The stagnant phase during cyclic phase α-γ transformations

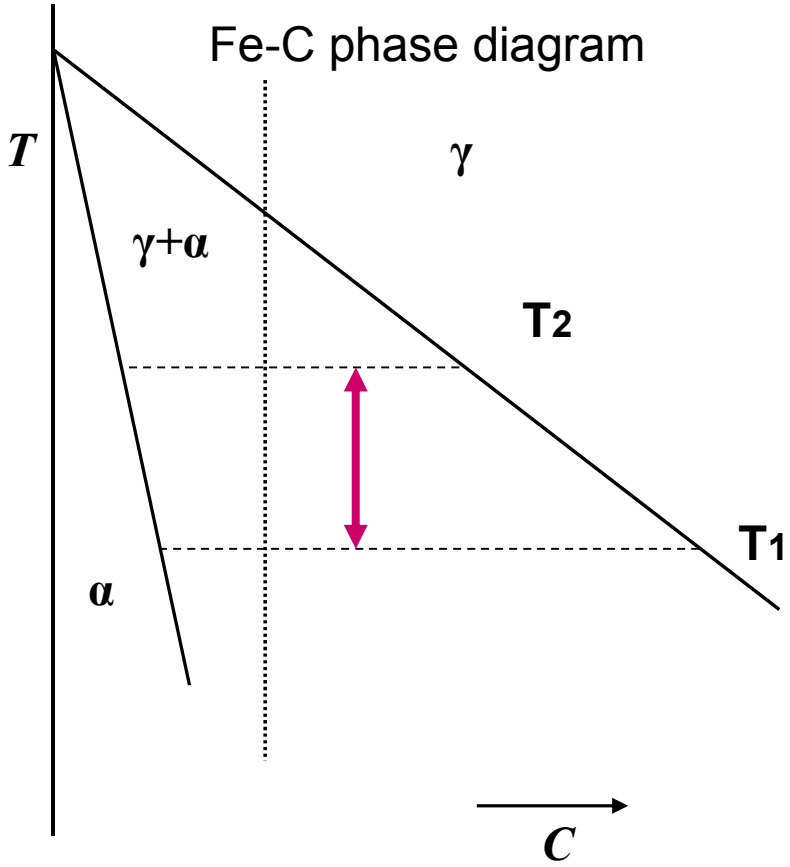
Hao Chen, Sybrand van der Zwaag

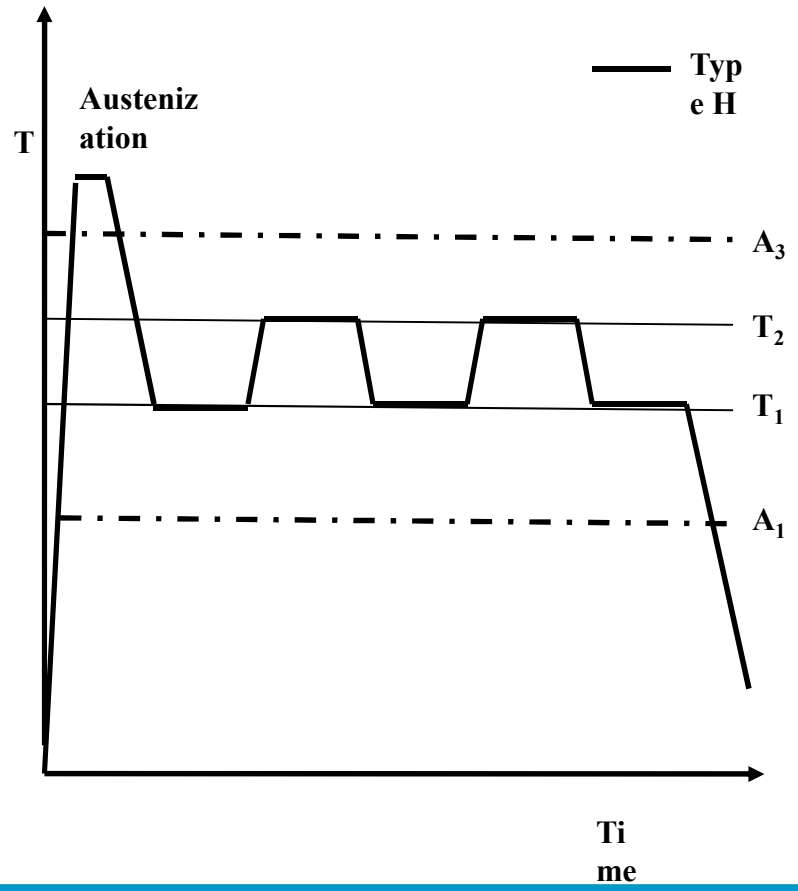
Novel Aerospace Materials group
Faculty of Aerospace Engineering, Delft University of Technology

In collaboration with **Mohamed Goune,** Arcelor-Mittal, France

TU Delft

The cyclic partial transformation concept





Chen and Van der Zwaag, Compu Mater Sci 49 (2010) 801-813

TU Delft

The cyclic partial phase transformation concept

The advantages :

1. Ferrite nucleation effects can be suppressed

2. The interface mobility for both the austenite to ferrite and ferrite to austenite transformation can be determined.

3. Development of element partitioning can be followed

Results to be presented

1- cyclic transformation curves at 10 K/min for a Fe-0.17Mn-0.02C alloy

2- comparison with PE and LE calculations

3- effects of heating and cooling rate on the stagnant stage

4- calculated behavior of ternary Fe-X-0.02 C alloys and quaternary alloys Fe-MN-C-X for X = Mn, Ni, Cu, Si,Co

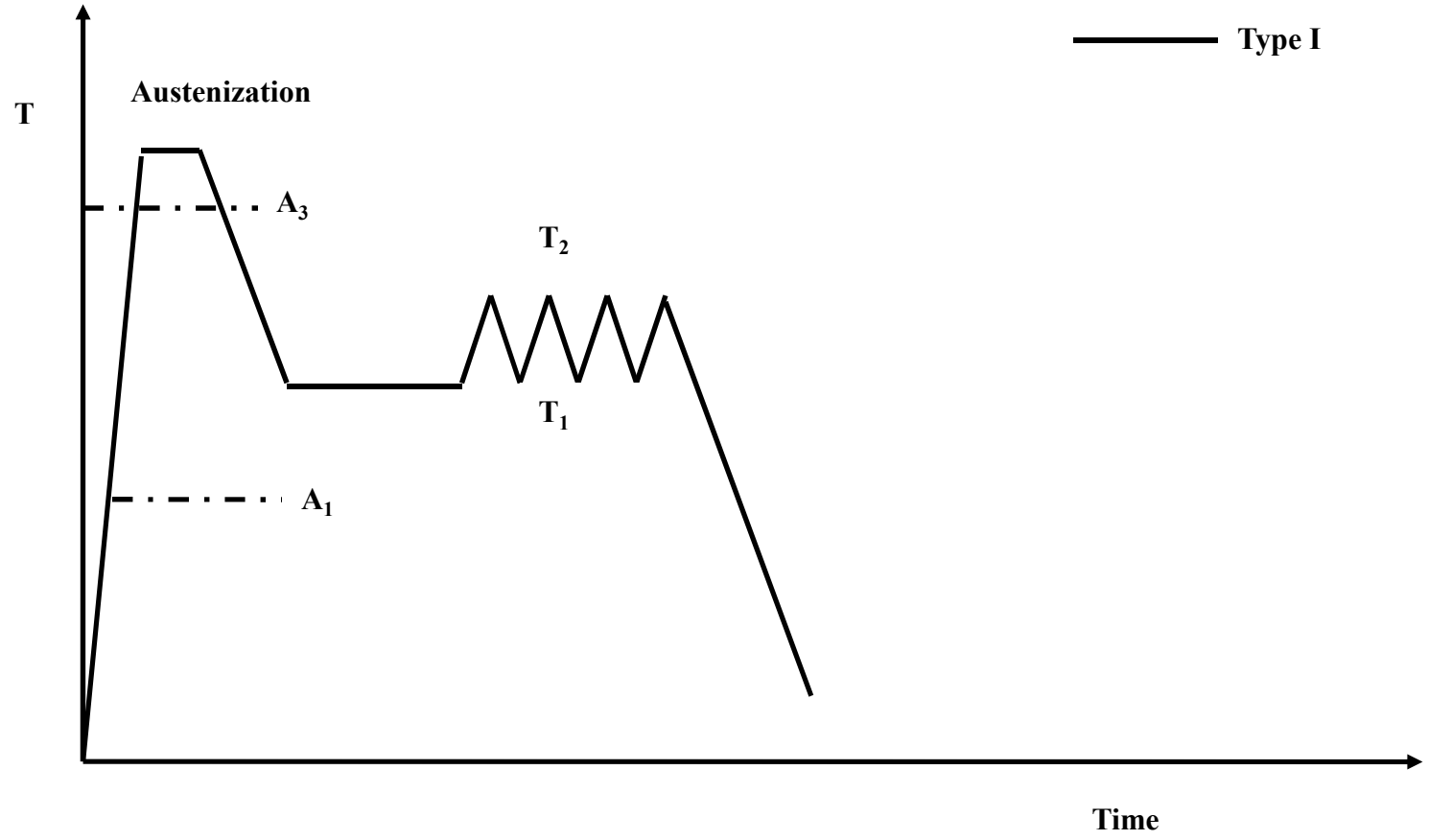
5- creating experimental indirect evidence for the Mn spike at the moving interface

The cyclic phase transformations in Fe-Mn-C alloys

Chen, Appolaire, Van der Zwaag, Acta Materialia 59 (2011) 6751-6760

TU Delft

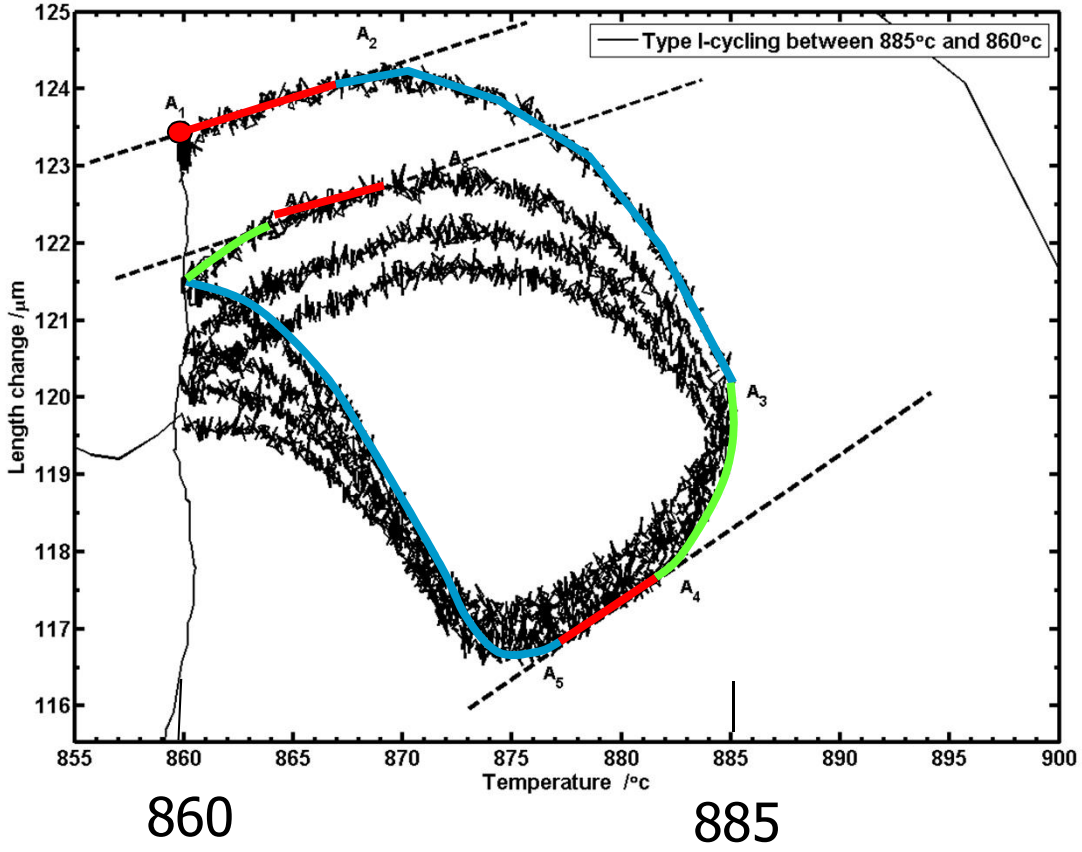
Immediate (type I)
Cyclic Phase transformations for Fe-Mn-C



