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Modelling of Microstructure Evolution and Rolling Force during Multi-pass Hot Rolling of Steels

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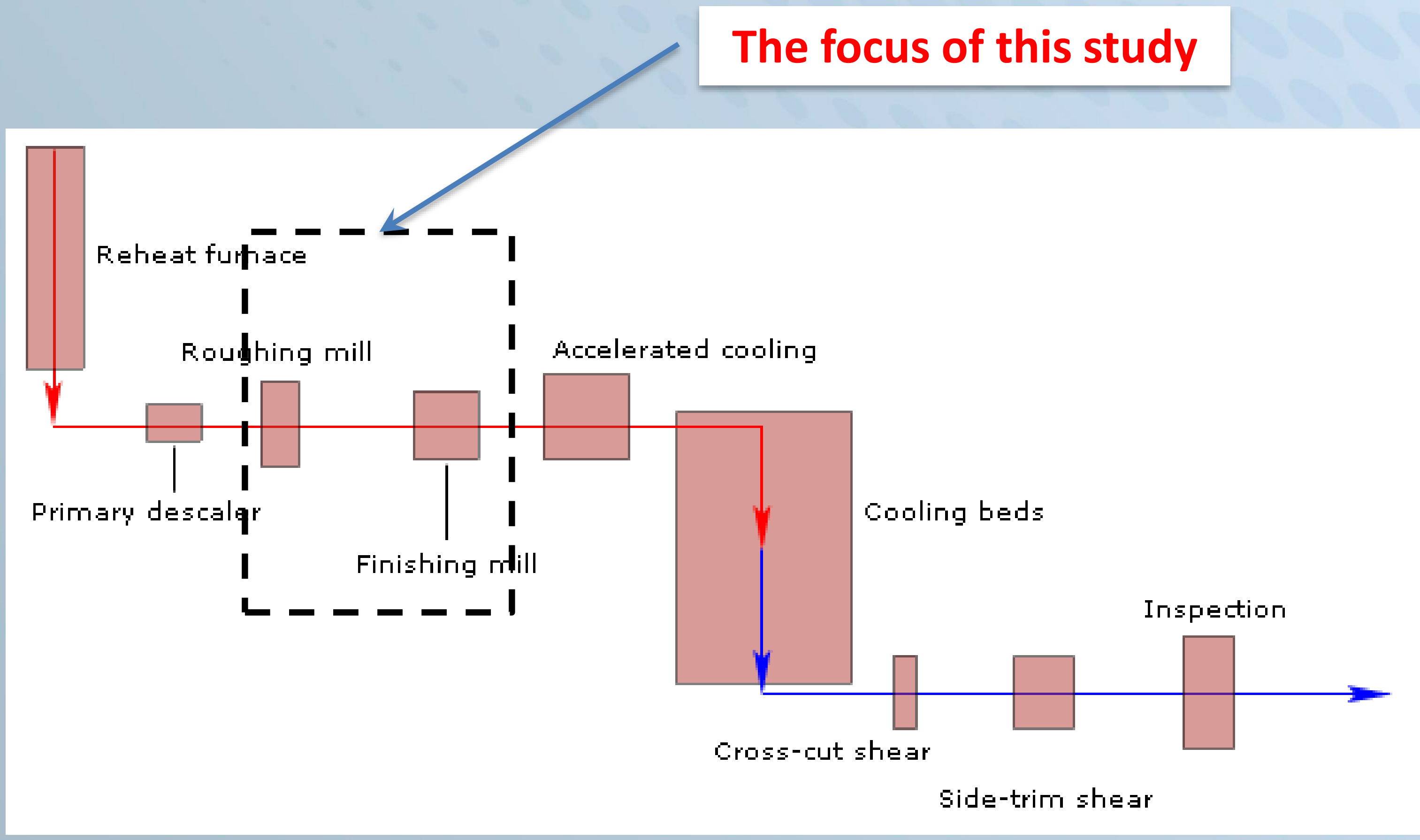
Overview of Hot Rolling Process

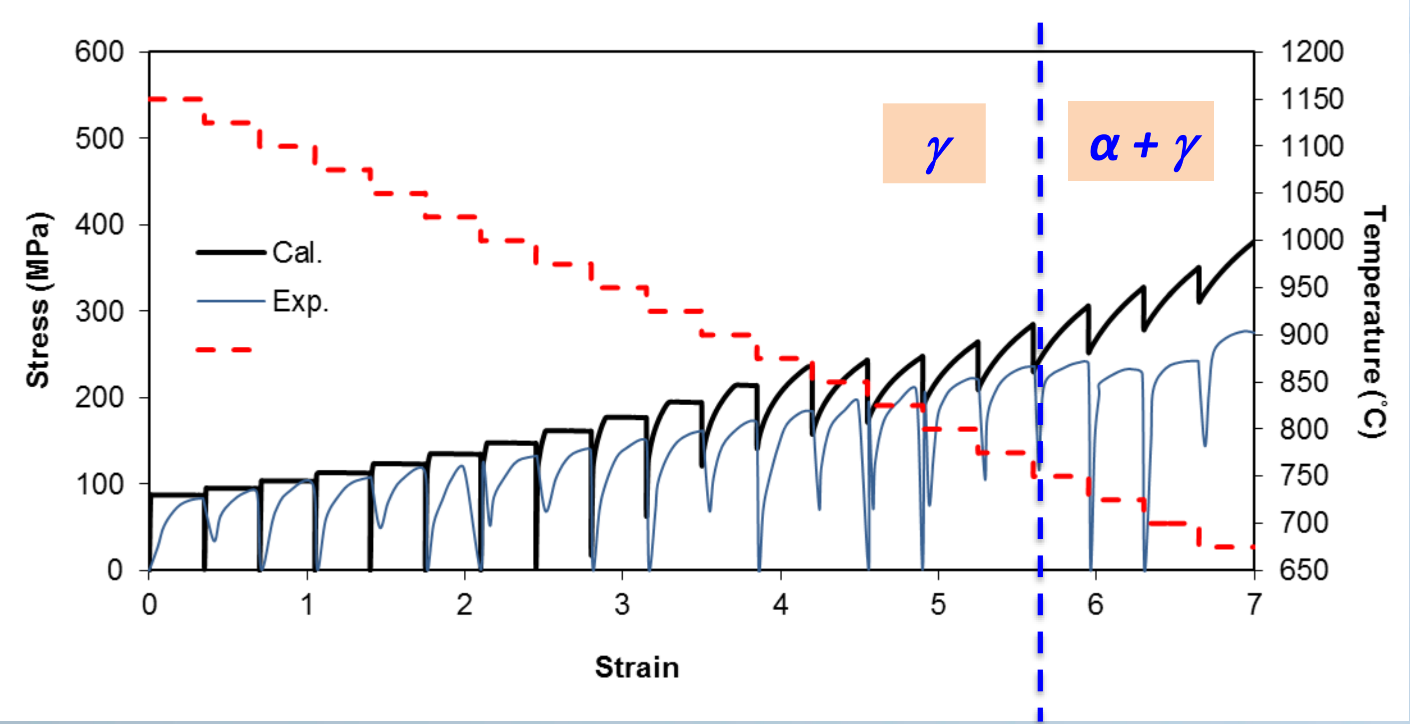


Previous Work Reported at TMP 2012

- **Deformation-induced precipitation of M(C,N) in austenite**
  - JMA type modelling of precipitation kinetics.
  - Deformation affected number of nucleation sites.
  - Precipitation at grain boundaries and inside grains.
  - Evolution of size and fraction of precipitates.
- **Static recrystallisation**
  - JMA type modelling of recrystallisation kinetics.
  - Evolution of recrystallisation during hot rolling.
- **Evolution of grain size during hot rolling**
  - Effective strain and recrystallisation.
  - Effective strain on grain size.

Z. Guo, A.P. Miodownik, Materials Science Forum, 706-709 (2012) 2728-2733.

Rolling Force Prediction at TMP-2012



Rolling force profile during multi-pass hot rolling at the time of TMP-2012.

Present Work – Evolution of Rolling Force

Physical phenomena taking place

- Precipitation of MX carbides or carbonitrides
- Recrystallisation kinetics
- Grain refinement and growth (coarsening)
- Phase transformation – austenite decomposition to ferrite, pearlite, bainite and martensite

Interactions considered

- Interactions between precipitation and recrystallisation
- Effect of recrystallisation and precipitation on grain size
- Effect of grain size on phase transformation kinetics
- Effect of recrystallisation (effective strain), grain size (Hall-Petch effect) and phase transformations (microstructure) on rolling force

