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)

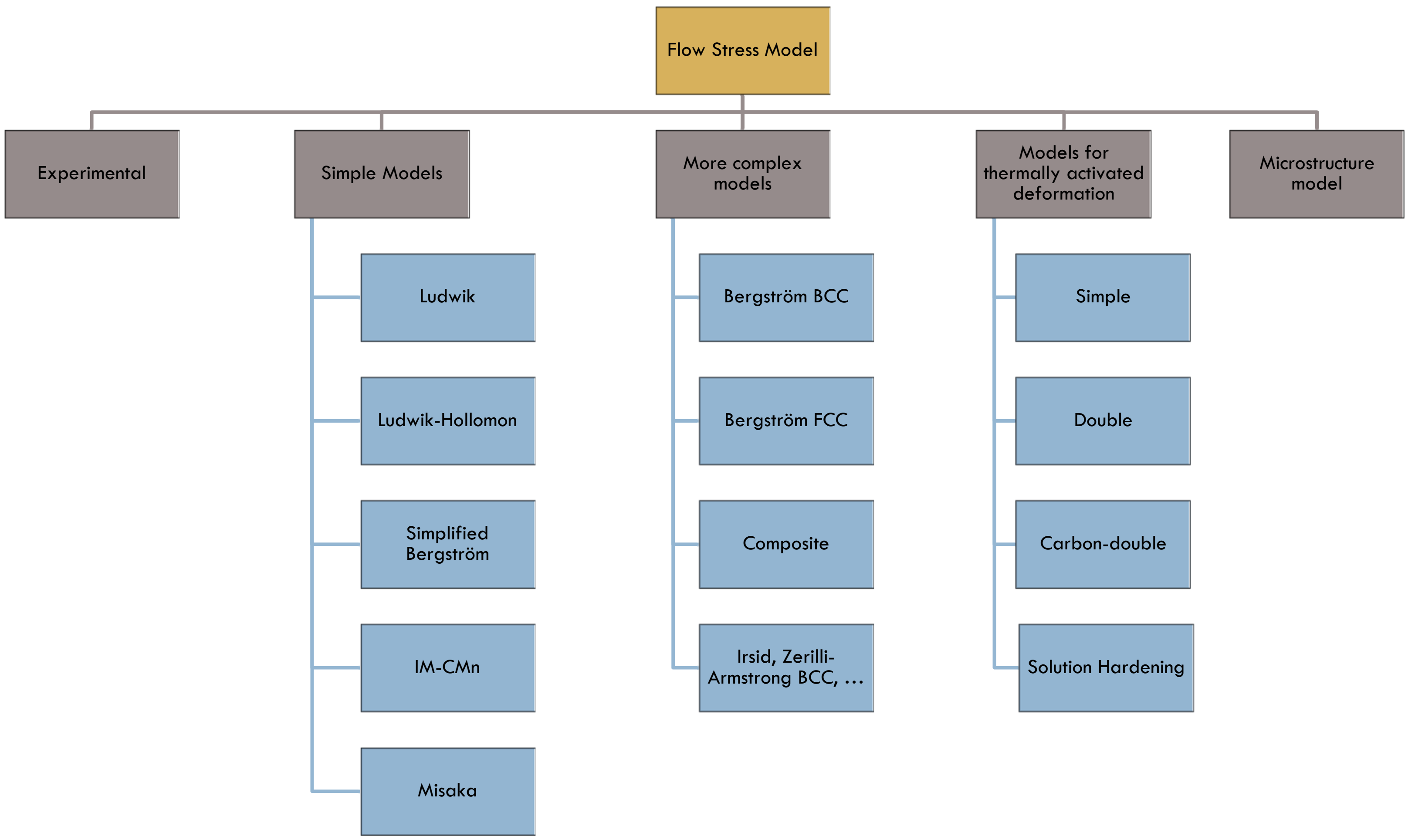
- Literature survey on microstructure evolution in hot working
- Learning the “MIKRAB Toolbox” by G. Engberg and model the hot deformation of 13C26
- Run a gap analysis between Toolbox and logged process data from the rolling mill
- Publish first technical paper from the results[2015]
- PhD courses (60-90 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)

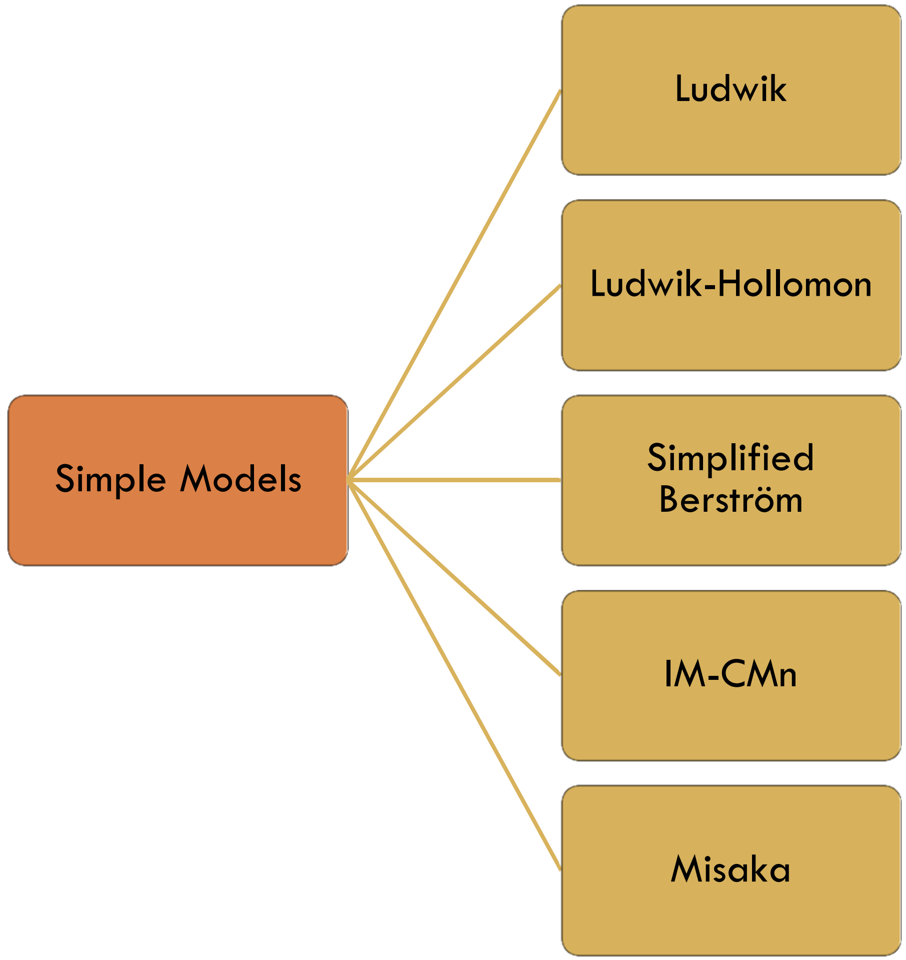
MIKRAB Toolbox



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 $\sigma = \sigma_0 + k \cdot \sqrt{\varepsilon_{plastic}}$
- Ludwik-Hollomon $\sigma = \sigma_0 + k \cdot \varepsilon^n_{plastic} \cdot \dot{\varepsilon}^m$
- Simplified Bergström for BCC $\sigma = \sigma_0 + k \cdot \sqrt{1 - e^{-\Omega \varepsilon_{plastic}}}$

The initial dislocation density is neglected in this simplified version.

Dislocation evolution models (Complex models)

More complex models

Bergström for BCC

$$\sigma = \sigma_0 + k \cdot \sqrt{\rho} \qquad \frac{d\rho}{d\varepsilon} = U - \Omega \cdot \rho$$

Bergström for FCC

$$\sigma = \sigma_0 + k \cdot \sqrt{\rho}$$

$$\frac{d\rho}{d\varepsilon} = \frac{k}{L} - \Omega \cdot \rho, \quad L = L_{final} + \left(L_{start} - L_{final}\right) \cdot e^{k \cdot \varepsilon_{plastic}}$$

Composite

$$\sigma_{soft} = \sigma_{0,soft} + \frac{k}{\sqrt{d}} + m\alpha Gb \cdot \sqrt{\rho_{soft}}$$

$$\frac{d\rho_{soft}}{d\varepsilon_{plastic,soft}} = U + g_0 \frac{f_{hard}}{r_{hard}} - \Omega \cdot \rho_{soft}$$

$$\sigma_{hard} = \sigma_{0,hard} + m\alpha Gb \cdot \sqrt{\rho_{hard}}$$

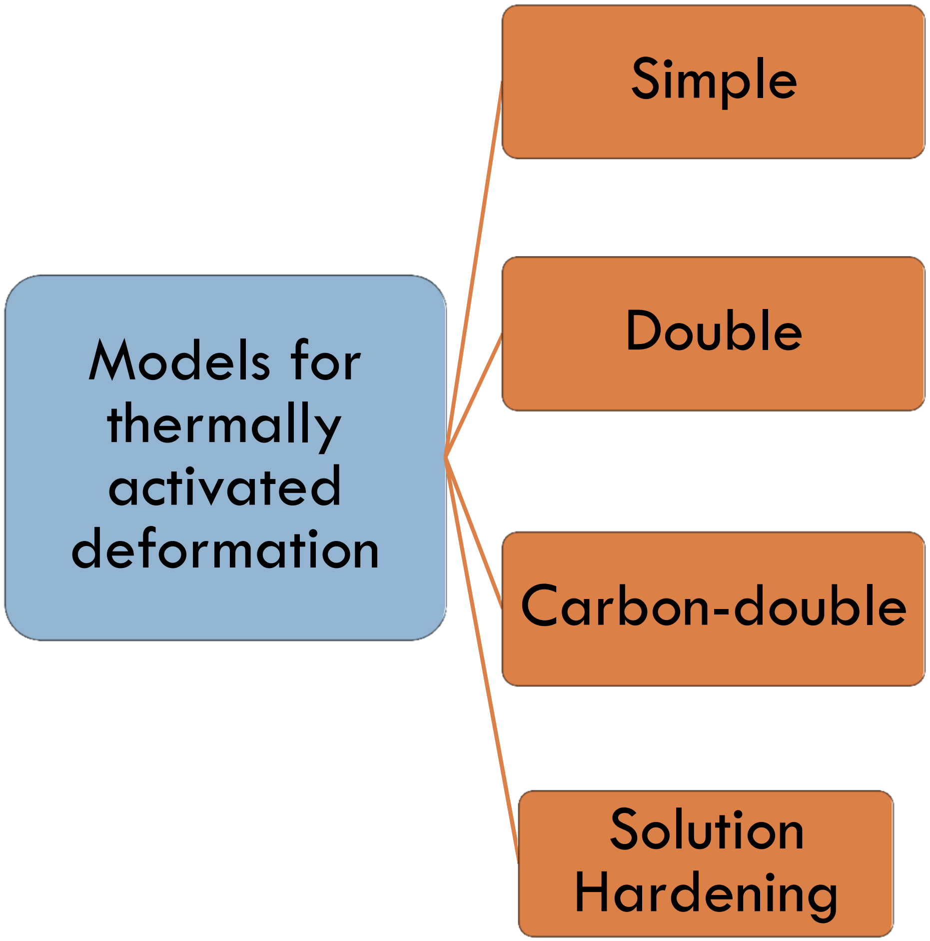
$$\frac{d\rho_{hard}}{d\varepsilon_{plastic,hard}} = U + g_0 \frac{f_{hard\ phase}}{r_{hard\ phase}} - \Omega \cdot \rho_{hard}$$

