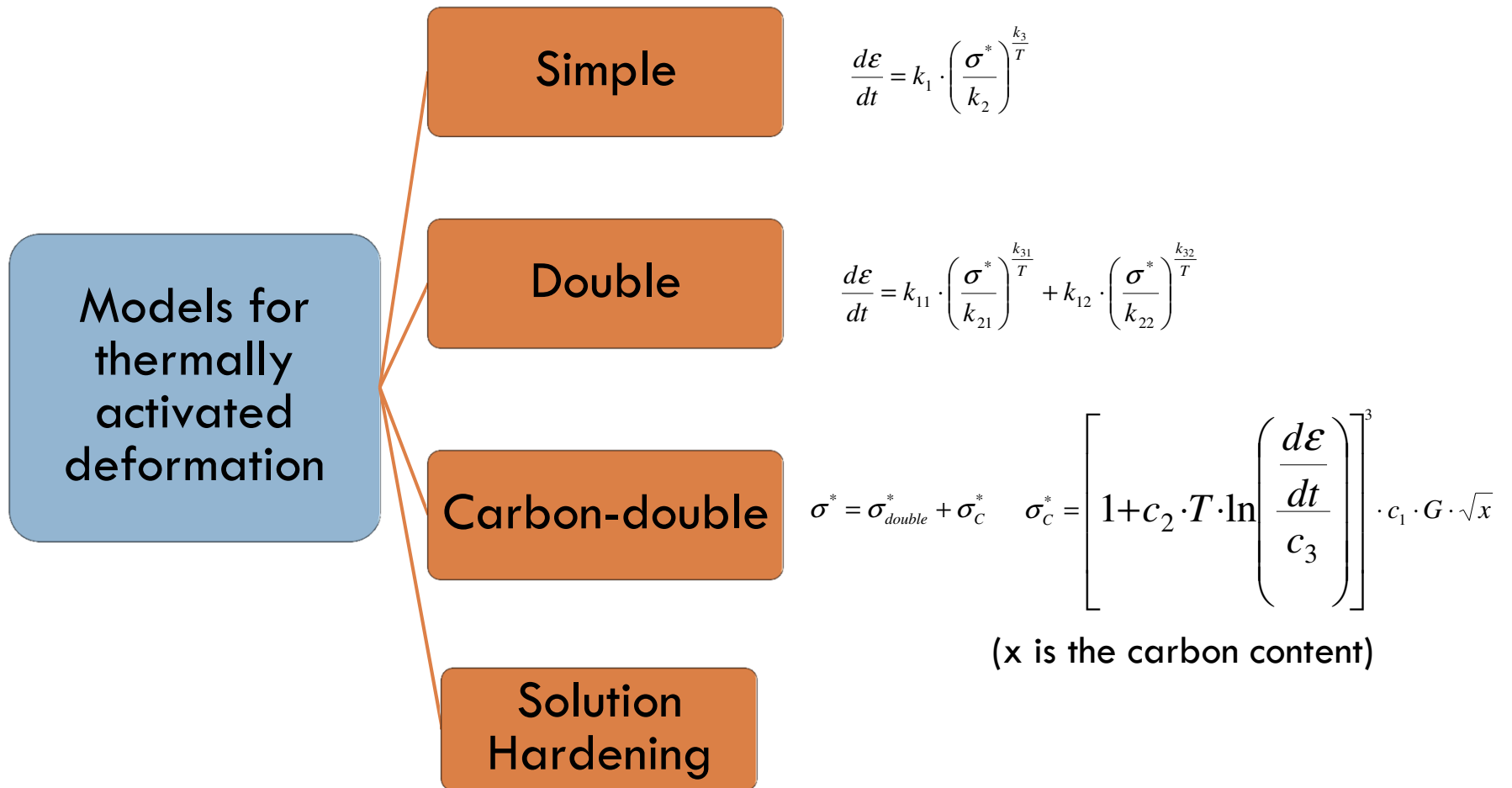


# Composite microstructure model



- Composite microstructures is referring to a mixed microstructure as for example in DP-steels.
- This model uses the Bergström equations for BCC and Ashby's concept of geometrically necessary dislocations.
- This model can deal with up to 5 different microstructure constituents with the possibility of each constituent to be composed of one hard and one soft phase.

# Thermally activated deformation models



# Thermally activated deformation models

## Simple:

- Simple Peierls-Nabarro model which works in many cases

## Double:

- Peierls-Nabarro model for covering larger temperatures and strain rate intervals than the previous

## Carbon-double:

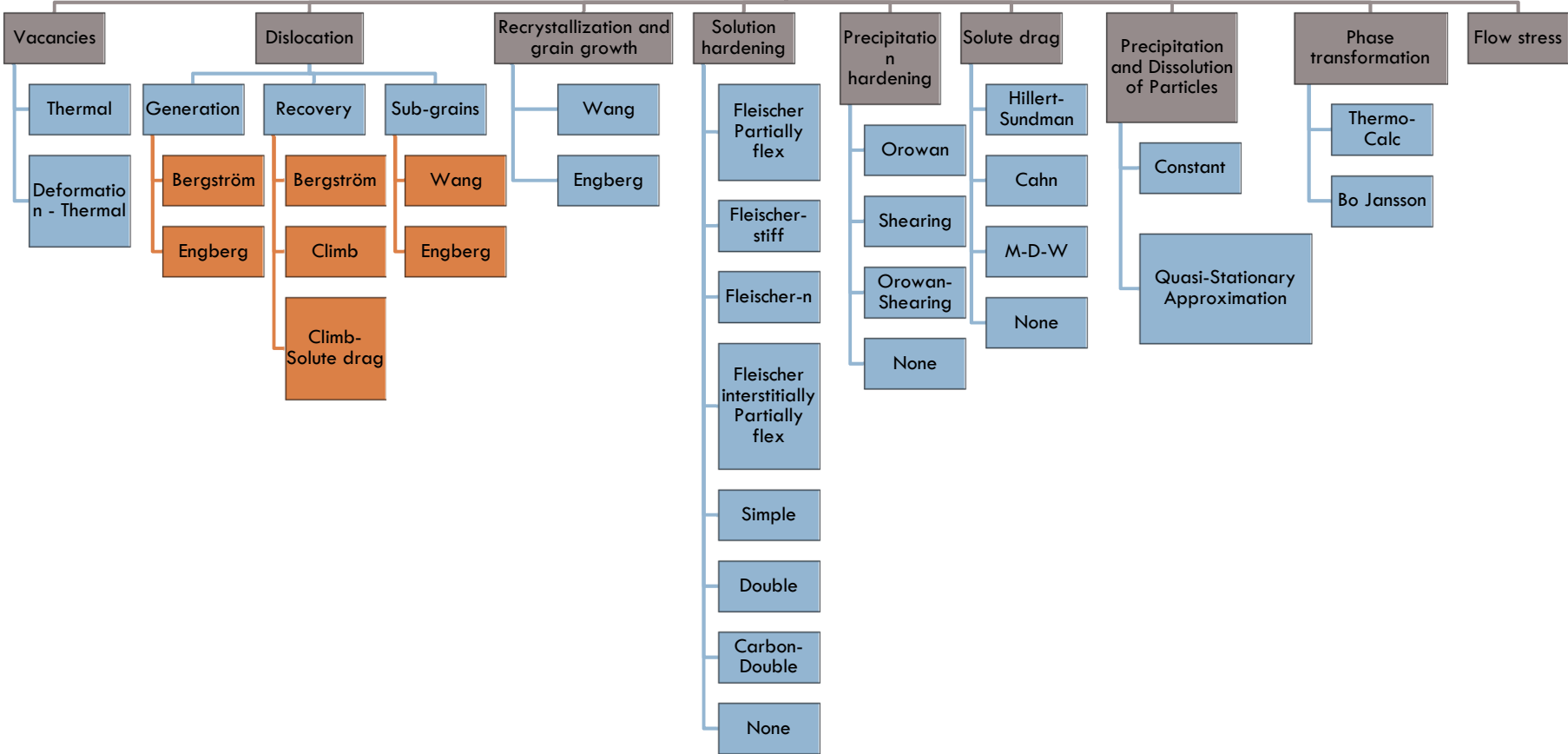
- It is similar to double, plus includes the influence of interstitial elements especially carbon in ferrite.

