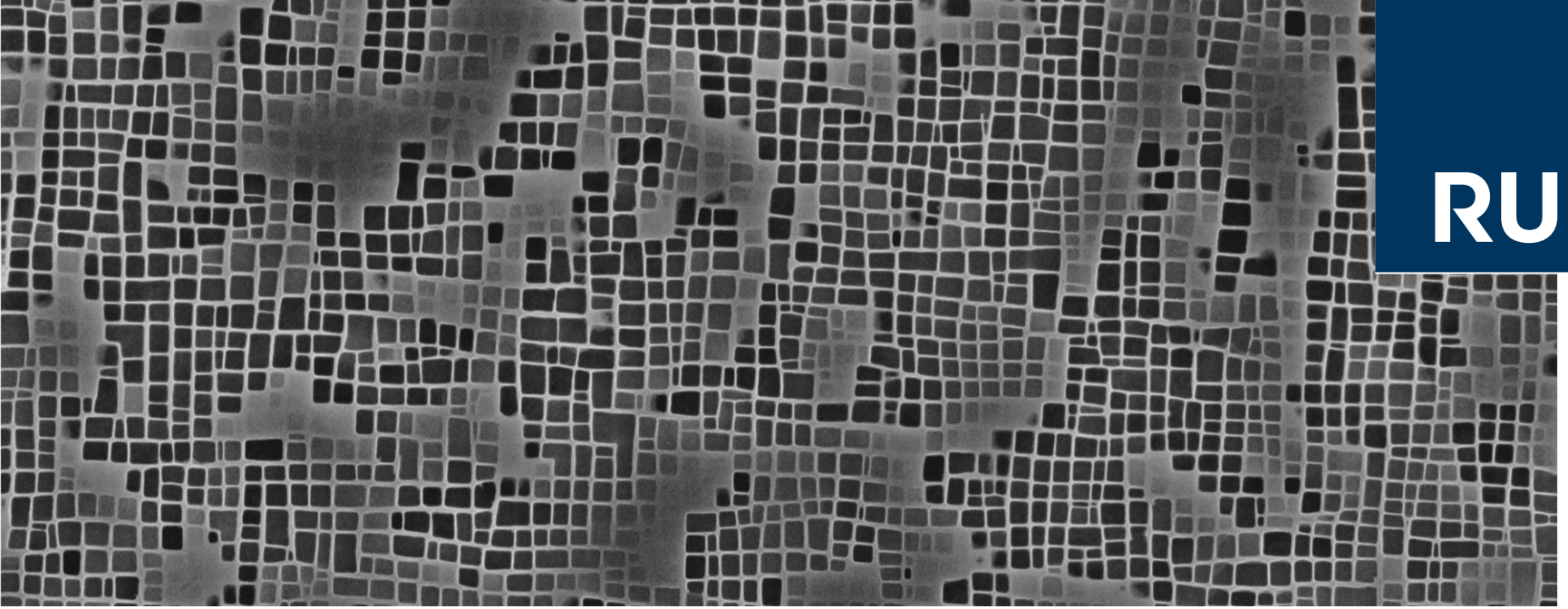


RUB

RUHR-UNIVERSITÄT BOCHUM

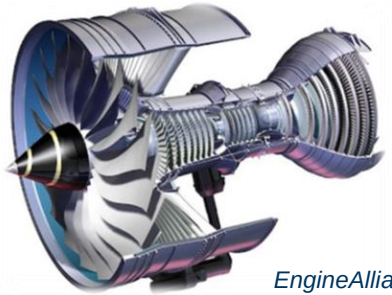
ADVANCED HEAT-TREATMENTS OF TURBINE BLADE MATERIALS