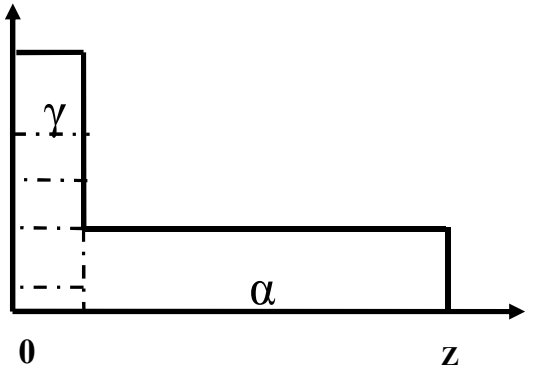
TU Delft

Experimental results for a type I experiment

Fe-0.17Mn-0.023C (wt. %) alloy



860 885



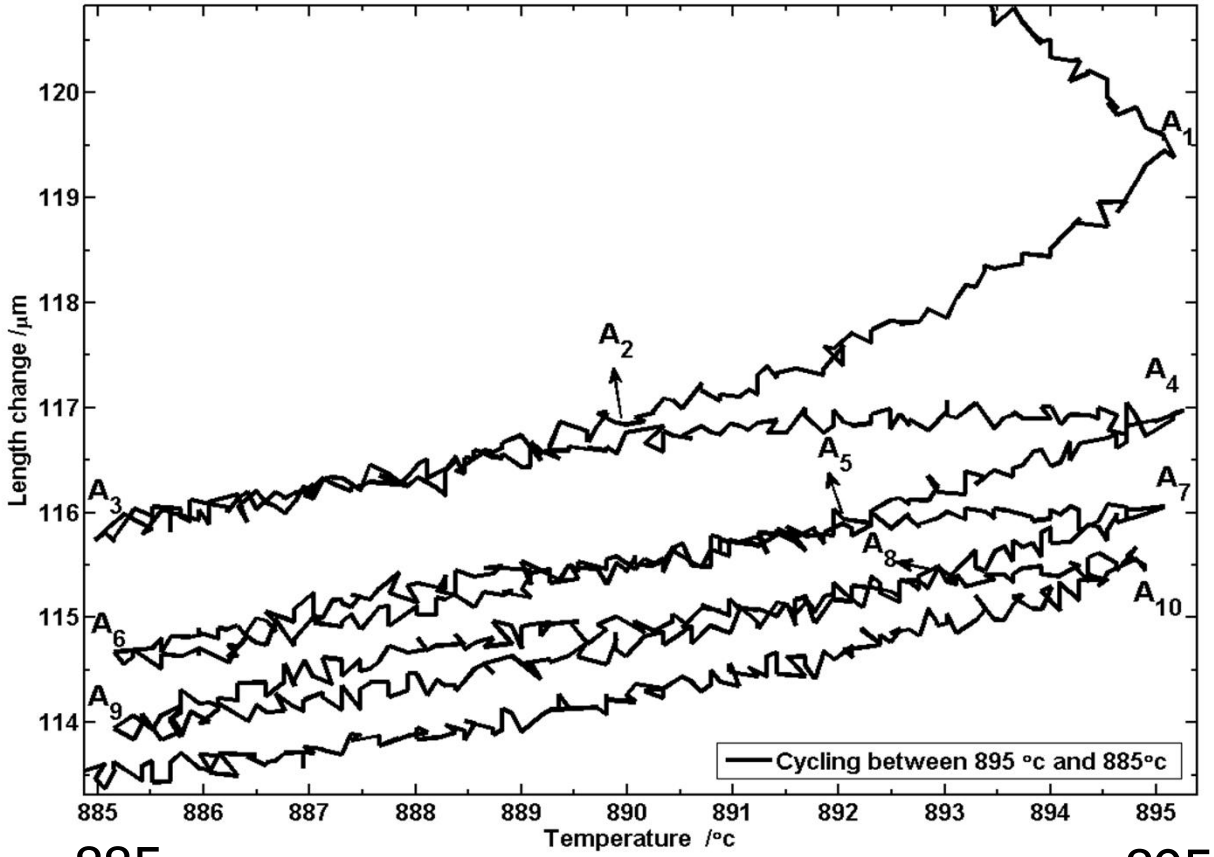
A_1-A_2 and A_4-A_5 stagnant stage

A_3-A_4 Inverse phase transformation stage

Chen, Appolaire, Van der Zwaag, Acta Materialia 59 (2011) 6751-6760

TU Delft

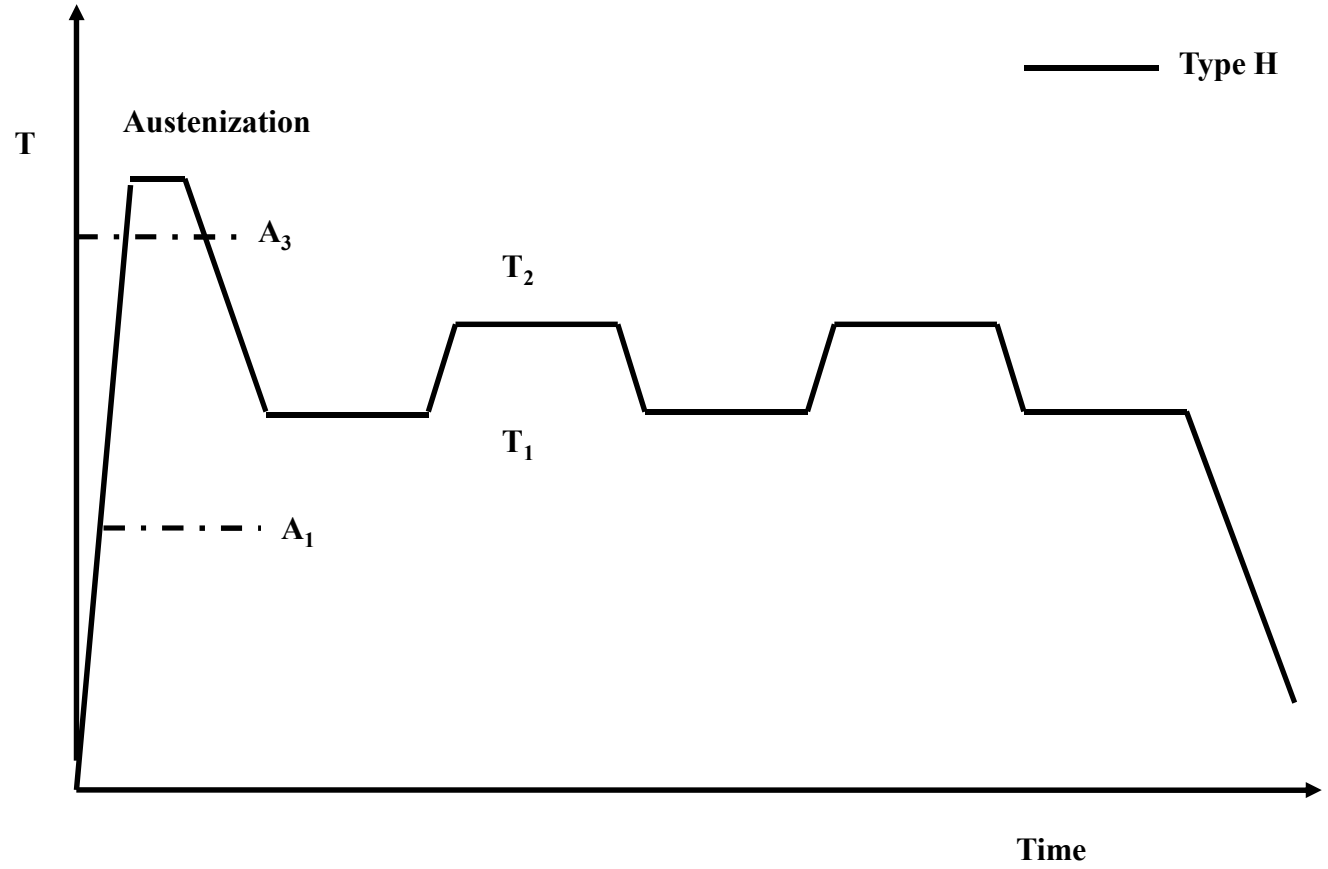
Cycling in the stagnant stage



885 895

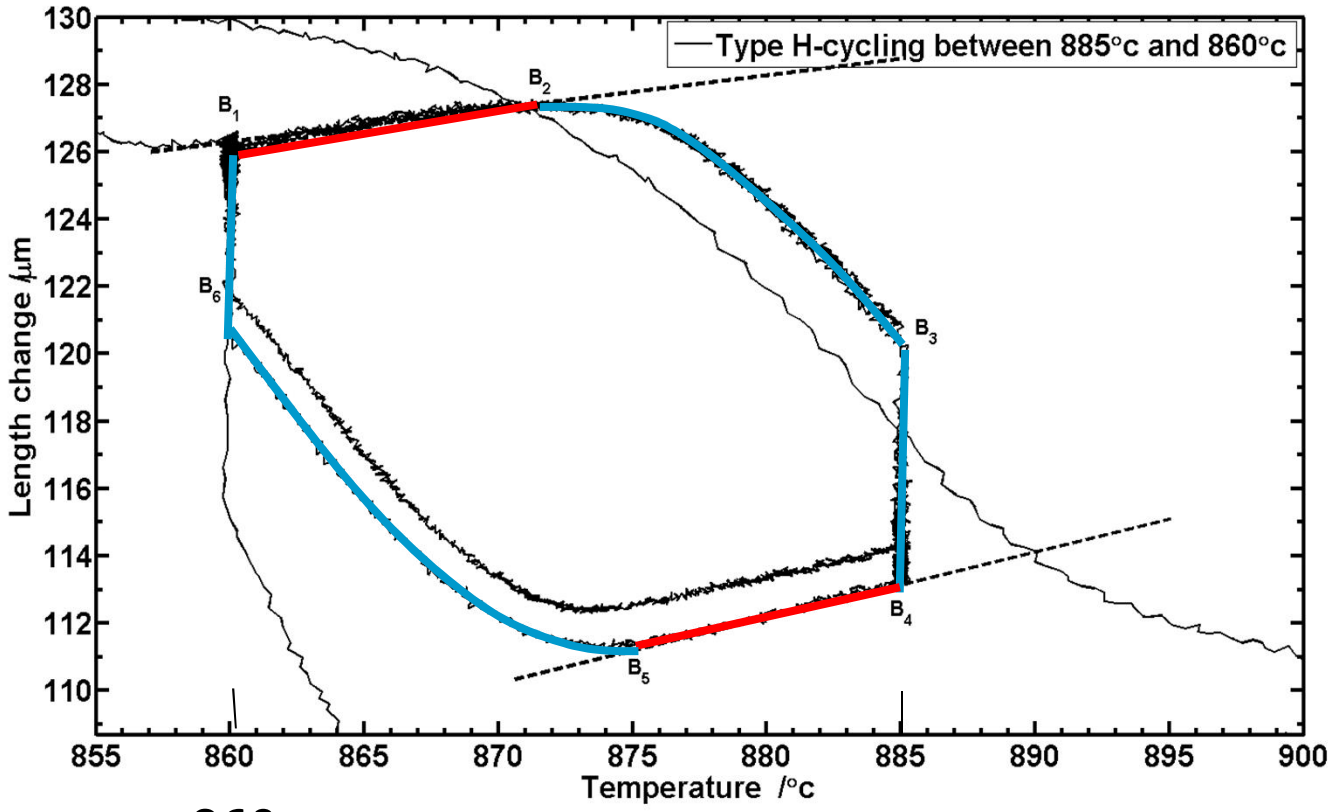
TU Delft

Holding (type H)
Cyclic phase transformations for Fe-Mn-C



TU Delft

Experimental results for a type H experiment



860 885

TU Delft

Modelling 1

Local equilibrium model for Fe-C-M (LE-NP and LE-P)

In the LE model, the carbon and the substitutional element M partitionings according to local equilibrium assumptions, which means the chemical potential of carbon and M across the interface should be constant:

$$\mu_i^{\gamma} = \mu_i^{\alpha} \qquad \text{i=M or C}$$

Diffusion equations:

$$\frac{\partial X_i^{\phi}(r,t)}{\partial t} = \frac{1}{r^{k-1}} \frac{\partial}{\partial r}\left(r^{k-1} D_i^{\phi}\left(X_i^{\phi}(r,t)\right) \frac{\partial X_i^{\phi}(r,t)}{\partial r} \right)$$

Boundary conditions:

$$\left.\frac{\partial X_i^{\phi}(r,t)}{\partial r}\right|_{\substack{r=0 \\ r=L}} = 0 \qquad \Phi = \gamma \text{ or } \alpha \text{ and i=M or C}$$

Mass balance at the interface:

$$J_i^{\gamma} - J_i^{\alpha} = v\left(X_i^{\gamma} - X_i^{\alpha}\right) \qquad \text{i=M or C}$$

TU Delft

Modelling the cyclic transformations

Paraequilibrium model for Fe-C-M

In the paraequilibrium model, the substitutional element M does not redistribute and the chemical potential of C is a constant across the interface. The chemical potential equations can be described as:

$$\mu_C^{\gamma} = \mu_C^{\alpha}$$

$$\left(\mu_M^{\gamma} - \mu_M^{\alpha}\right) = -\frac{X_{Fe}}{X_M}\left(\mu_{Fe}^{\gamma} - \mu_{Fe}^{\alpha}\right)$$

Diffusion equations:

$$\frac{\partial X_i^{\phi}(r,t)}{\partial t} = \frac{1}{r^{k-1}}\frac{\partial}{\partial r}\left(r^{k-1} D_i^{\phi}\left(X_i^{\phi}(r,t)\right)\frac{\partial X_i^{\phi}(r,t)}{\partial r}\right)$$

Boundary conditions:

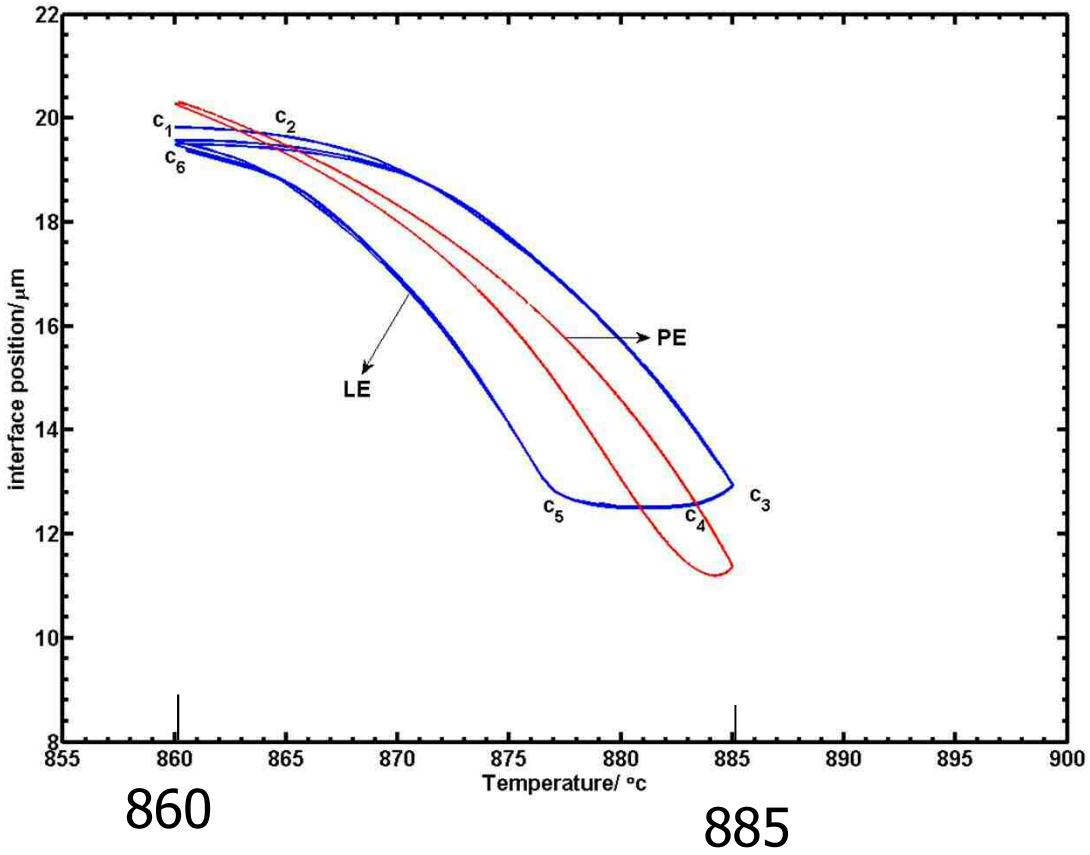
$$\left.\frac{\partial X_i^{\phi}(r,t)}{\partial r}\right|_{\substack{r=0 \\ r=L}} = 0 \qquad \Phi = \gamma \text{ or } \alpha \text{ and } i = C$$

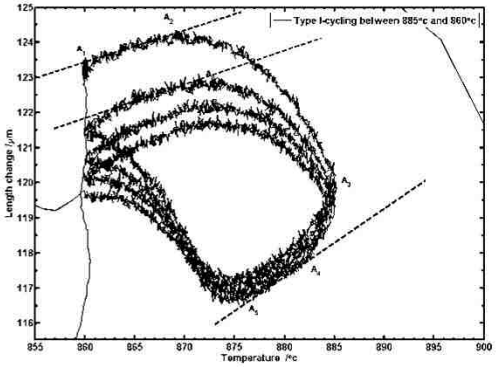
Mass balance at the interface:

$$J_i^{\gamma} - J_i^{\alpha} = v\left(X_i^{\gamma} - X_i^{\alpha}\right) \qquad i = C$$