*(These 3 mentioned models are not applicable for high temperatures.)*

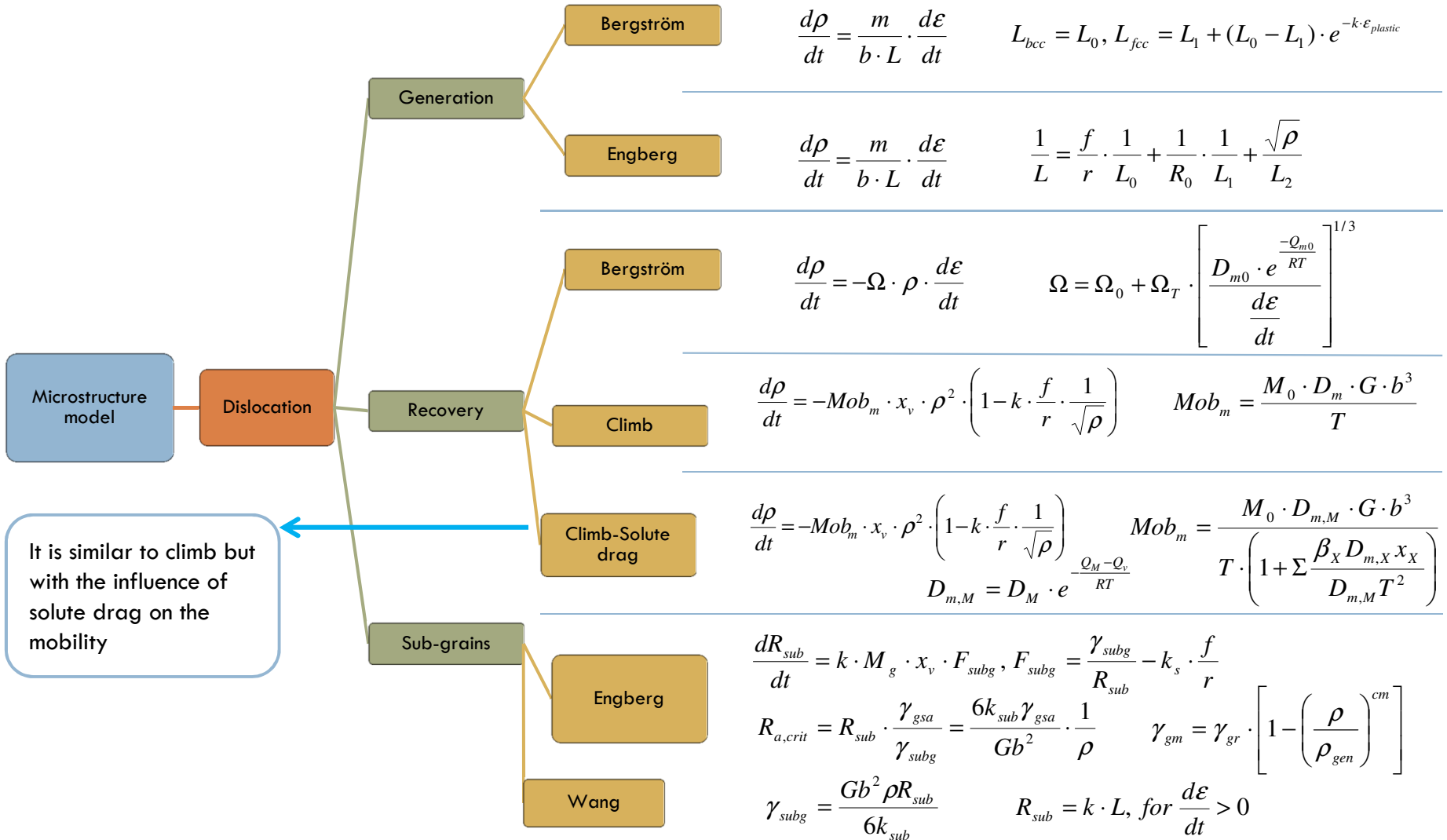
- Solution hardening

# Microstructure models and sub-models

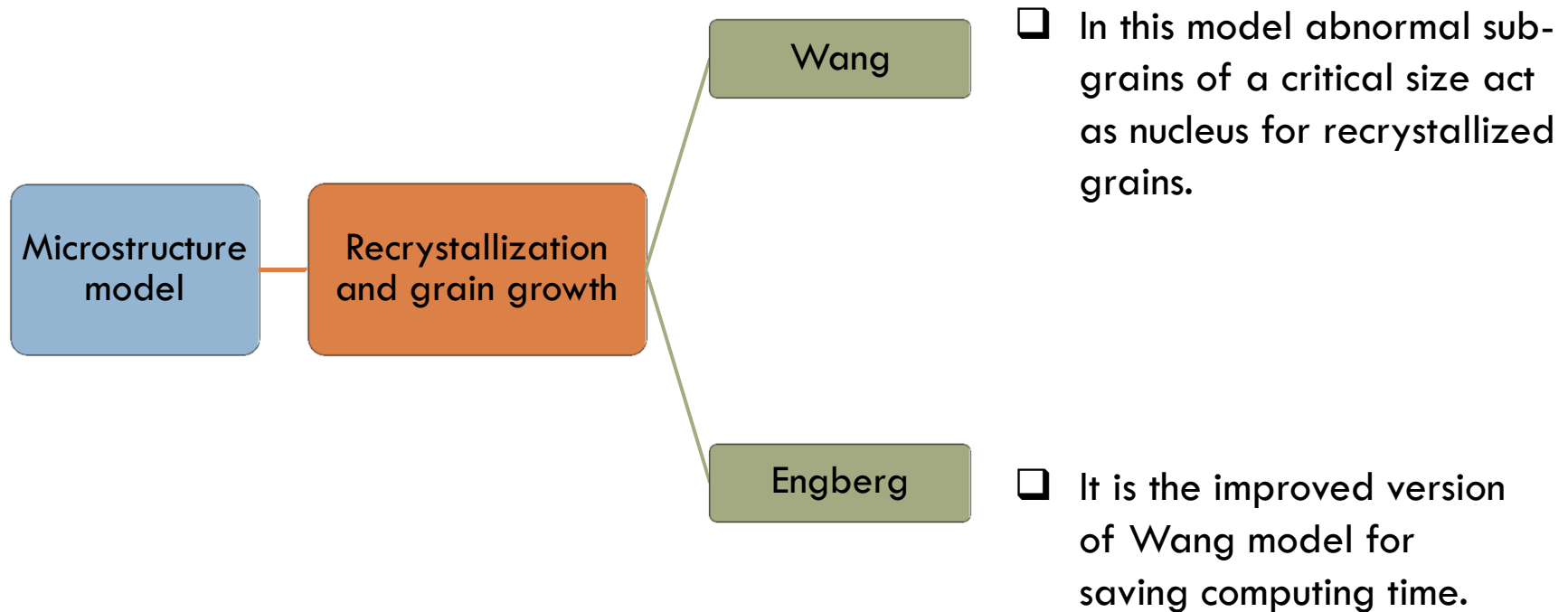
Microstructure model



# Microstructure models and sub-models: Dislocation



# Microstructure models and sub-models: Recrystallization and grain growth





# Engberg recrystallization and grain growth model

$$R_{crit} = \frac{\gamma_{gr} - \gamma_{gm}}{cd \cdot G \cdot b^2 \cdot (\rho - \rho_0) - k_{ps} \cdot f/r} \quad \frac{dR_{grow}}{dt} = kg \cdot M_g \cdot x_{v,rec} \cdot F_{grow}, \quad F_{grow} = \frac{\gamma_{gb}}{R_{rec}} - kpg \cdot \frac{f}{r} \quad \frac{dR_{recg}}{dt} = kr \cdot M_g \cdot 0.5 \cdot (x_{v,def} + x_{v,rec}) \cdot F_{recg}$$

$$F_{recg} = -\frac{\gamma_{gr}}{R_{rec}} + \frac{\gamma_{gm}}{R_{sub}} + cd \cdot G \cdot b^2 \cdot (\rho_{def} - \rho_{rec}) - kps \cdot \frac{f}{r} \quad \text{Rekristallisation om } R_{crit} \leq R_{sub} \text{ och } \gamma_{gm} \geq 0.75 \cdot \gamma_{gr}$$

$$N_{sites} = \frac{(1 - F_{rec})}{cf \cdot R_{def} \cdot R_{sub}^2} \quad cf = 4 \cdot \pi/3 \quad N_{reco} = \frac{1 - F_{rec}}{cf \cdot R_{def} \cdot R_{rec}^2} \quad N_{reco} = N_{rec} \text{ for } N_{reco} > N_{rec}, \quad N_{reco} = N_{reco} \text{ for } N_{reco} \leq N_{rec}$$

$$N_{recint} = N_{rec} - N_{reco} \text{ for } N_{rec} \geq N_{reco} \quad \frac{dN_{reco}}{dt} = N_{sites} \cdot kN \cdot e^{-\frac{Q_N}{R \cdot T}} \quad \frac{dN_{recint}}{dt} = -3 \cdot \frac{dR_{grow}}{dt} \cdot \frac{N_{recint}}{R_{rec}} \quad \frac{dN_{rec}}{dt} = \frac{dN_{reco}}{dt} + \frac{dN_{recint}}{dt}$$

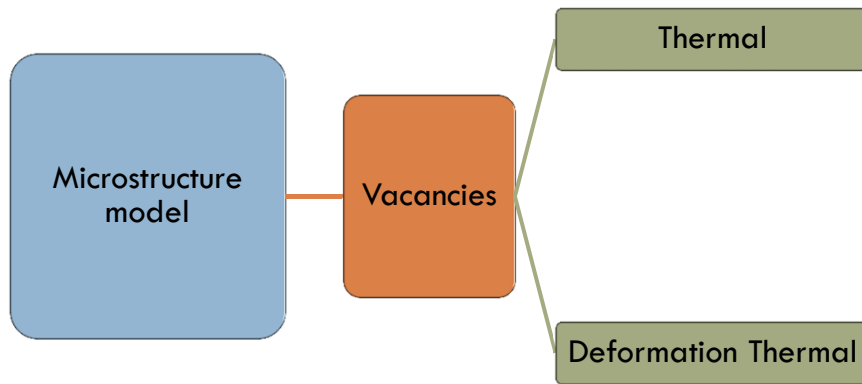
$$\frac{dR_{rec}}{dt} = \frac{dR_{grow}}{dt} \text{ for } F_{rec} = 1 \quad \frac{dR_{rec}}{dt} = \frac{N_{recint} \cdot 3 \cdot R_{rec}^2 \cdot \frac{dR_{grow}}{dt} + N_{reco} \cdot 3 \cdot R_{rec}^2 \cdot \frac{dR_{recg}}{dt} - R_{rec}^3 \cdot \frac{dN_{reco}}{dt} + R_{sub}^3 \cdot \frac{dN_{reco}}{dt}}{3 \cdot R_{rec}^2 \cdot N_{rec}}$$

$$\frac{dF_{rec}}{dt} = cf \cdot \left( \frac{dN_{rec}}{dt} \cdot R_{rec}^3 + N_{rec} \cdot 3 \cdot R_{rec}^2 \cdot \frac{dR_{rec}}{dt} \right) \quad \frac{d\rho_{rec}}{dt} = \frac{\frac{dN_{recint}}{dt} \cdot \rho_{rec} + N_{rec} \cdot \left( \frac{d\rho_{rec}}{dt} \right)_{climb} + \frac{dN_{reco}}{dt} \cdot \rho_0 - \frac{dN_{rec}}{dt} \cdot \rho_{rec}}{N_{rec}}$$

$$\frac{dR_{def}}{dt} = -\frac{R_{def0}}{3} \cdot \frac{dF_{rec}}{dt} \cdot (1 - F_{rec})^{-2/3} \quad \frac{d\varepsilon_{rec}}{dt} = \frac{d\varepsilon_{def}}{dt} = \frac{d\varepsilon}{dt} \text{ if } N_{recint} = 0$$

$$\frac{d\varepsilon}{dt} = F_{rec} \cdot \frac{d\varepsilon_{rec}}{dt} + (1 - F_{rec}) \cdot \frac{d\varepsilon_{def}}{dt}, \quad \sigma_{rec} = \sigma_{def} \text{ if } N_{recint} > 0 \quad \frac{d\rho_{g,rec}}{dt} = g_0 \cdot \left( \frac{1 - F_{rec}}{R_{def}} \right) \cdot \left( 1 - \frac{d\varepsilon_{def}}{d\varepsilon_{rec}} \right) \cdot \frac{d\varepsilon_{rec}}{dt}$$