lwt Lehrstuhl Werkstofftechnik Materials Technology

I. Lopez-Galilea | Lehrstuhl Werkstofftechnik | Ruhr-Universität Bochum

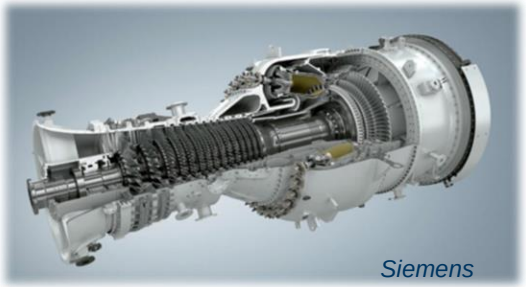
Gas turbines

- Aerospace:
  - Airplanes / Helicopters
  - Engine

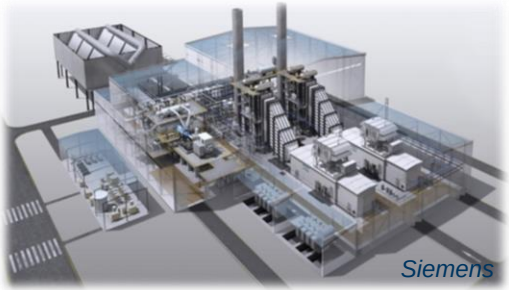


EngineAlliance

- Energy sector:
  - Gas / Steam Power plants
  - Power supply



Siemens



Siemens

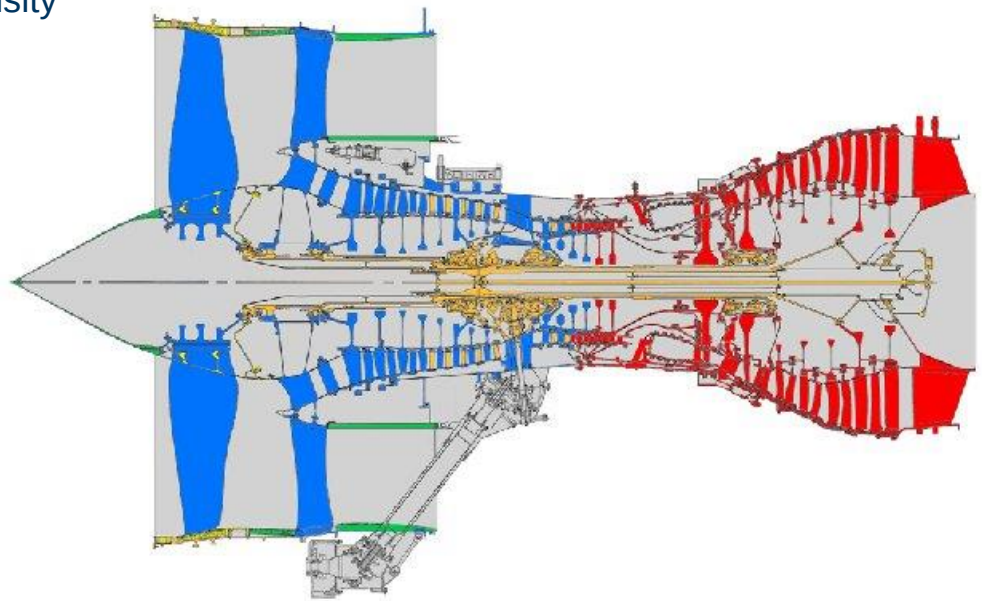
RUHR UNIVERSITÄT BOCHUM RUB

Gas turbines: Geometries of turbine blades

- Geometry is directly dependent of:
  - Location within the Gas Turbine
  - Temperature and load regime

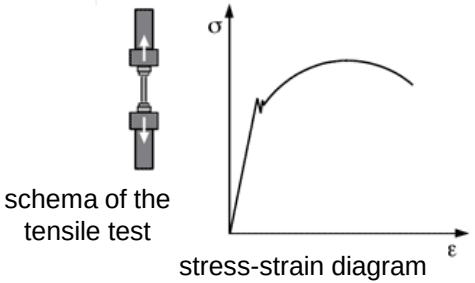
Material groups in gas turbines

- Titanium and its alloys: High strength, low density
- Steels (static parts of the compressor)
  - Martensitic 9-12% Cr steels
  - Austenitic Cr-Ni steels
- Superalloys (T > 0.7 Tsol)
  - Nickel
  - Cobalt
  - Iron-Nickel
- Aluminum alloys
- Magnesium alloys



http://www.phase-trans.msm.cam.ac.uk/2003/Superalloys/coatings/materials.html

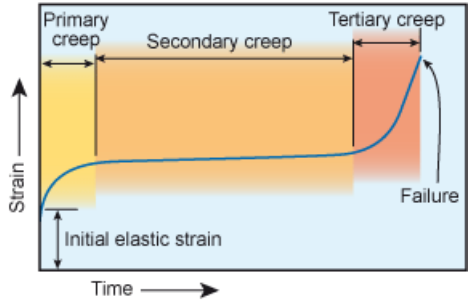
Types of loads on turbine blades:



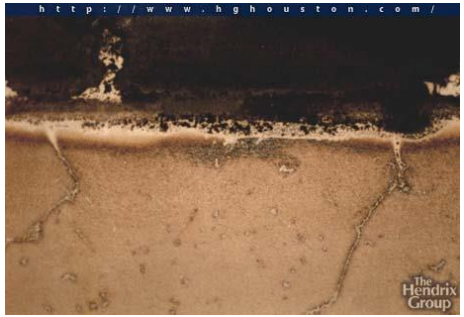
schema of the tensile test

stress-strain diagram

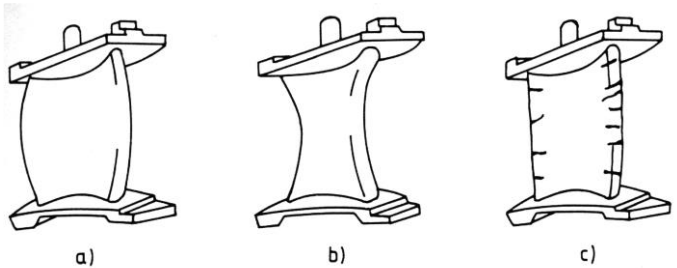
High-temperature strength



Creep resistance



HT- corrosion resistance



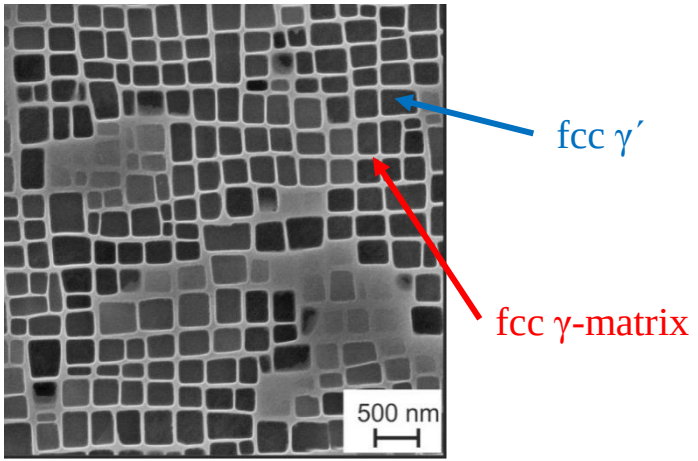
Thermal shock resistance

Blades behind the combustion chamber

SINGLE-CRYSTAL (**SX**) Ni base superalloys

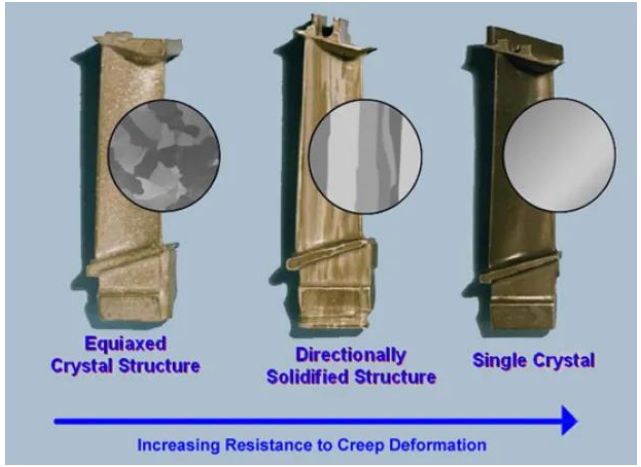
- Excellent thermal and mechanical properties at ↑T

Animation content from: https://youtu.be/wYHch5QIWTQ

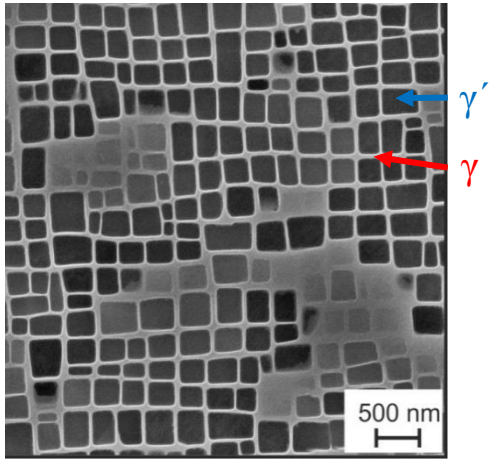


Important !