TU Delft

Modelling results for type I experiment for Local Equilibrium and Paraequilibrium

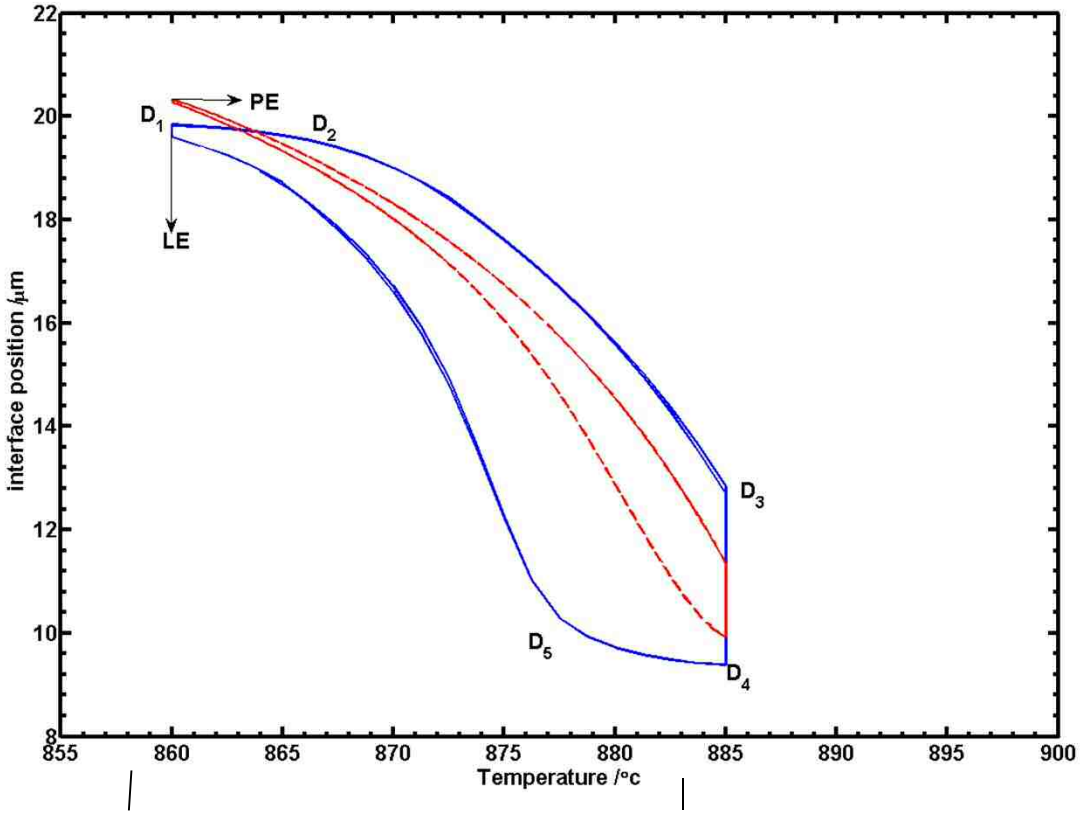




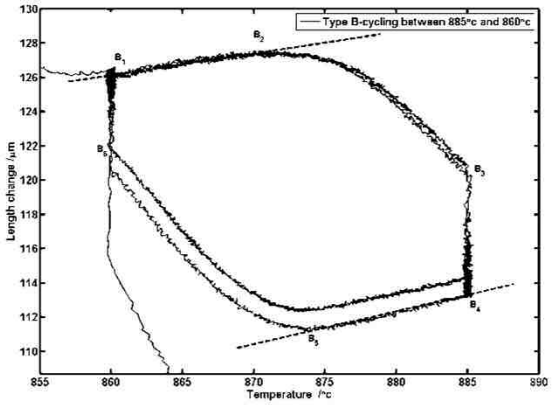
Experimental results

TU Delft

Modelling results for type H experiment



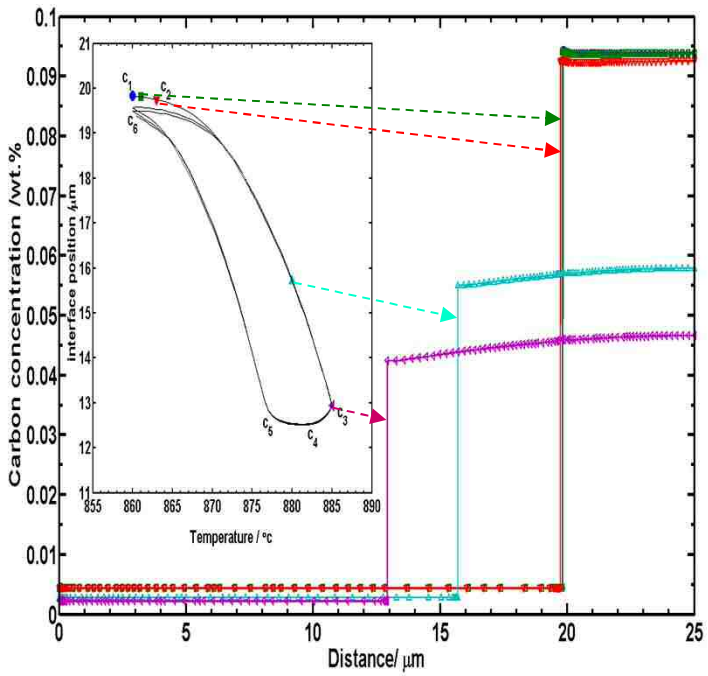
860 885



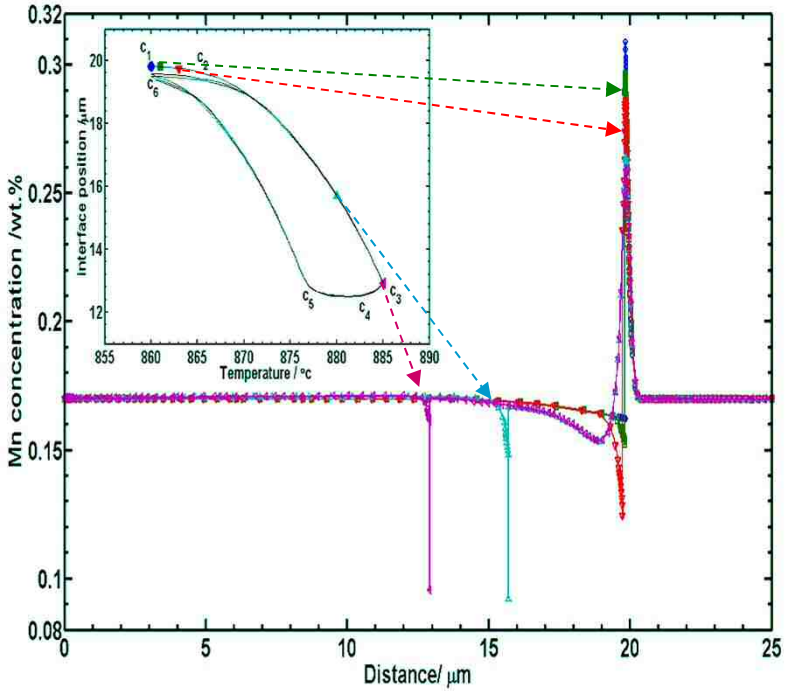
Experimental results

TU Delft

Concentration profiles during 1st heating cycle



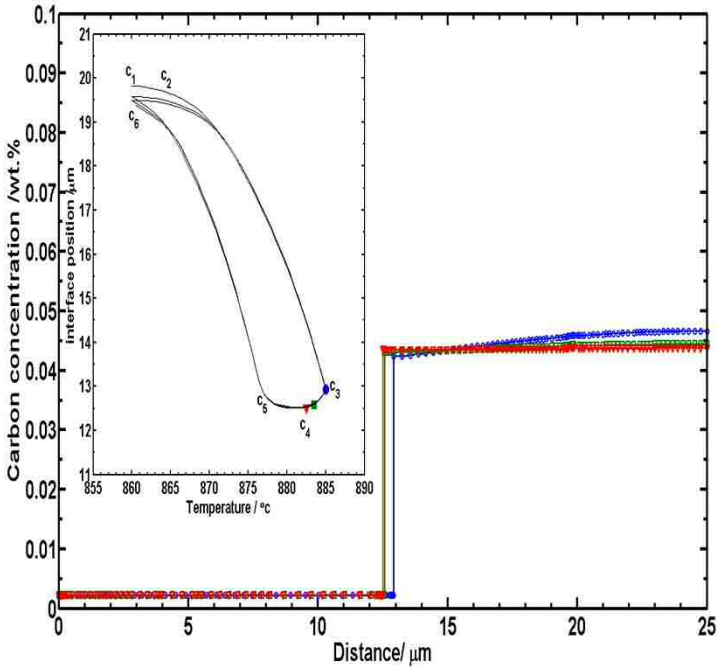
Carbon profiles



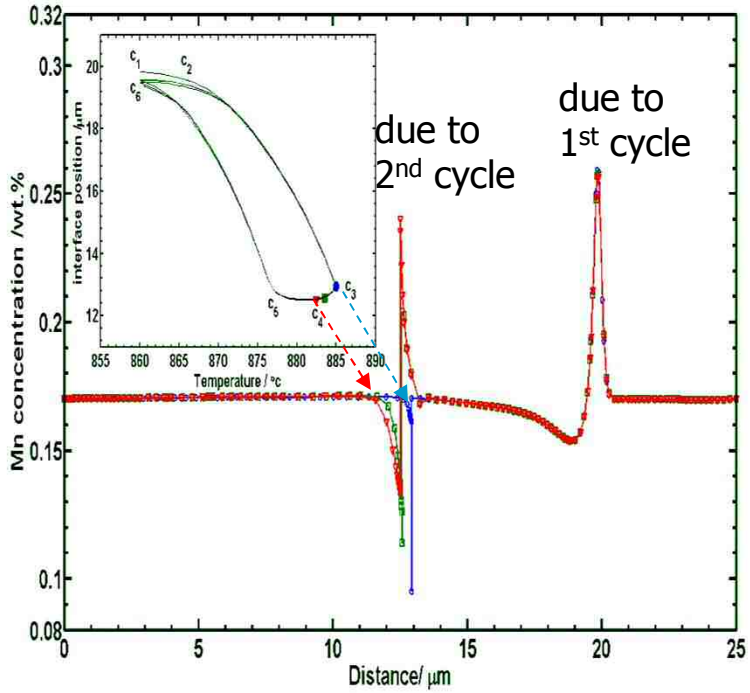
Mn profiles

TU Delft

Concentration profiles for the 1st cooling stage



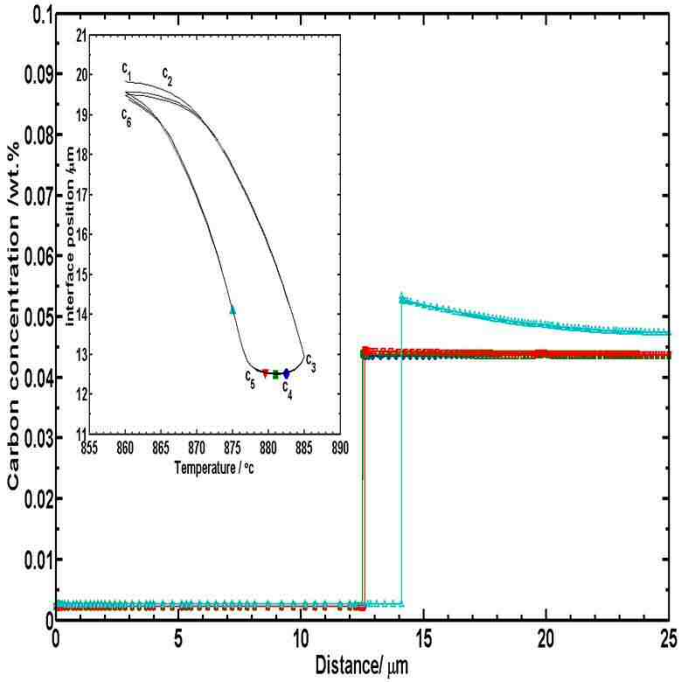
Carbon profile



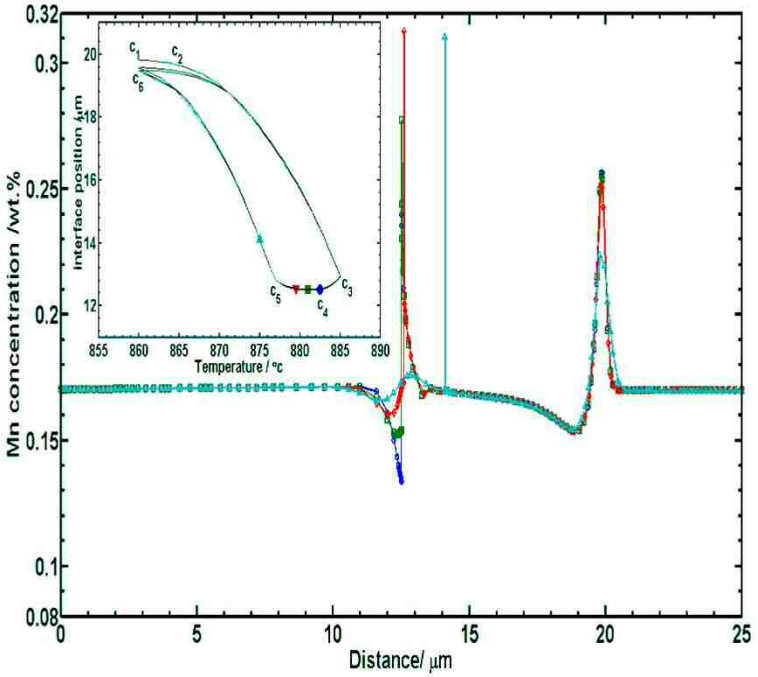
Mn profile

TU Delft

The stagnant stage in more detail



Carbon profile



Mn profile

TU Delft

The effect of cooling rate and heating rate on the stagnant stage and inverse transformation stage

Chen, Goune, Van der Zwaag, Compu Mater Sci 55(2012)34

TU Delft

Simulation

115 different combinations of cooling and heating rate have been simulated by local equilibrium model.