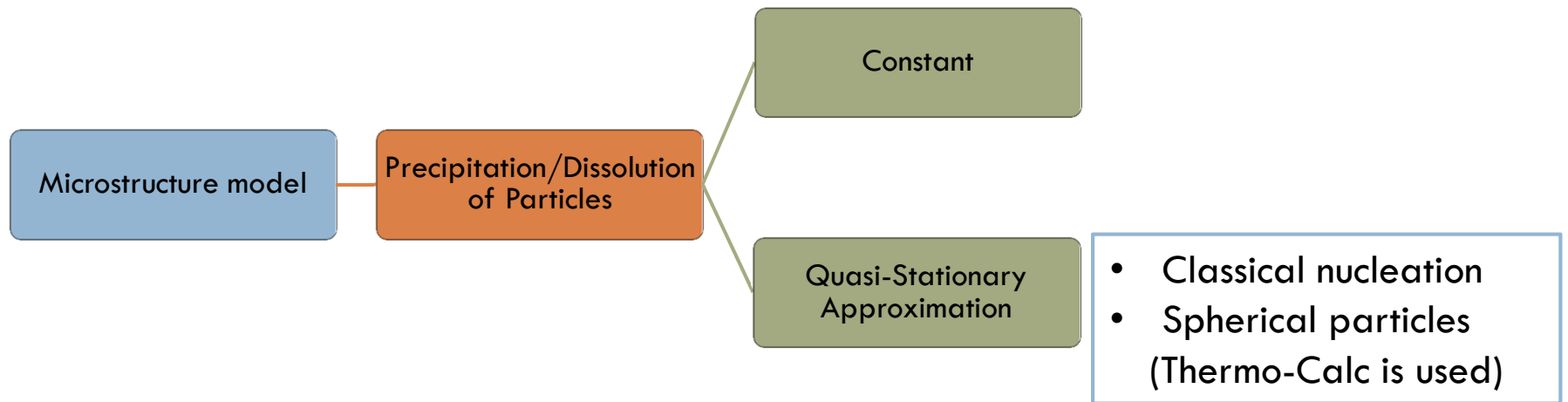
# Microstructure models and sub-models: Vacancies



$$x_{v0} = e^{\frac{-Q_v}{RT}}$$

$$\frac{dx_v}{dt} = \frac{dx_{v0}}{dt} + k_{v1} \cdot \sqrt{\rho} \cdot \left[ b \cdot \frac{d\varepsilon}{dt} - k_{v2} \cdot x_v \cdot D_m \cdot (x_v - x_{v0}) \right]$$

# Microstructure models and sub-models: Precipitation/Dissolution of particles



$$\frac{dn^\beta}{dt} = c_{11} \cdot S_v \cdot D_{mx}^\alpha \cdot x_M^\alpha \cdot \exp\left(-\frac{c_{12} \cdot \Delta G^*}{kT}\right)$$

$$\Delta G^* = \frac{16\pi}{3} \frac{\gamma^3}{(\Delta G_m/V_m)^2}$$

$$S_v = 1/R$$

$$D_{mx} = x_{0x}^\alpha \cdot D_{0x} \cdot e^{\frac{Q_v - Q_x}{R \cdot T}}$$

$$\frac{dr}{dt} = x_v \cdot D_m \cdot \frac{\Omega}{r \cdot \left(1 - \frac{r}{R}\right)}, \quad \Omega = \frac{x_0^\alpha - x^{\alpha/\beta}}{x^\beta - x^{\alpha/\beta}}, \quad R = \min(R_{diff}, R_{dist})$$

# Microstructure models and sub-models: Phase transformation

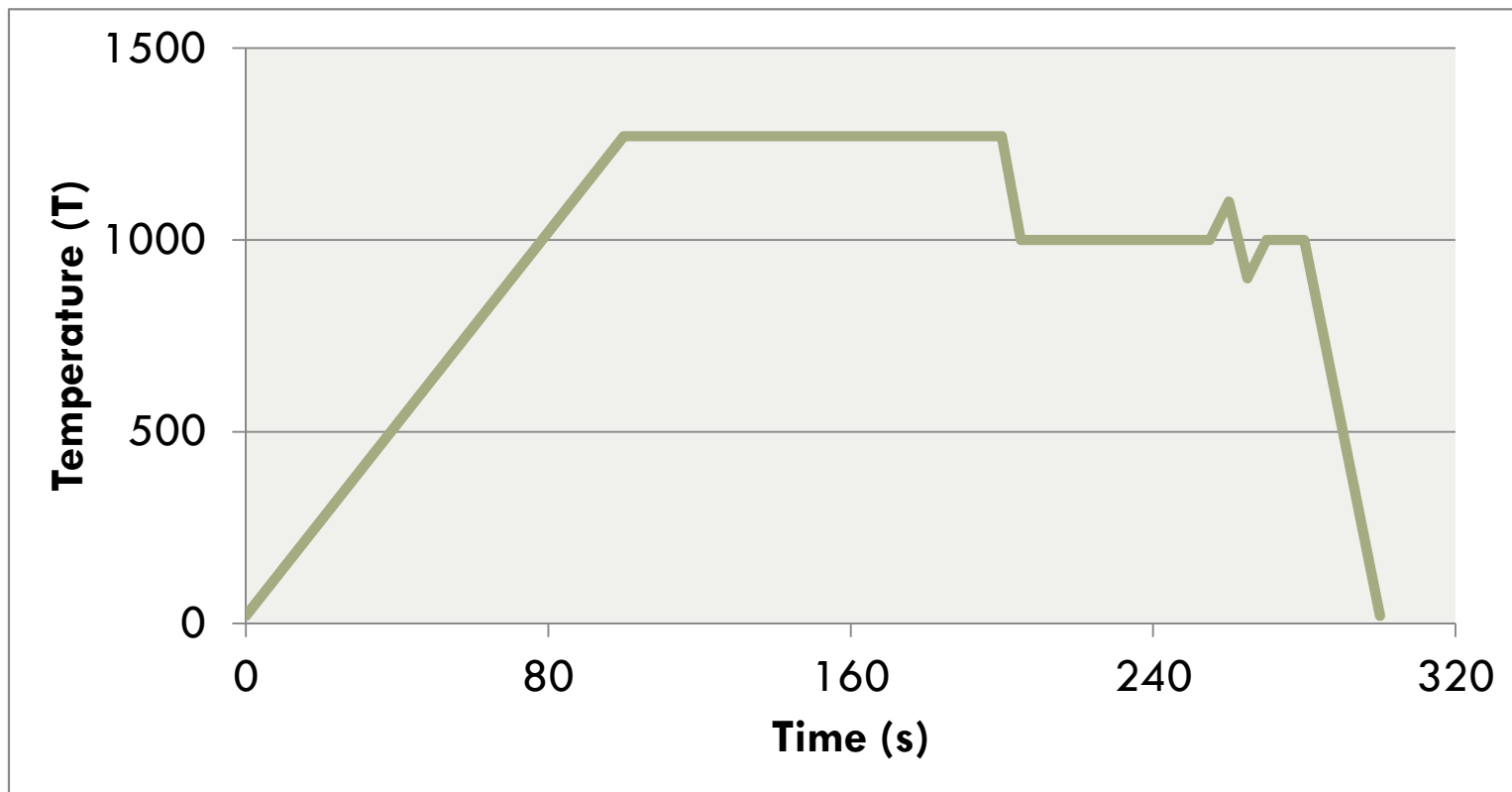


# Necessary Input data



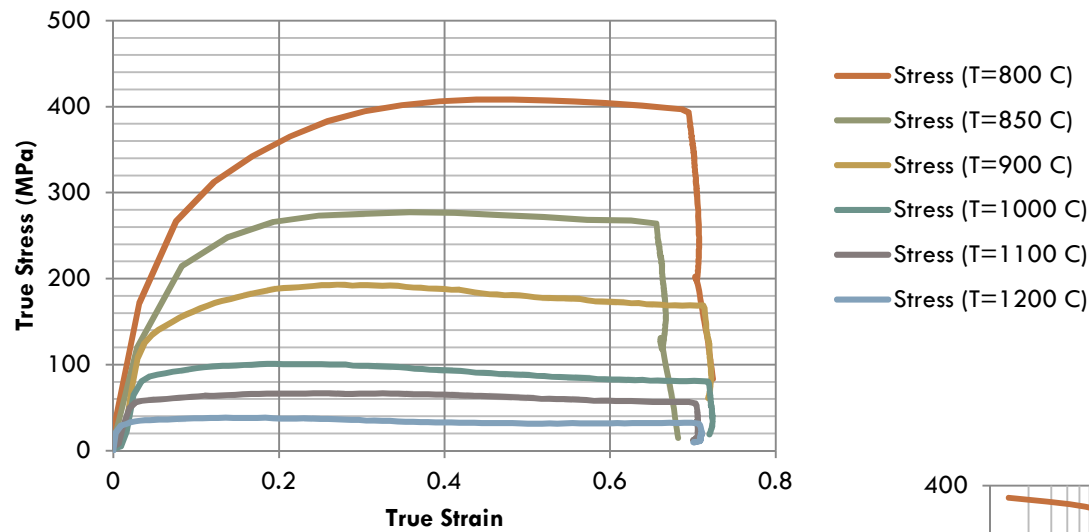
1. From Gleeble tests: Stress and Strain curves in various Strain rates and Temperature
2. Rolling data: e.g. roller size, E modulus, Poison's ratio, rolling speed, force, and torque
3. Work piece (sheet) data: e.g. Thickness, width, Temperature, E and density
4. Grain size, particles fraction, particles size and Recrystallization fraction of material before rolling (Metallographically)