Irsid, Zerilli-Armstrong BCC, …

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



Simple:

$$\frac{d\varepsilon}{dt} = k_1 \cdot \left(\frac{\sigma^*}{k_2}\right)^{\frac{k_3}{T}}$$

Double:

$$\frac{d\varepsilon}{dt} = k_{11} \cdot \left(\frac{\sigma^*}{k_{21}}\right)^{\frac{k_{31}}{T}} + k_{12} \cdot \left(\frac{\sigma^*}{k_{22}}\right)^{\frac{k_{32}}{T}}$$

Carbon-double:

$$\sigma^* = \sigma^*_{double} + \sigma^*_C \qquad \sigma^*_C = \left[1 + c_2 \cdot T \cdot \ln\left(\frac{\frac{d\varepsilon}{dt}}{c_3}\right)\right]^3 \cdot c_1 \cdot G \cdot \sqrt{x}$$

(x is the carbon content)

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

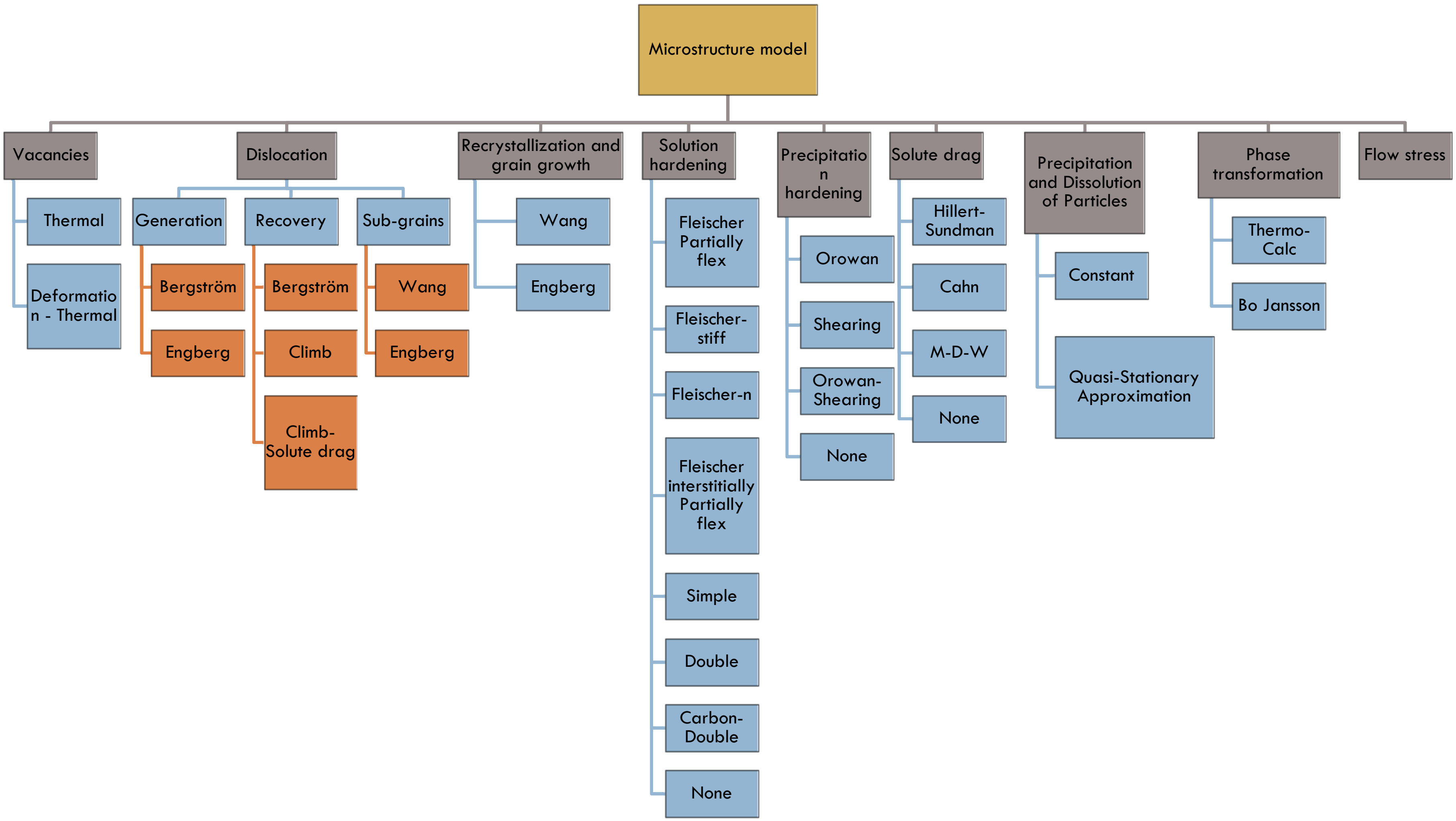
Carbon-double:

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

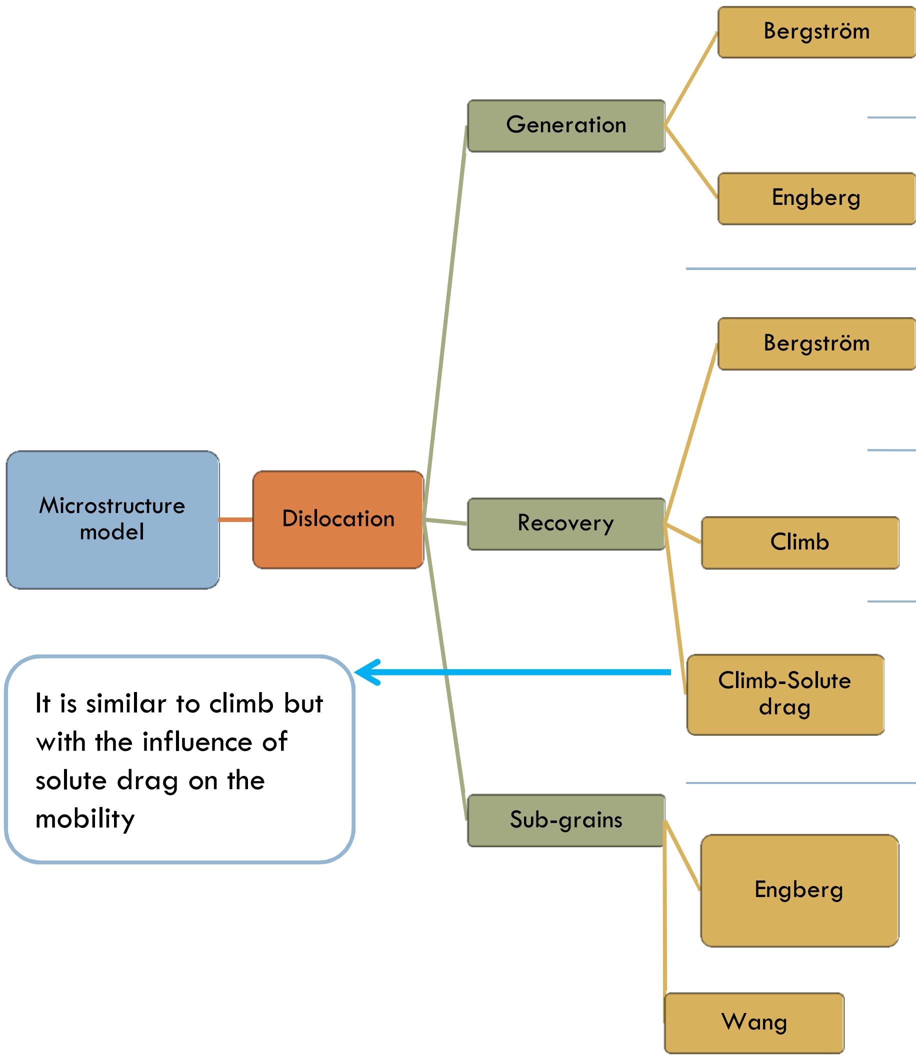
(These 3 mentioned models are not applicable for high temperatures.)

- Solution hardening

Microstructure models and sub-models



Microstructure models and sub-models: Dislocation



Generation – Bergström

$$\frac{d\rho}{dt}=\frac{m}{b\cdot L}\cdot\frac{d\varepsilon}{dt}\qquad L_{bcc}=L_0,\ L_{fcc}=L_1+(L_0-L_1)\cdot e^{-k\cdot\varepsilon_{plastic}}$$

Generation – Engberg

$$\frac{d\rho}{dt}=\frac{m}{b\cdot L}\cdot\frac{d\varepsilon}{dt}\qquad \frac{1}{L}=\frac{f}{r}\cdot\frac{1}{L_0}+\frac{1}{R_0}\cdot\frac{1}{L_1}+\frac{\sqrt{\rho}}{L_2}$$

Recovery – Bergström

$$\frac{d\rho}{dt}=-\Omega\cdot\rho\cdot\frac{d\varepsilon}{dt}\qquad \Omega=\Omega_0+\Omega_T\cdot\left[\frac{D_{m0}\cdot e^{\frac{-Q_{m0}}{RT}}}{\frac{d\varepsilon}{dt}}\right]^{1/3}$$

Recovery – Climb

$$\frac{d\rho}{dt}=-Mob_m\cdot x_v\cdot\rho^2\cdot\left(1-k\cdot\frac{f}{r}\cdot\frac{1}{\sqrt{\rho}}\right)\qquad Mob_m=\frac{M_0\cdot D_m\cdot G\cdot b^3}{T}$$

Recovery – Climb-Solute drag

$$\frac{d\rho}{dt}=-Mob_m\cdot x_v\cdot\rho^2\cdot\left(1-k\cdot\frac{f}{r}\cdot\frac{1}{\sqrt{\rho}}\right)\qquad Mob_m=\frac{M_0\cdot D_{m,M}\cdot G\cdot b^3}{T\cdot\left(1+\Sigma\frac{\beta_X D_{m,X}x_X}{D_{m,M}T^2}\right)}$$

$$D_{m,M}=D_M\cdot e^{-\frac{Q_M-Q_v}{RT}}$$

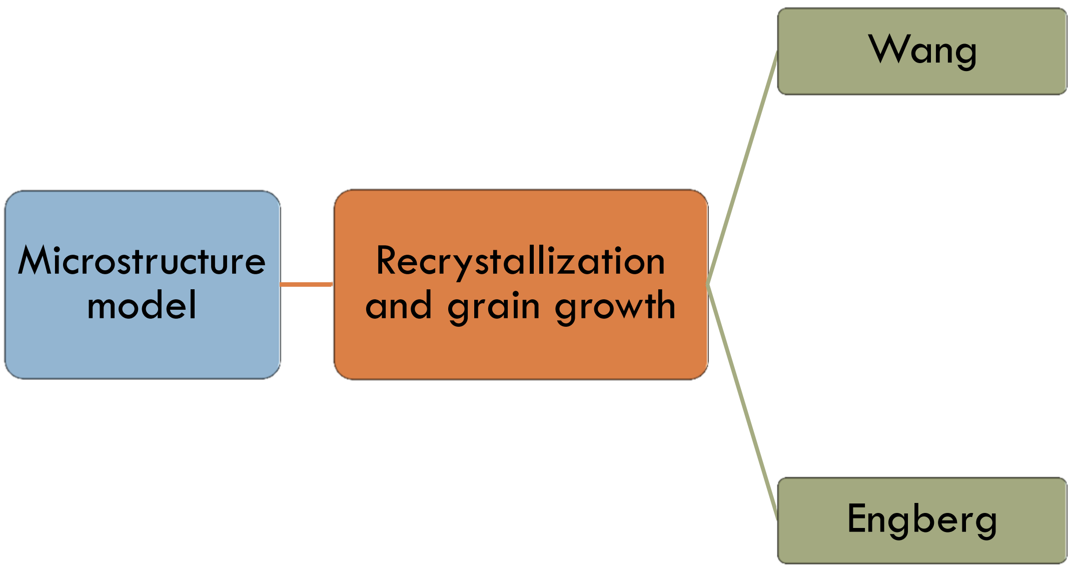
Sub-grains – Engberg / Wang

$$\frac{dR_{sub}}{dt}=k\cdot M_g\cdot x_v\cdot F_{subg},\ F_{subg}=\frac{\gamma_{subg}}{R_{sub}}-k_s\cdot\frac{f}{r}$$

$$R_{a,crit}=R_{sub}\cdot\frac{\gamma_{gsa}}{\gamma_{subg}}=\frac{6k_{sub}\gamma_{gsa}}{Gb^2}\cdot\frac{1}{\rho}\qquad \gamma_{gm}=\gamma_{gr}\cdot\left[1-\left(\frac{\rho}{\rho_{gen}}\right)^{cm}\right]$$

$$\gamma_{subg}=\frac{Gb^2\rho R_{sub}}{6k_{sub}}\qquad R_{sub}=k\cdot L,\ for\ \frac{d\varepsilon}{dt}>0$$

Microstructure models and sub-models: Recrystallization and grain growth



- In this model abnormal sub-grains of a critical size act as nucleus for recrystallized grains.
- It is the improved version of Wang model for saving computing time.