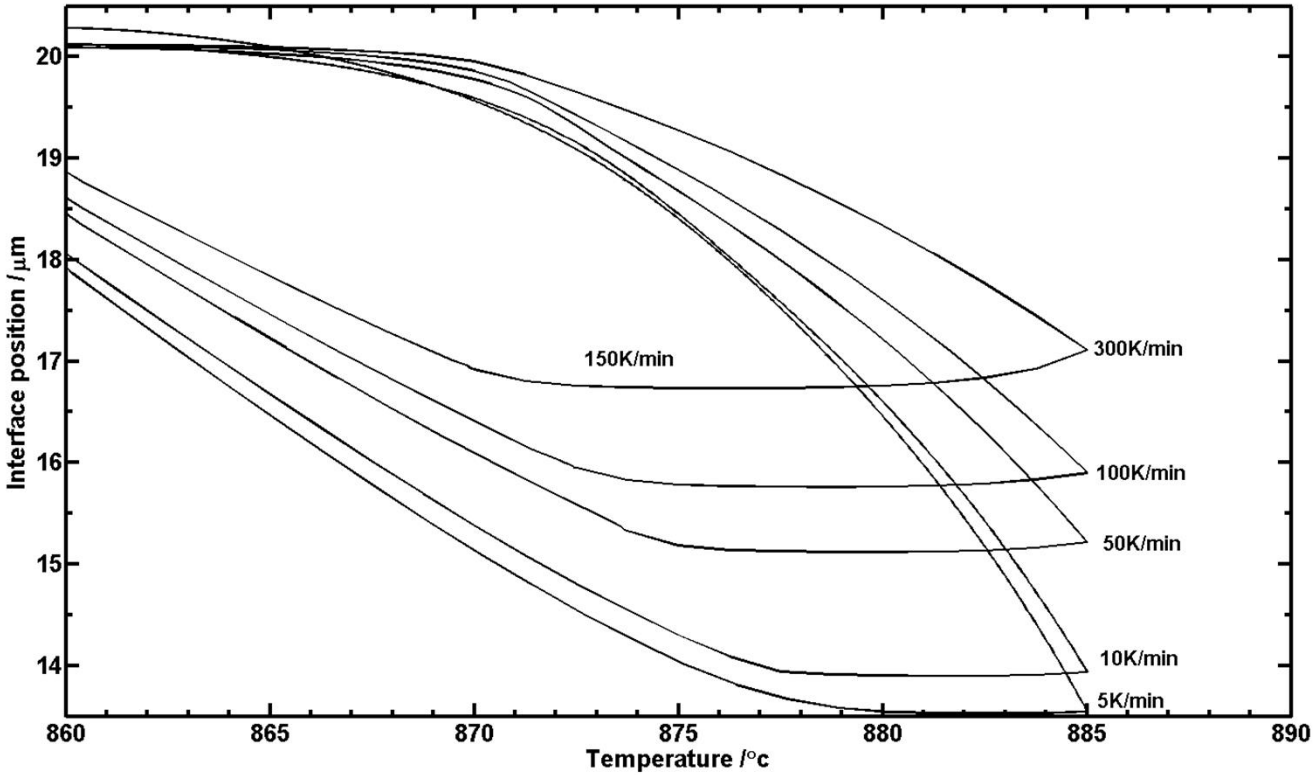
The range of cooling and heating rate is from 5K/min to 1500K/min

The studied alloy is **Fe-0.2Mn-0.02C**

Varying heating rate

Heating rate fixed at 10 K/min

Fe-0.2Mn-0.02C



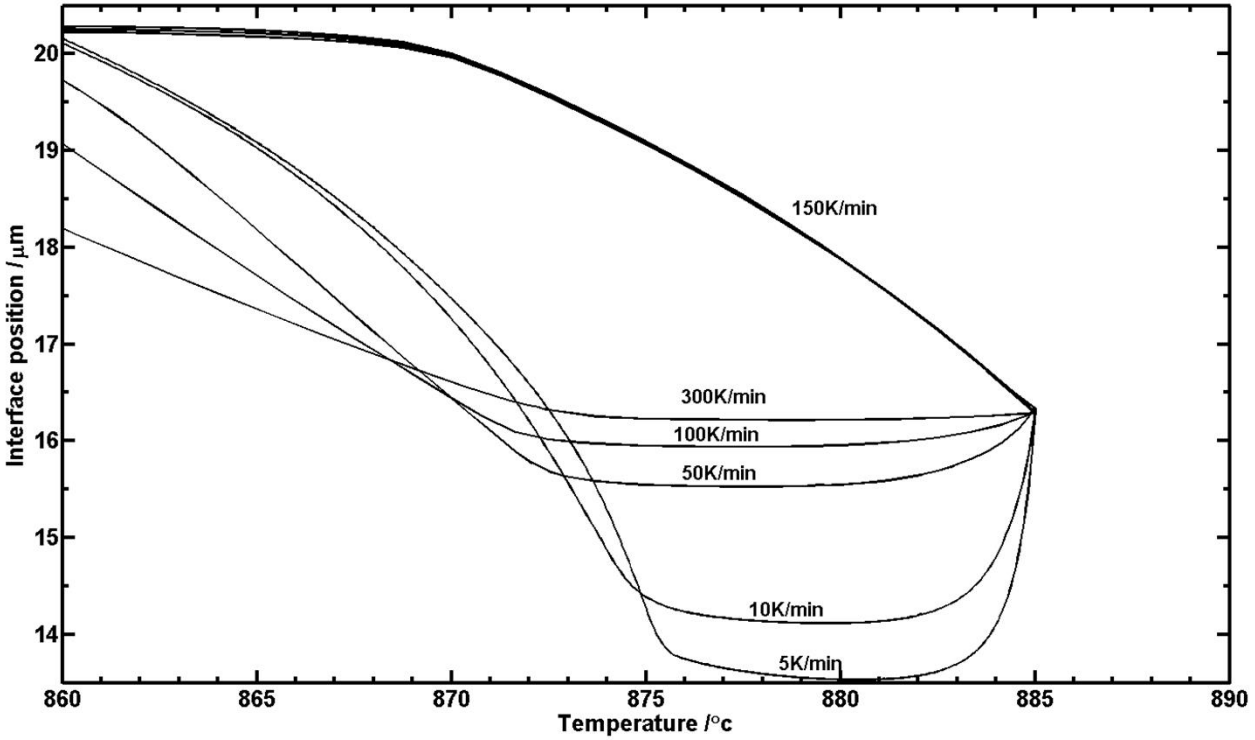
Equilibrium interface position at 885C is 11μm

TU Delft

Varying cooling rate

Cooling rate fixed at 10 K/min

Fe-0.2Mn-0.02C



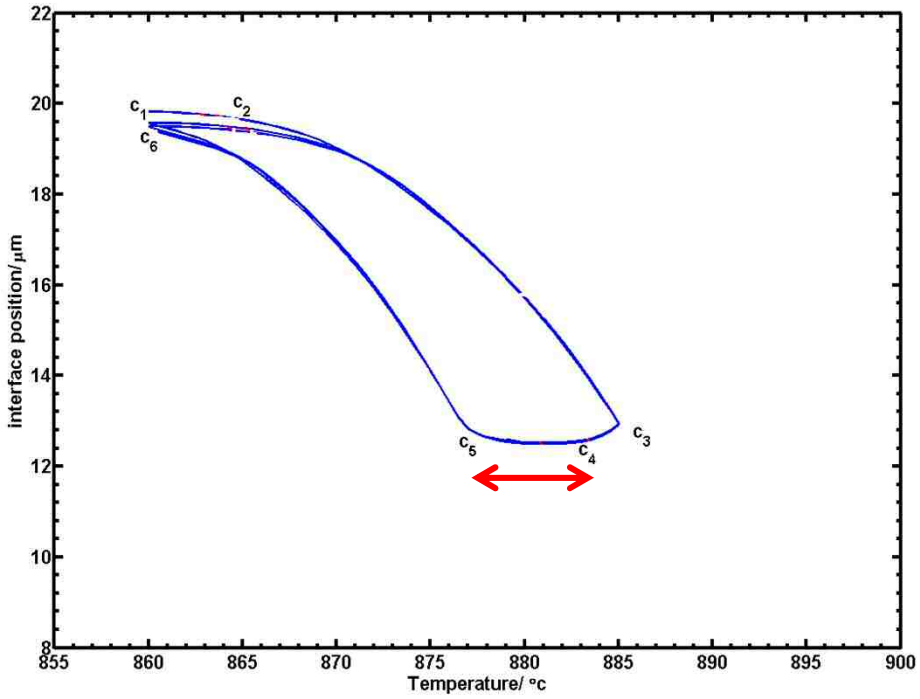
Equilibrium interface position at 885C is 11μm

TU Delft

Definitions

Length of stagnant stage:

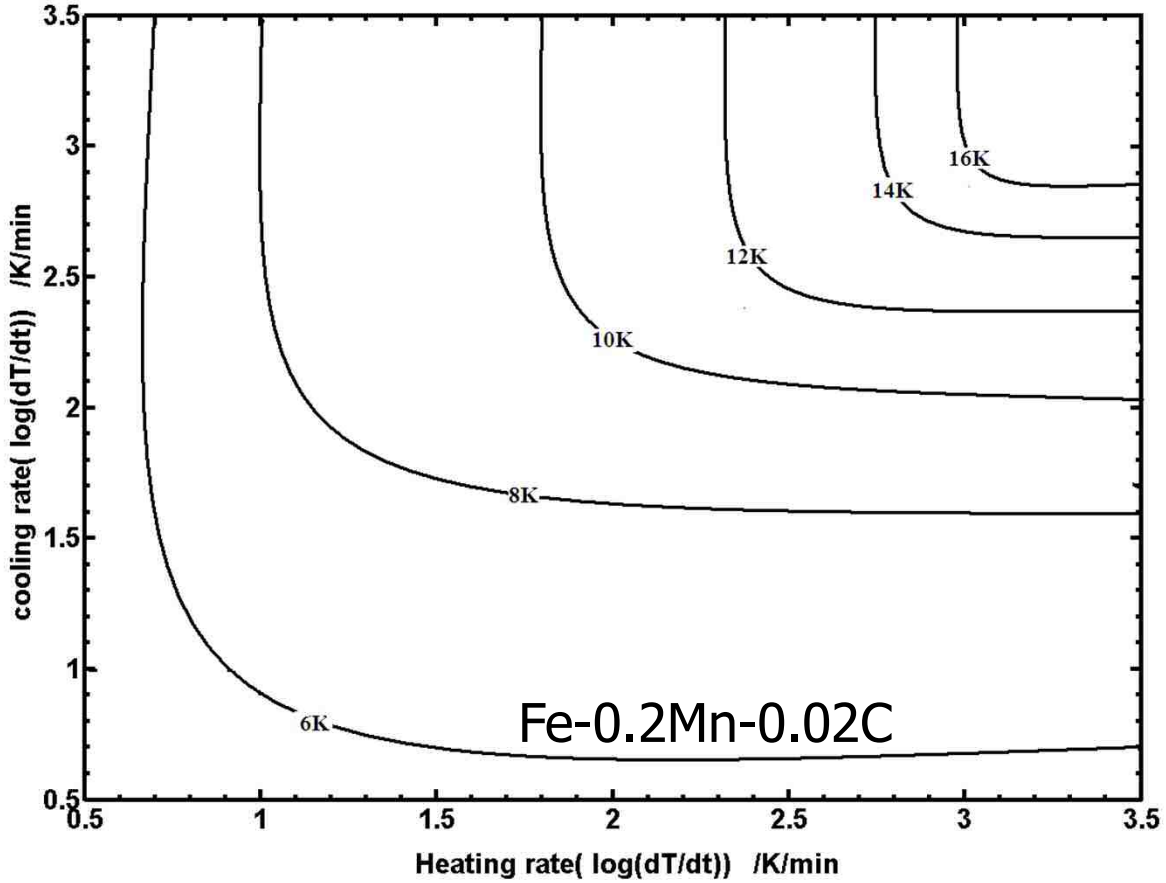
$$\Delta T = T_{C_4} - T_{C_5}$$



TU Delft

The stagnant stage

Length of stagnant stage



TU Delft

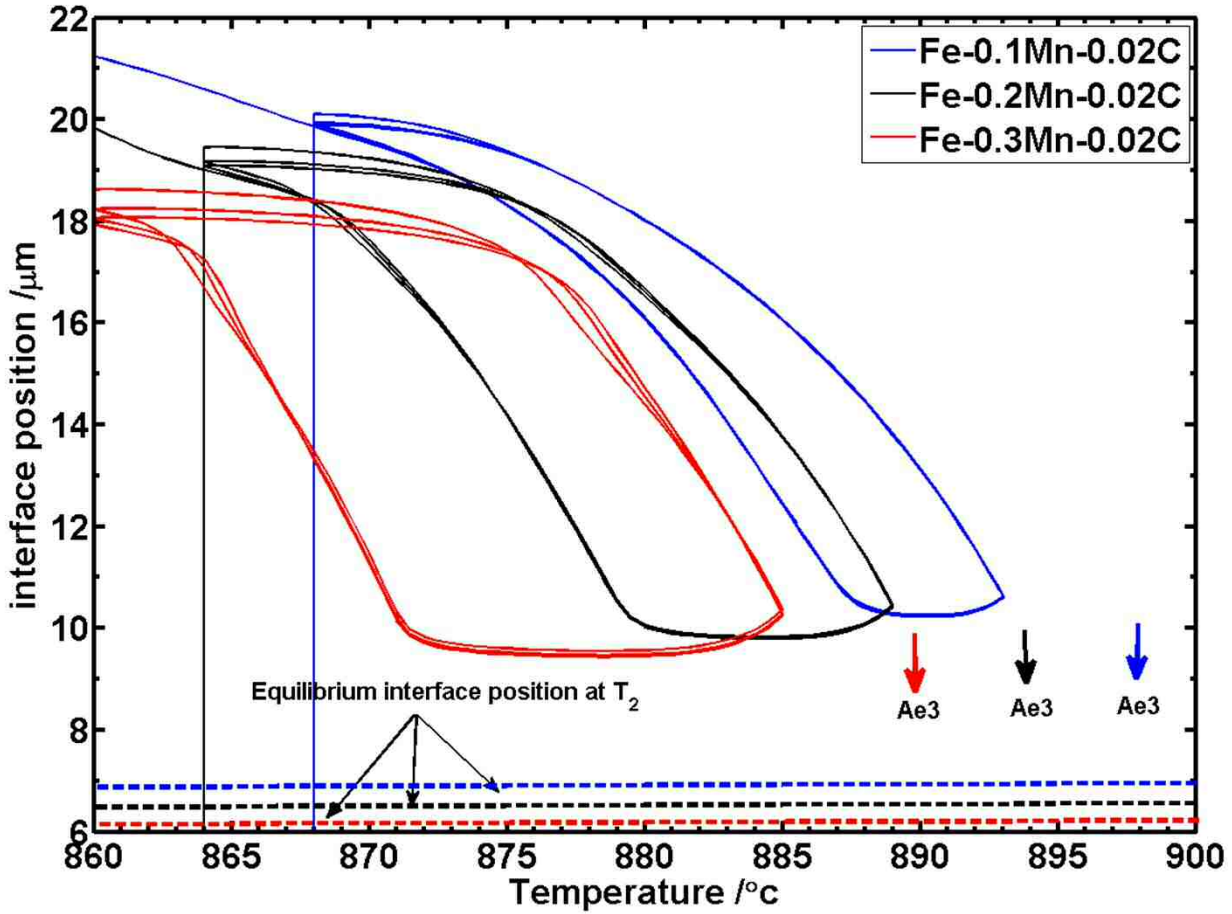
The calculated effect of substitutional element in Fe-X-C alloys