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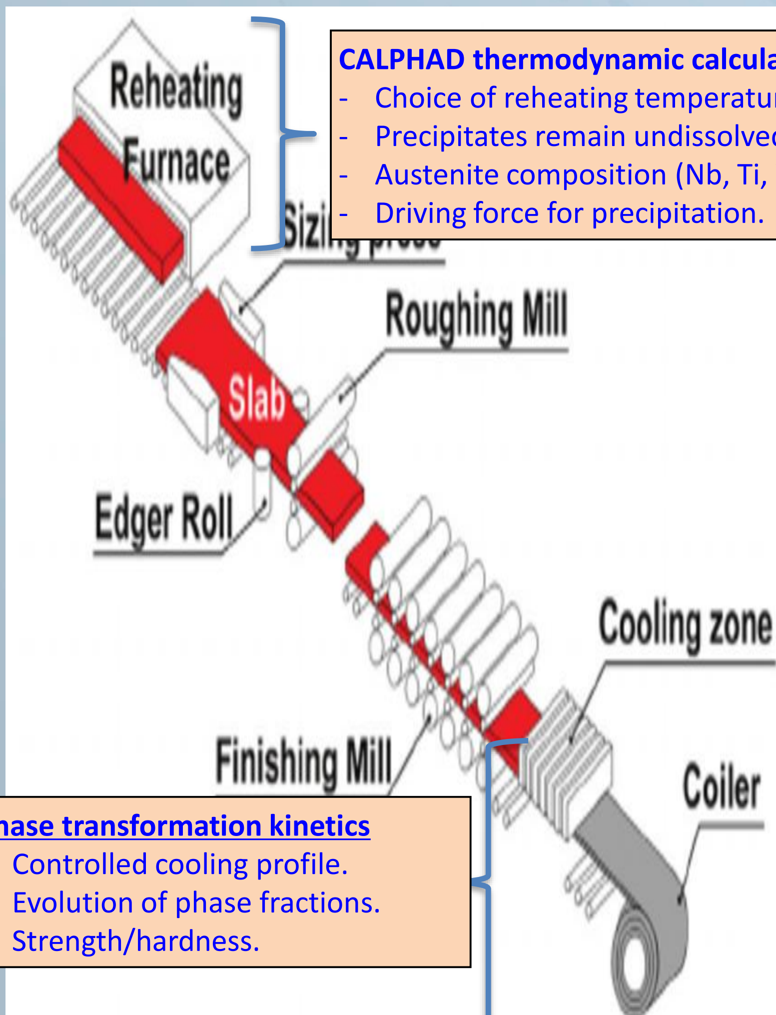
Modelling Procedures



CALPHAD thermodynamic calculation
- Choice of reheating temperature.
- Precipitates remain undissolved?
- Austenite composition (Nb, Ti, V).
- Driving force for precipitation.

Phase transformation kinetics
- Controlled cooling profile.
- Evolution of phase fractions.
- Strength/hardness.

High temperature strength and flow stress curve
- As a function of deformation temperature, strain and strain rate.
- Flow stress → dislocation density → number of nucleation sites.

Precipitation kinetics – evolution of size and fraction
- Johnson-Mehr-Avrami type kinetics model.
- Precipitates at grain boundaries and dislocations (inside matrix).
- Lifshitz-Slyozov-Wagner type coarsening model.
- Evolution of austenite composition.

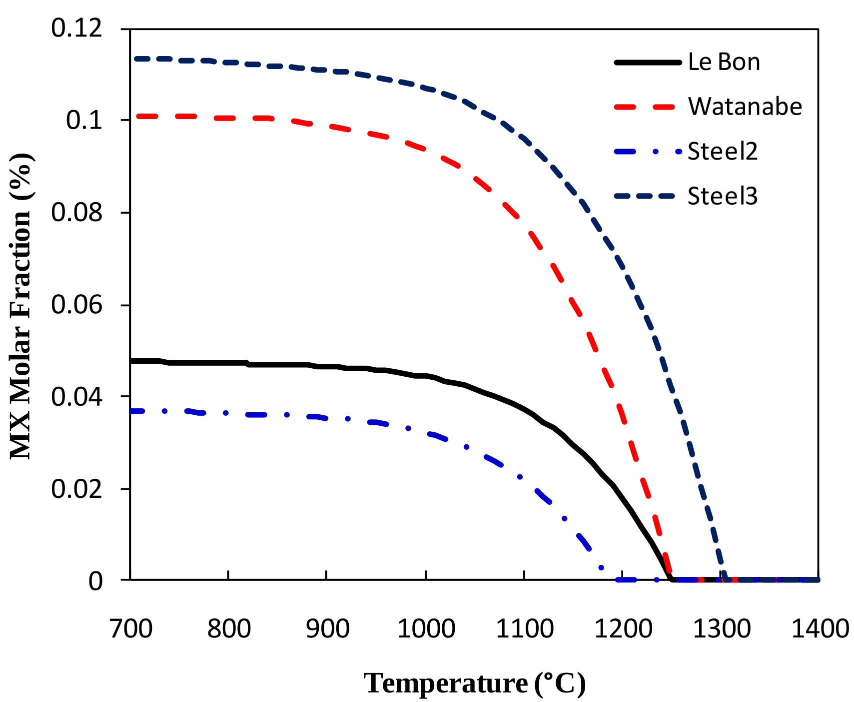
Recrystallisation kinetics – evolution of effective strain
- Empirical model of Rodriguez-Ibabe and Lopez et al.
- Dependence on austenite composition (Nb, Ti and V).
- Dependence on effective strain and grain size.

Grain refinement and coarsening
- Empirical model of Rodriguez-Ibabe and Lopez et al.
- Dependence on effective strain.

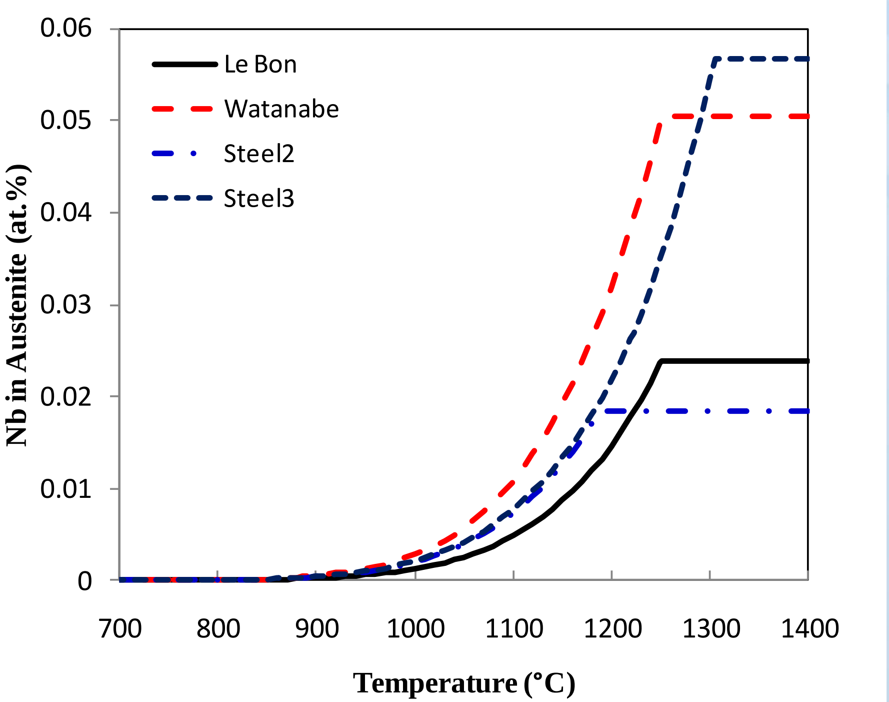
Phase transformation kinetics
- Kirkaldy type model for ferrite, pearlite and bainite formation.
    - Dependence on prior austenite grain size.
    - Redistribution of carbon during transformation.
        - Affecting Bs and Ms temperatures.
- Koisinen and Marburger type model for martensite formation.

Strength and flow stress curve of ferrite, austenite etc. phases.
- Solution strengthening and Hall-Petch effect.
- Working hardening and flow softening (creep).

Thermodynamic Calculation – CALPHAD



Molar fraction of MX in the fours steels calculated using JMatPro.



Nb in austenite in the fours steels calculated using JMatPro.

Johnson-Mehl-Avrami Theory

Original JMA theory:

$$x = \frac{V}{V_{eq}(T)} = 1 - \exp\left(-\frac{\pi}{3} N_r G_r^3 t^4 \right)$$

When steady state nucleation operates:

$$x = 1 - \exp\left(-f \, \frac{l_c^{3-p}}{p+1} N_r G_r^p t^{p+1} \right)$$

f: shape factor

l_c: critical dimension

When nucleant site saturation has been reached:

$$x = 1 - \exp\left(-f \, l_c^{3-p} N_o G_r^p t^p \right)$$

Li, Miodownik, Saunders, Mater. Sci. Technol. 18 (2002) 861-868

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Nucleation Rate and Growth Rate

Nucleation rate:

$$N_r = x_\alpha \frac{N_o D}{a_o^2} \exp\left(-\frac{16\pi\alpha^3}{3NkT} f(\theta) \frac{\Delta H_m^3}{\Delta G_m^2} \right)$$

Growth rate:

$$G_r = \kappa D \left[\frac{\Delta G_m}{RT} \right]$$

θ: wetting angel
α: constant
κ: constant

Li, Miodownik, Saunders, Mater. Sci. Technol. 18 (2002) 861-868

N_0 vs Dislocation Density vs Flow Stress

- N_0 vs. dislocation density ρ - from Dutta and Sellars:

$$N_0 = 0.5\rho^{1.5}$$

- Dislocation density ρ vs. flow stress σ - from strengthening theory:

$$\Delta\rho = \left(\frac{\sigma - \sigma_y}{\alpha M \mu b} \right)^2$$

- Calculation of N_0 in the present study:

$$N_0 = 0.5(\rho_0 + \Delta\rho)^{1.5} = 0.5\left(\rho_0 + \left(\frac{\sigma - \sigma_y}{\alpha M \mu b} \right)^2 \right)^{1.5}$$