# Schematic diagram showing the thermal cycle experienced by samples (Gleeble)

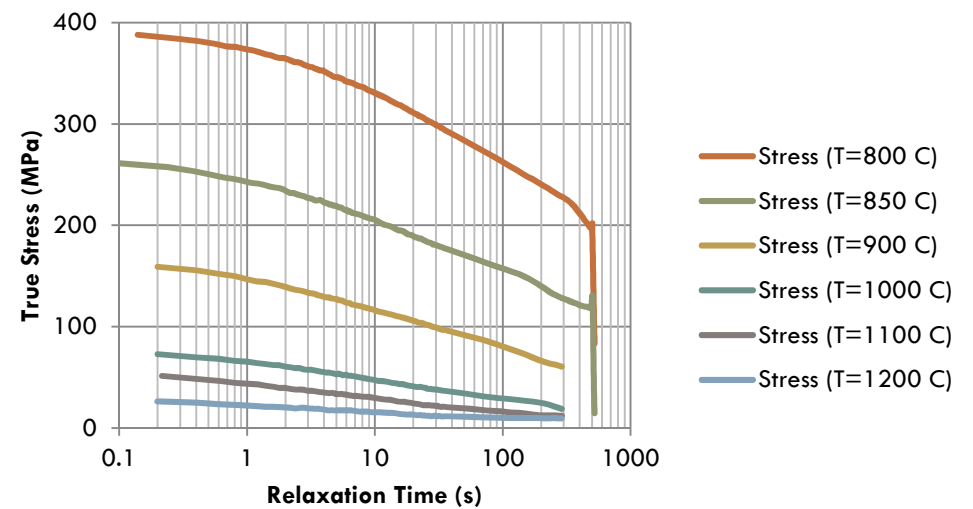


# Results from Gleeble tests

Strain rate 0.01 (1/s)



Strain rate 0.01 (1/s)



# Second particles fraction from TC

	Temperature (K / C)									
	1073.15 / 800	1133.15 / 860	1173.15 / 900	1223.15 / 950	1273.15 / 1000	1323,15 / 1050	1373.15 / 1100	1423,15 / 1150	1473.15 / 1200	1553,15 / 1280
Volume fraction of second phases (%)	4.1976	0.6512	0	0	0	0.00	0.00	0.00	0.00	0.00
	6.0472	7.8429	7.6731	6.7148	5.5589	4.19500	2.62160	0.84070	0.000000	0.00
	0.0176	0.0149	0.0098	0	0	0.00	0.00	0.00	0.00	0.00
	0.0335	0.0335	0.0335	0.0335	0.0335	0.03340	0.03340	0.03330	0.033100	0.032400
	0.1648	0.0252	0.0243	0.0238	0.0243	0.02310	0.02270	0.02190	0.020600	0.016800
Fraction Sum (%)	10.4607	8.5677	7.7407	6.7721	5.6167	4.2515	2.6777	0.8959	0.0537	0.0492



# Grain size measurement ( 900<sup>o</sup> C)

**Kornstorlek**

Bildälla  
 Kamera  
 Fil >>> Kalibrera

Hämta bild

Kongränser  
 Gränser  
 Faser

Histo Limits Area  
100 µm<sup>2</sup>  
2000 µm<sup>2</sup>  
20 Bins

Större ^  
Mindre v

Editera kongränser  
Rita Sudda

Detektera och räkna bort Porer  
Detektera Porer Edit Porer

Mak Histogram  
Visa Nr Denna bild  
Display Ackumulerat

ASTM 1.467 Quit

**Feature Histogram**

Distribute: Number  
Versus: EquivDiam

From: 1  
To: 2000  
Bins: 200

in Histogram: 1

Logarithmic X-axis  
Y axis

Range 0 % Log

Type:  
 Vertical  
 Horizontal  
 Differential  
 Cumul +  
 Cumul -

MEASURE Clear  
Display Classify Scatter  
User Defined... OK

**Running Kornstorlek: Field 1/1**

Klassgränser och antalet Bins kan justeras för att passa kornstorlek.  
Nedre klassgränser kan justeras uppåt för att eliminera artefakter.  
Ändringar ligger kvar för resterande mätningar.

Continue Quit

**Feature Histogram 1: EquivDiam**

Bin	EquivDiam (µm)	Count	Count (%)
1	1.00 - 11.0	0	0.00
2	11.0 - 21.0	0	0.00
3	21.0 - 31.0	0	0.00
4	31.0 - 41.0	1	0.53
5	41.0 - 51.0	0	0.00
6	51.0 - 61.0	3	1.58
7	61.0 - 71.0	3	1.58
8	71.0 - 81.0	4	2.11
9	81.0 - 91.0	5	2.63
10	91.0 - 101	7	3.68
11	101 - 111	8	4.21
12	111 - 121	4	2.11
13	121 - 131	6	3.16
14	131 - 141	7	3.68
15	141 - 151	7	3.68

**Results**

File	Edit								
1	179	63981.68	445.43	301.32	1471.68				
1	180	60721.08	393.03	218.95	1144.15				
1	181	27175.73	248.92	165.95	716.19				
1	182	50079.63	323.16	257.65	1061.18				
1	183	18059.94	296.96	113.54	790.43				
1	184	98030.30	484.74	275.12	1262.06				
1	185	7914.34	148.48	87.34	441.07				
1	186	3280.16	82.97	56.77	240.19				
1	187	4462.54	113.54	61.14	305.69				
1	188	16343.58	187.78	135.38	554.61				
1	189	48496.77	331.89	196.51	943.27				
1	190	79334.07	502.21	292.59	1650.73				1.5

**Feature Histogram 1: EquivDiam**

File Edit

Number

# Grain size measurement Results

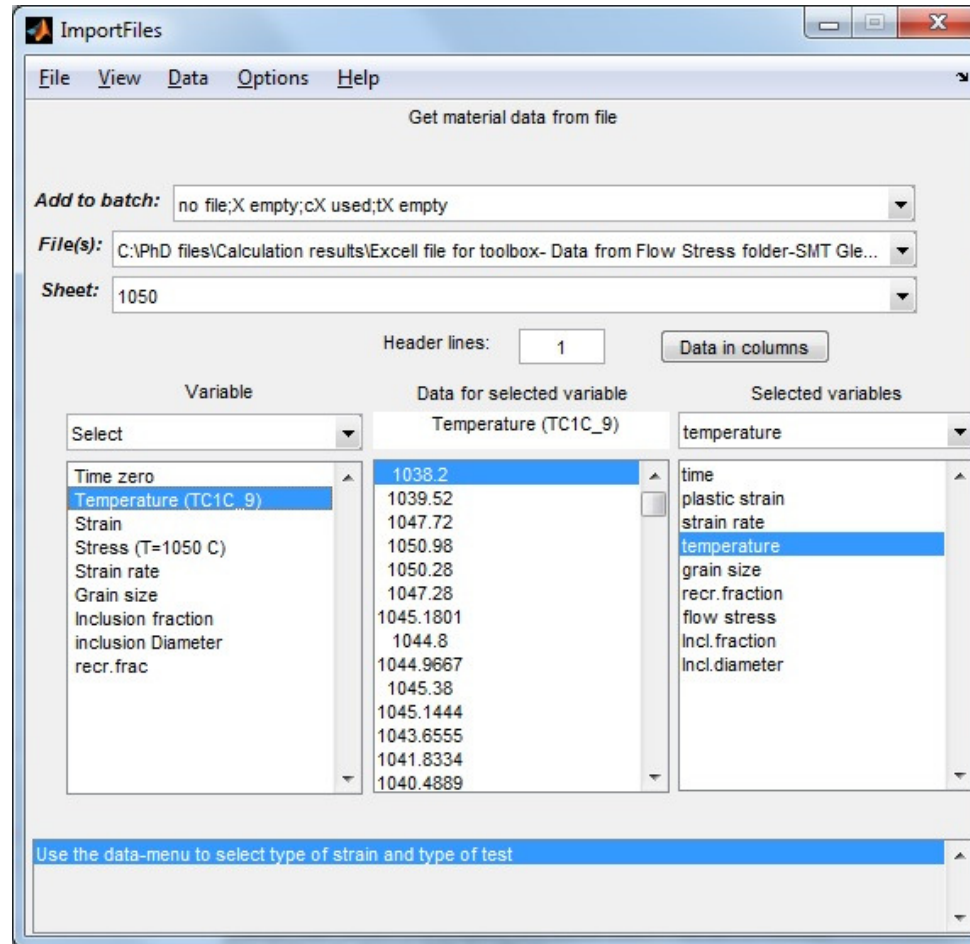
- Sample preparation, polishing, and grain measurement were carried out according to ASTM E112.