Engberg recrystallization and grain growth model

$$R_{crit} = \frac{\gamma_{gr} - \gamma_{gm}}{cd \cdot G \cdot b^2 \cdot (\rho - \rho_0) - k_{ps} \cdot f/r}$$

$$\frac{dR_{grow}}{dt} = kg \cdot M_g \cdot x_{v,rec} \cdot F_{grow}, \quad F_{grow} = \frac{\gamma_{gb}}{R_{rec}} - kpg \cdot \frac{f}{r}$$

$$\frac{dR_{recg}}{dt} = kr \cdot M_g \cdot 0.5 \cdot (x_{v,def} + x_{v,rec}) \cdot F_{recg}$$

$$F_{recg} = -\frac{\gamma_{gr}}{R_{rec}} + \frac{\gamma_{gm}}{R_{sub}} + cd \cdot G \cdot b^2 \cdot (\rho_{def} - \rho_{rec}) - kps \cdot \frac{f}{r}$$

Rekristallisation om $R_{crit} \le R_{sub}$ och $\gamma_{gm} \ge 0.75 \cdot \gamma_{gr}$

$$N_{sites} = \frac{(1 - F_{rec})}{cf \cdot R_{def} \cdot R_{sub}^2} \qquad cf = 4 \cdot \pi/3 \qquad N_{recs} = \frac{1 - F_{rec}}{cf \cdot R_{def} \cdot R_{rec}^2}$$

$$N_{recsurf} = N_{rec} \;\; for \; N_{recs} > N_{rec}, \quad N_{recsurf} = N_{recs} \;\; for \; N_{recs} \le N_{rec}$$

$$N_{recint} = N_{rec} - N_{recsurf} \;\; for \; N_{rec} \ge N_{recsurf}$$

$$\frac{dN_{recsurf}}{dt} = N_{sites} \cdot kN \cdot e^{-\frac{Q_N}{R \cdot T}}$$

$$\frac{dN_{recint}}{dt} = -3 \cdot \frac{dR_{grow}}{dt} \cdot \frac{N_{recint}}{R_{rec}}$$

$$\frac{dN_{rec}}{dt} = \frac{dN_{recsurf}}{dt} + \frac{dN_{recint}}{dt}$$

$$\frac{dR_{rec}}{dt} = \frac{dR_{grow}}{dt} \;\; \text{for } F_{rec} = 1$$

$$\frac{dR_{rec}}{dt} = \frac{N_{recint} \cdot 3 \cdot R_{rec}^2 \cdot \frac{dR_{grow}}{dt} + N_{recsurf} \cdot 3 \cdot R_{rec}^2 \cdot \frac{dR_{recg}}{dt} - R_{rec}^3 \cdot \frac{dN_{recsurf}}{dt} + R_{sub}^3 \cdot \frac{dN_{recsurf}}{dt}}{3 \cdot R_{rec}^2 \cdot N_{rec}}$$

$$\frac{dF_{rec}}{dt} = cf \cdot \left(\frac{dN_{rec}}{dt} \cdot R_{rec}^3 + N_{rec} \cdot 3 \cdot R_{rec}^2 \cdot \frac{dR_{rec}}{dt} \right)$$

$$\frac{d\rho_{rec}}{dt} = \frac{\frac{dN_{recint}}{dt} \cdot \rho_{rec} + N_{rec} \cdot \left(\frac{d\rho_{rec}}{dt} \right)_{climb} + \frac{dN_{recsurf}}{dt} \cdot \rho_0 - \frac{dN_{rec}}{dt} \cdot \rho_{rec}}{N_{rec}}$$

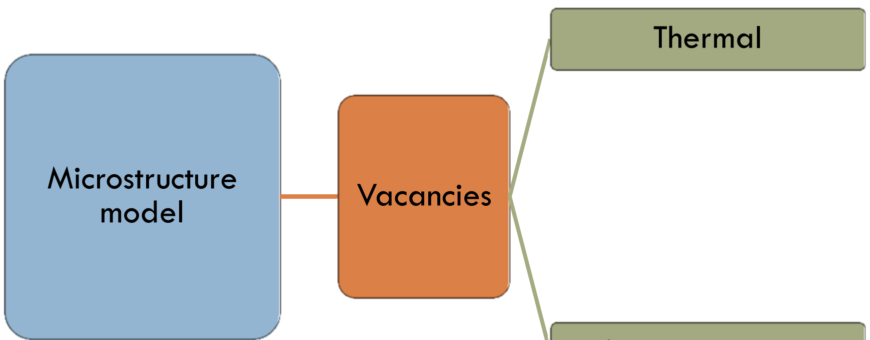
$$\frac{dR_{def}}{dt} = -\frac{R_{def0}}{3} \cdot \frac{dF_{rec}}{dt} \cdot (1 - F_{rec})^{-2/3}$$

$$\frac{d\varepsilon_{rec}}{dt} = \frac{d\varepsilon_{def}}{dt} = \frac{d\varepsilon}{dt} \quad if \quad N_{recint} = 0$$

$$\frac{d\varepsilon}{dt} = F_{rec} \cdot \frac{d\varepsilon_{rec}}{dt} + (1 - F_{rec}) \cdot \frac{d\varepsilon_{def}}{dt}, \quad \sigma_{rec} = \sigma_{def} \quad if \quad N_{recint} > 0$$

$$\frac{d\rho_{g,rec}}{dt} = g_0 \cdot \left(\frac{1 - F_{rec}}{R_{def}} \right) \cdot \left(1 - \frac{d\varepsilon_{def}}{d\varepsilon_{rec}} \right) \cdot \frac{d\varepsilon_{rec}}{dt}$$

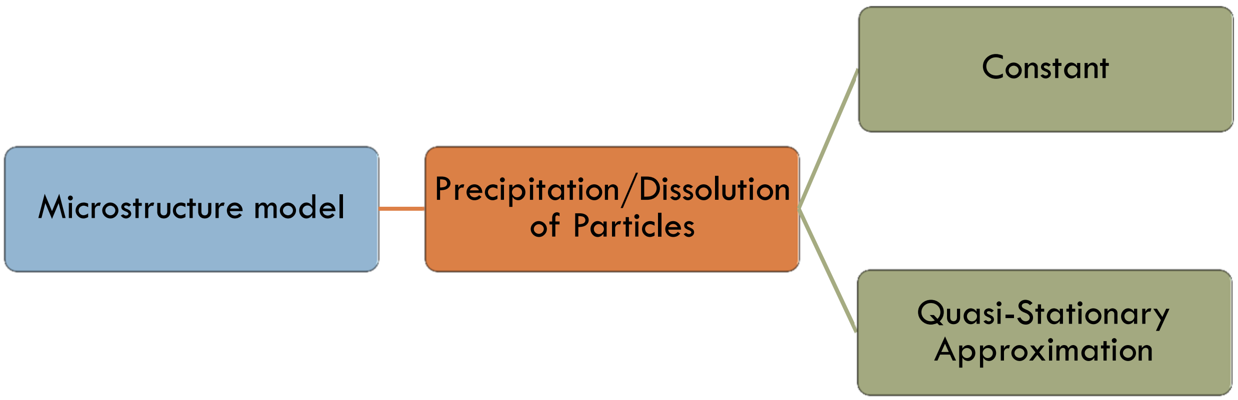
Microstructure models and sub-models: Vacancies



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

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

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



- Classical nucleation
- Spherical particles

(Thermo-Calc is used)

$$\frac{dn^\beta}{dt} = c_{11}\cdot S_v \cdot D^\alpha_{mx}\cdot x^\alpha_M \cdot exp\left(-\frac{c_{12}\cdot\Delta G^*}{kT}\right)$$

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

Sv=1/R

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

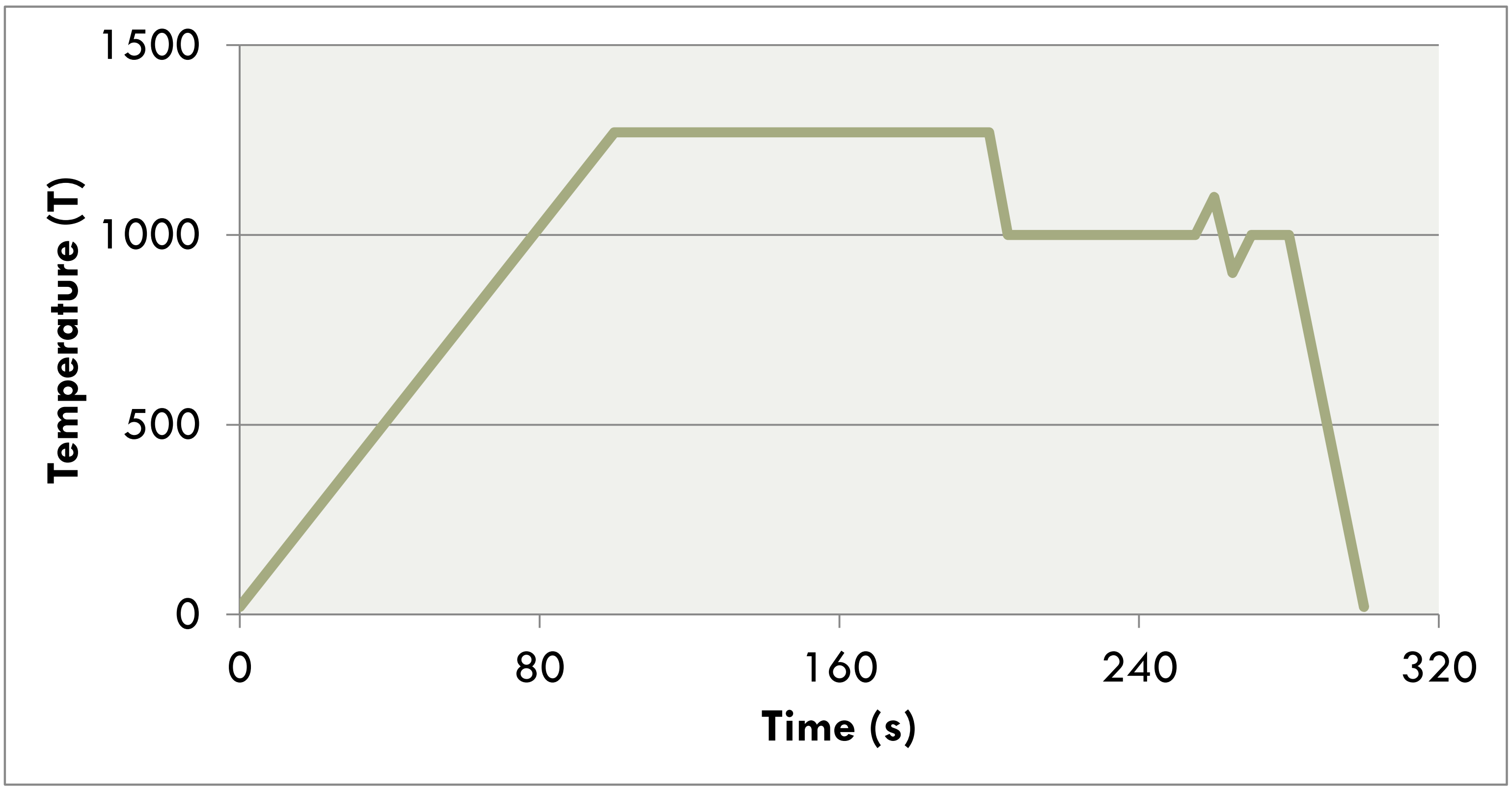
$$\frac{dr}{dt} = x_v \cdot D_m \cdot \frac{\Omega}{r\cdot(1-\frac{r}{R})},\quad \Omega = \frac{x_0^\alpha - x^{\alpha/\beta}}{x^\beta - x^{\alpha/\beta}},\quad R = min(R_{diff}, R_{dist})$$