SINGLE-CRYSTAL (**SX**) Ni base superalloys



Make Magazine



- Technical single crystal
  - Two-phase microstructure
- No grain boundaries
- Nickel: High melting point
- **Strengthening mechanisms**:
  - Solid solution strengthening
  - Particle hardening through coherent γ´ precipitates

wt.%	Co	Al	Cr	W	Ti	Ta	Re	Hf	Mo	Ni
ERBO/1	9.7	5.6	6.4	6.4	1.0	6.5	3.0	0.1	0.6	Bal.

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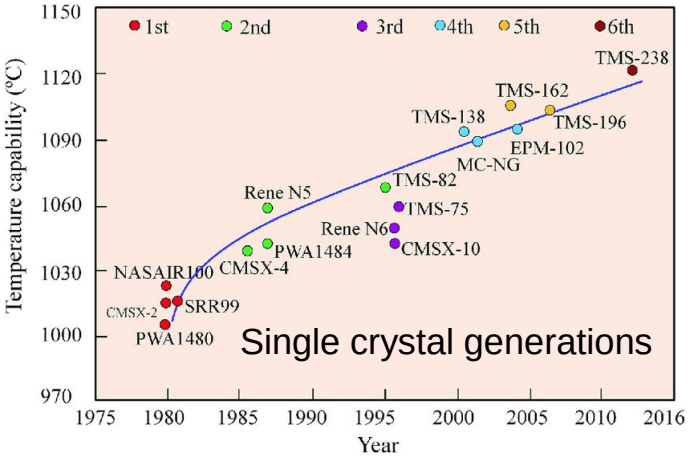
SINGLE-CRYSTAL (**SX**) Ni base superalloys

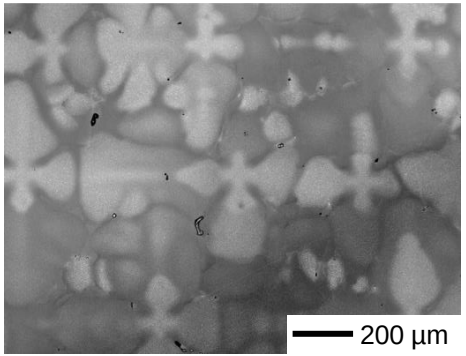


H. Long et al. Journal of Alloys and Compounds 743 (2018)

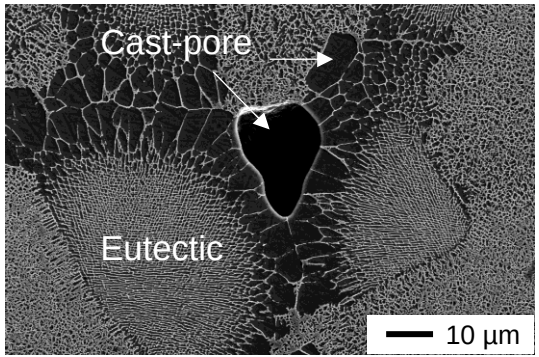
SX generation	Re content	Refractory content = Mo+Ta+W+Re
1st	0 wt.%	14 wt.%
2nd	3 wt.%	16.5 wt.%
3rd	6 wt.%	20 wt.%
4th….	…+ Ru !	…

CMSX-10K

Strong segregation



Interdendritic region (ID)



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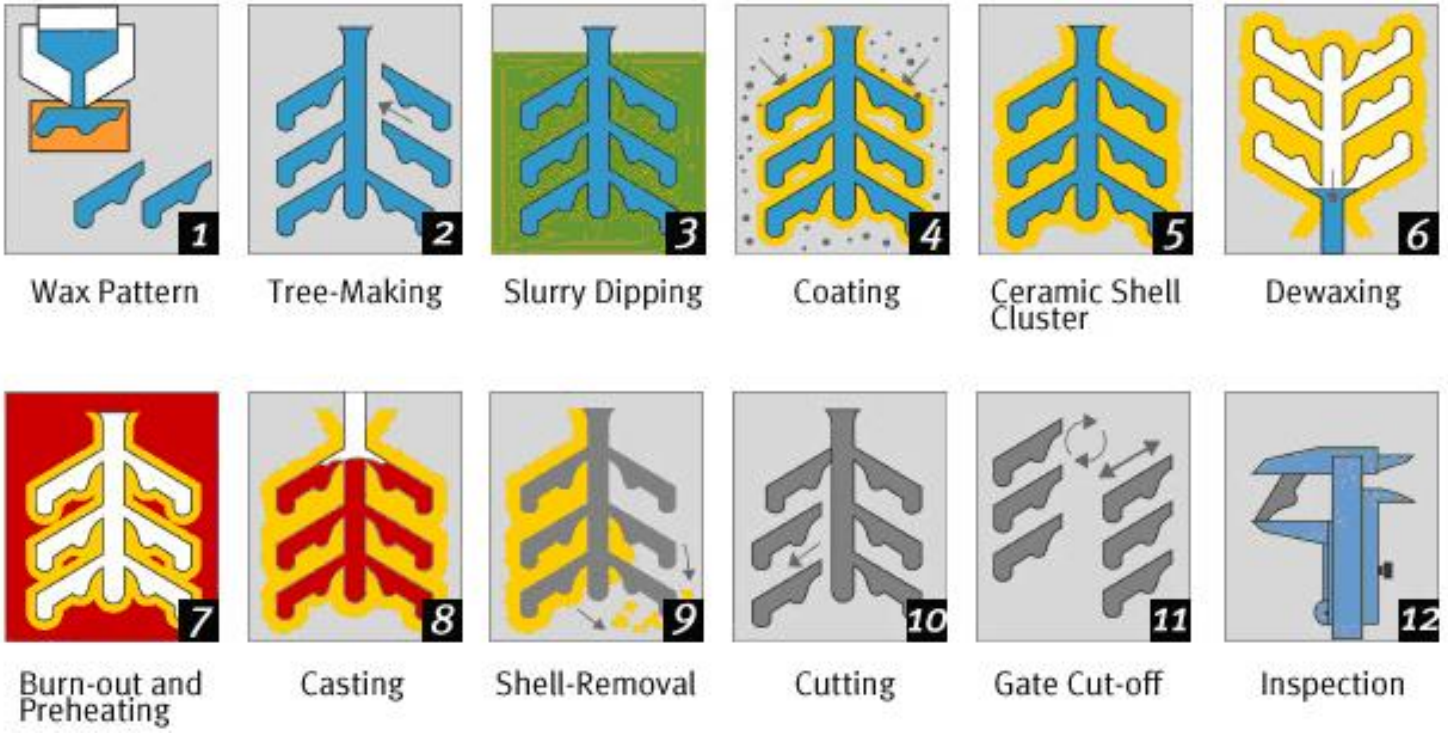
Important !