Chen, Goune, Van der Zwaag, Compu Mater Sci 55(2012)34

Fe-Mn-C

T_2-T_1=25K & A_3-T_2=5K

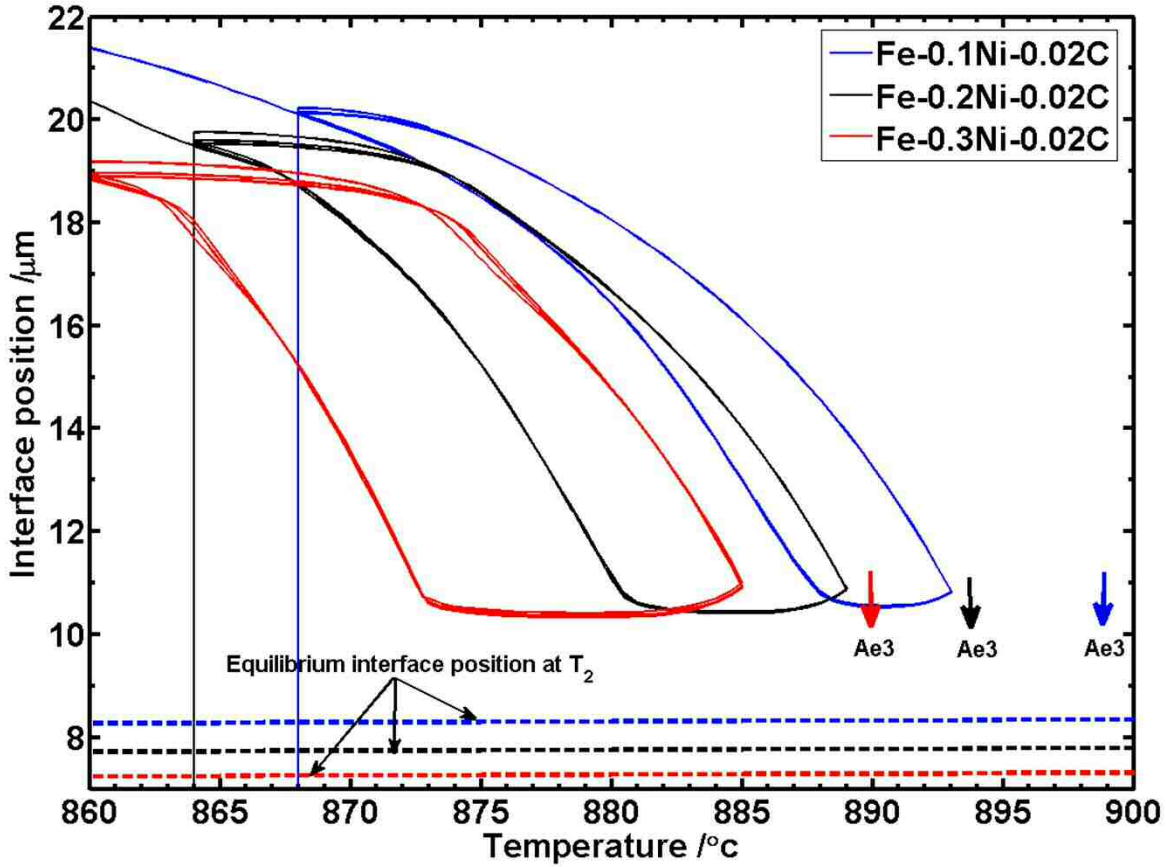
Heating & cooling rate fixed at 10 K/min