Microstructure models and sub-models: Phase transformation

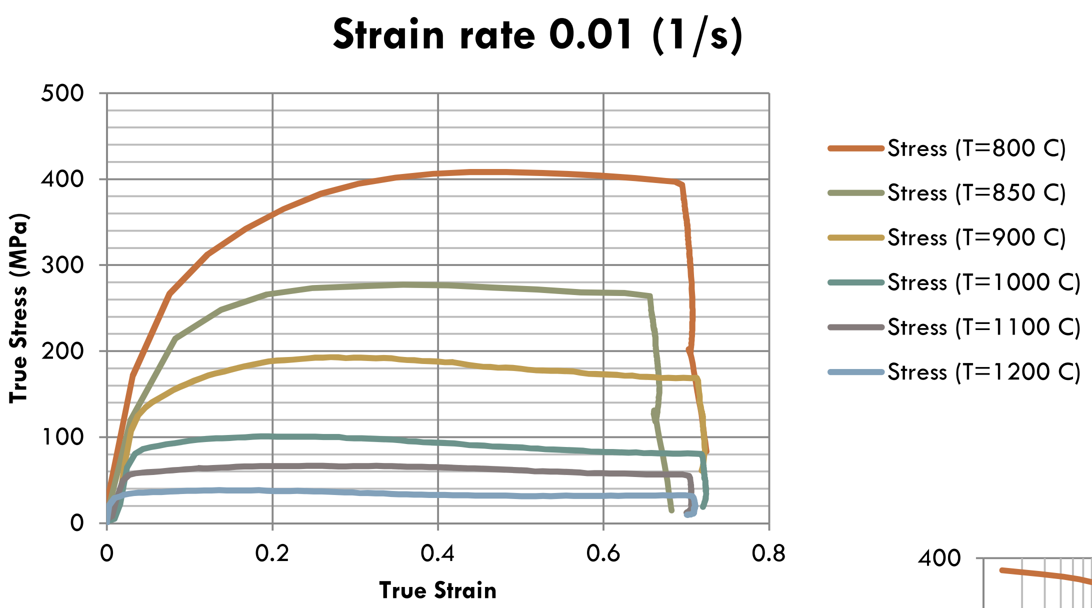
Necessary Input data

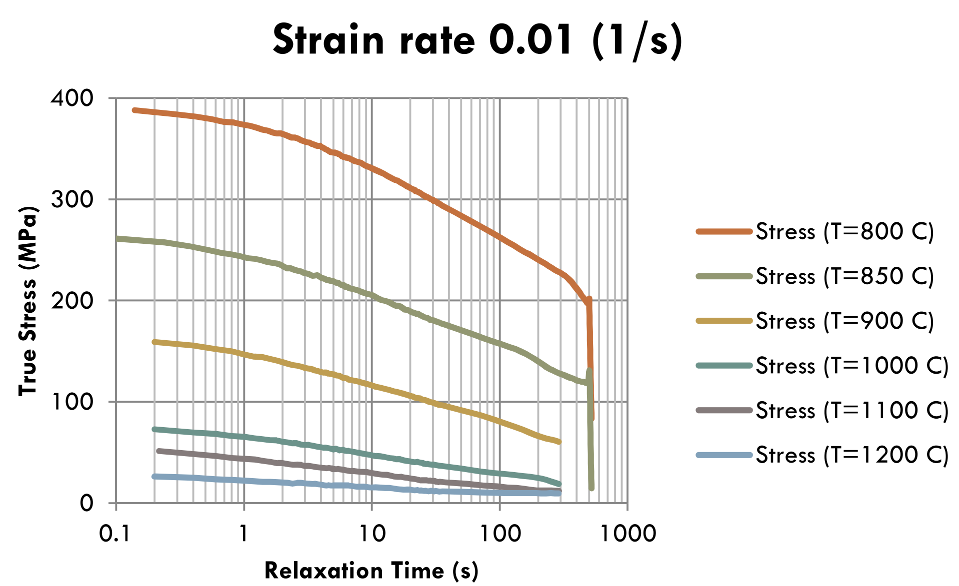
1. From Gleeble tests: Stress and Strain curves in various Strain rates and Temperature
2. Rolling data: e.g. roller size, E modulus, Poison's ratio, rolling speed, force, and torque
3. Work piece (sheet) data: e.g. Thickness, width, Temperature, E and density
4. Grain size, particles fraction, particles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

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



Results from Gleeble tests

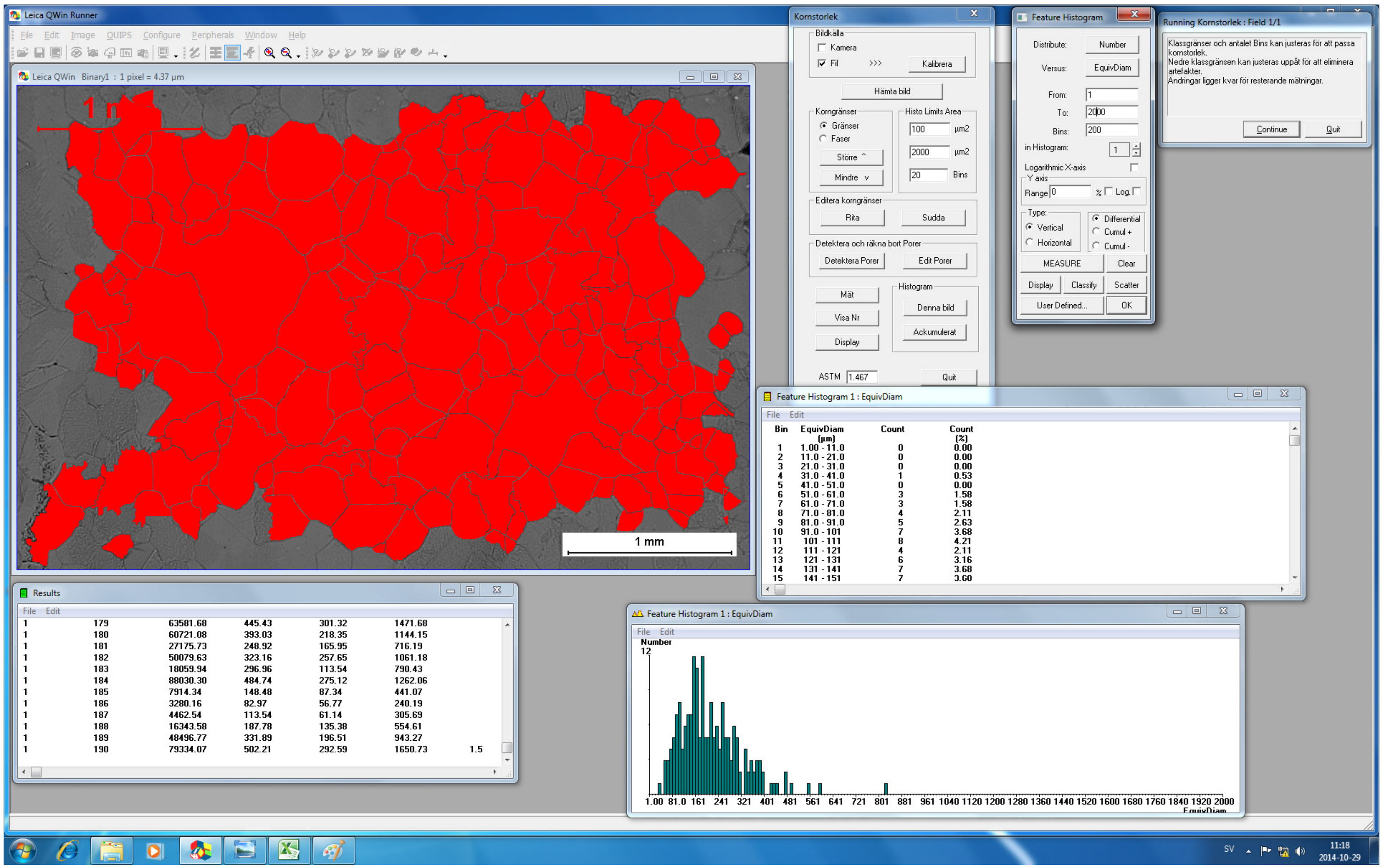




Second particles fraction from TC

	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^{o} C)