		Grain size ( $\mu\text{m}$ )						
	$^{\circ}\text{C}$	ASTM E112	25X	ASTM E112	ASTM category	50X	Histogram 25X	mean grain size ( $\mu\text{m}$ )
Temperature ( C )	900	1.5	253	1	6 to 10	226	216	231
	1050	1.2	255	0	2 to 8	353	221	276
	1150	1.2	275	0	4 to 11	302	226	267

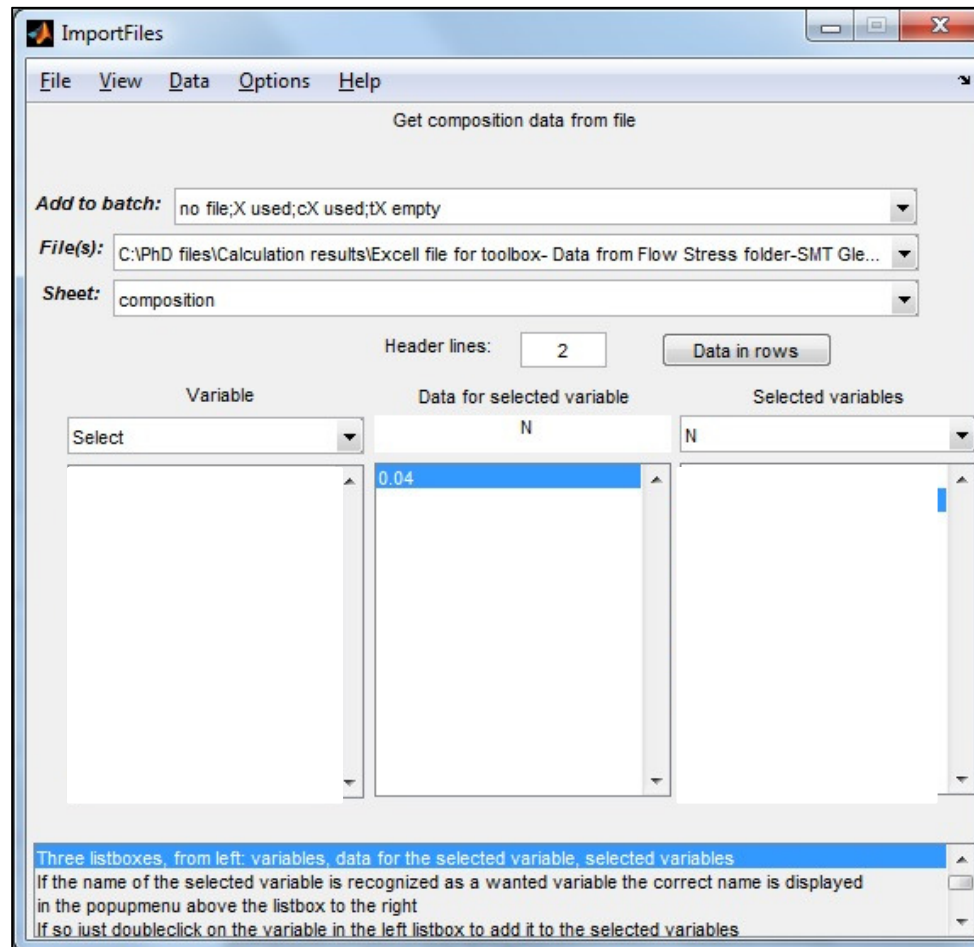


# Modeling with the Toolbox

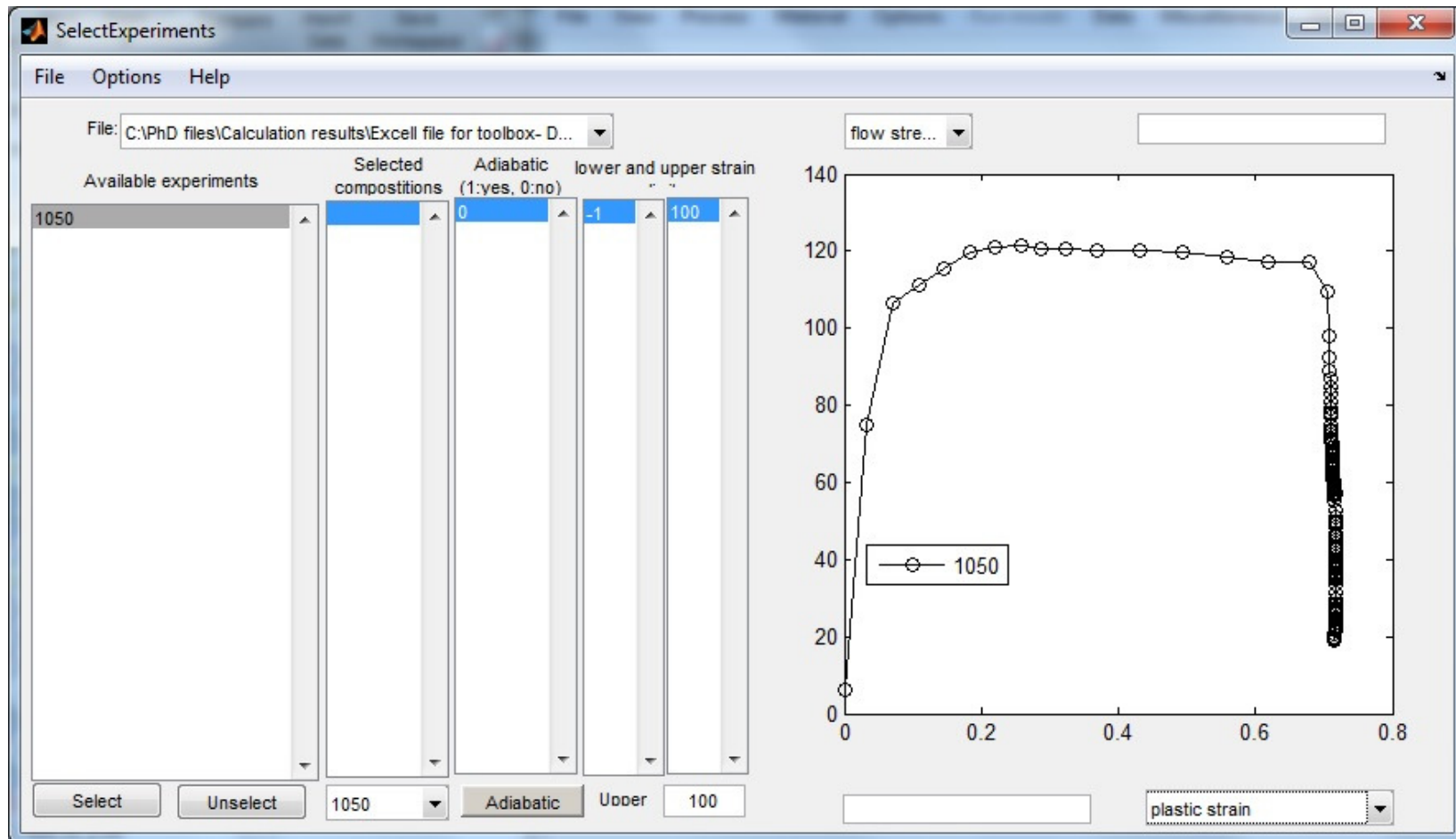
# Starting with importing data



# Material composition



# Selecting experiment



# Choosing models

Material data file:110824\_13Cr\_IM.txt

File Options Models Help

$DmM=Dm0 \cdot \exp[-(Qm0-Qv-Qmd)/(R \cdot T)]$   
 $DmR=Dm0 \cdot \exp[-(Qm0-Qv)/(R \cdot T)]$