TU Delft

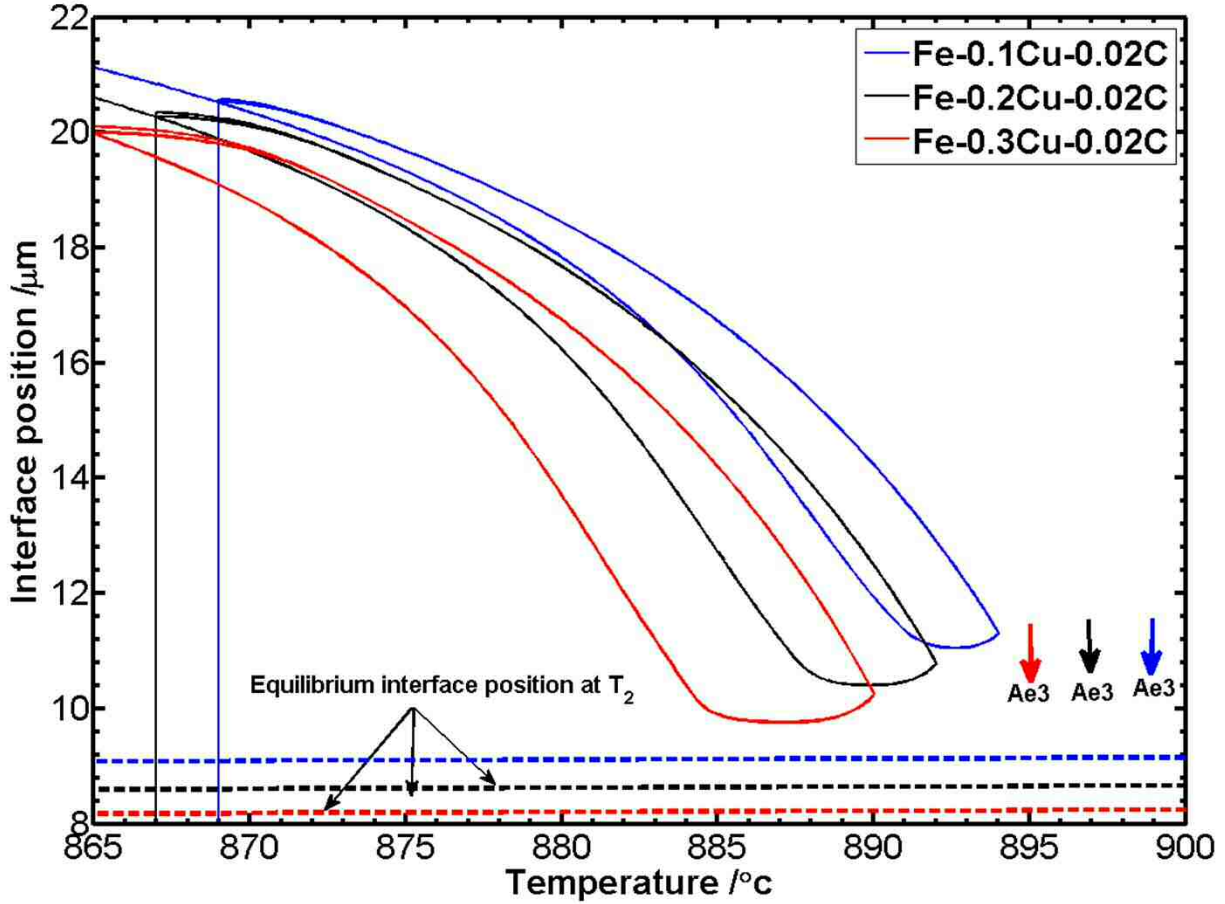
Fe-Ni-C

T_2-T_1=25K & A_3-T_2=5K



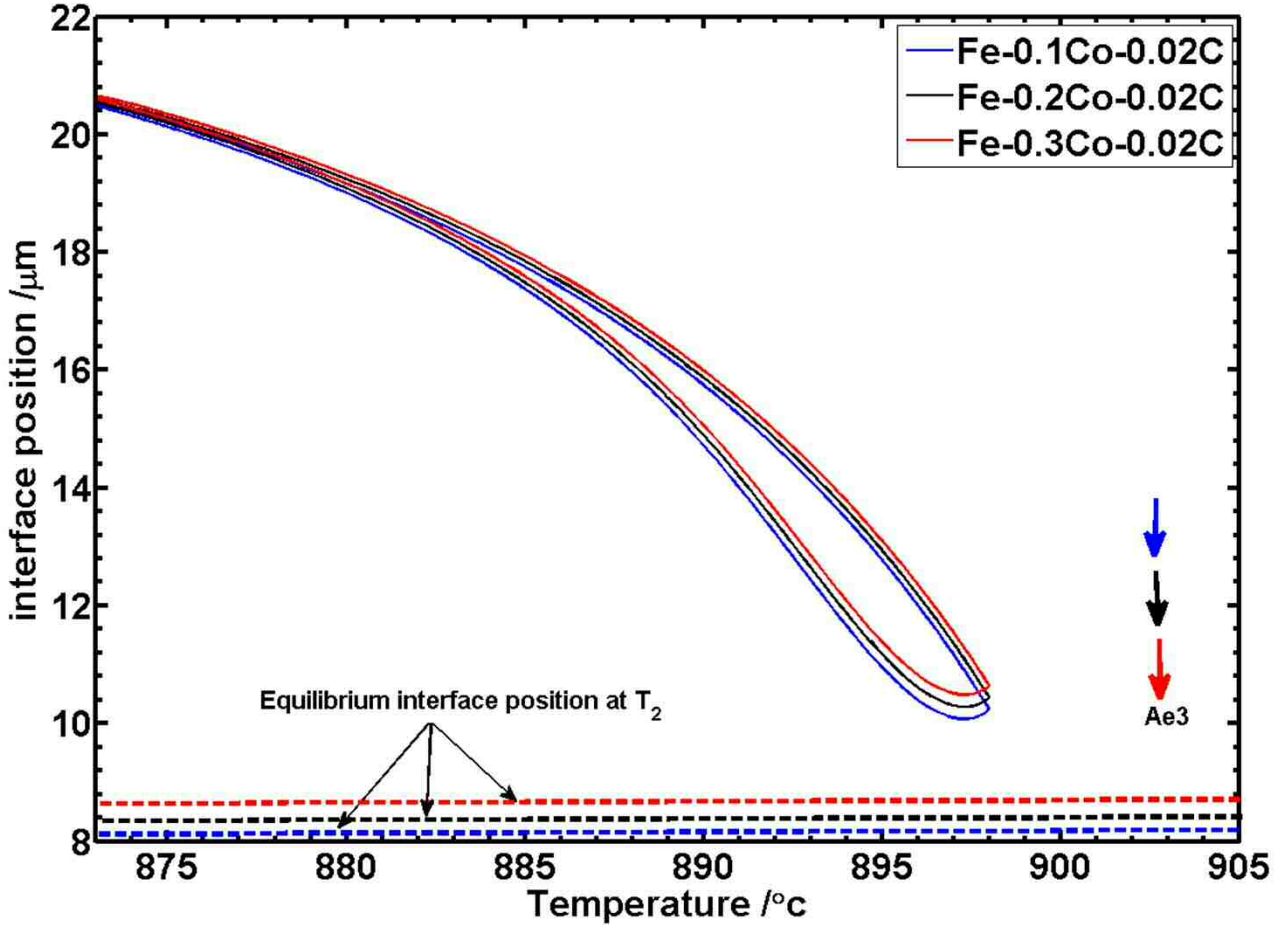
TU Delft

Fe-Cu-C



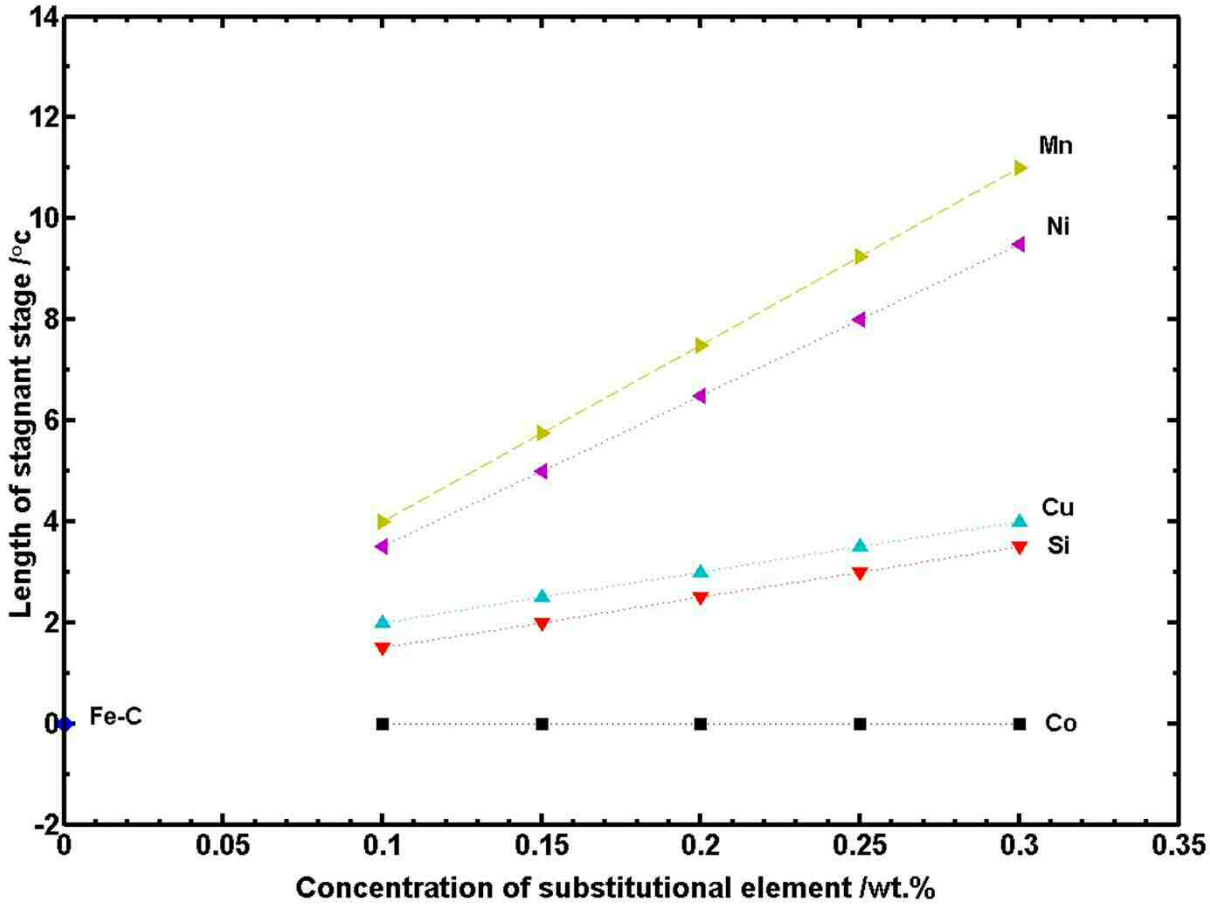
TU Delft

Fe-Co-C



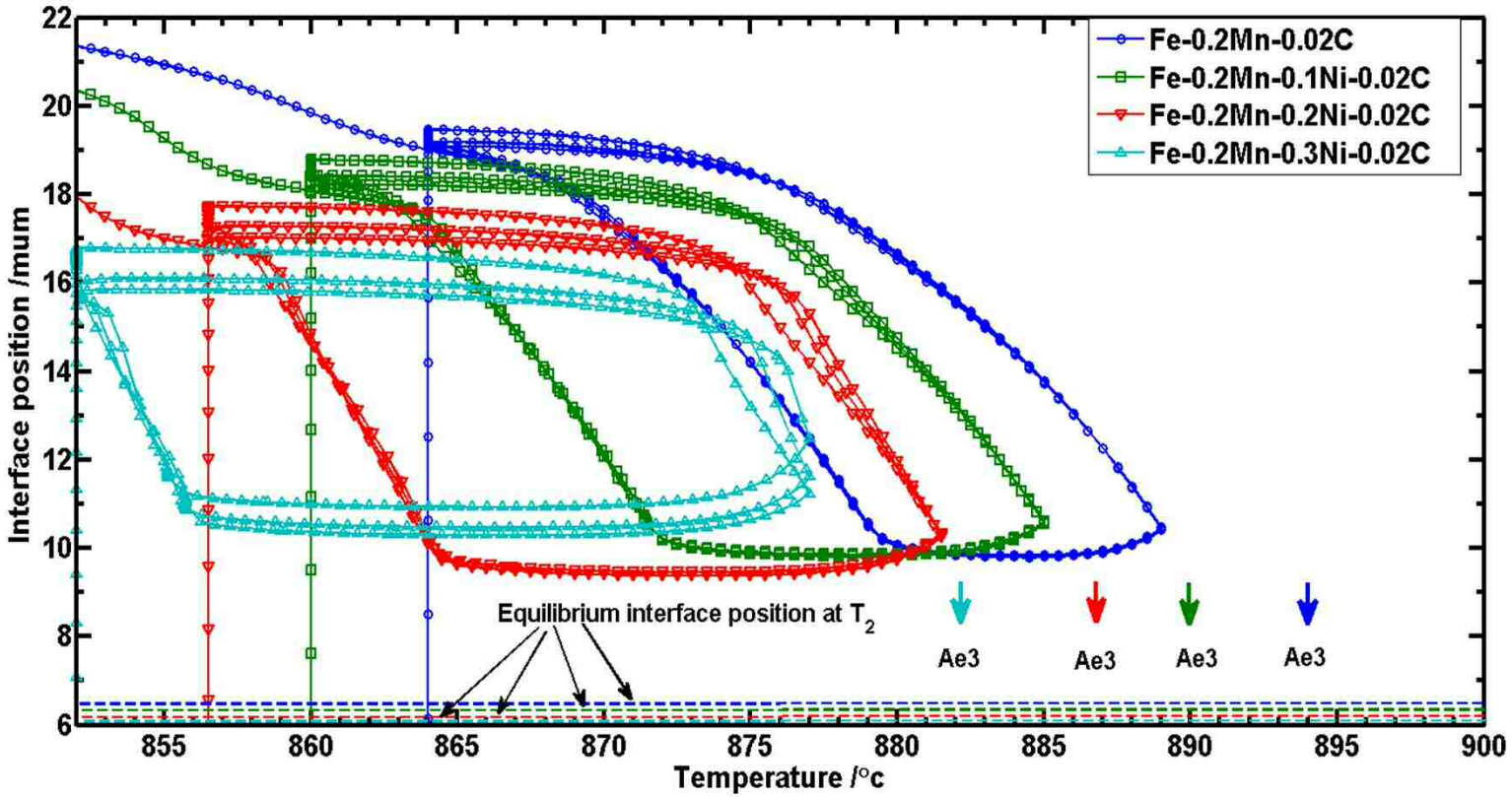
TU Delft

The effect of X concentration on the stagnant stage for Fe-0.02C- X



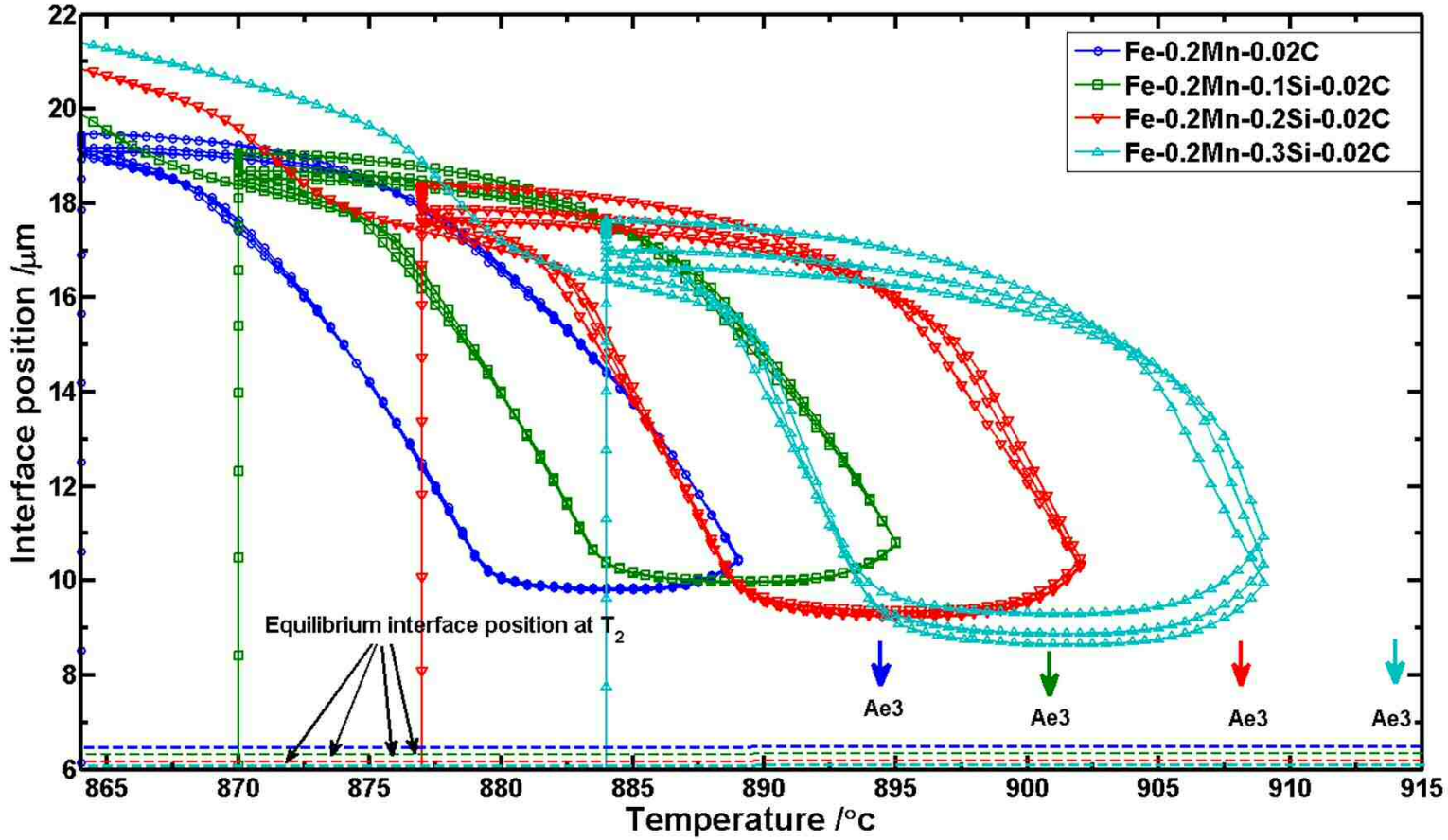
TU Delft

Fe-Mn-Ni-C quarternary system



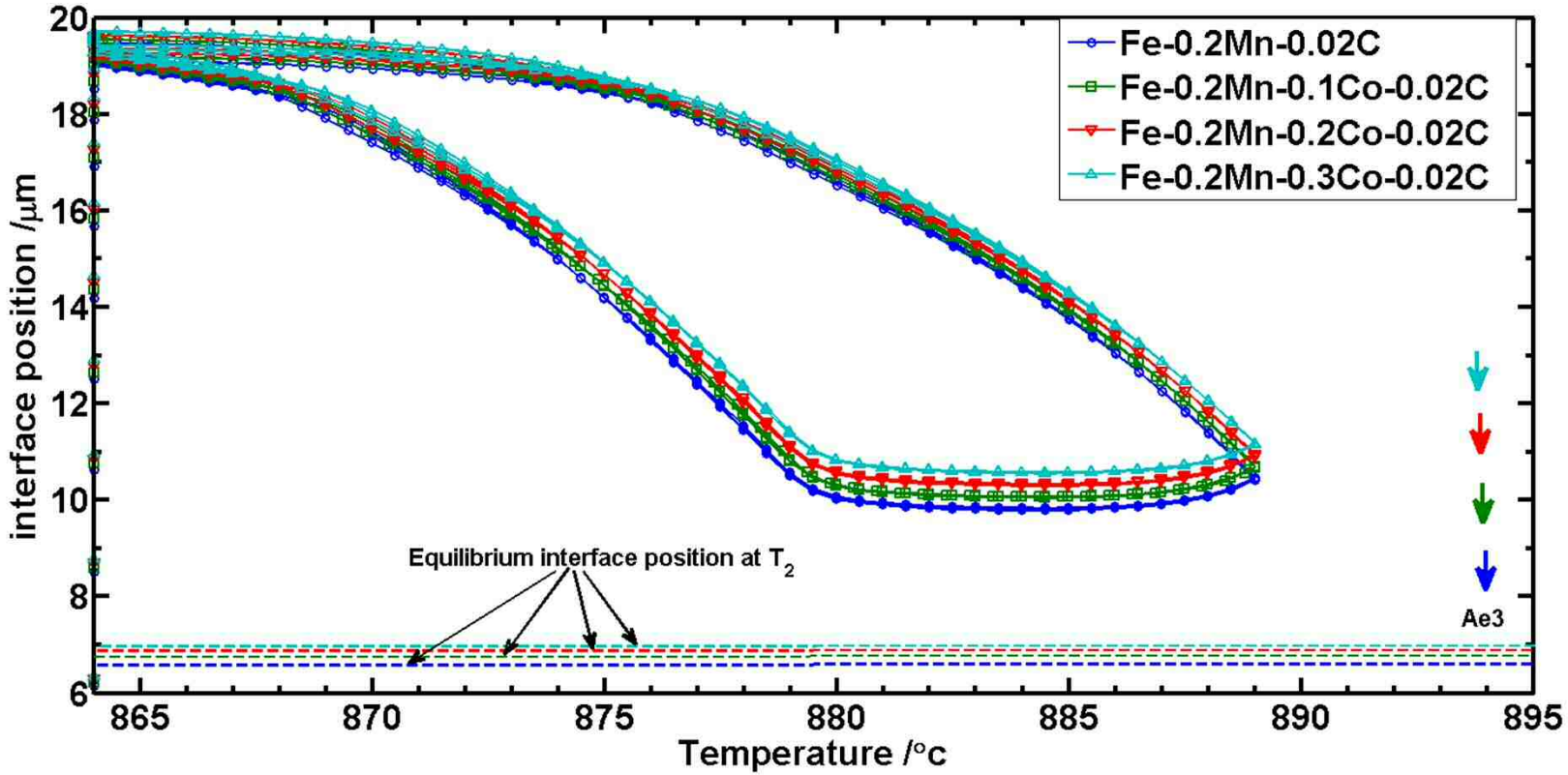
TU Delft

Fe-Mn-Si-C



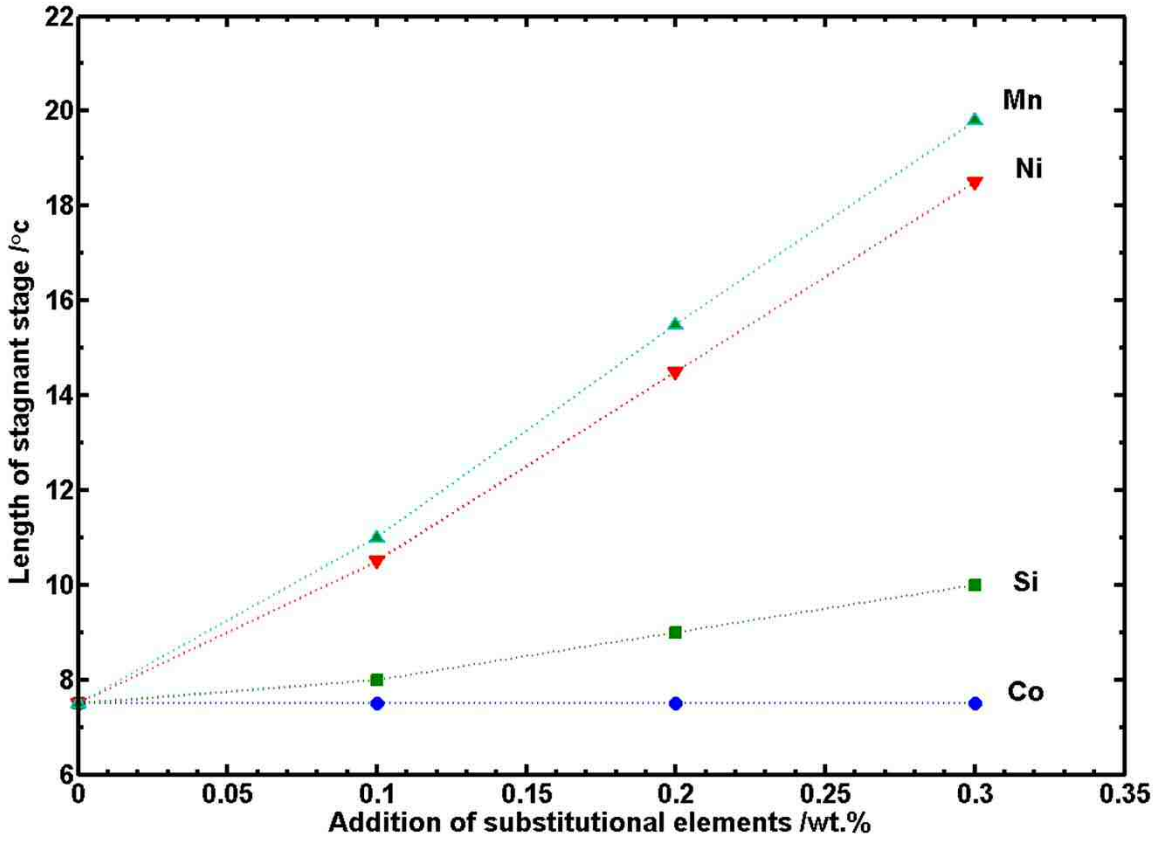
TU Delft

Fe-Mn-Co-C



TU Delft

Effect of X concentration on the stagnant stage for Fe-0.2Mn-0.02C-X



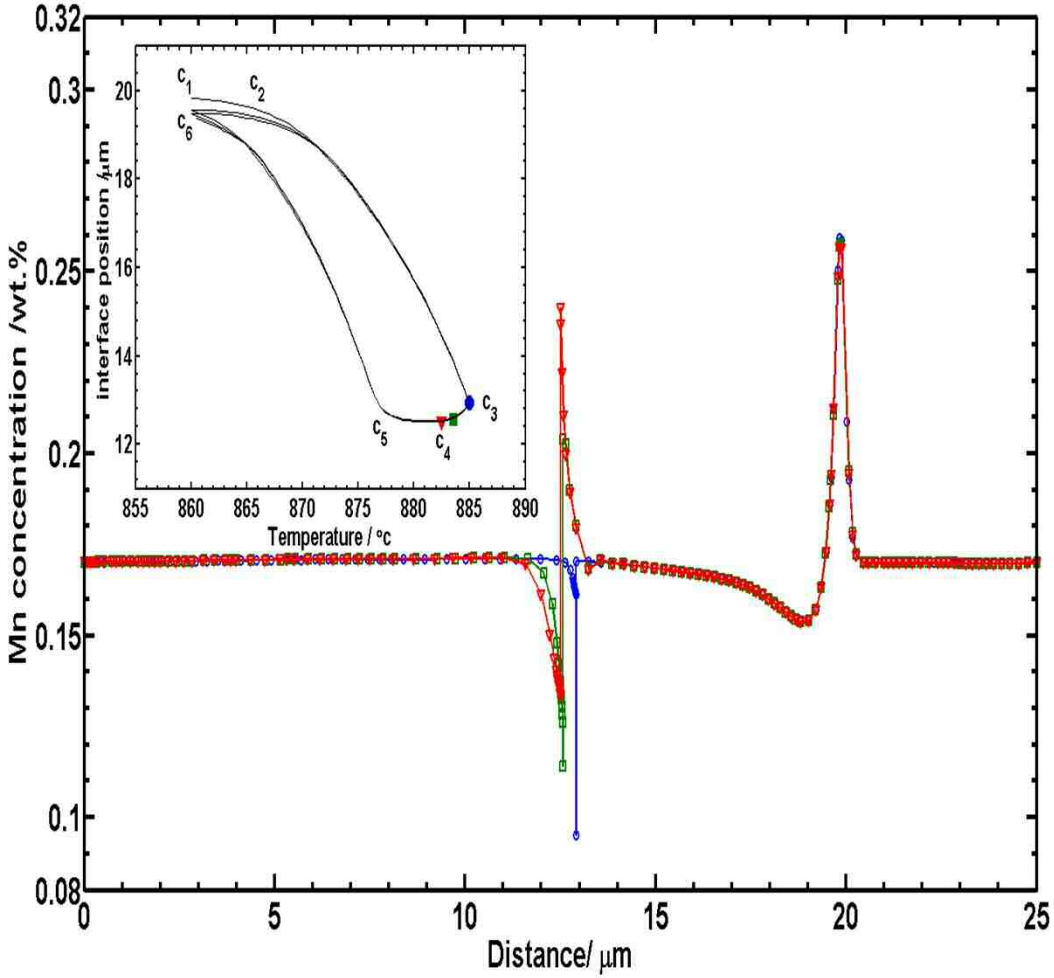
TU Delft

Creating evidence for the existence of the Mn –spike after cyclic transformations (spatial stagnant stage)