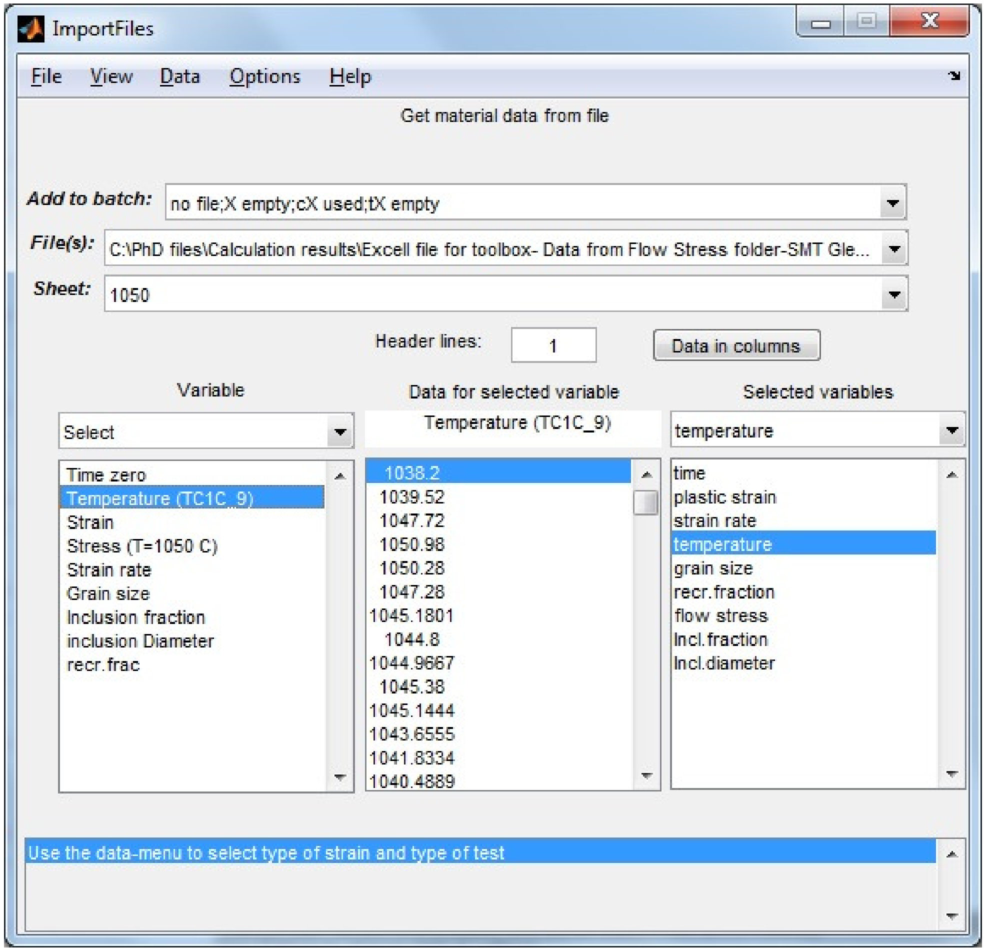
Grain size measurement Results

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

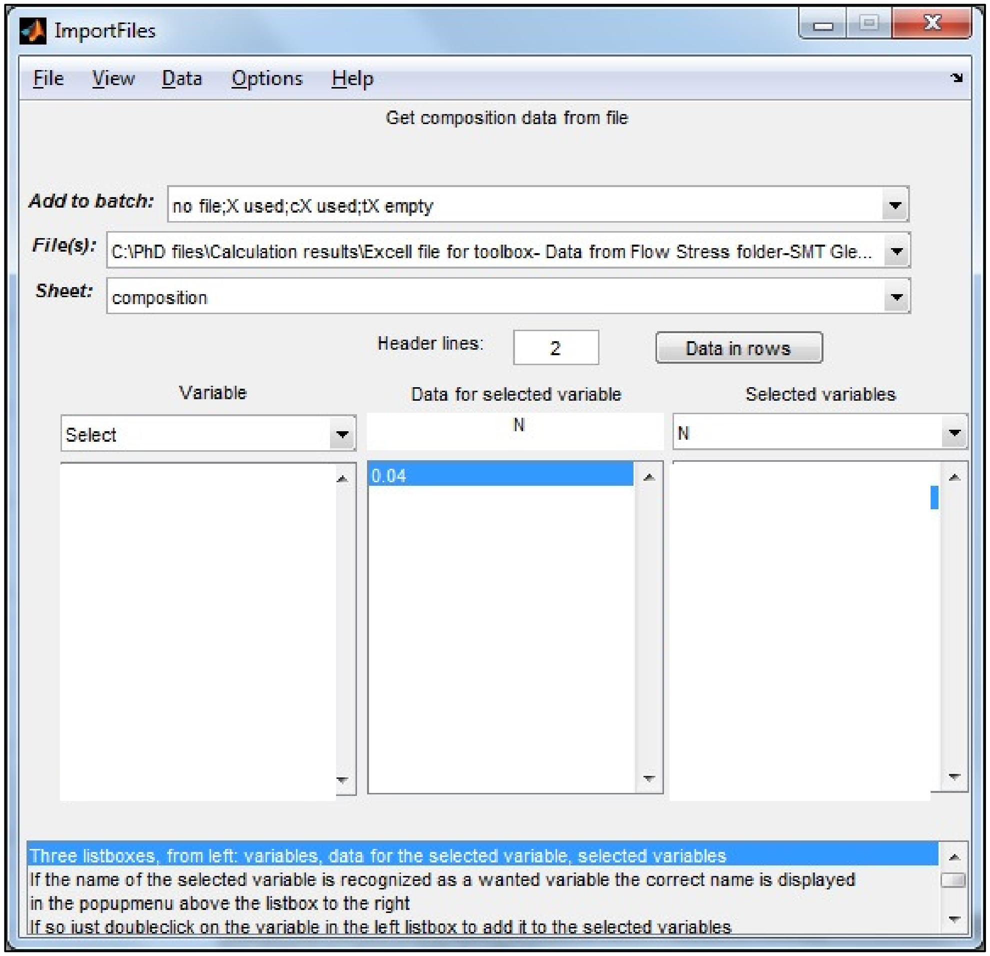
		Grain size (µm)						
	°C	ASTM E112	25X	ASTM E112	ASTM category	50X	Histogram 25X	mean grain size (µm)
Temperature (C)	900	1.5	253	1	6 to 10	226	216	231
	1050	1.2	255	0	2 to 8	353	221	276
	1150	1.2	275	0	4 to 11	302	226	267