austenite

Check parameter(s) to optimise

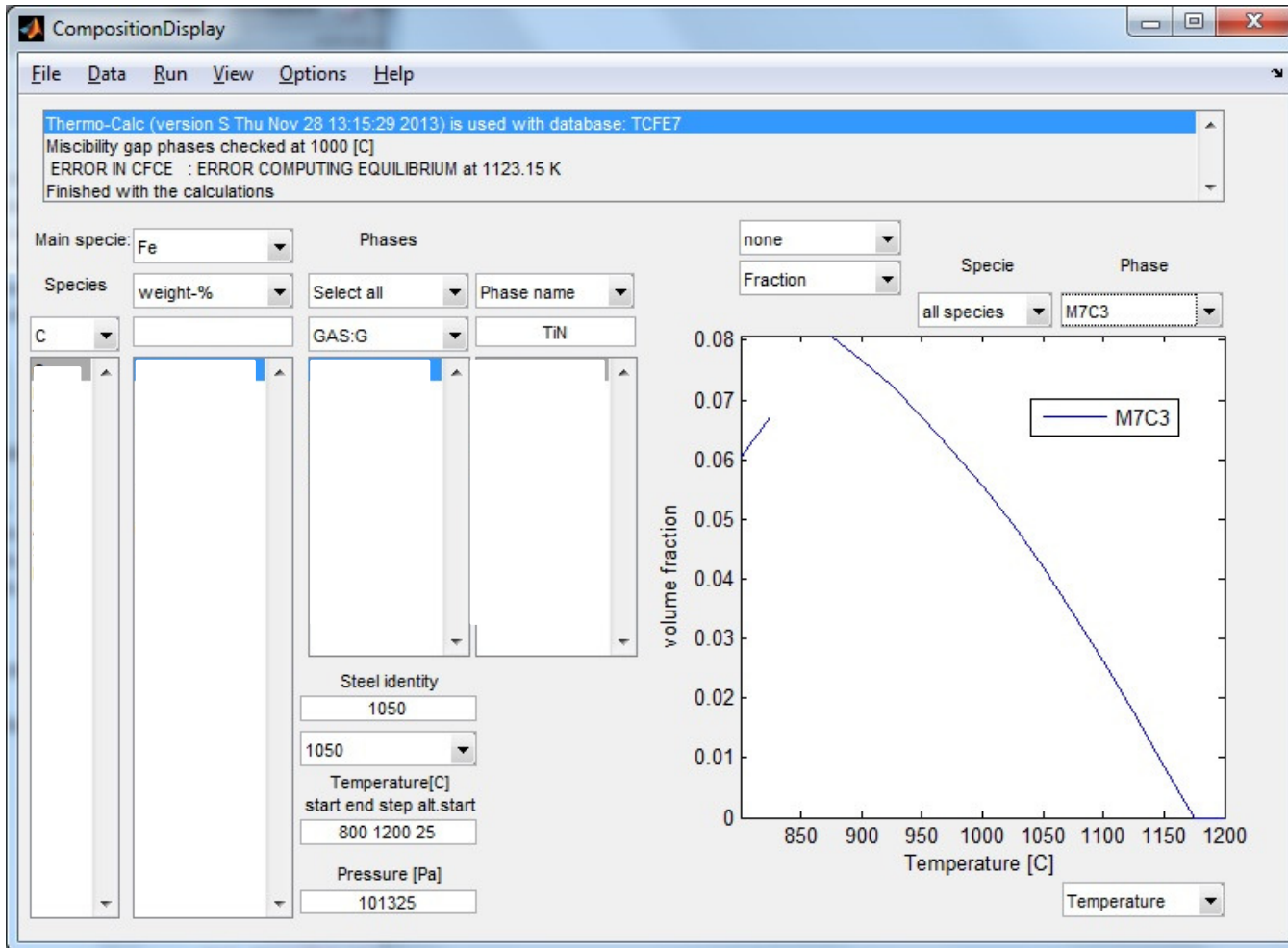
Dm0 7e-05 Selected for optimisation

Parameter	Value	Selected for optimisation
Dm0	7e-05	<input checked="" type="checkbox"/>
Qm0	286000	<input type="checkbox"/>
Qv	149000	<input type="checkbox"/>
Mg0	2.4	<input type="checkbox"/>
Qg	-20000	<input type="checkbox"/>
cv1	0.25	<input type="checkbox"/>
cv2	1.9935e+09	<input type="checkbox"/>
ra0	1.00142e+12	<input type="checkbox"/>
L00	0.25	<input type="checkbox"/>
L0	2	<input type="checkbox"/>
cl	11	<input type="checkbox"/>
M0	1e+24	<input type="checkbox"/>
Qmd	-60000	<input type="checkbox"/>
kpr	0.75	<input type="checkbox"/>
Omega	11	<input type="checkbox"/>
c2	1	<input type="checkbox"/>
ksub	0.2	<input type="checkbox"/>
kps	1.2	<input type="checkbox"/>
ysub	0.3	<input type="checkbox"/>
sgb	0.8	<input type="checkbox"/>
kpg	1.2	<input type="checkbox"/>
kg	0.55	<input type="checkbox"/>
QNs	137000	<input type="checkbox"/>
kNs	30000	<input type="checkbox"/>
kr	0.2	<input type="checkbox"/>
Rdef00	2.7697e-05	<input type="checkbox"/>
sgr0	0.8	<input type="checkbox"/>
Rrec0	1e-10	<input type="checkbox"/>
cd	0.5	<input type="checkbox"/>
cm	1	<input type="checkbox"/>
QNd	-270000	<input type="checkbox"/>
kNd	1e+09	<input type="checkbox"/>
kif	1	<input type="checkbox"/>
kir	1	<input type="checkbox"/>

Selected models

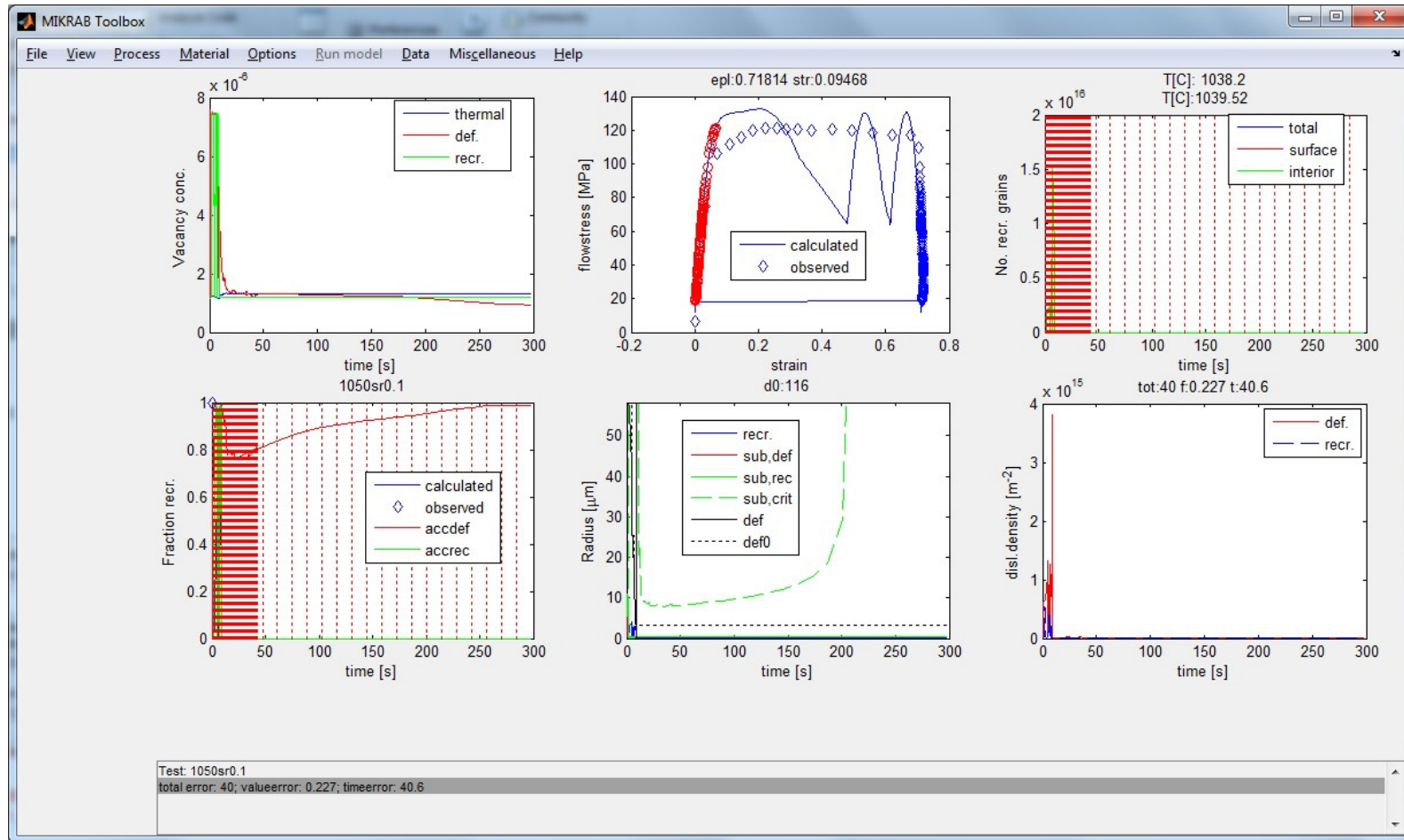
- precipitation\_hardening: none
- transformation: none
- precipitation: constant
- vacancies: deformation\_thermal
- recrystallisation: Engberg
- diffusion\_conditions: minimum
- subgrains: Engberg
- solutdrag: none
- crossslip: none
- dislocation\_recovery: climb

# Thermo-Calc calculations



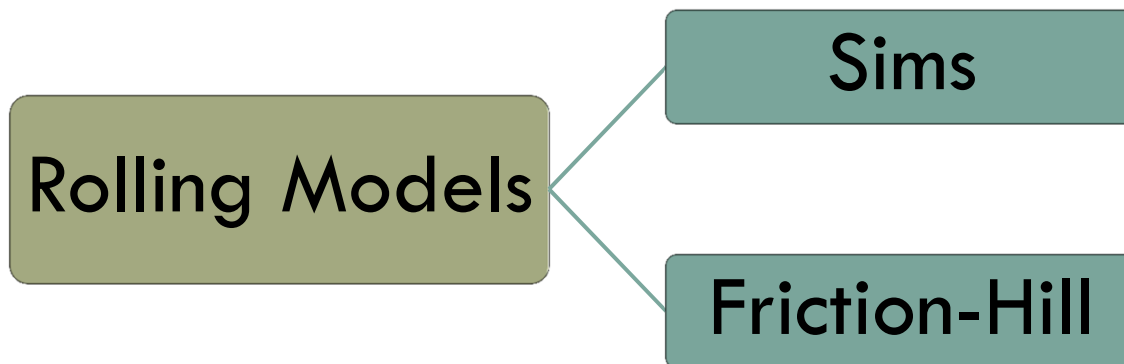


# Primary simulation results



# Rolling models

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# Inputting rolling data

The screenshot shows a software window titled "RollData" with a menu bar containing "File" and "Help". The main content area is titled "Check available rolling data" and is divided into three sections: "Rolling data", "Friction", and "Passes".

**Rolling data**

<input checked="" type="checkbox"/> Diameter	<input type="text"/>	mm
<input checked="" type="checkbox"/> Speed	<input type="text"/>	m/s
<input checked="" type="checkbox"/> Youngs modulus	<input type="text"/>	MPa
<input checked="" type="checkbox"/> Poissons const.	<input type="text"/>	
<input type="checkbox"/> Back tension	<input type="text"/>	
<input checked="" type="checkbox"/> Front tension	<input type="text"/>	MPa
<input checked="" type="checkbox"/> Roll force	<input type="text"/>	kN
<input checked="" type="checkbox"/> Roll torque	<input type="text"/>	kNm

**Friction**

<input type="checkbox"/> Friction coefficient	<input type="text" value="0.1"/>
<input type="checkbox"/> Friction factor	<input type="text" value="0.5"/>