SX manufacturing: precision casting



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SX manufacturing: precision casting

- From wax model to ceramic shell mold

Tree making

Slurry dipping and coating

SX manufacturing: precision casting

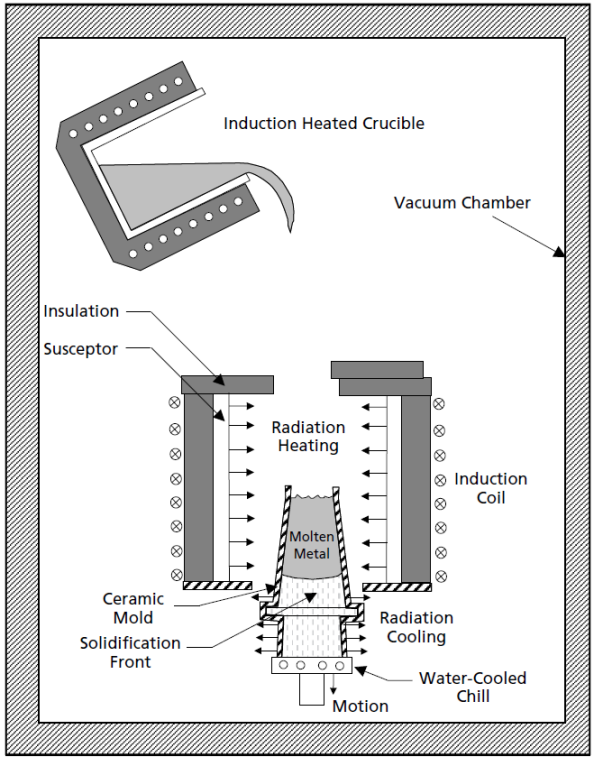
- From Burn-out to casting

Burn-out and pre-heating the shell

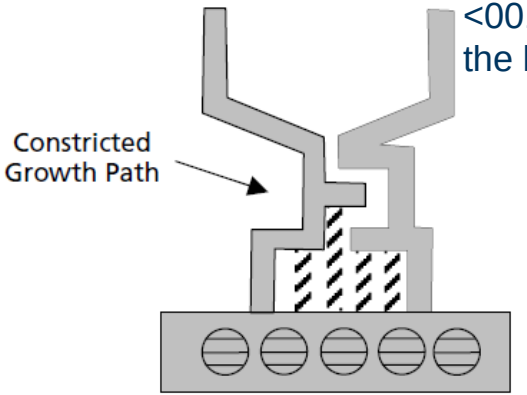
Casting in Vacuum

Shell removal

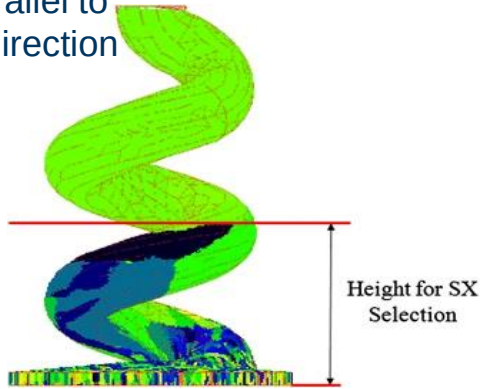
Vacuum investment casting: Bridgman process