Modeling with the Toolbox

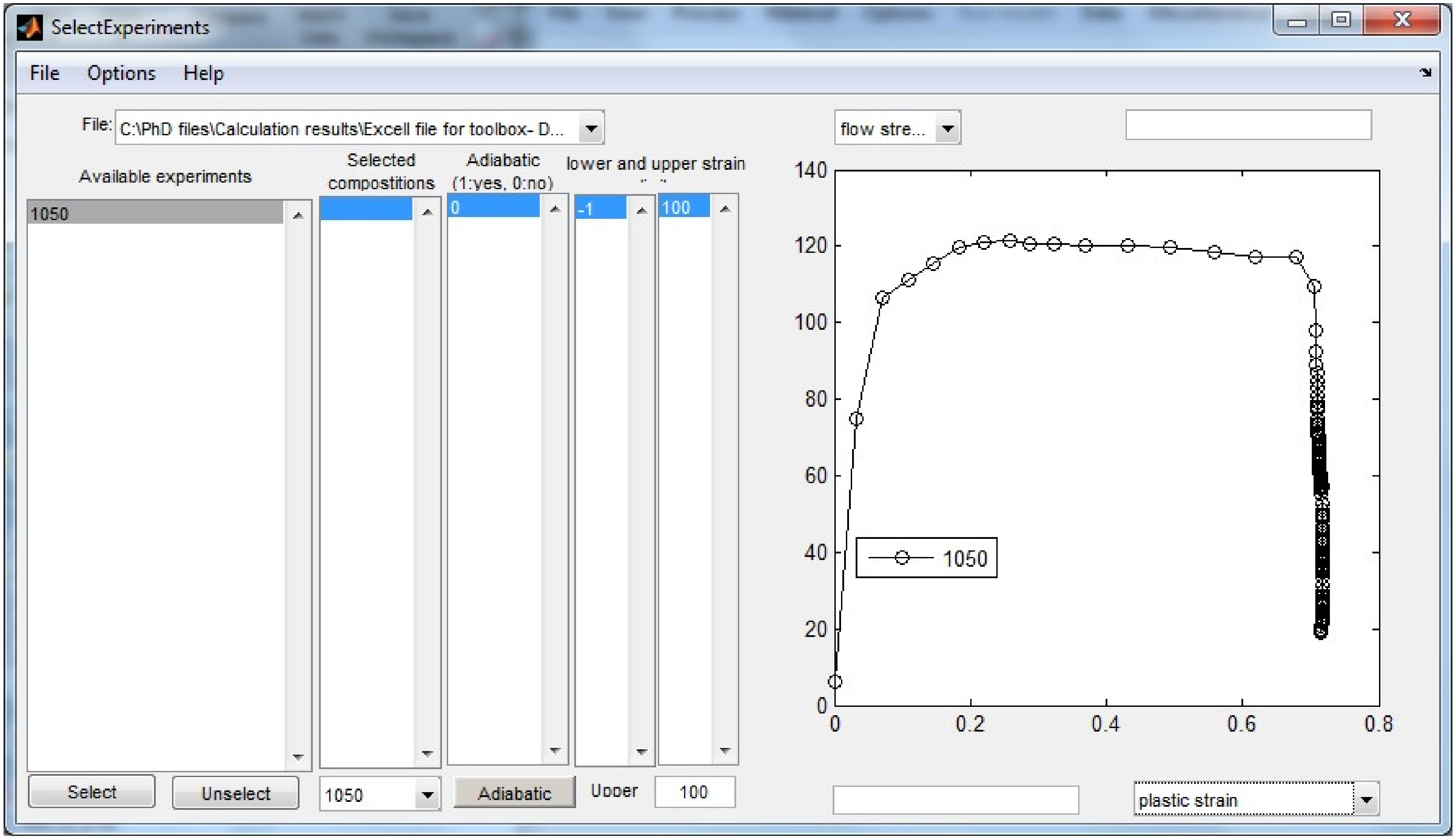
Starting with importing data



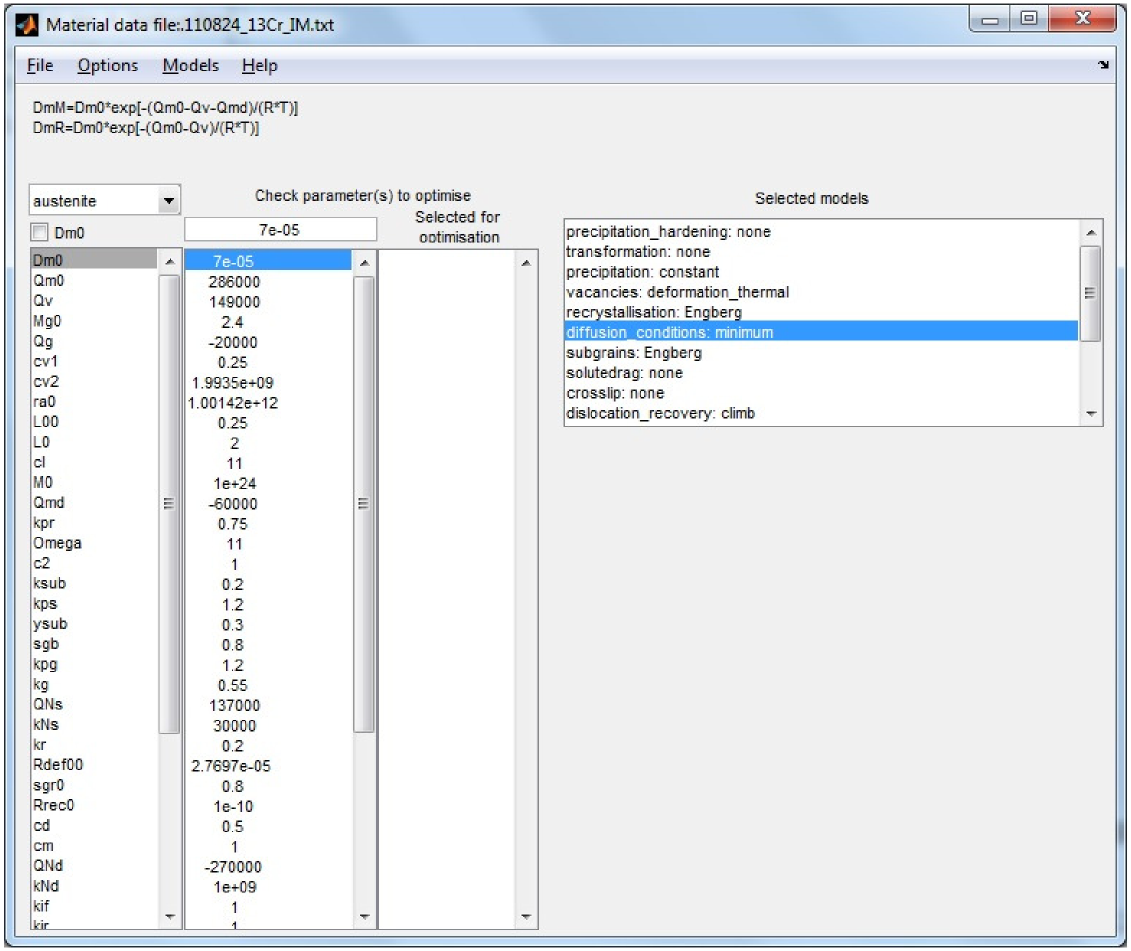
Material composition



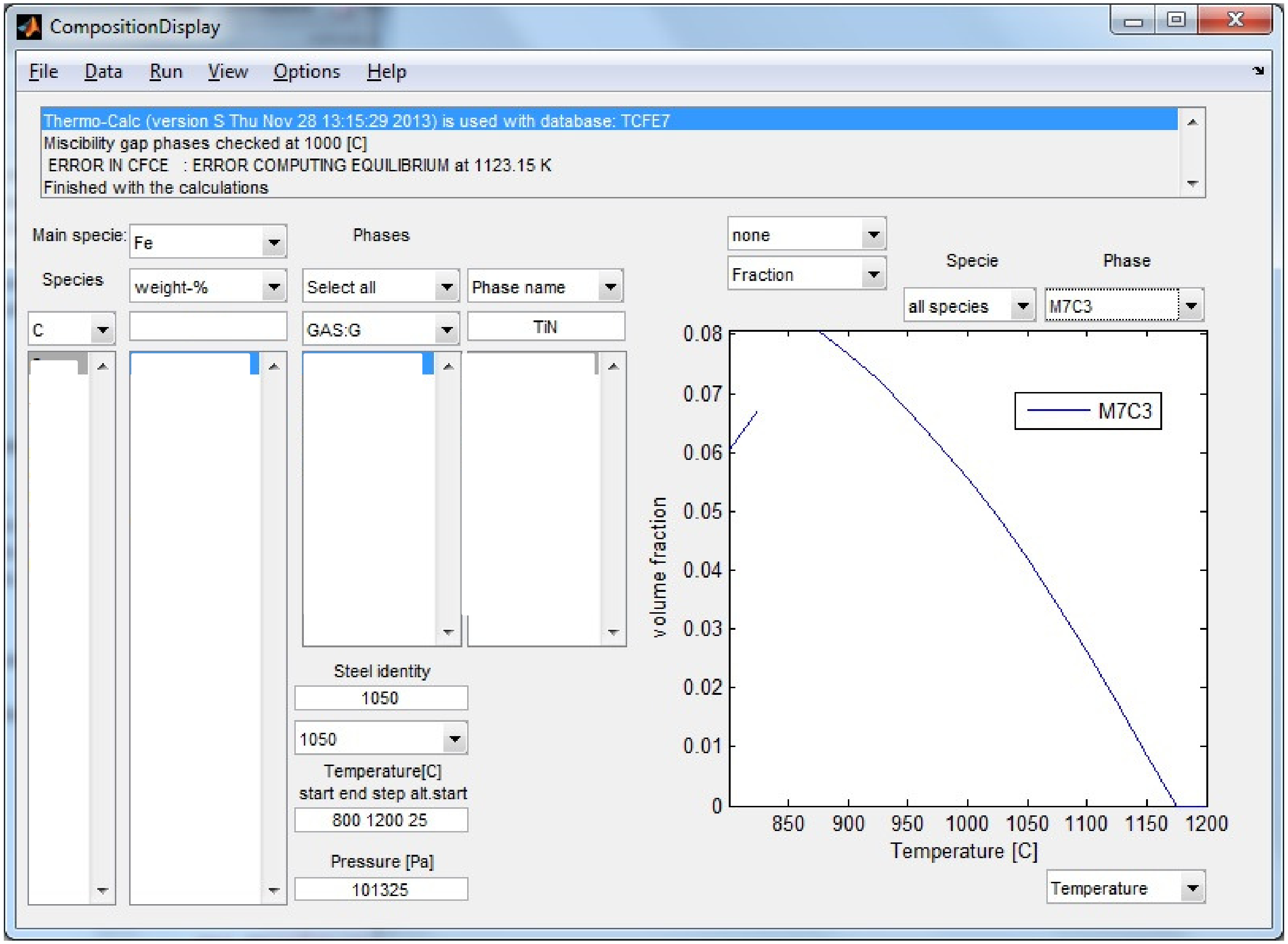
Selecting experiment



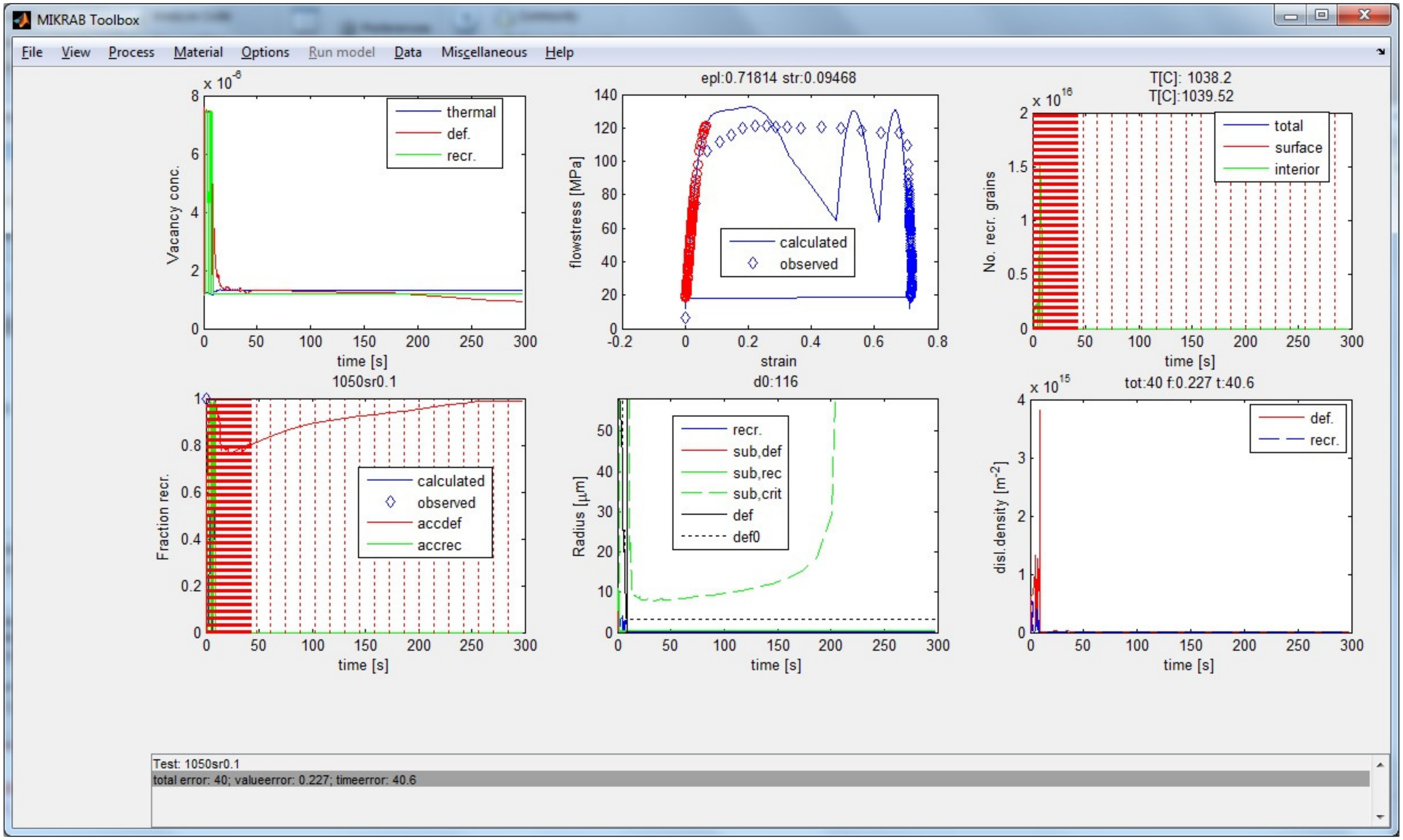
Choosing models



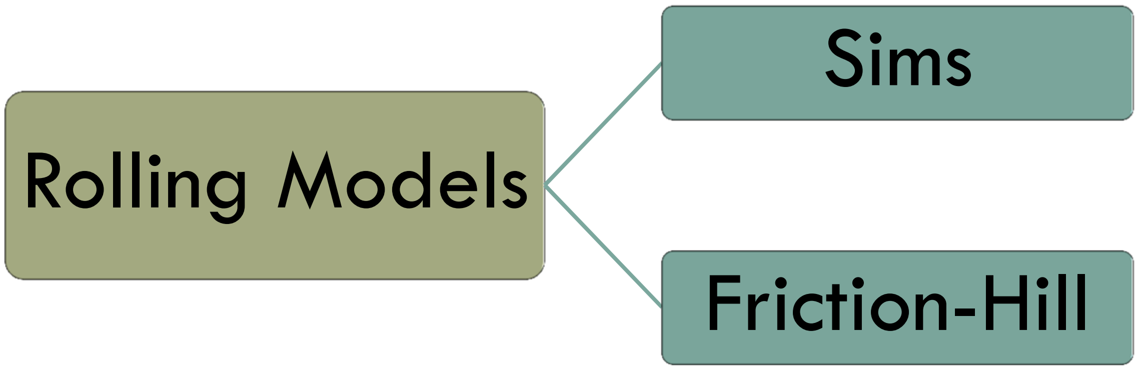