Dutta, Valdes, and Sellars: Acta Metall. Mater. 40 (1992) 653

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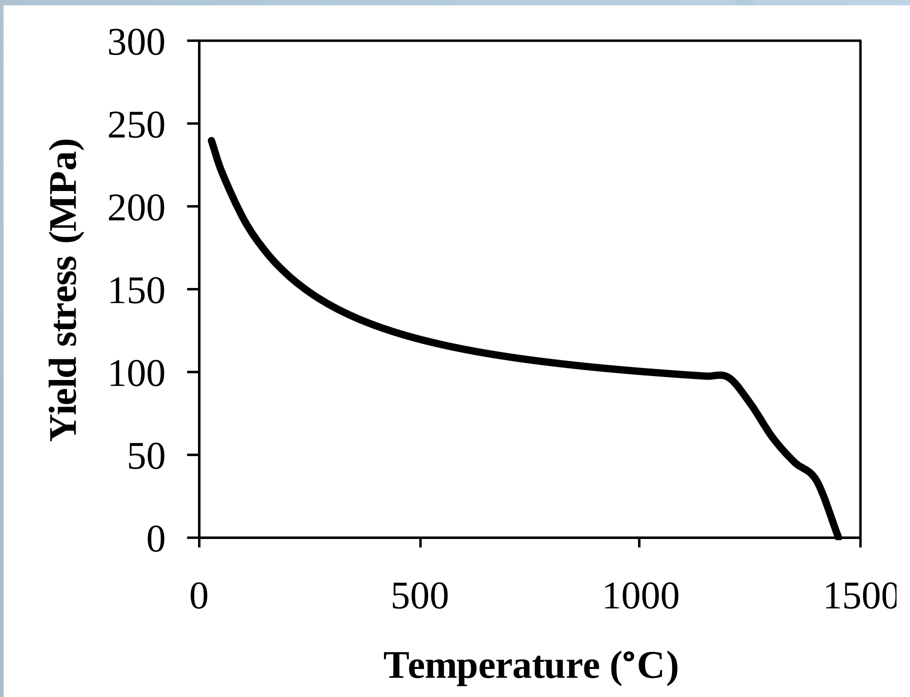
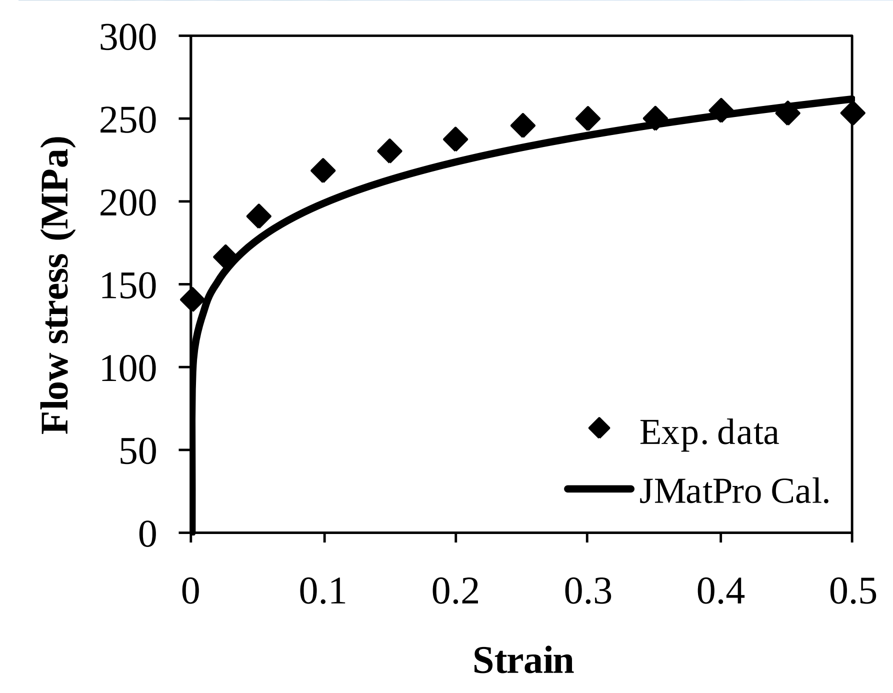
Flow Stress Calculation vs. Experiment



Yield stress of austenite as a function of temperature calculated at strain rate 10 s^{-1}.



Flow stress curve at 950° C at strain rate 10 s^{-1}, experimental data from Ref. .

Quoted by Dutta et al.: Fe-30Ni alloy (by Rainforth et al.)
Deformation temperature: 950°C, at strain rate: 10 s^{-1}.

Precipitate Coarsening Theory

Original Lifshitz-Slyozov-Wagner theory:

$$\left[\bar{r}_t^{\,3} - \bar{r}_o^{\,3}\right]^{1/3} = kt^{1/3}$$

k is calculated as below in this study:

$$k = \left[\frac{8D\sigma N_\alpha(1-N_\alpha)V_m}{9(N_\beta - N_\alpha)^2 RT}\right]^{1/3}$$