**Passes**

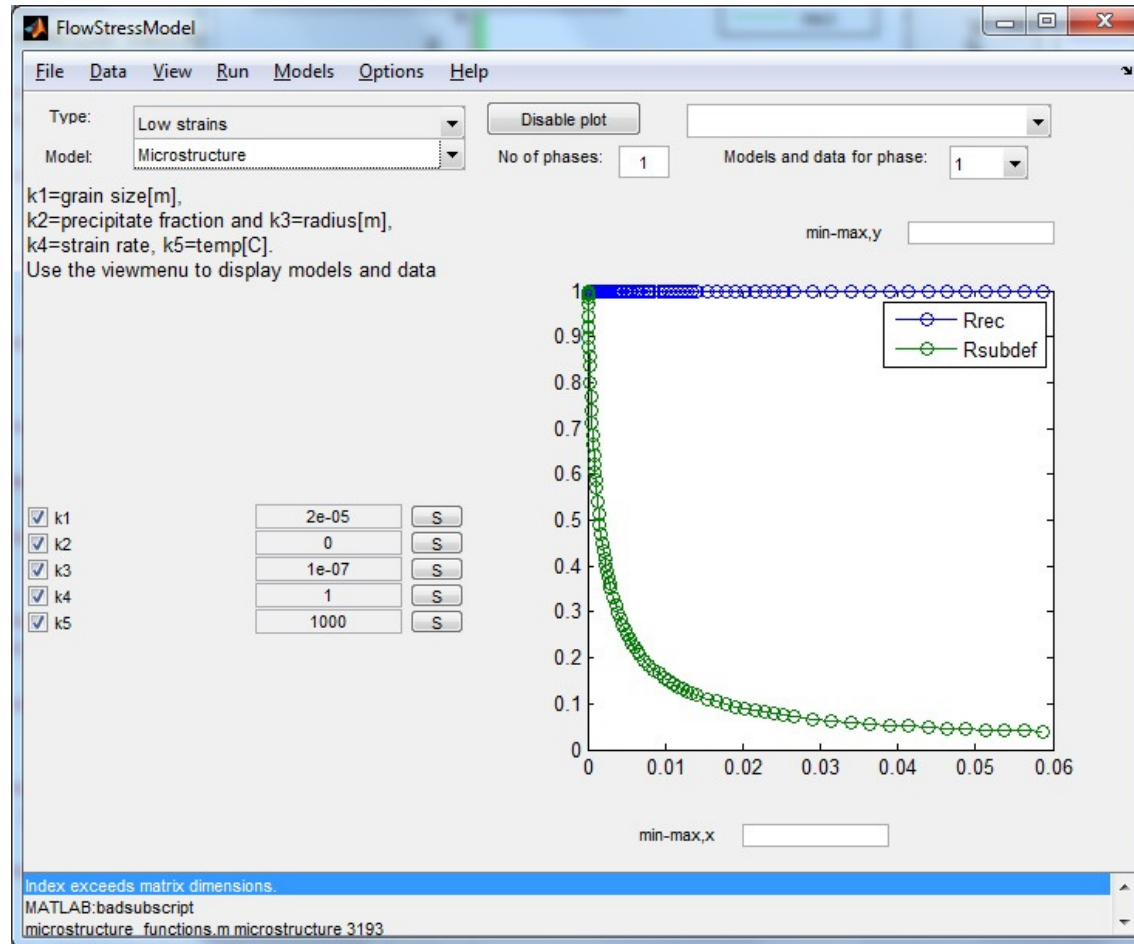
No. of passes	<input type="text" value="1"/>
Choose pass no.	<input type="text" value="1"/>

# Inputting work piece data

The screenshot shows a software window titled "WorkpieceData" with a menu bar containing "File" and "Help". The main content area is divided into three sections:

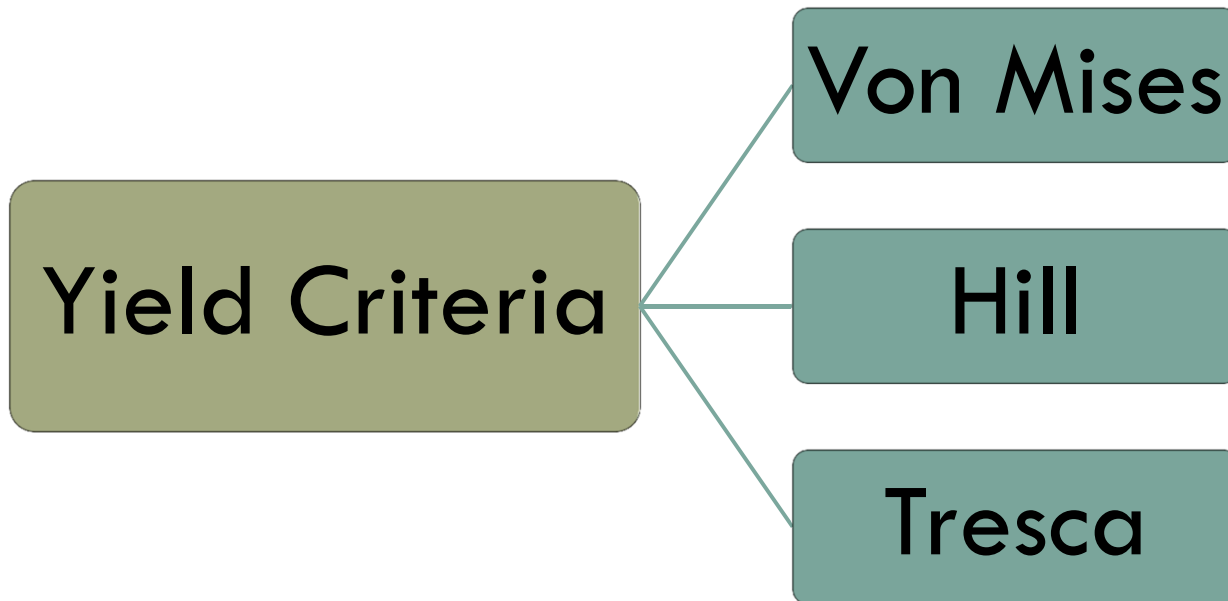
- Check available strip data**
  - Strip data**
    - Width: [ ] mm
    - Initial thickness: [ ] mm
    - Final thickness: [ ]
    - Youngs modulus: [ ] MPa
    - Poissons const.: [ ]
  - Models**
    - No. of models: [ 1 ]
    - Choose model no.: [ 1 ]
  - Temperature**
    - Type of calculation: [ Isothermal ] [ individual ]
    - initial: [ ] Celsius
    - Specific heat: [ ] J/kg\*degree
    - Density: [ ] kg/mm^3