Bürgel, Hochtemperaturwerkstofftechnik



<001> aprox. parallel to the longitudinal direction



Dai et al. 2011

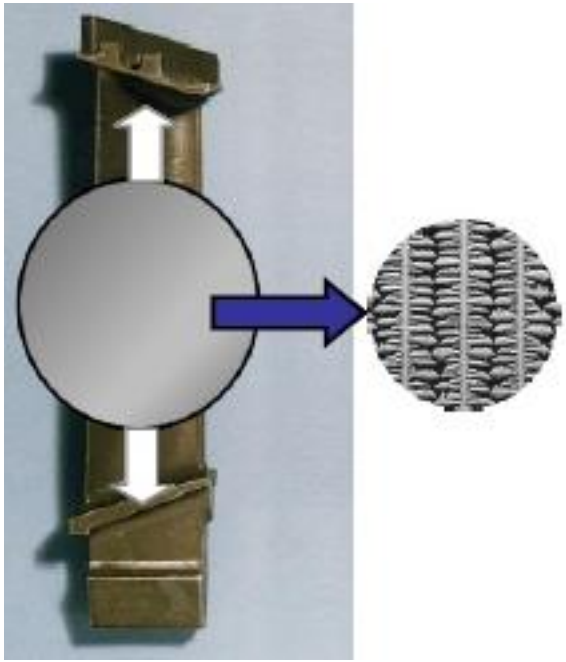
High Rate Solidification

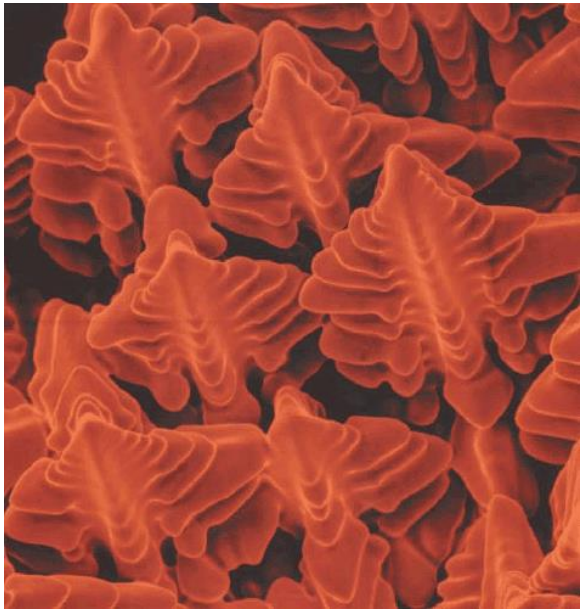
- Strong T gradient:
  - 70-130 K/cm
- Withdrawal rate:
  - 30 cm/h

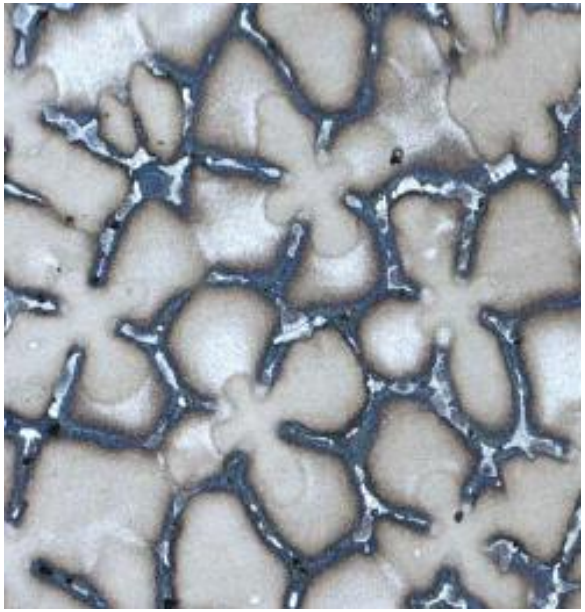
<u>Grain selector (helix)</u>

- Principle: On the cooling plate polycrystalline solidification, only one grain may grow

Vacuum investment casting: Dendritic solidification



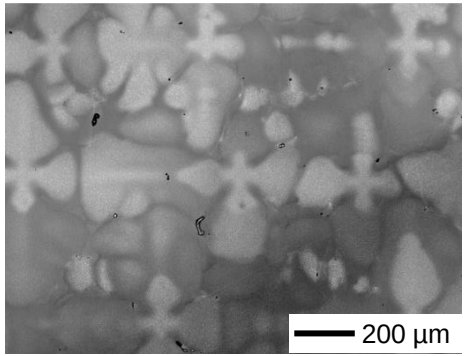




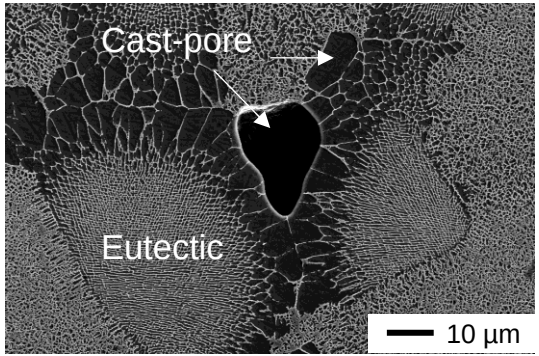
Vacuum investment casting: Dendritic solidification

- Inhomogeneities / defects

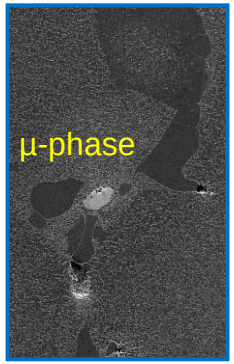
Strong chemical segregation



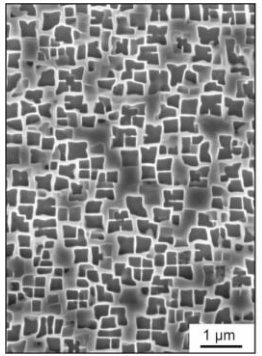
Interdendritic region (ID)