Chen, Van der Zwaag, Phil Mag Letters, 92(2012)86

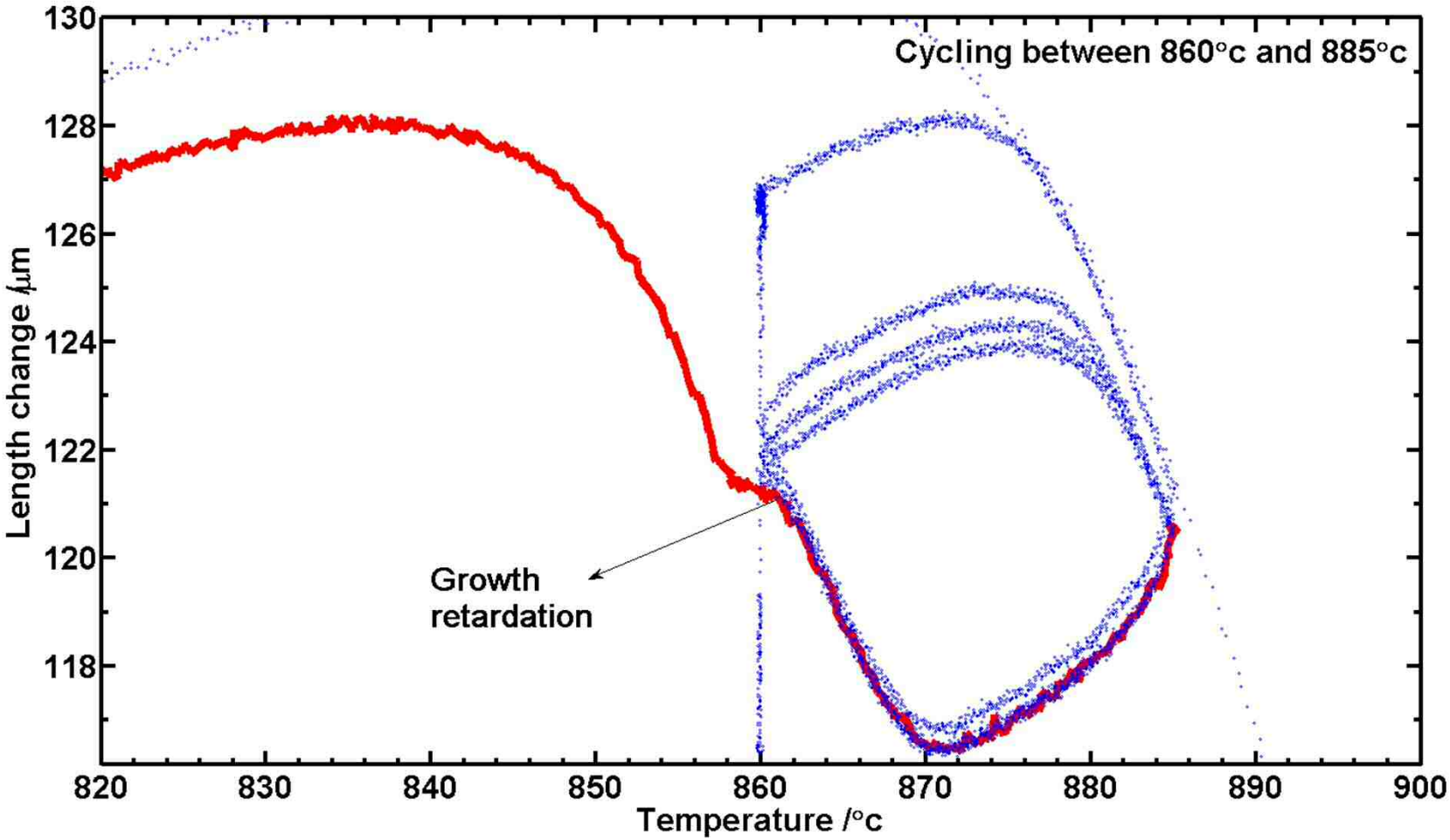
Spike is really there???