# Choosing Flow Stress model

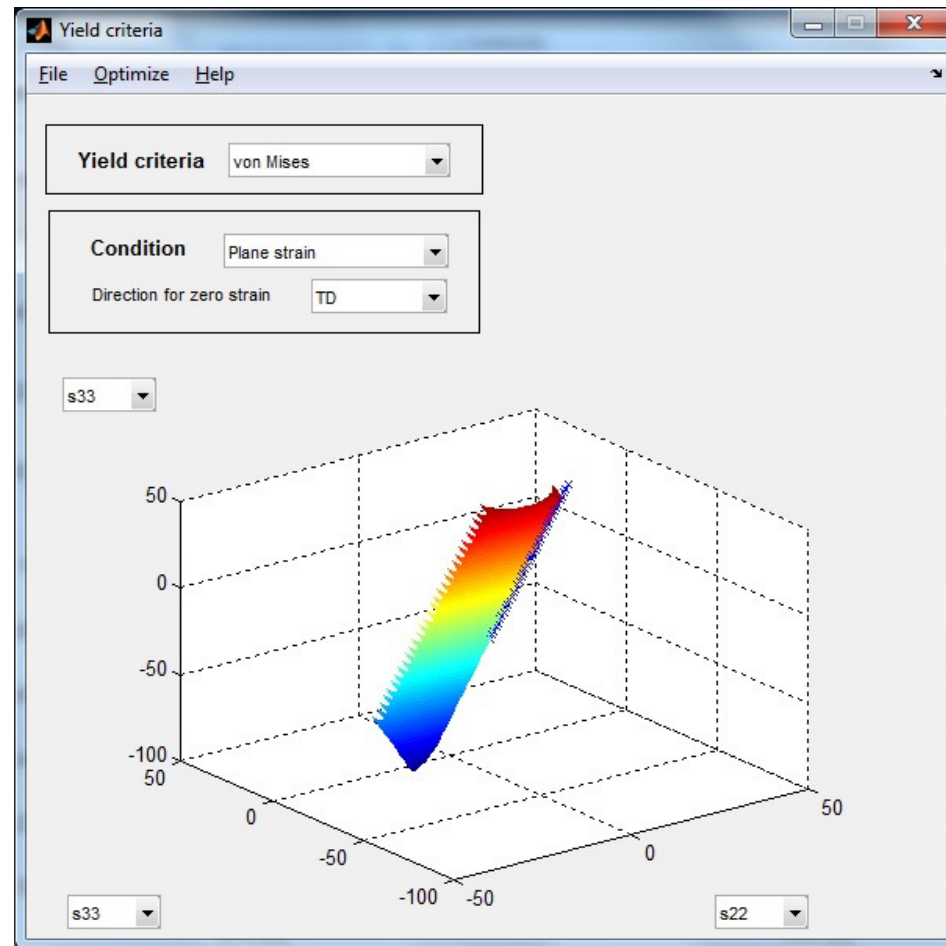


# Yield criteria

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# Yield criteria



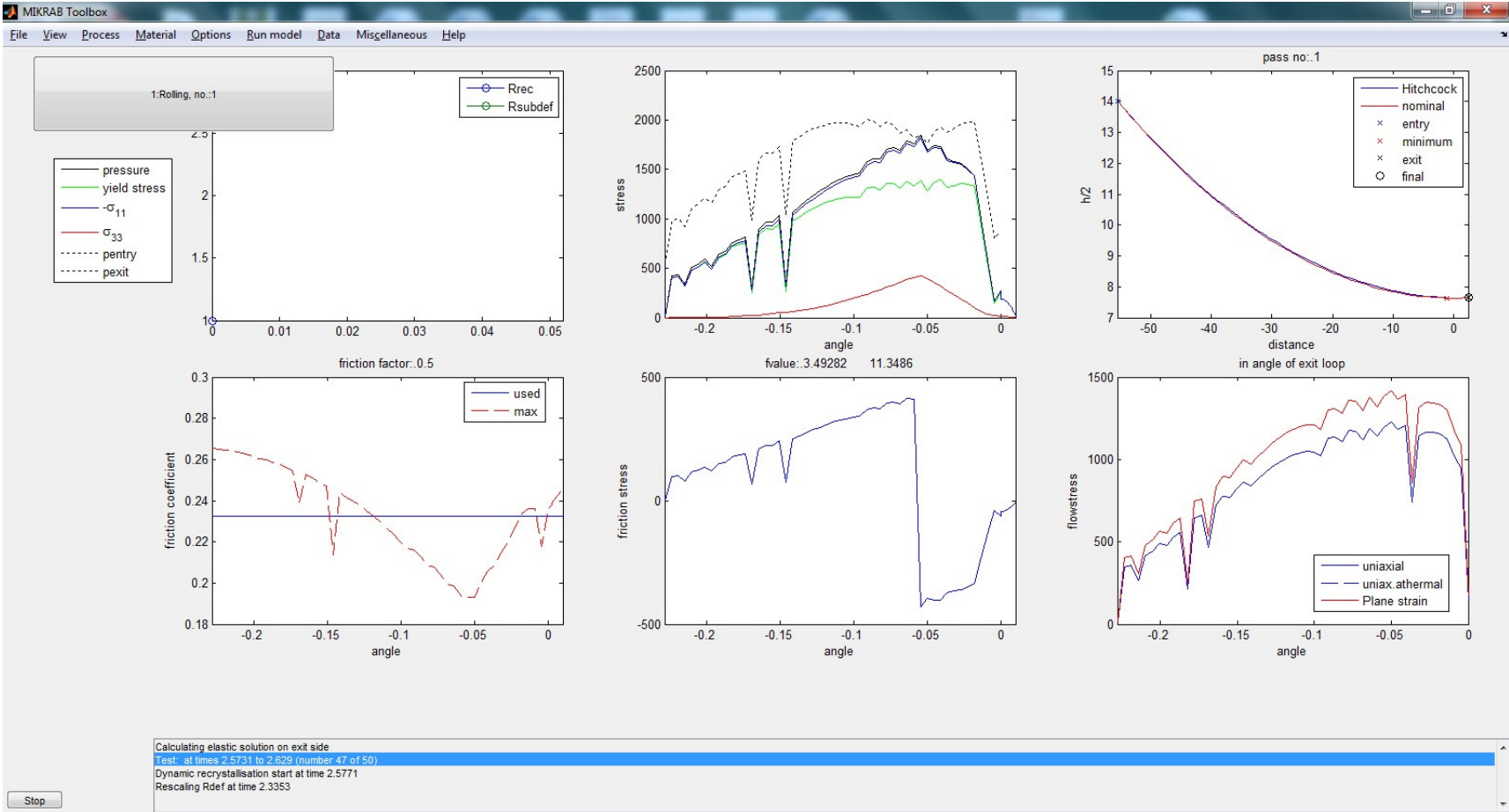
# Model parameters

The screenshot shows the 'ModelParameters' window with a menu bar (File, View, Help) and two dropdown menus at the top: 'Friction-Hill' and 'Hitchcock'. The main area is a table with three columns: 'Parameter (calc.param)', 'Given value', and 'Calc. value'. The parameters are listed with checkboxes and their corresponding values.

Parameter (calc.param)	Given value	Calc. value
<input checked="" type="checkbox"/> Roll diameter (flattend)		0
<input checked="" type="checkbox"/> Roll speed (av. strain-rate)		0
<input type="checkbox"/> Back tension		
<input checked="" type="checkbox"/> Front tension		
<input checked="" type="checkbox"/> Roll force		0
<input checked="" type="checkbox"/> Roll torque		0
<input checked="" type="checkbox"/> Roll E-modulus		
<input checked="" type="checkbox"/> Roll Poissons const.		
<input checked="" type="checkbox"/> Strip width (L/hm)		0
<input checked="" type="checkbox"/> Strip entry thickness		
<input checked="" type="checkbox"/> Strip exit thickness (eq.pl.strain)		0
<input checked="" type="checkbox"/> Strip E-modulus		
<input checked="" type="checkbox"/> Strip Poissons const.		
<input type="checkbox"/> Friction coefficient		
<input type="checkbox"/> Friction factor		
Temperature calculation		
Initial temperature (1000/T[K])	Isothermal	
	1100	
Yield criterion		
	von Mises	
Strain-rate model		
<input checked="" type="checkbox"/> flowstress,low-1 (p/2k)	none	0
<input checked="" type="checkbox"/> flowstress,low-2	2e-05	
<input checked="" type="checkbox"/> flowstress,low-3	0	
<input checked="" type="checkbox"/> flowstress,low-4	1e-07	
<input checked="" type="checkbox"/> flowstress,low-5	1	
identity	1000	
	not given	



# Calculation



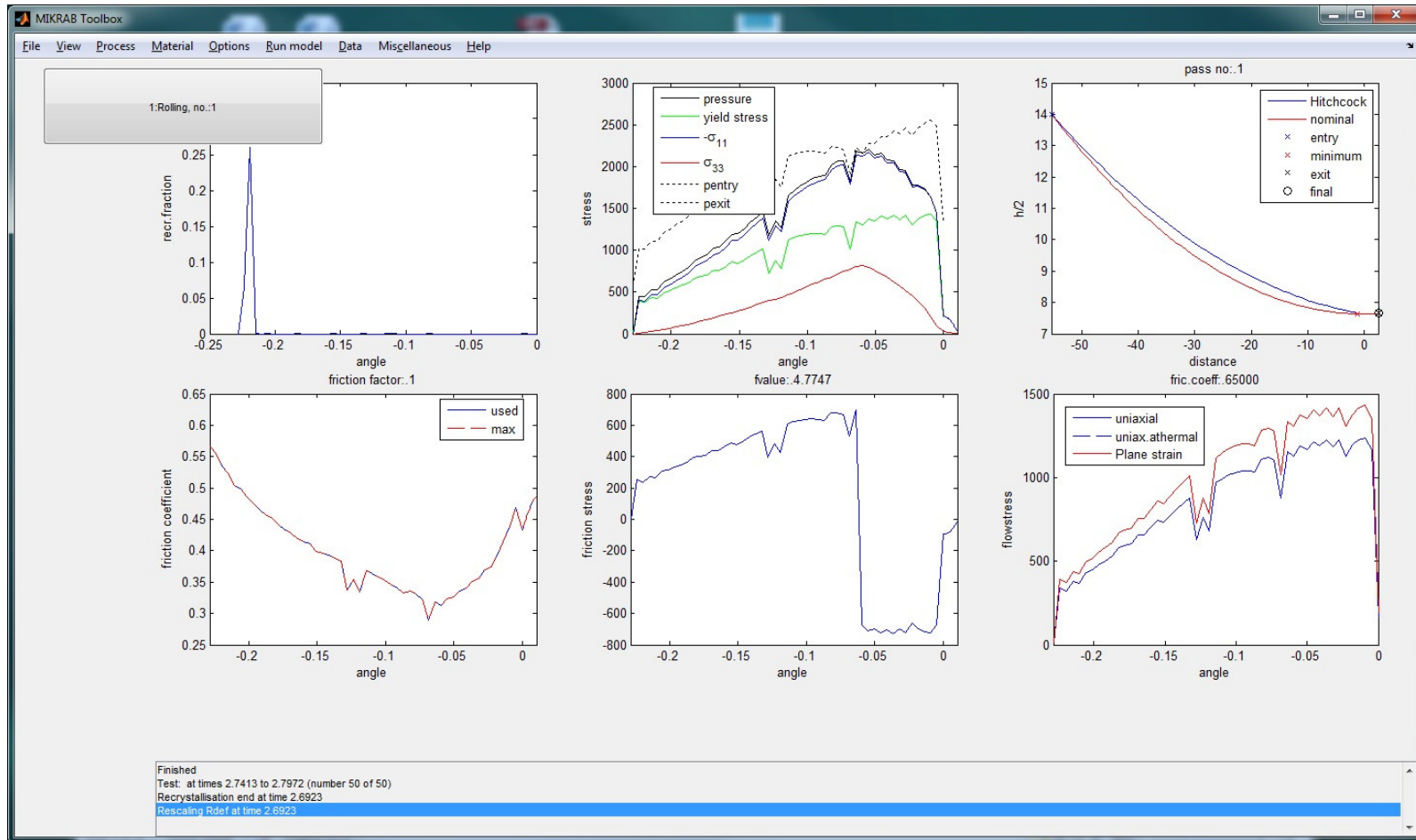
# Model variables

The screenshot shows the ODEoptions dialog box with the following settings:

- Time: 0.38411
- Scale time:
- max time step: 10
- Relative error: 1e-06
- ODE solver: ode113ny
- Scale factor: 1000000
- Redraw figures:
- Va0: 1e-06
- Min timestep for output: 0.001
- Continue on exit:

	Absolute errors	Final values	Scale factors
Va0	1e-06	2.148019852798898e-06	1000000
Varec	1e-06	2.148019852798898e-06	465545.045450575
Vadef	1e-06	0.0001242717644219869	15960.3305559681
raadef	1e-06	3479429365406791	1.13666970582385e-15
raarec	1e-06	1001420000000	9.98582013540772e-13
ragdef	1e-06	6.600833345039976e+16	1.51496022960711e-17
ragrec	1e-06	1001420000000	9.98582013540772e-13
Rdef	1e-06	2.638959844031741e-06	621389.141417289
Nrec	1e-06	1e-10	10000000000
Rrec	1e-06	9.498715597640547e-09	105277391.424204
Rsubdef	1e-06	9.498715597640547e-09	51160456.5819216
eprec	1e-06	19.05360200470383	0.151388217681525
Temp	1e-06	1373.15	0.000785453402976868
Rsubrec	1e-06	9.498715597640547e-09	51086384.1898644
inclusion-ng1	1e-06	8733380538398586	1.14503197885772e-16
inclusion-rg1	1e-06	2.499999993688107e-07	4000000.01009903

# Results for rolling (pass 1)





And

To be continued!

**Thank you !**



HÖGSKOLAN  
DALARNA