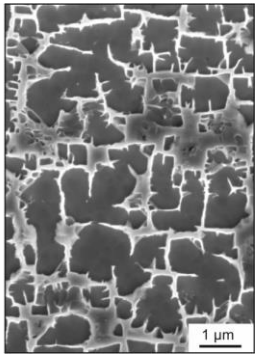
TCP – phases

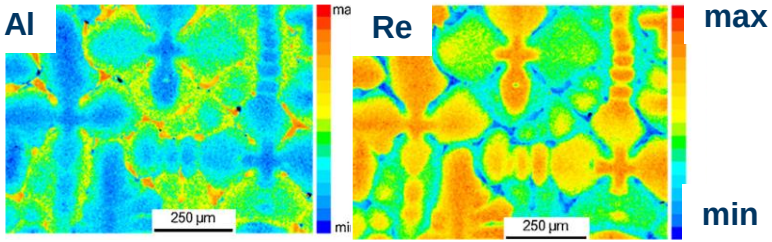


Dendritic



Interdendritic





Parsa et al. 2015

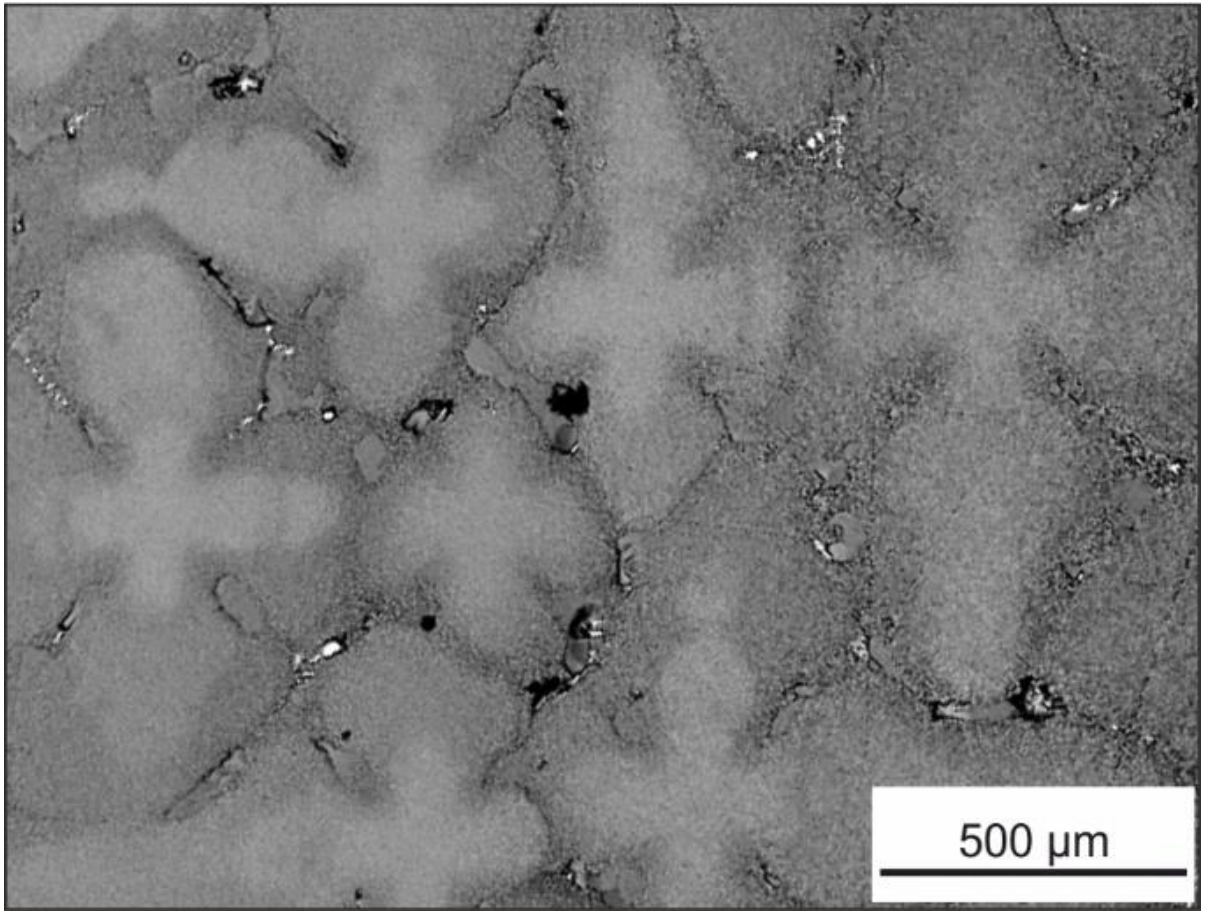
- Large-scale (chemical) heterogeneities: Dendritic structure, chemical segregation, eutectics, TCP, pores
- Small-scale heterogeneity: γ/γ’ microstructure

Exercise Nr.1

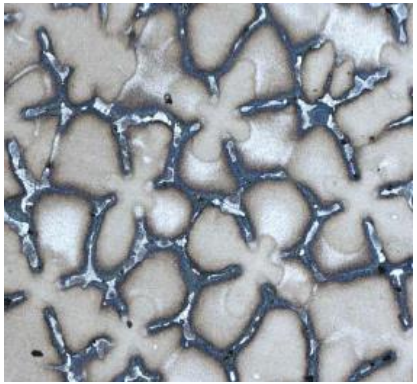
- Position:

1. Dendrite core
2. Dendrite arm
3. Interdendritic
4. Pore
5. Eutectic
6. TCP

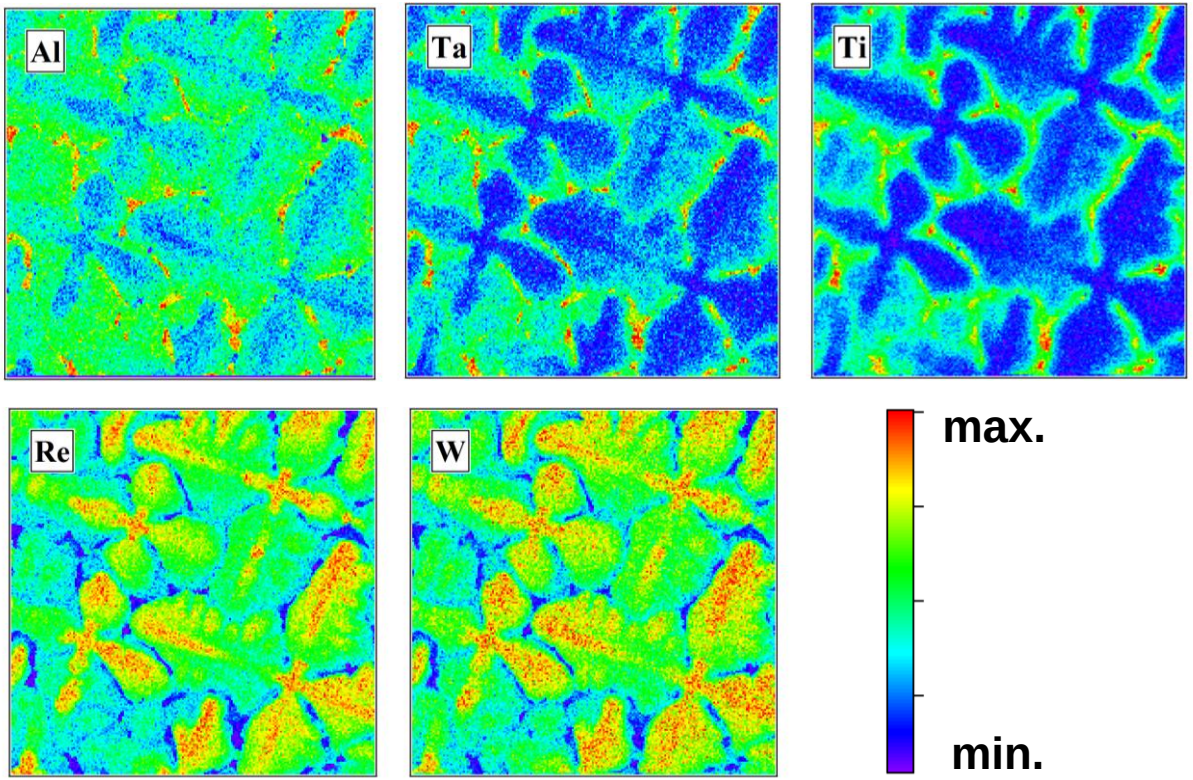
Dendrite arm spacing?