Mn profile



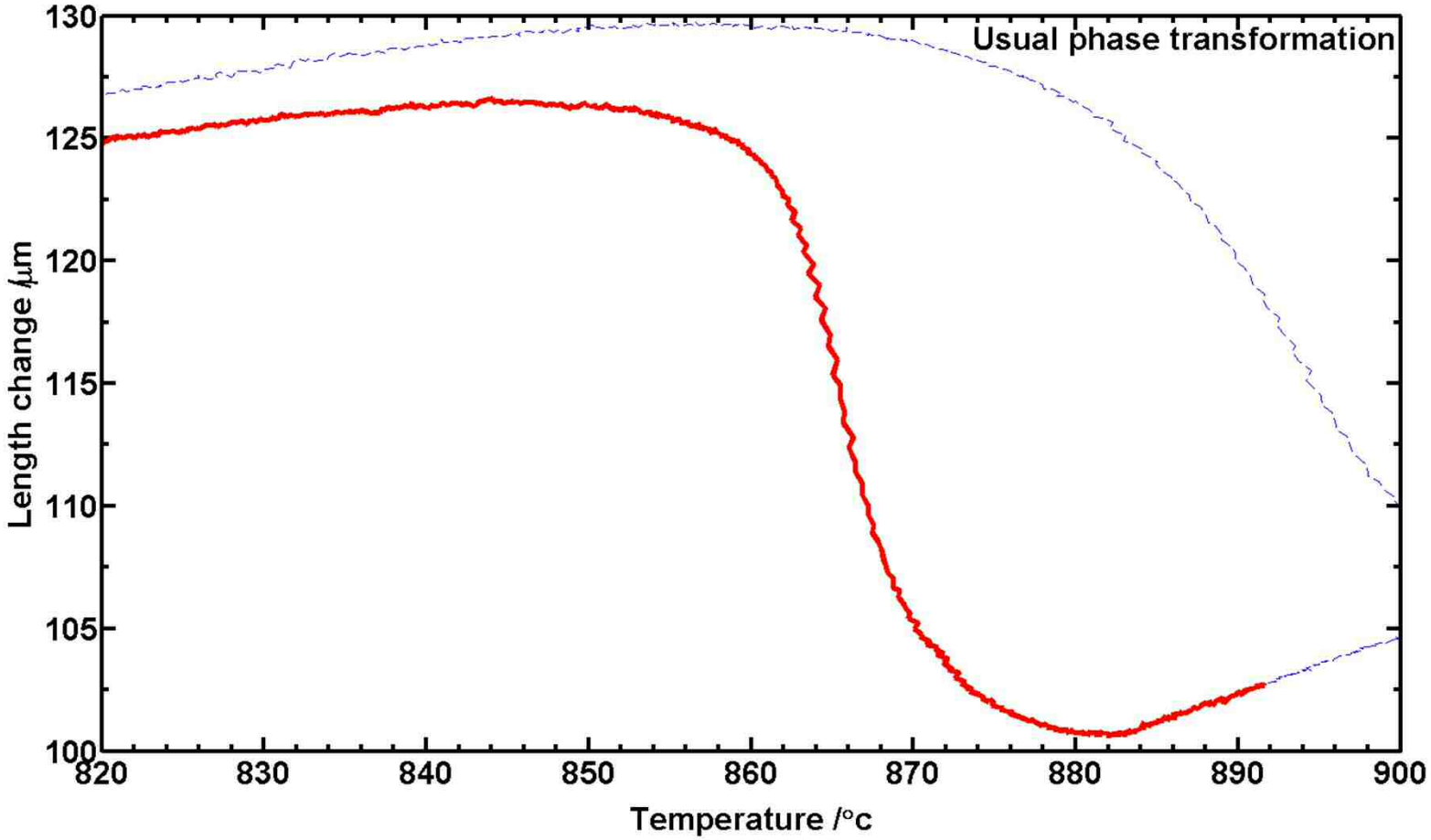
TU Delft

Experiments



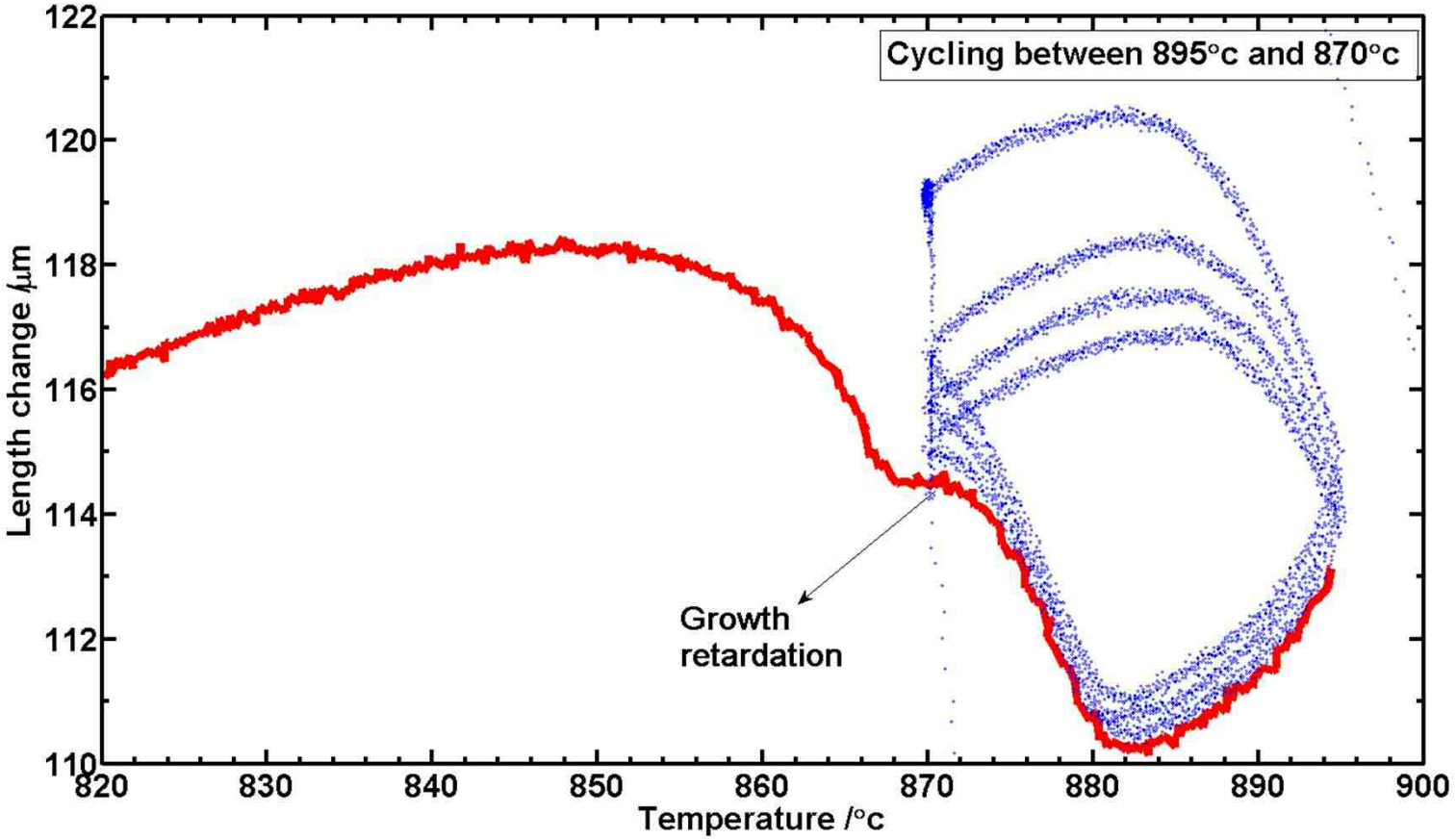
TU Delft

Experiments



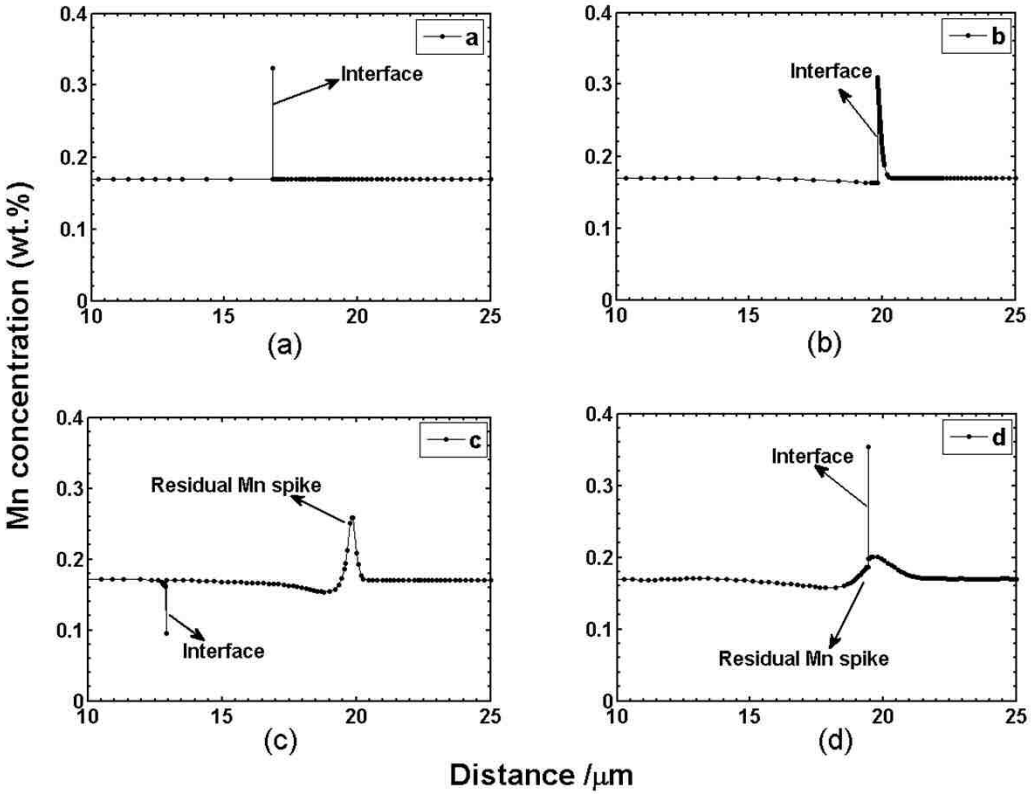
TU Delft

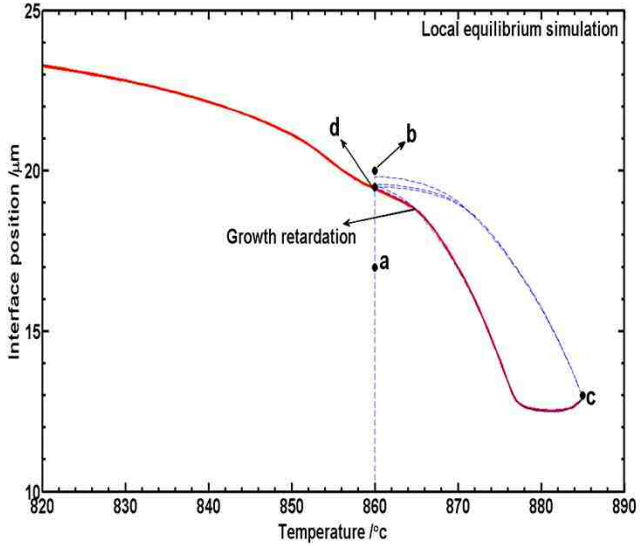
Experiments



TU Delft

Mn profiles as calculated by LE model

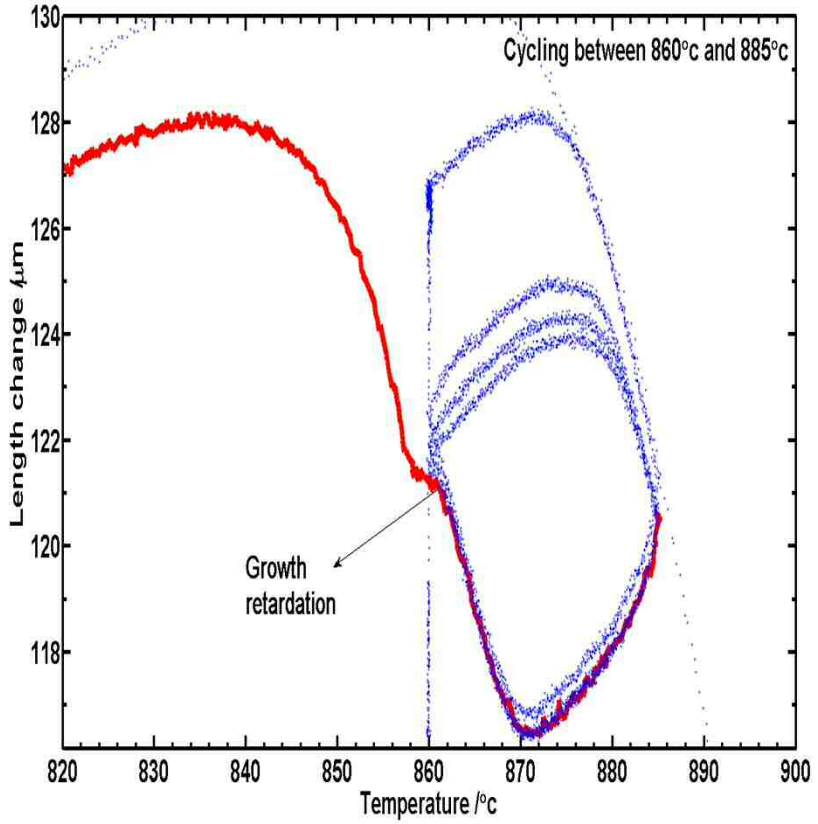




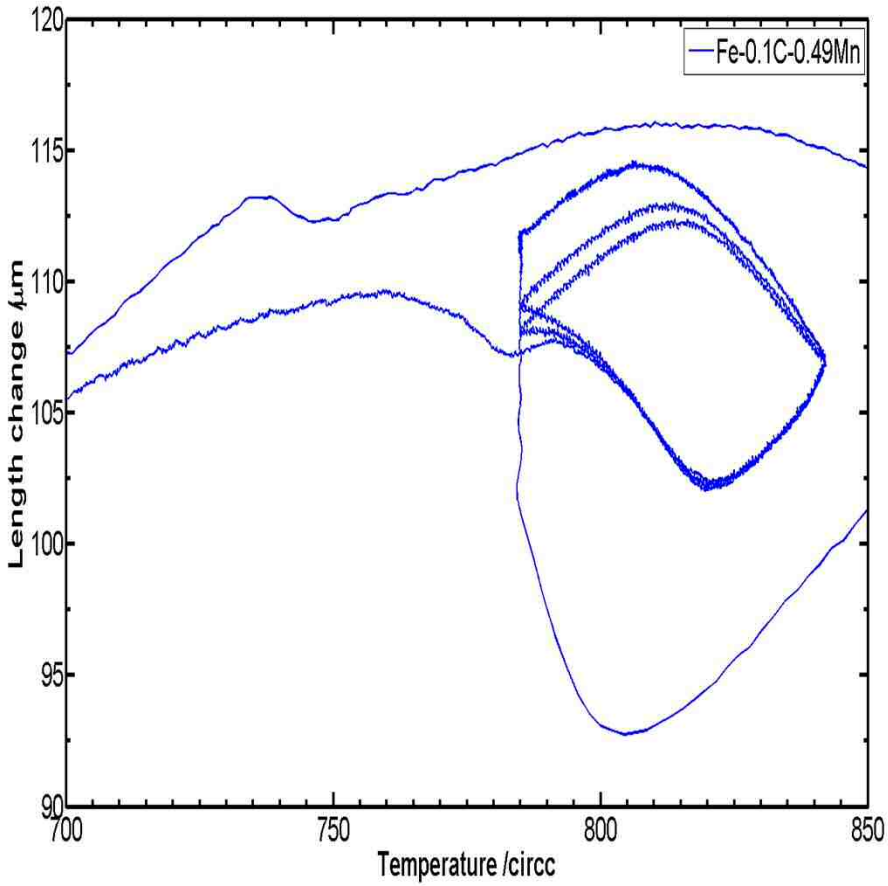
TU Delft

The effect of Mn concentration on local stagnant stage

Fe-0.023C-0.17Mn

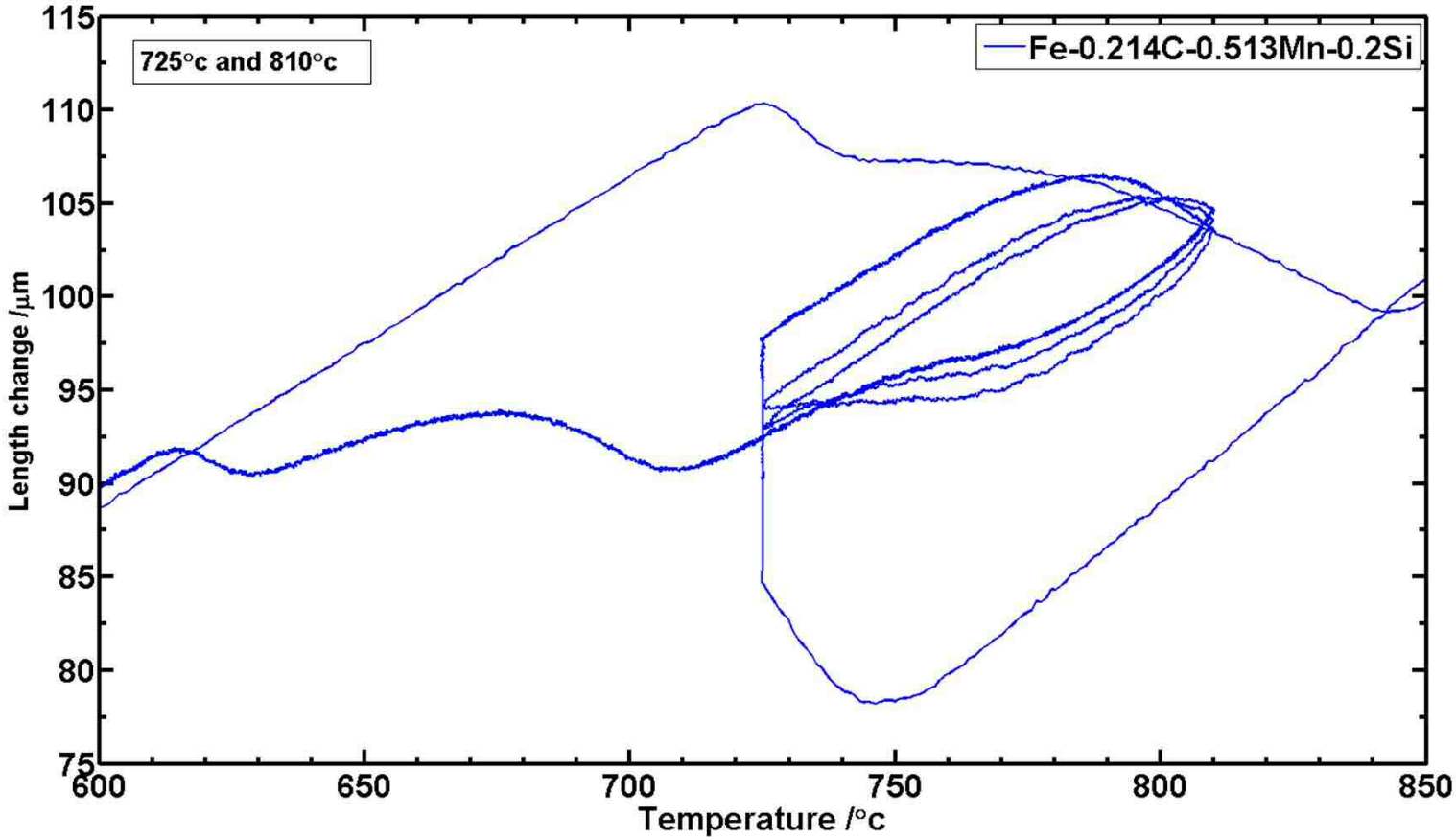


Fe-0.1C-0.49Mn



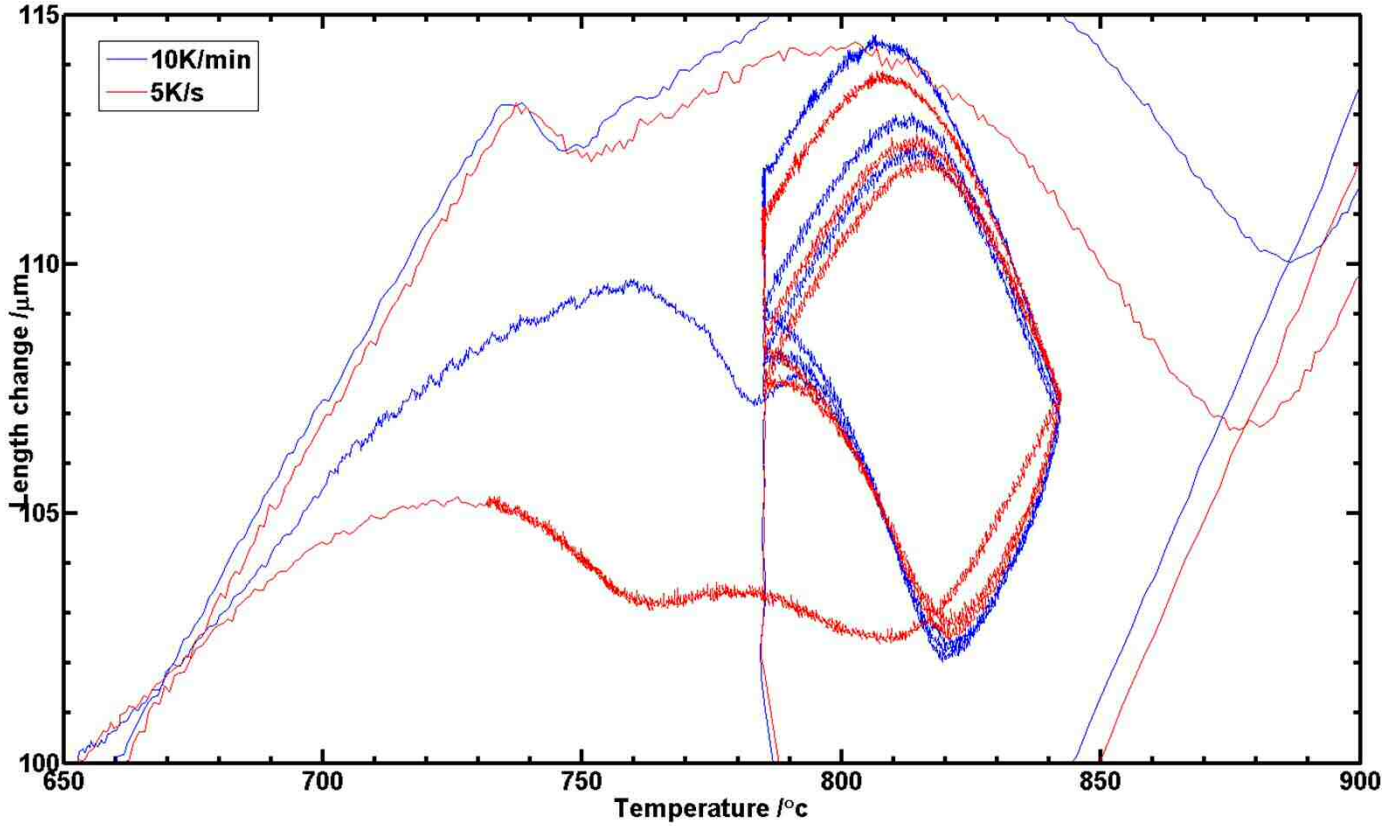
TU Delft

Addition of Si and a higher Mn %



TU Delft

Temperature or position dependent??



TU Delft

Conclusions

1. Substitutional element partitioning is responsible for the stagnant stage
2. The degree of partitioning depends on chemical element, heating rate and cooling rate
3. The effect of chemical elements on stagnant stage seems additive
4. The partitioning related to the stagnant stage can affect the kinetics of subsequent transformations (provided the interface moves in the same direction)