D is the diffusion coefficient

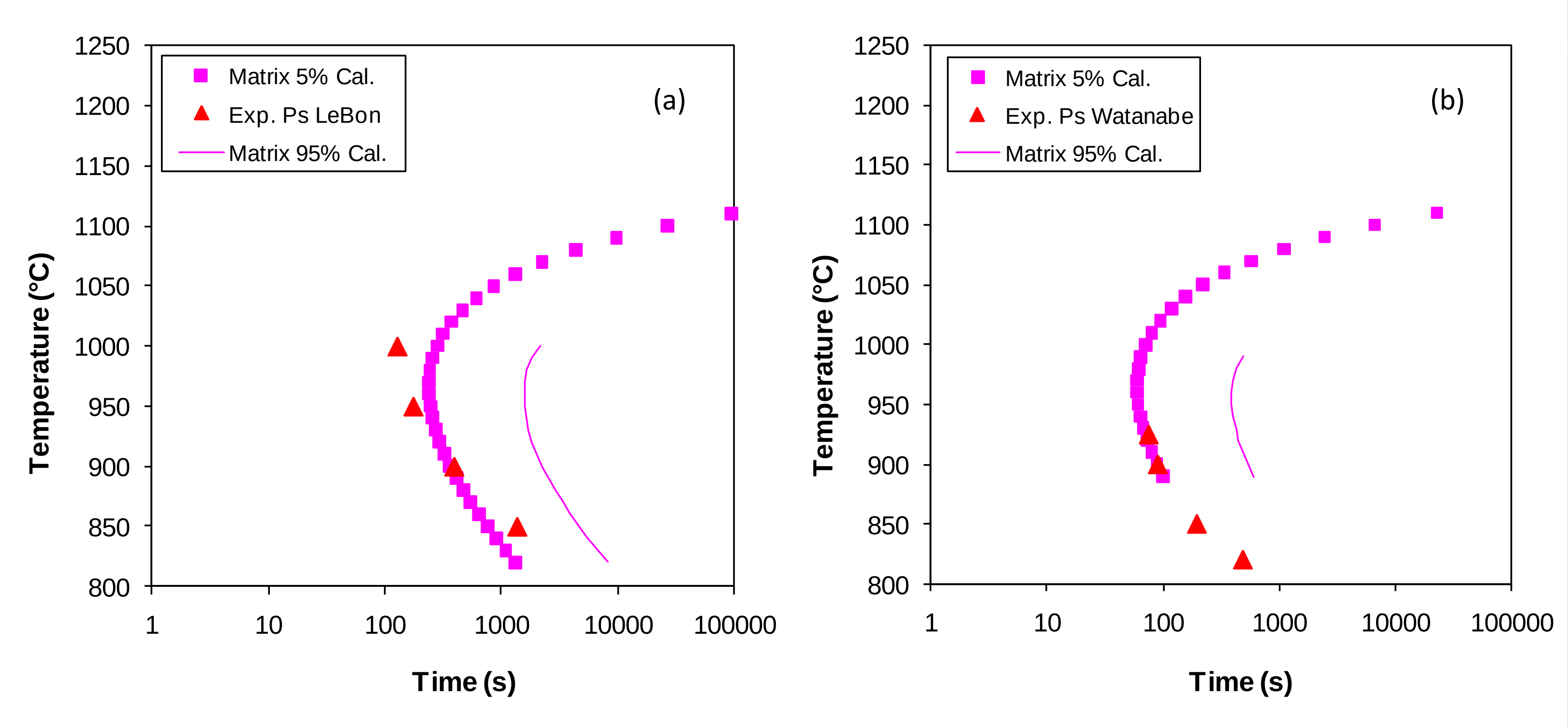
σ: surface energy

N_α and N_β are the mole fractions of solute in matrix and precipitate

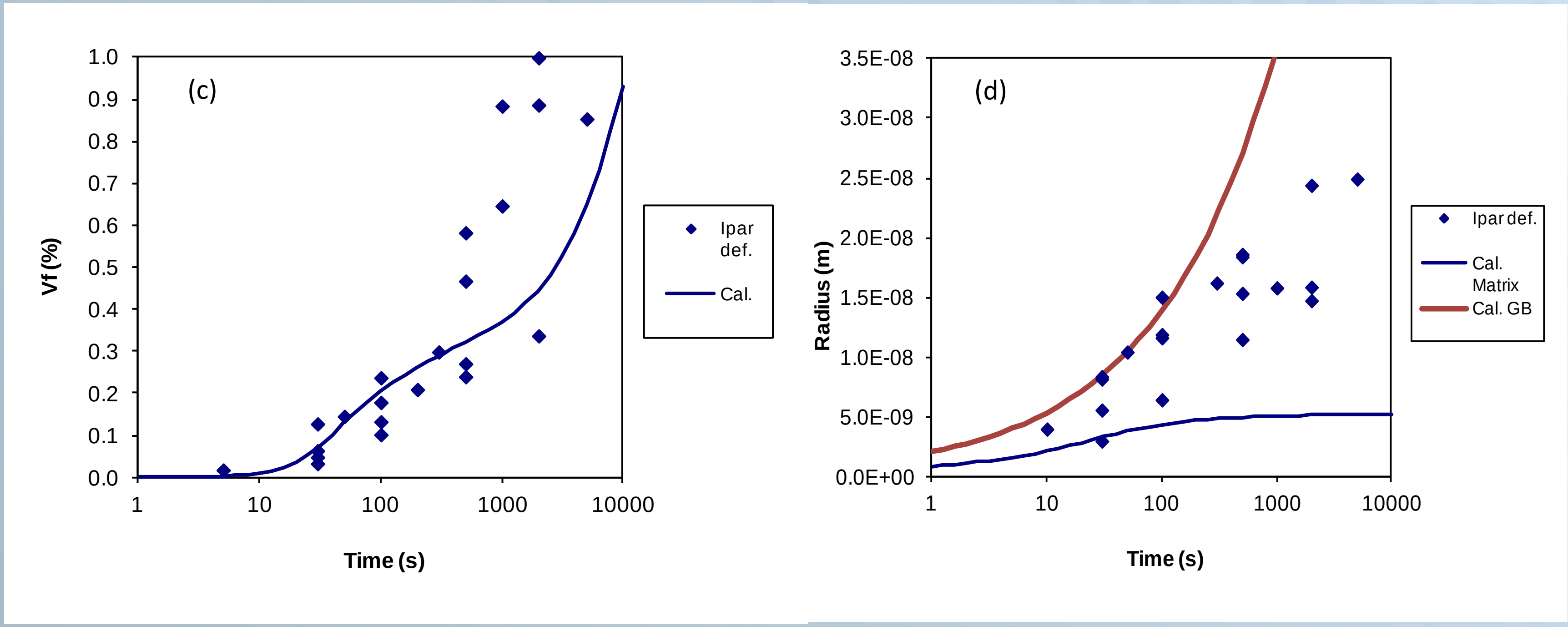
V_m is the molar volume of precipitate

Li, Saunders, Miodownik, Metall. Trans. 33A (2002) 3367-3373

Calculated TTP Diagram vs. Experimental Data



Evolution of Amount and Size of M(C,N) during Isothermal Holding



Calculated isothermal precipitation kinetics at 1000°C of Ipar steel in deformed condition: (c) volume fraction, and (d) radius. GB is for grain boundary precipitates and Matrix is for precipitates inside the grain.

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Recrystallisation, Grain Refinement and Growth

JMA type precipitation kinetics:

$$t_{0.5} = C_1 \cdot D_0 \cdot \varepsilon^{C_2 D_0^{-0.15}} \cdot \dot{\varepsilon}^{C_3} \cdot \exp\left(\frac{Q_1}{RT}\right) \cdot \exp\left[\left(\frac{Q_2}{T} - C_4\right) \cdot \left([Nb] + C_5[Ti] + C_6[V]\right)\right]$$

Effective strain:

$$\varepsilon_{eff} = \varepsilon_{i-1} + \lambda(1 - X_i)\varepsilon_i$$

Grain refinement:

$$d_i = K d_{i-1}^{m} \varepsilon_i^{p}$$

Grain coarsening:

$$D^n = d_{rex}^n + C_7 t_q \exp\left(-\frac{Q_3}{RT}\right)$$

C_1 to C_7: various constants.
Q_1, Q_2 and Q_3: various activation energies.
λ, K, m, p and n: material constants.
X_i: recrystallised fraction.
t_q: time after complete recrystallisation.

Abad, Fernández, López and Rodriguez-Ibabe, ISIJ International, 41 (2001), 1373–1382

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Transformation Kinetics – Kirkaldy Model

$$\tau(x,T) = \frac{1}{\alpha D \Delta T^{q}} \int_{0}^{x} \frac{dx}{x^{2(1-x)/3}(1-x)^{2x/3}}$$

$\alpha = \beta 2^{(G-1)/2}$, where β is an empirical coefficient,
G is the ASTM grain size,
D is an effective diffusion coefficient,
ΔT is the undercooling,
q is an exponent dependent on the diffusion mechanism
x is the fraction transformed.

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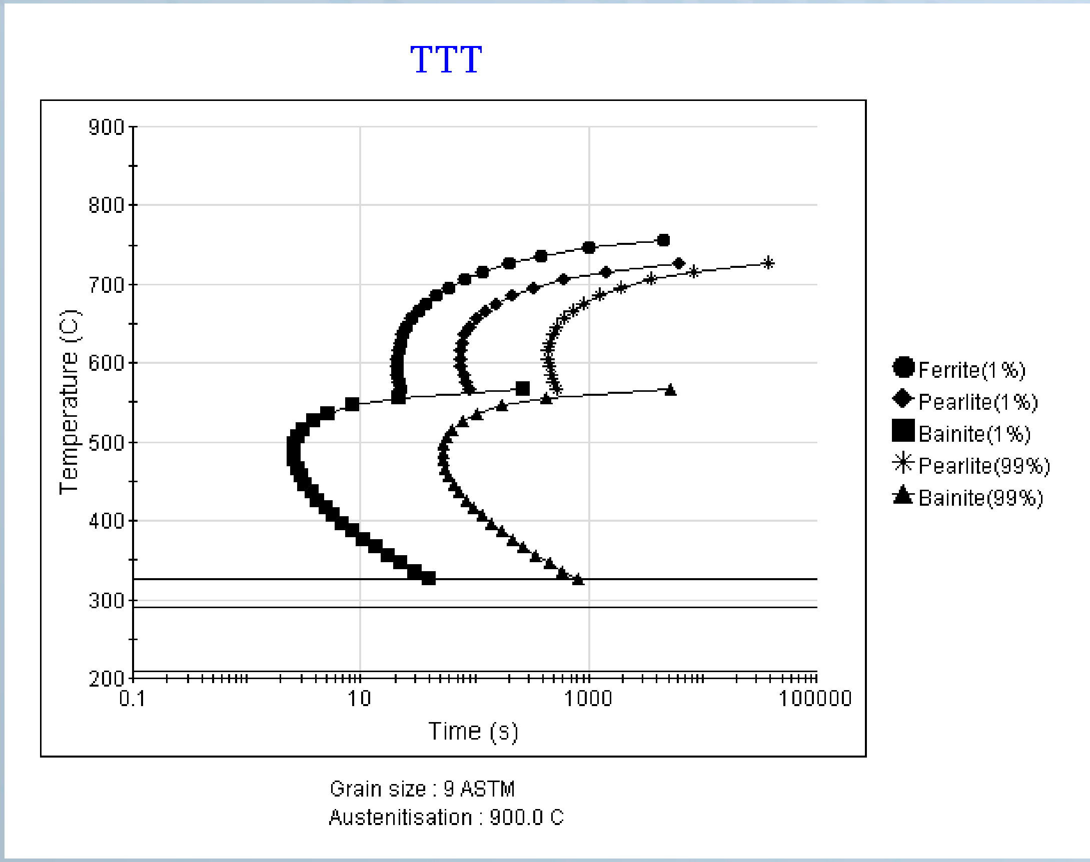
Example of TTT Diagram



Austenisation temperature 900°C, Grain size ASTM 9.