Exercise Nr.2



250 µm



Exercise Nr.2

- Spotscans / point measurements of element concentration in different regions (Values in weight pct).

Measurement#	Al	Ti	Cr	Co	Ni	Mo	Ta	W	Re
Interdendritic 1	5.69	1.07	5.99	9.63	60.56	0.72	7.54	6.01	2.77
…									
Interdendritic 5	5.85	1.18	5.77	9.51	60.38	0.72	7.8	6.4	2.4
Dendrite core 1	5.47	1.01	6.43	9.85	58.62	0.58	5.93	8.15	3.69
…									
Dendrite core 5	5.46	0.82	6.38	9.96	58.67	0.69	5.25	8.89	3.87

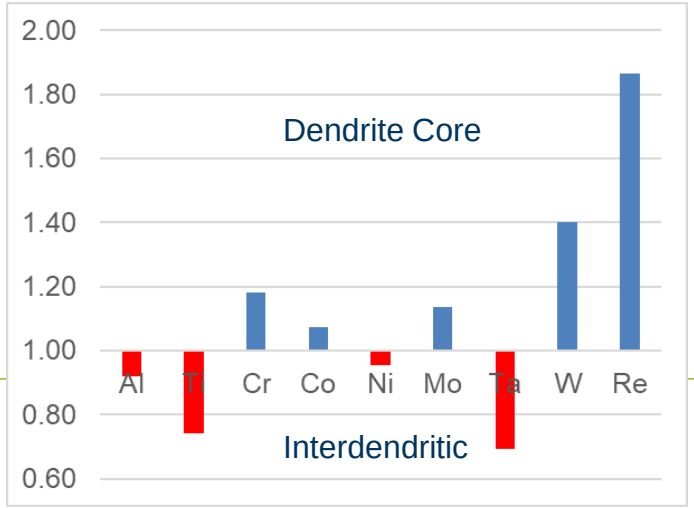
- The following relation exists:

$$k_i^{'} = \frac{C_{D,i}}{C_{ID,i}}$$

Exercise Nr.2

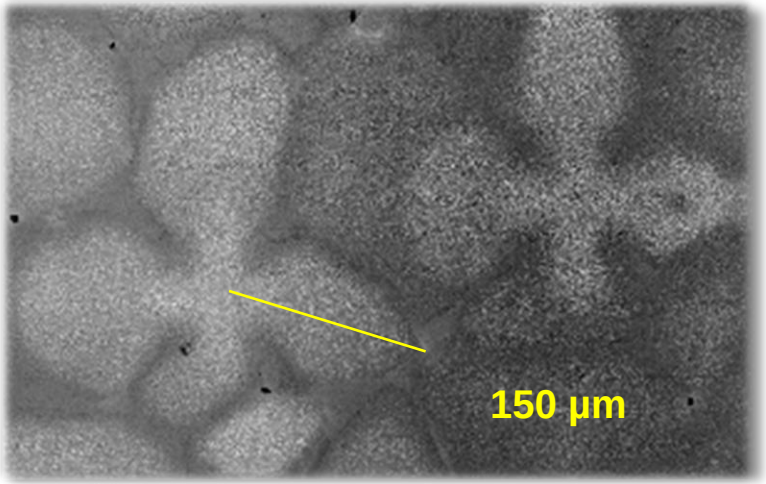
- Spotscans / point measurements of element concentration in different regions (Values in weight pct).

	Al	Ti	Cr	Co	Ni	Mo	Ta	W	Re
Interdendritic	6.01	1.20	5.29	9.14	Bal.	0.62	8.02	6.13	1.98
Dendrite core	5.53	0.89	6.24	9.81	Bal.	0.71	5.56	8.59	3.70
Segregation coefficient ki	**0.92**	**0.74**	**1.18**	**1.07**	**0.96**	**1.14**	**0.69**	**1.40**	**1.86**
Nominal	5.6	1	6.4	9.7	Bal.	0.6	6.5	6.4	3



Exercise Nr.2

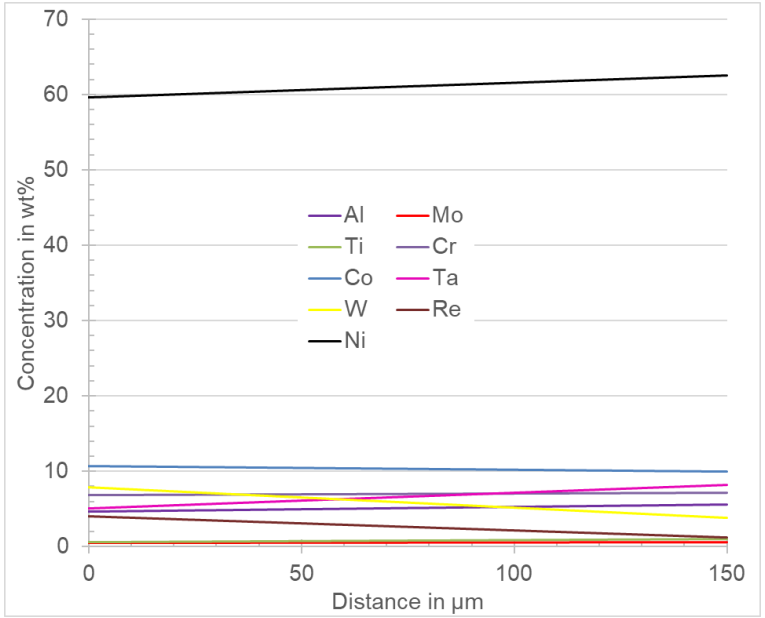
Line-scan. Raw data of detected element concentration as a function of distance of 150 µm (Values in weight pct)