Thermo-Calc calculations



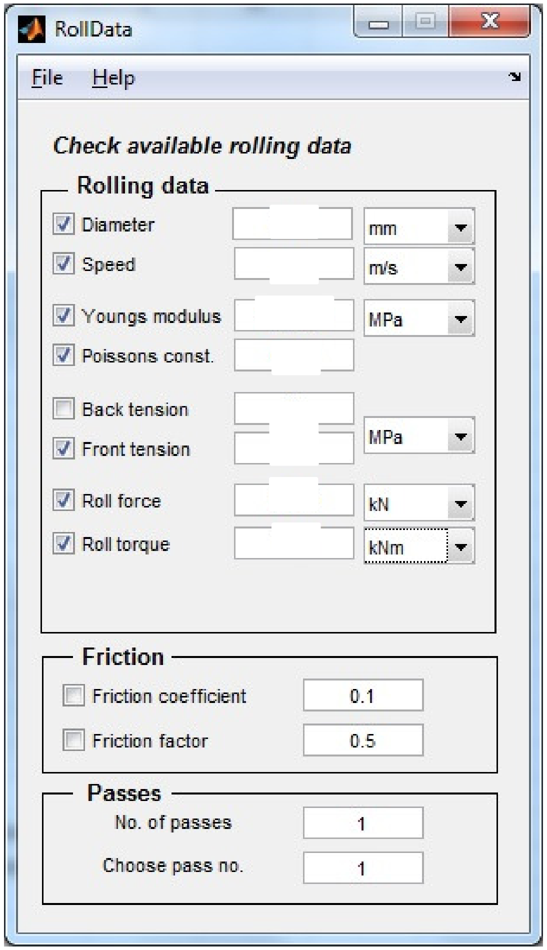
Primary simulation results



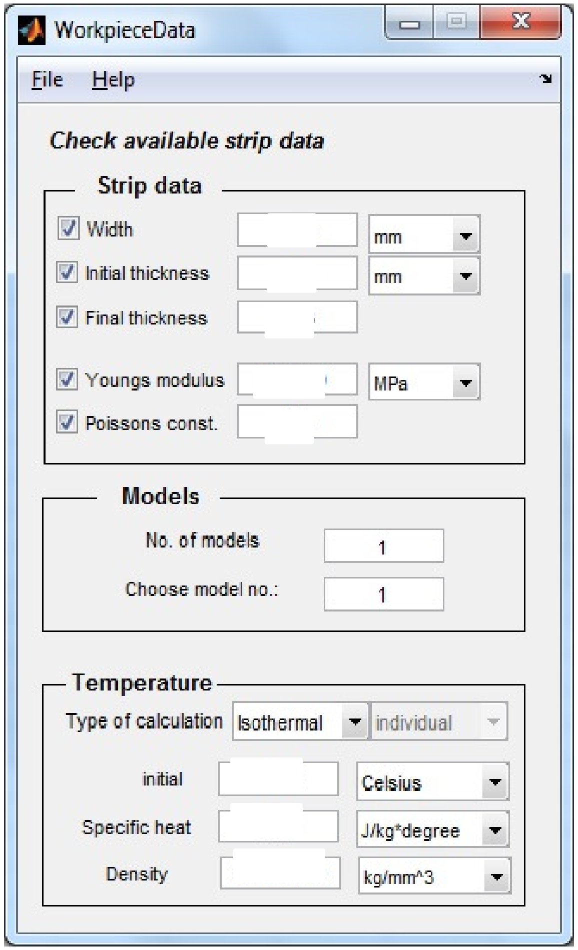
Rolling models



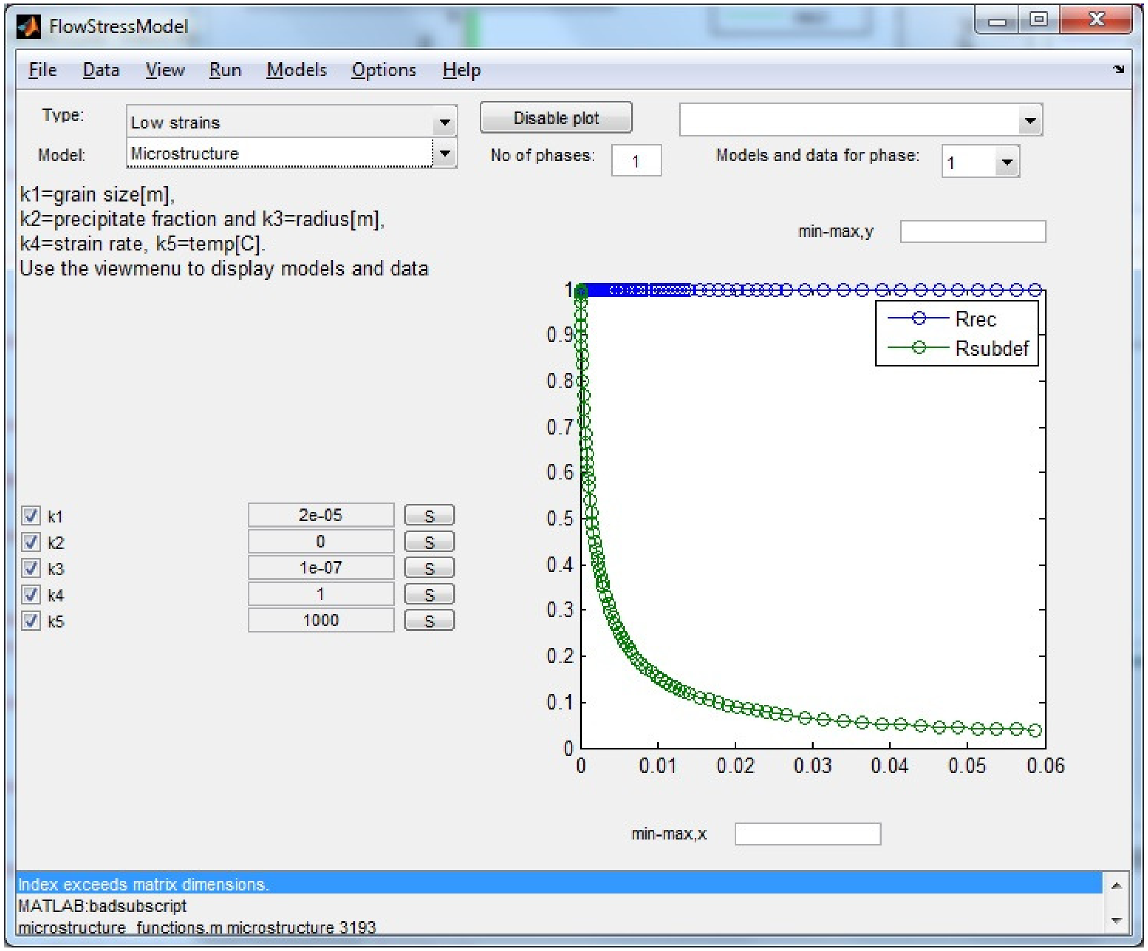
Inputting rolling data



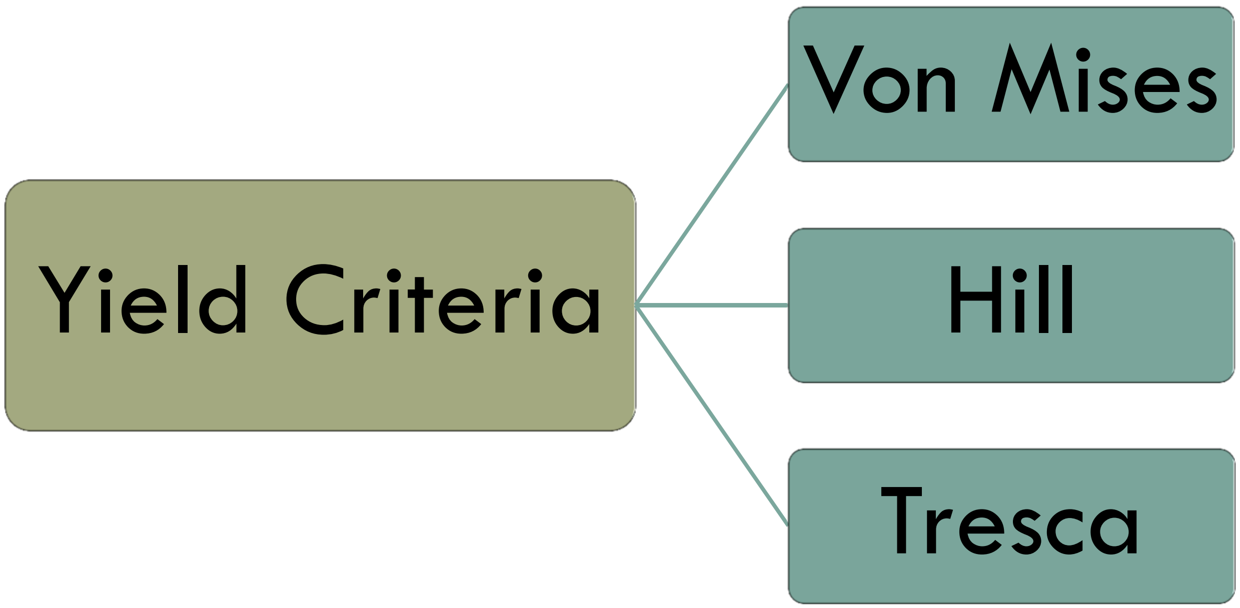
Inputting work piece data



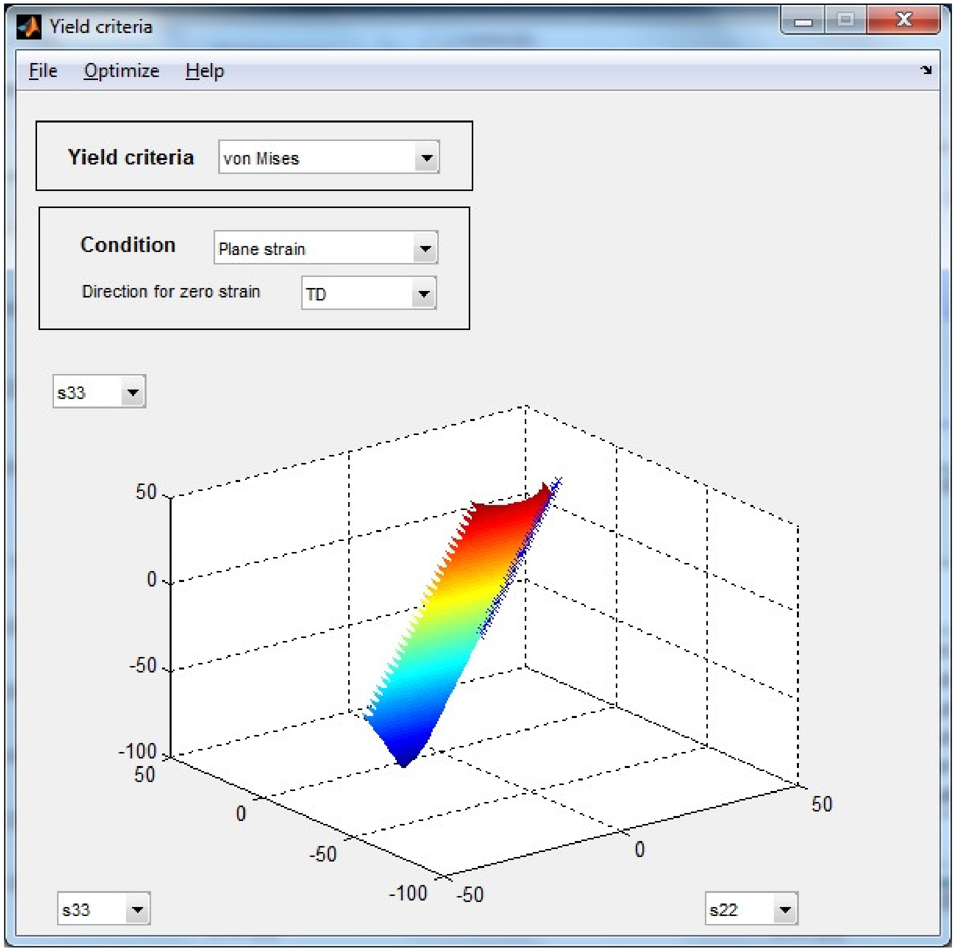