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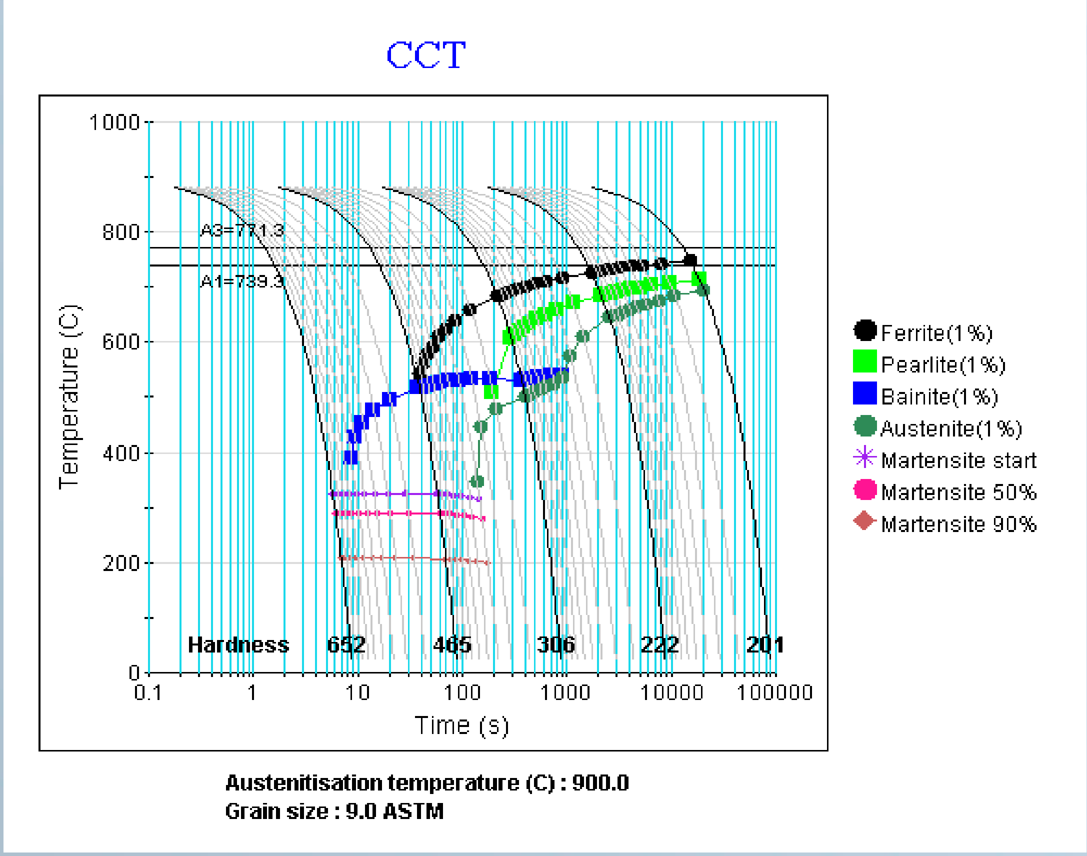
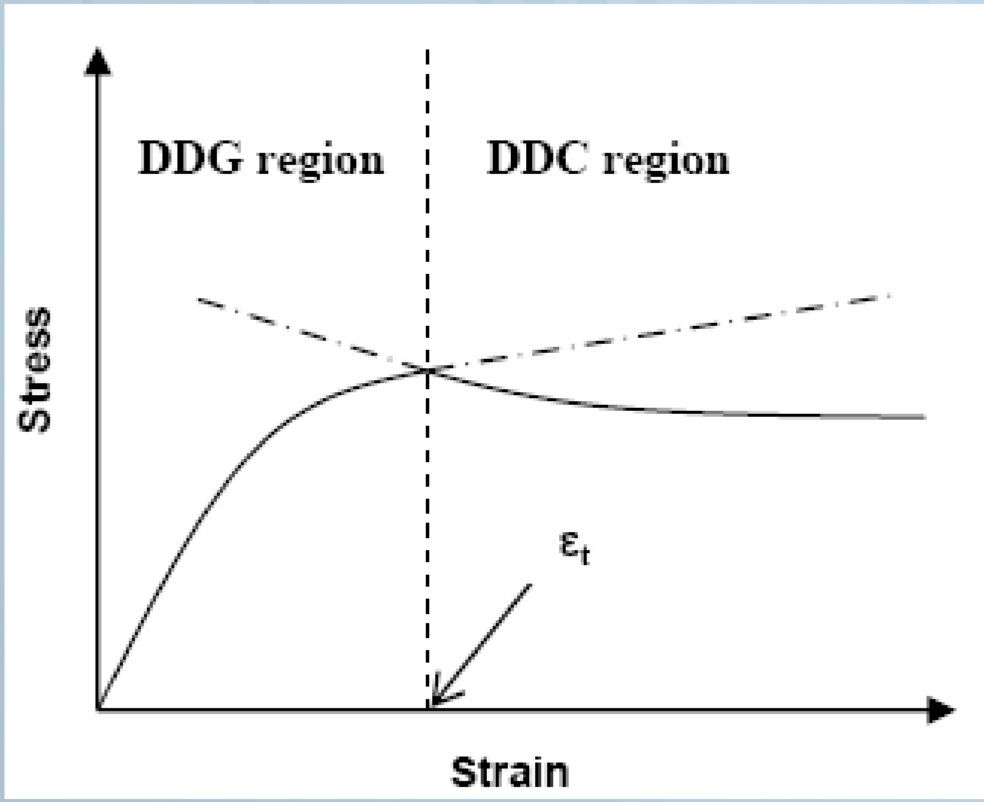
Example of CCT Diagram



Austenisation temperature 900°C, Grain size ASTM 9.

Modelling of Flow Stress Curve



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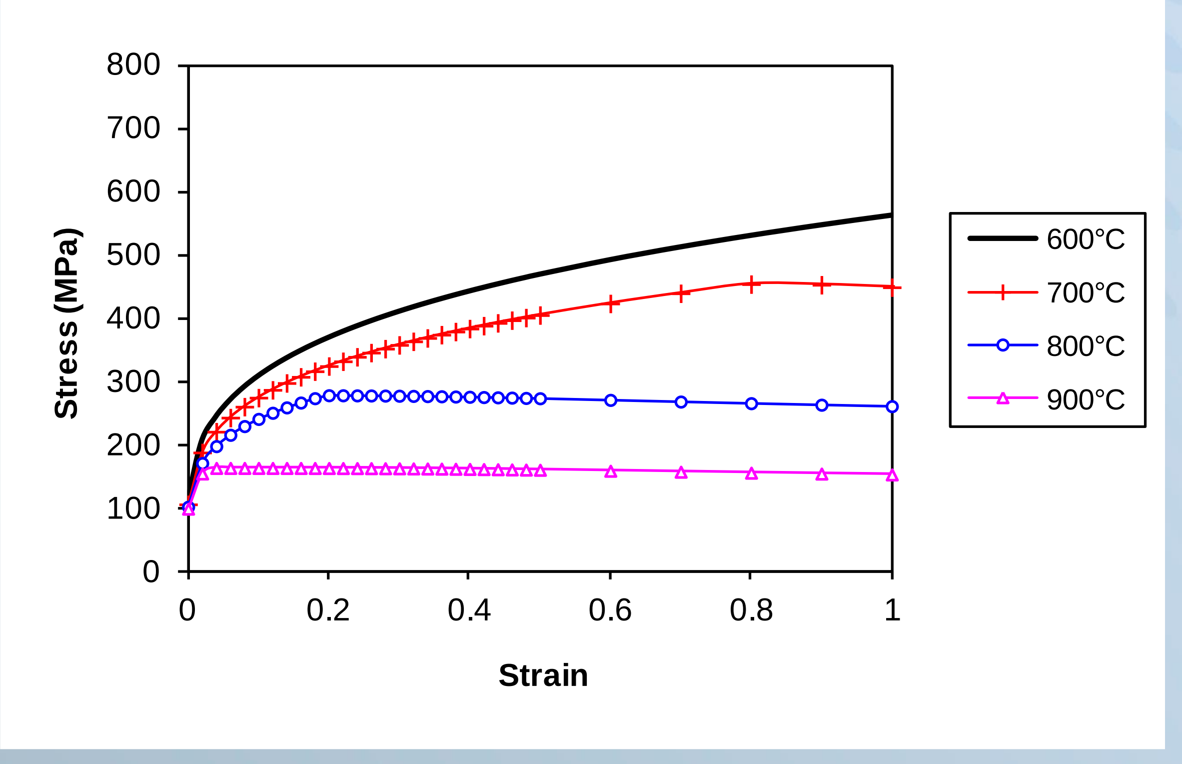
Flow Stress Curves of Austenite



Strain rate 1.0 s^{-1}

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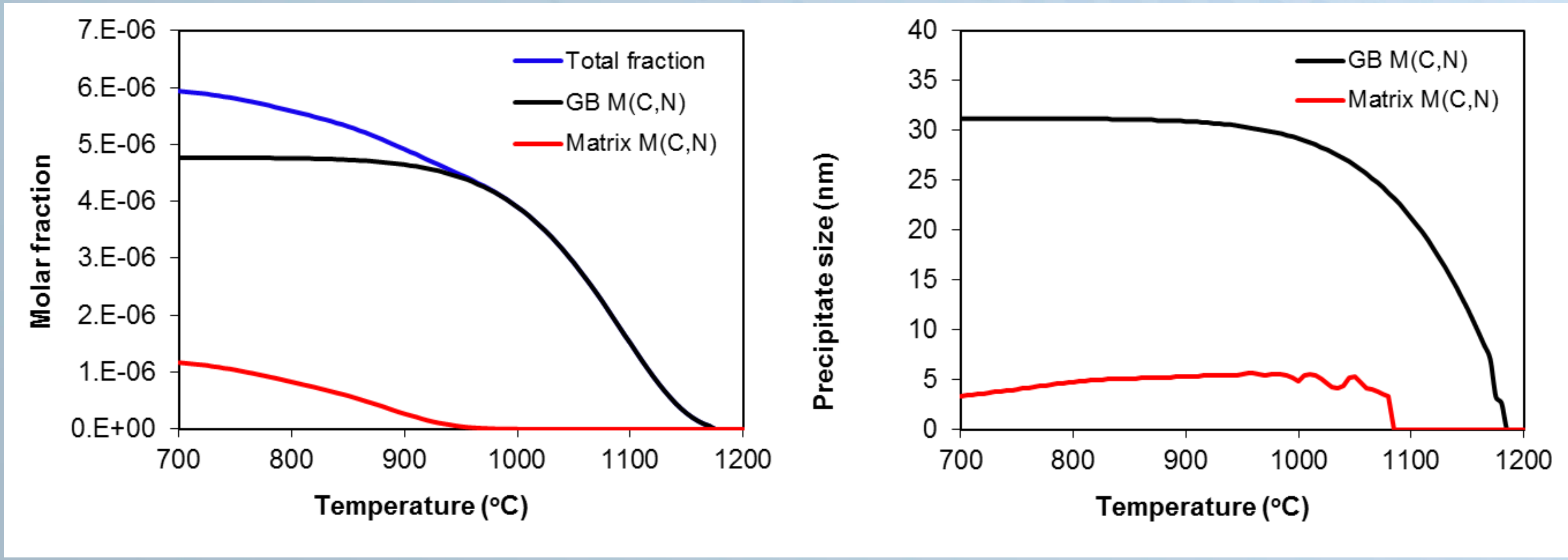
Example Calculations of a Microalloyed Steel

Experimental details:

- Alloy composition (wt.%): Fe-0.1C-0.31Si-1.42Mn-0.0053N-0.035Nb.
- Solution treatment at 1200 or 1400°C, initial grain size 129 or 806 μm.
- Multi-pass torsion tests: 17 passes from 1180 to 700°C at 30°C interval.
- Deformation strain 0.1 – 0.4 at strain rate 1.0/s.
- Interpass time 30s, 17 passes at 30°C interval (cooling at 1°C/s)

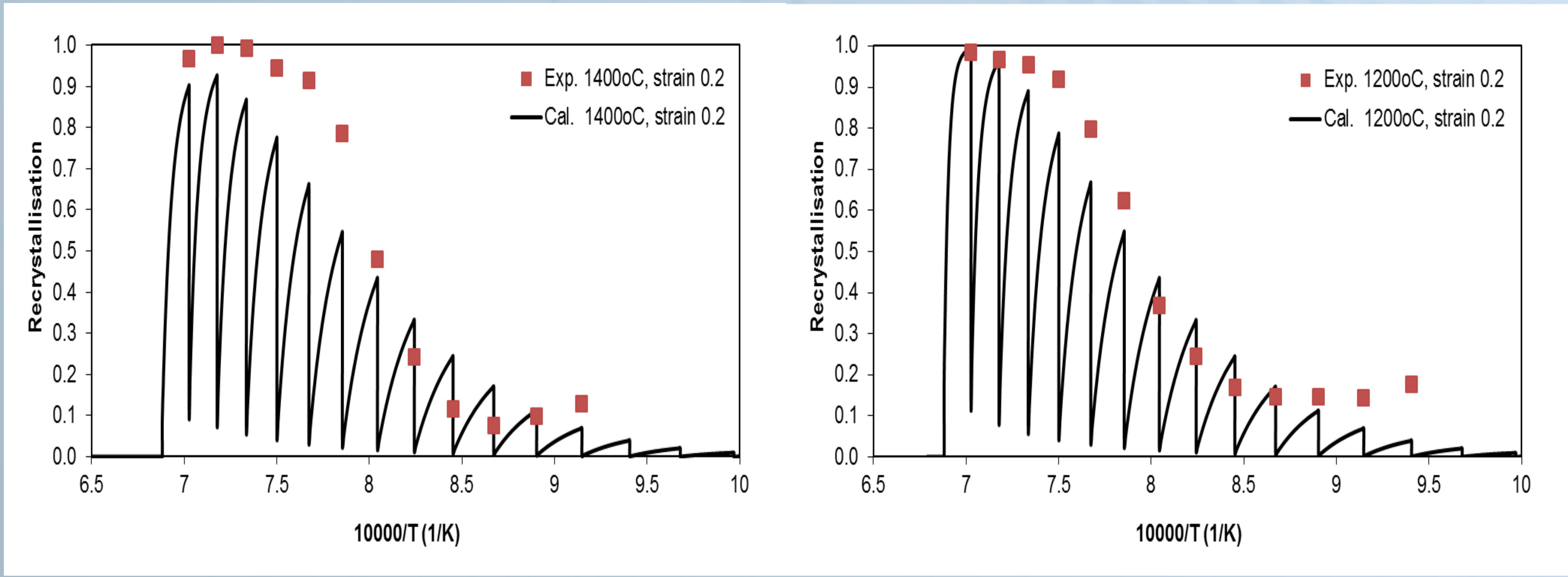
R. Abad, A.I. Fernández, B. López and J.M. Rodriguez-Ibabe, ISIJ International, 41 (2001), 1373–1382. (CEIT, Spain)

Example Calculations – MX Precipitation



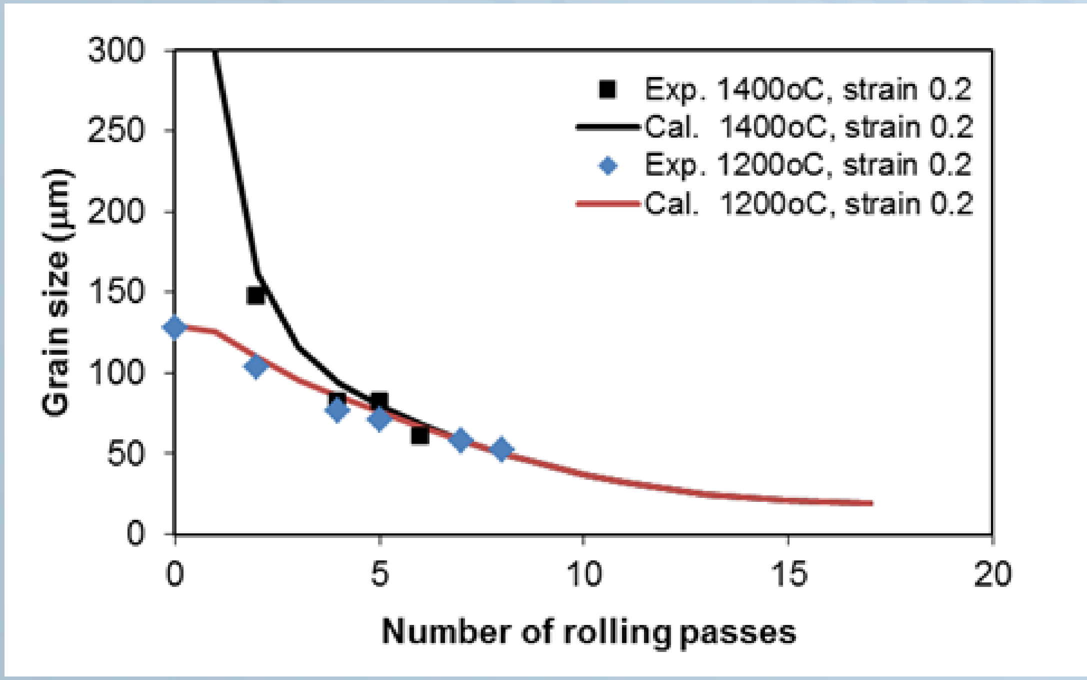
Evolution of M(C,N) precipitation at grain boundary (GB) and inside matrix at strain per pass 0.3 after reheating at 1200°C, precipitate amount, and precipitate size.

Example Calculations – Recrystallisation



Evolution of recrystallisation fraction during deformation at strain per pass 0.2 after reheating at different temperatures, (a) 1400°C, and (b) 1200°C.

Example Calculations – Grain Size



Evolution of grain size after reheating at 1400°C and 1200°C, prior austenite grain size as 806 and 129 µm, respectively.