Choosing Flow Stress model



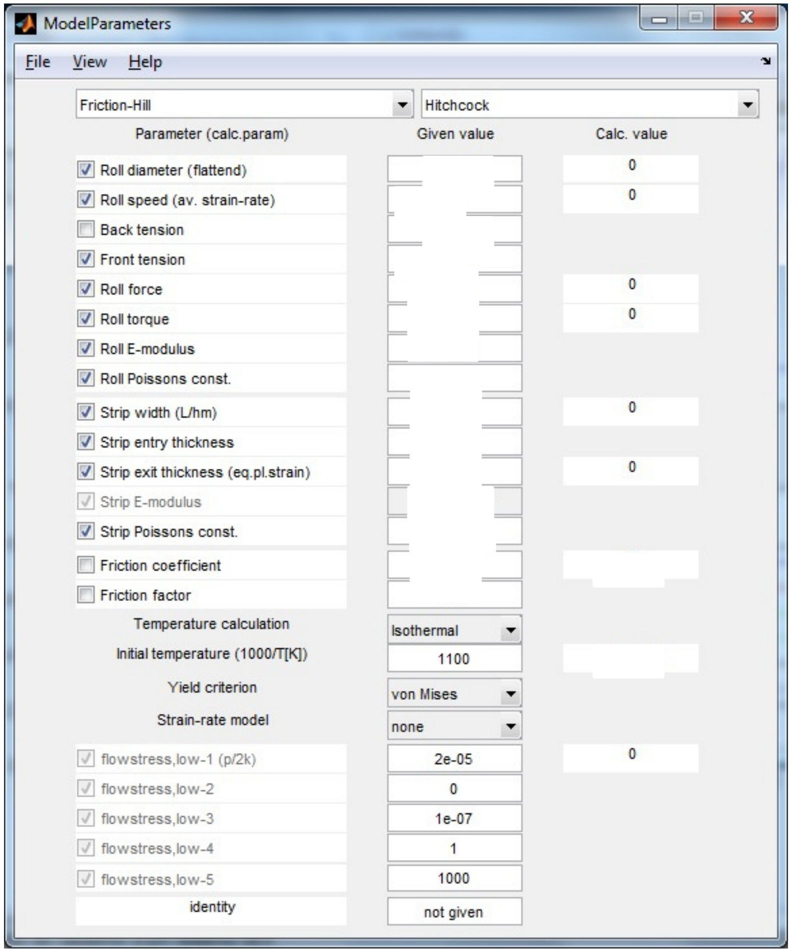
Yield criteria



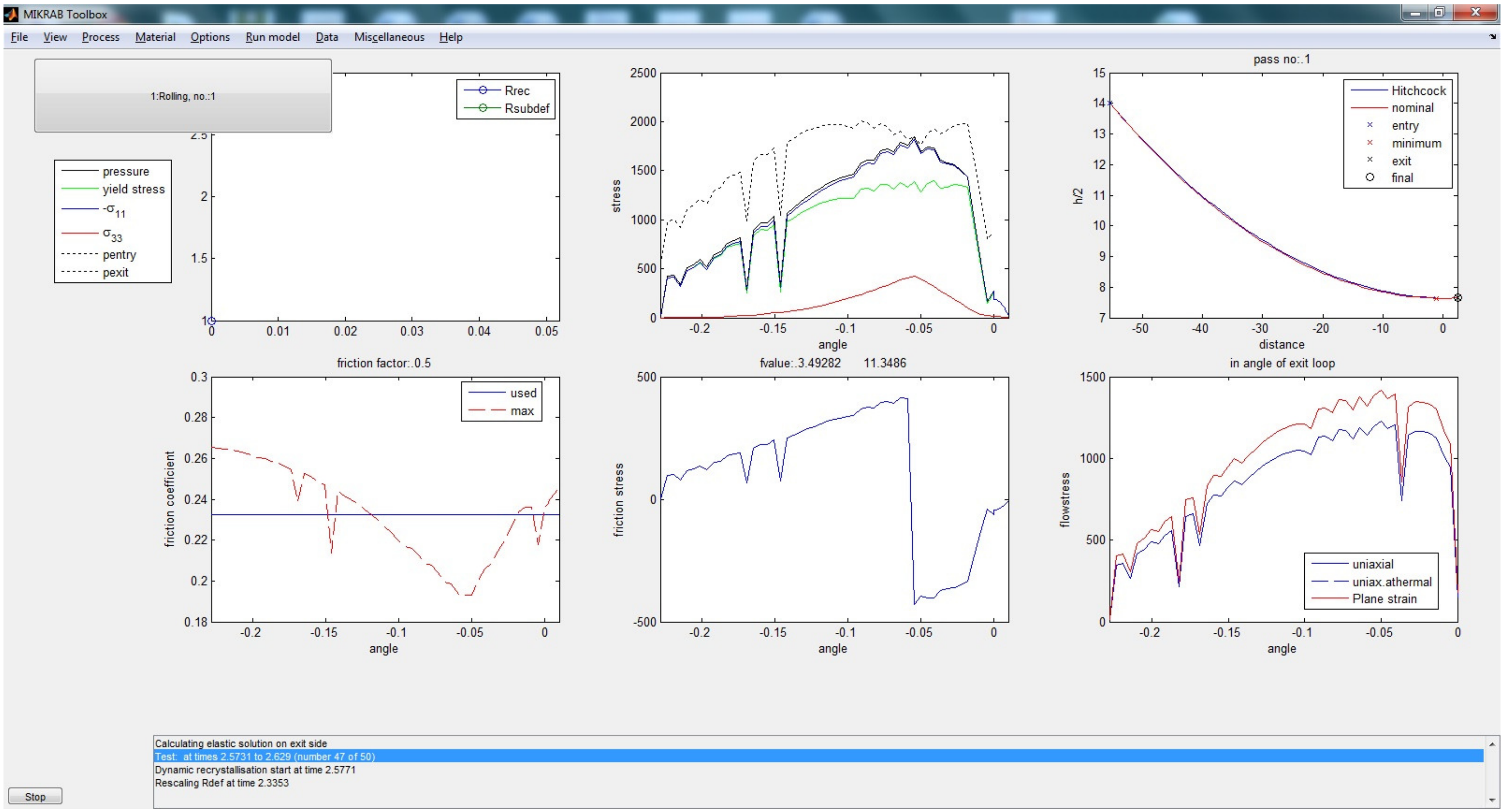
Yield criteria



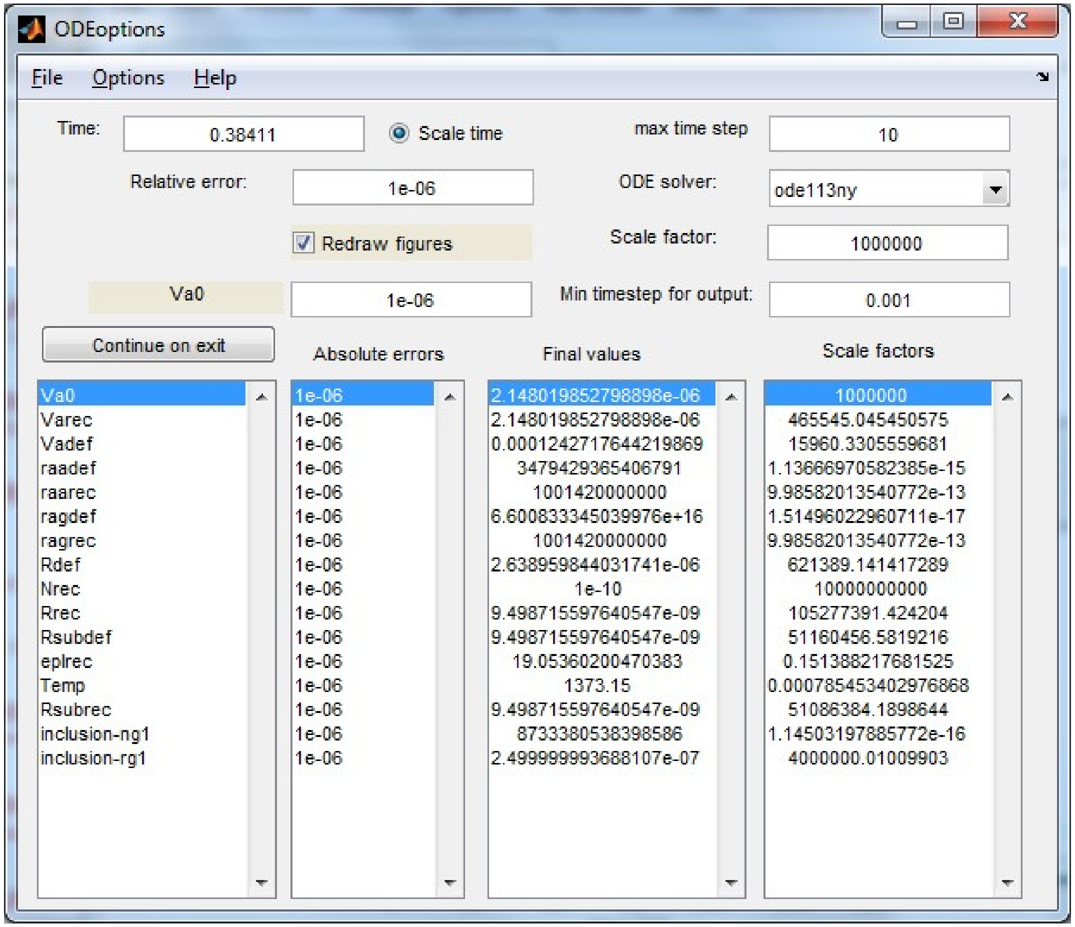
Model parameters



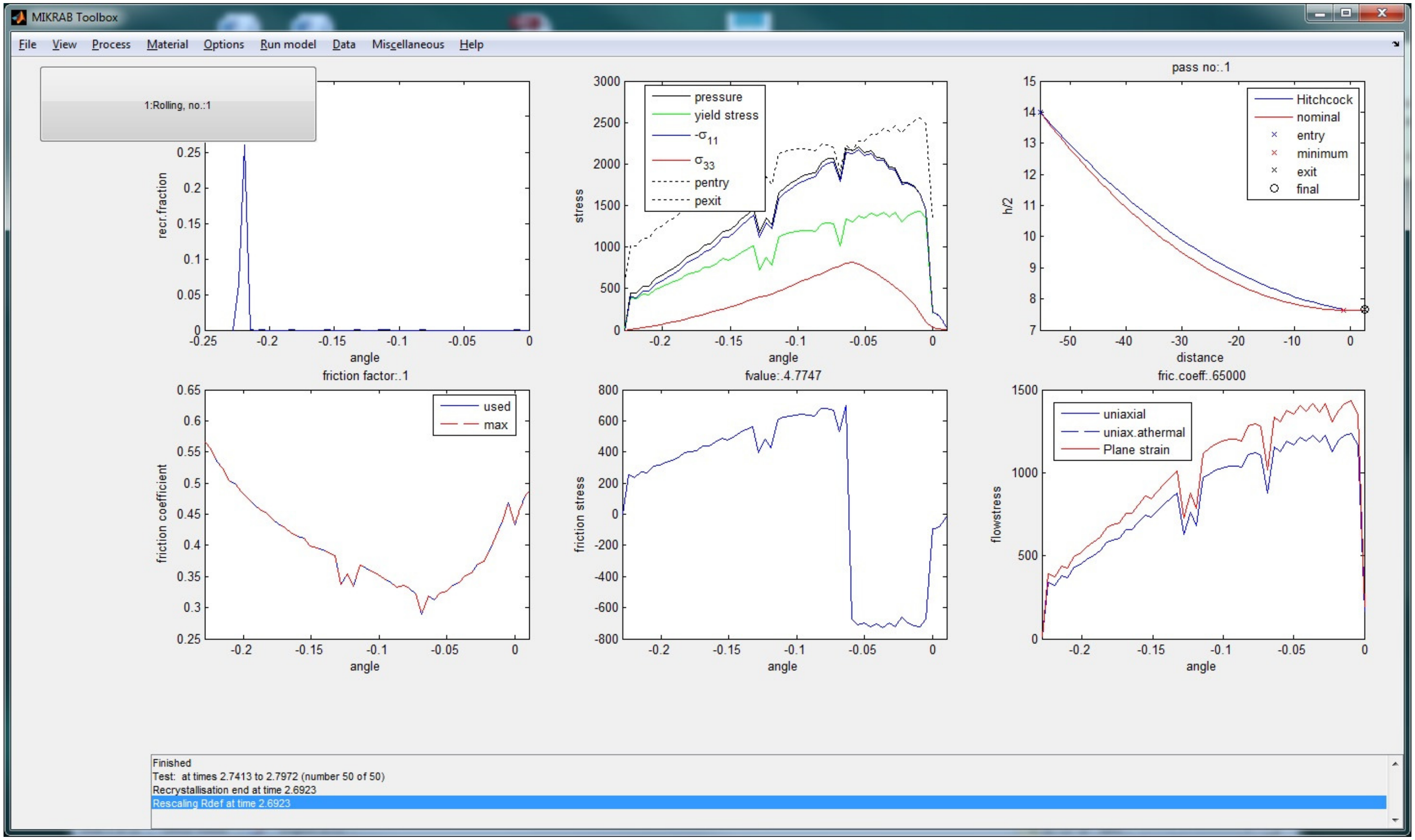
Calculation



Model variables



Results for rolling (pass 1)



And

To be continued!

Thank you !