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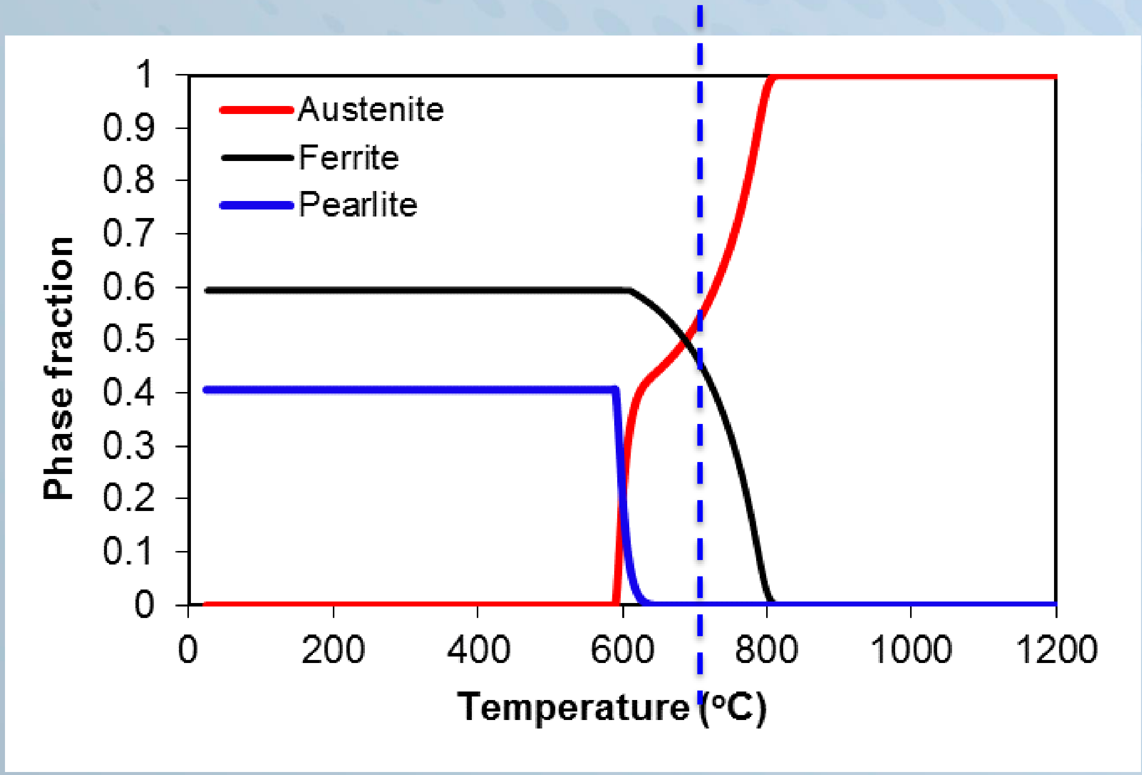
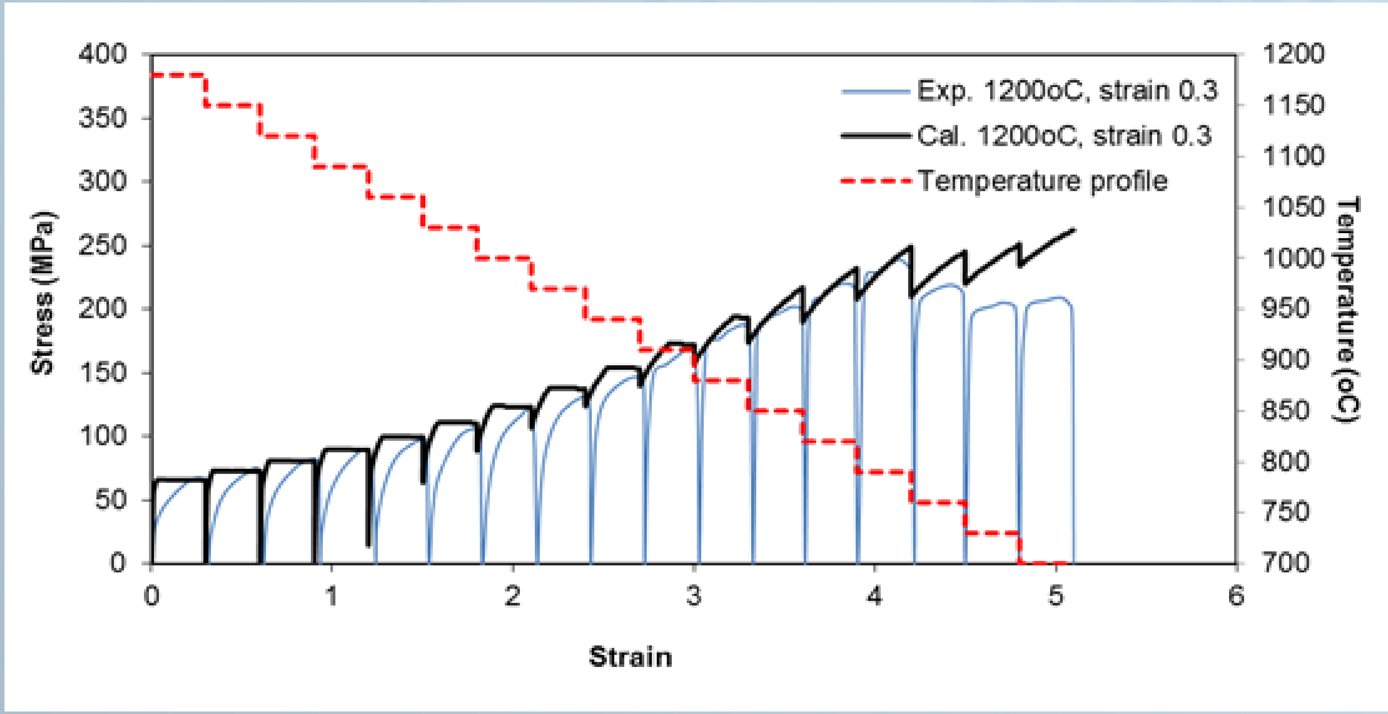
Example Calculations – Phase Transformations



Evolution of austenite decomposition during cooling at strain per pass 0.3 after reheating at 1200°C. The cooling rate is assumed to be 1 °C/s after deformation.

Example Calculations – Rolling Force



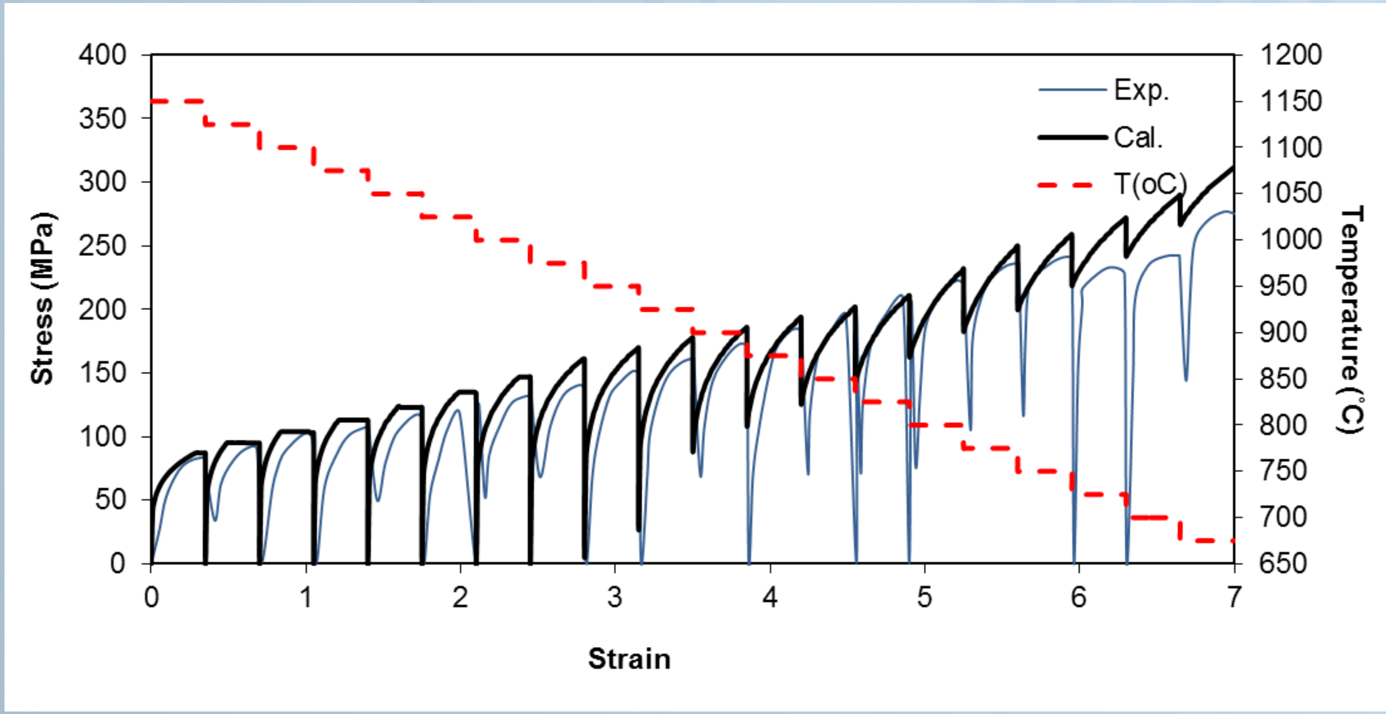
Rolling force profile during multi-pass hot rolling of the microalloyed steel.

Alloys Studied and Deformation Schedule

Table 1. Alloy information and deformation schedule.

Alloy composition (wt%)	Deformation schedule	Ref.
Fe-0.2C-0.2Si-1.0Mn-0.007Nb-0.0056N	Reheating at 1250°C 20 passes, 1st pass at 1150°C, last pass at 675°C Interpass time 20 s, temperature step 25°C Strain rate is 3.63 s^{-1} and strain per pass 0.35	Gomez et al. [5]
Fe-0.05C-1.58Mn-0.04Si-0.03Nb-0.16Mn-0.005N	Reheating at 1410-1430°C 20 passes, 1st pass at 1150°C, last pass at 770°C Interpass time 10 s, temperature step 20°C Strain rate is 1.0 s^{-1} and strain per pass 0.4	Pereda et al. [6]
Fe-0.05C-0.29Mn-0.15Si-0.025Cu-0.01Ni-0.057Cr-0.006Mn	Reheating at 1280°C 20 passes, 1st pass at 1220°C, last pass at 600°C Interpass time 30 s, temperature step 32.63°C Strain rate is 2.0 s^{-1} and strain per pass 0.3	Samuel et al. [7]
Fe-0.07C-0.57Mn-0.18Si-0.027Nb-0.031Cu-0.017Ni-0.024Cr-0.004Mo	Reheating at 1280°C 20 passes, 1st pass at 1260°C, last pass at 760°C Interpass time 30 s, temperature step 26.32°C Strain rate is 2.0 s^{-1} and strain per pass 0.3	Samuel et al. [7]

Example Calculations – Rolling Force



Rolling force profile during multi-pass hot rolling of steel in Gomez et al. [5]

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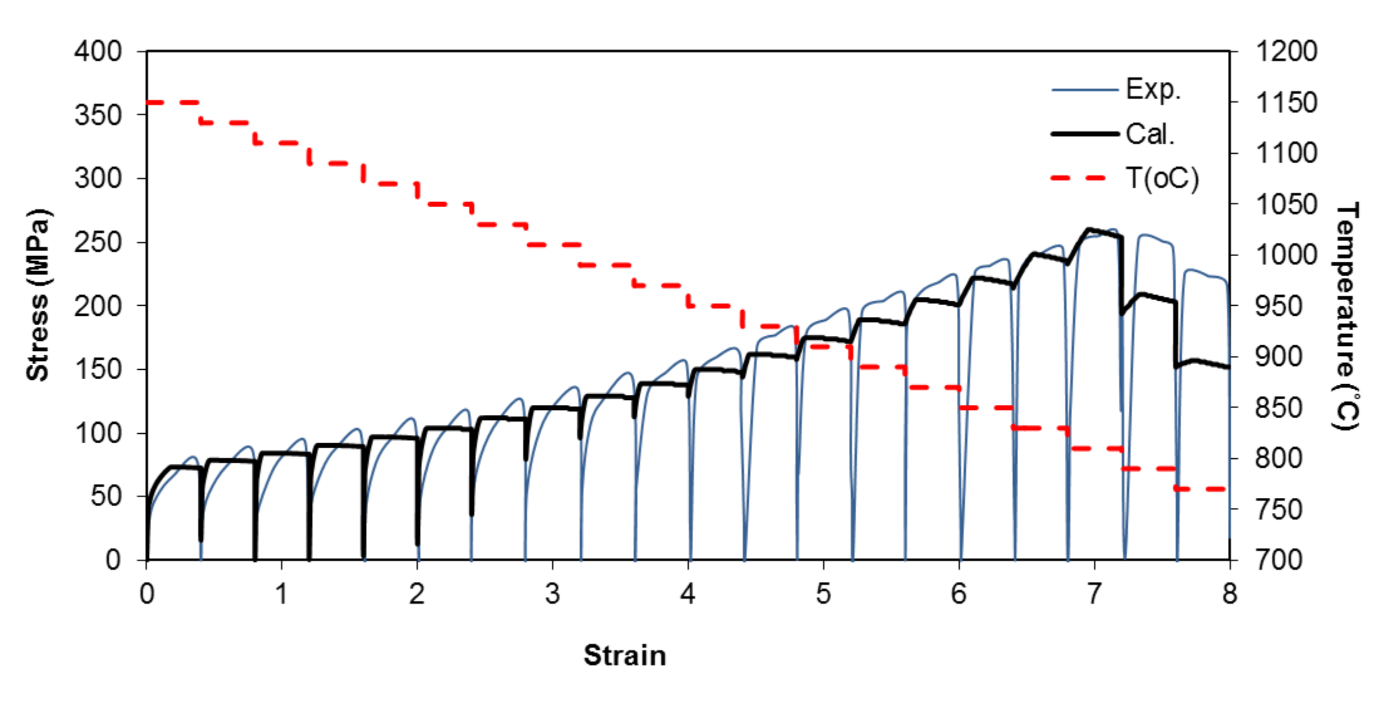
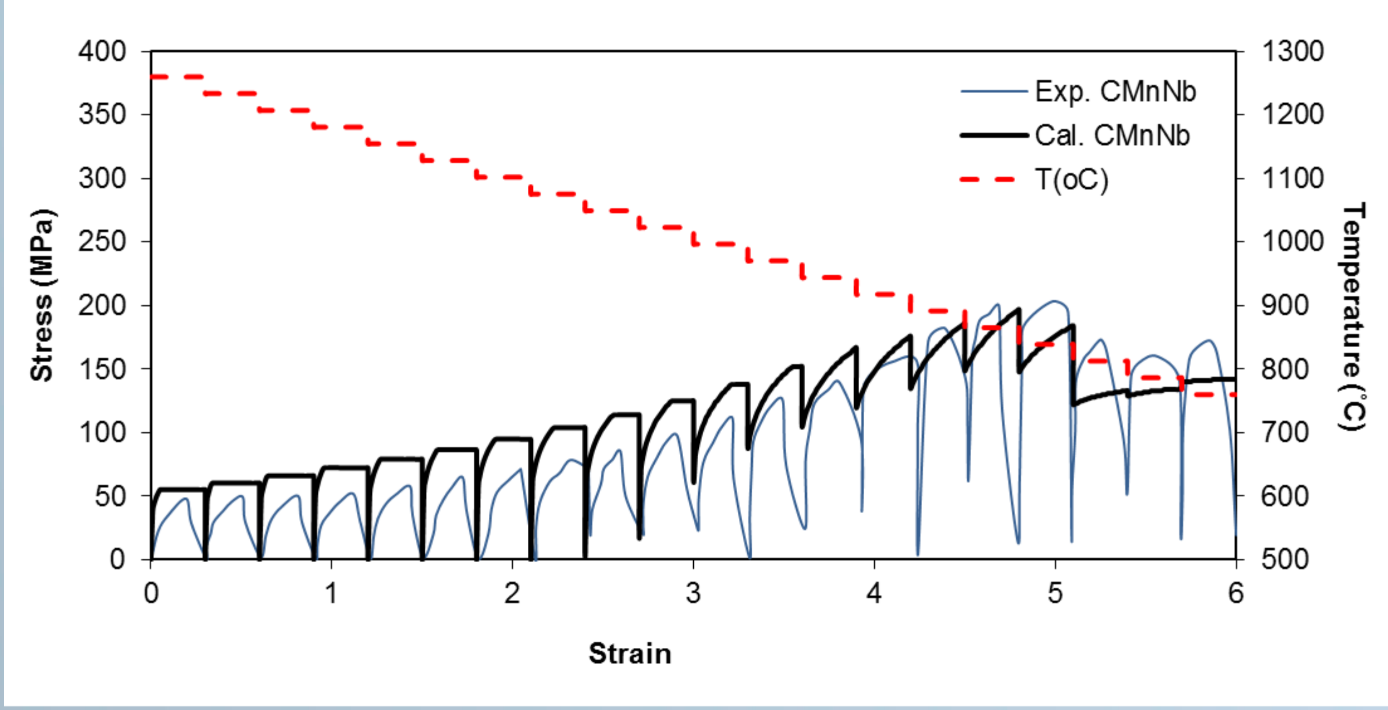
Example Calculations – Rolling Force



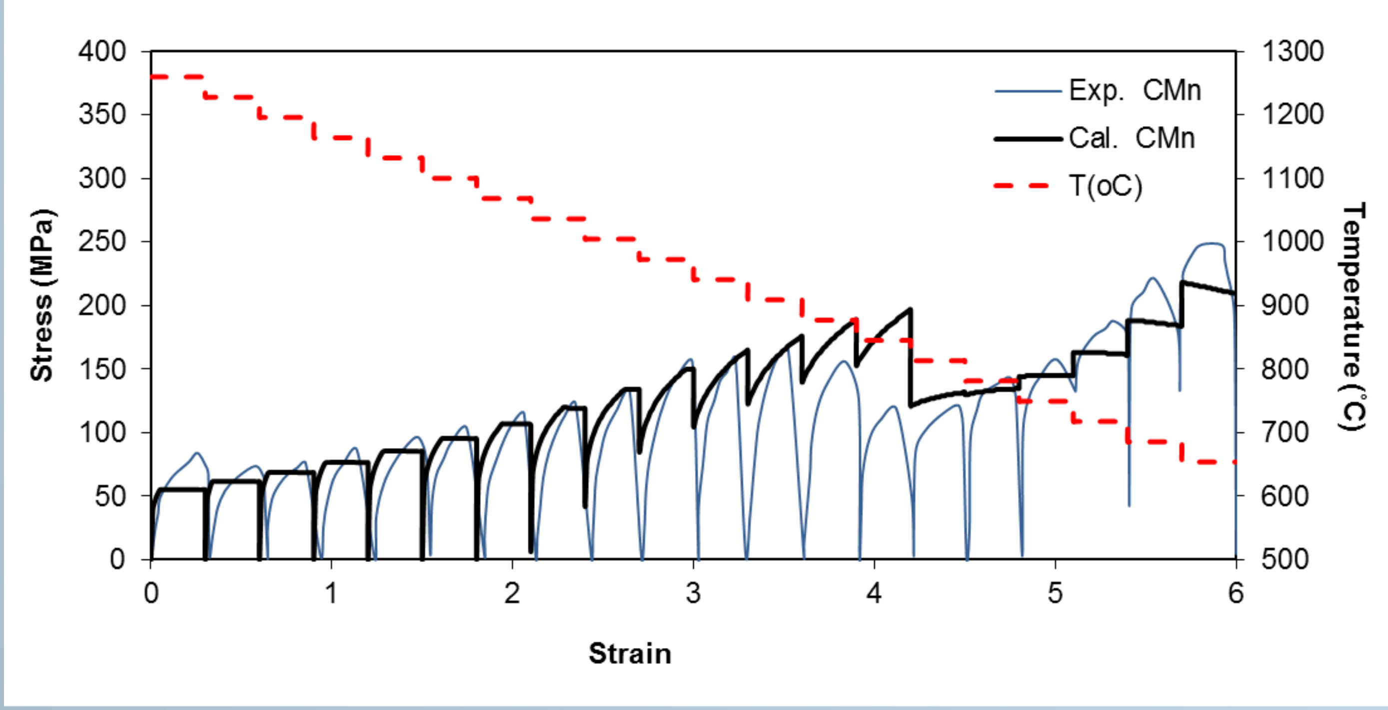
Rolling force profile during multi-pass hot rolling of steel in Pereda et al. [6]

Example Calculations – Rolling Force



Rolling force profile during multi-pass hot rolling of a CMnNb steel in Samuel et al. [7]

Example Calculations – Rolling Force



Rolling force profile during multi-pass hot rolling of a CMn steel in Samuel et al. [7]

Summary and Future Research

The present model:

- calculates the evolution of precipitate size and amount.
- deals with rolling down to ferrite + austenite regime.
- deals with microalloying elements, such as Nb, Ti and V.
- can cope both CMn steels and microalloyed steels.

Future development:

- Precipitation from ferrite or ferrite/austenite interface.
- Strength/hardness at the end of rolling production line.
- Effect of deformation on austenite decomposition and precipitation kinetics.