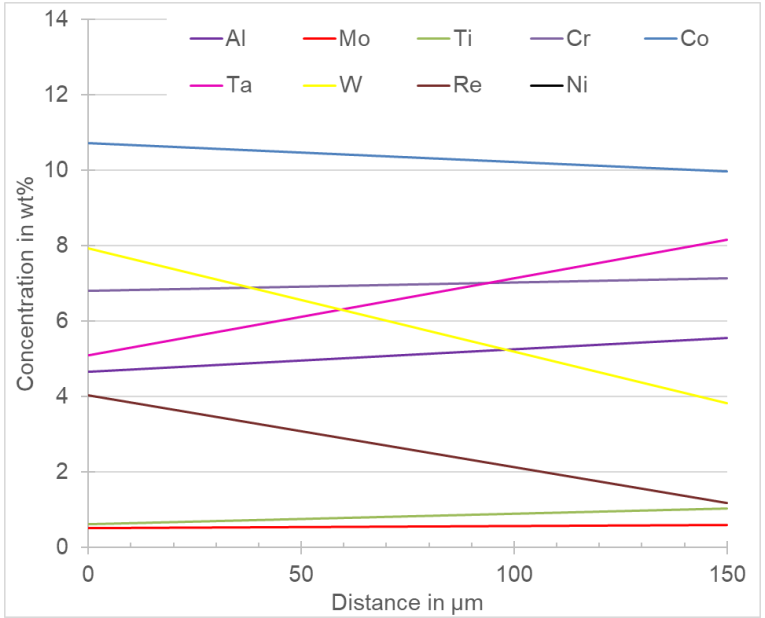


Point	Distance	Al	Mo	….	Re	Ni
1	0	4.66	0.52		4.03	59.62
2	1	4.666	0.5205		4.011	59.64
3	2	4.672	0.521		3.992	59.659
…..						…….
….						…….
150	149	5.554	0.5945		1.199	62.526
151	150	5.56	0.595		1.18	62.545

Exercise Nr.2

Line-scan





Exercise Nr.3

Characteristic temperatures calculated via Thermo-Calc

Equilibrium calculations for CMSX-4 (nominal, DC and ID)

a. Determination of the main transformation temperatures of the different phases that coexist in equilibrium conditions and calculation of the processing-window temperature for this alloy.
b. Representation of the evolution of amount of phases with temperature.

Average values	Al	Ti	Cr	Co	Ni	Mo	Ta	W	Re
Interdendritic	6.01	1.20	5.29	9.14	Bal.	0.62	8.02	6.13	1.98
Dendrite core	5.53	0.89	6.24	9.81	Bal.	0.71	5.56	8.59	3.70
Nominal	5.6	1.0	6.4	9.7	Bal.	0.6	6.5	6.4	3.0

T in Kelvin	**Liquidus**	**Solidus**	**γ´ solvus**	**….**	**….**
Interdendritic					
Dendrite core					
Nominal					

TASK number 3 (dendritic composition)

Thermo - Calc 2023b

SYS: SET_LOG_FILE

Heading:

SYS:GOTO_MODULE

MODULE NAME: DATA

TDB_TCFE10:SWITCH_DATABASE

DATABASE NAME /TCFE10/:TCNi10

TDB_TCNI10:DEFINE_ELEMENTS

ELEMENTS:Al Ti Cr Co Ni Mo Ta W Re

TDB_TCNI10:GET_DATA

TDB_TCNI10:GOTO_MODULE

MODULE NAME: POLY 3

POLY: SET_CONDITION

State variable expression: T=1700 p=1e+05 n=1

POLY: SET_CONDITION w(al)=0.0553

..

POLY: SET_CONDITION w(..)=…

POLY: LIST_CONDITIONS

POLY: COMPUTE_EQUILIBRIUM

POLY: LIST_EQUILIBRIUM

OUTPUT TO SCREEN OR FILE /SCREEN/:

Options /VWCS/:

FIRST RESULT (LIQUID)

POLY: SET_AXIS_VARIABLE

Axis number: /1/:1

Condition /NONE/:T

Min value /0/:1000

Max value /1/:1700

Increment /22.5/:10

POLY: STEP_WITH_OPTIONS

Option? /NORMAL/: NORMAL

No initial equilibrium, using default

Step will start from axis value 1700.00

...OK

…. (see next slide)

….

POLY: POST

TASK number 3 (dendritic composition)

No initial equilibrium, using default

Step will start from axis value 1700.00

...OK

Phase Region from 1700.00 for:

LIQUID

Global check of adding phase at 1.66050E+03

Calculated 6 equilibria

Phase Region from 1677.70 for:

LIQUID

FCC_L12#1

Global check of removing phase at 1.62529E+03

Calculated 8 equilibria

Phase Region from 1625.29 for:

FCC_L12#1

Global test at 1.55000E+03 .... OK

Phase Region from 1522.54 for:

FCC_L12#1

FCC_L12#2

Global test at 1.45000E+03 .... OK

Phase Region from 1417.93 for:

FCC_L12#1

FCC_L12#2

SIGMA

Global test at 1.34000E+03 .... OK

Phase Region from 1064.77 for:

FCC_L12#1

FCC_L12#2

R_PHASE

SIGMA

Terminating at 1000.00

TASK number 3 (DC)

Thermo - Calc 2023b

SYS: POST

POST:SET_DIAGRAM_AXIS

AXIS (X, Y OR Z) :X

VARIABLE :T-C

POST:SET_DIAGRAM_AXIS

AXIS (X, Y OR Z) :y

VARIABLE :VPV(*)

COLUMN NUMBER /*/:*

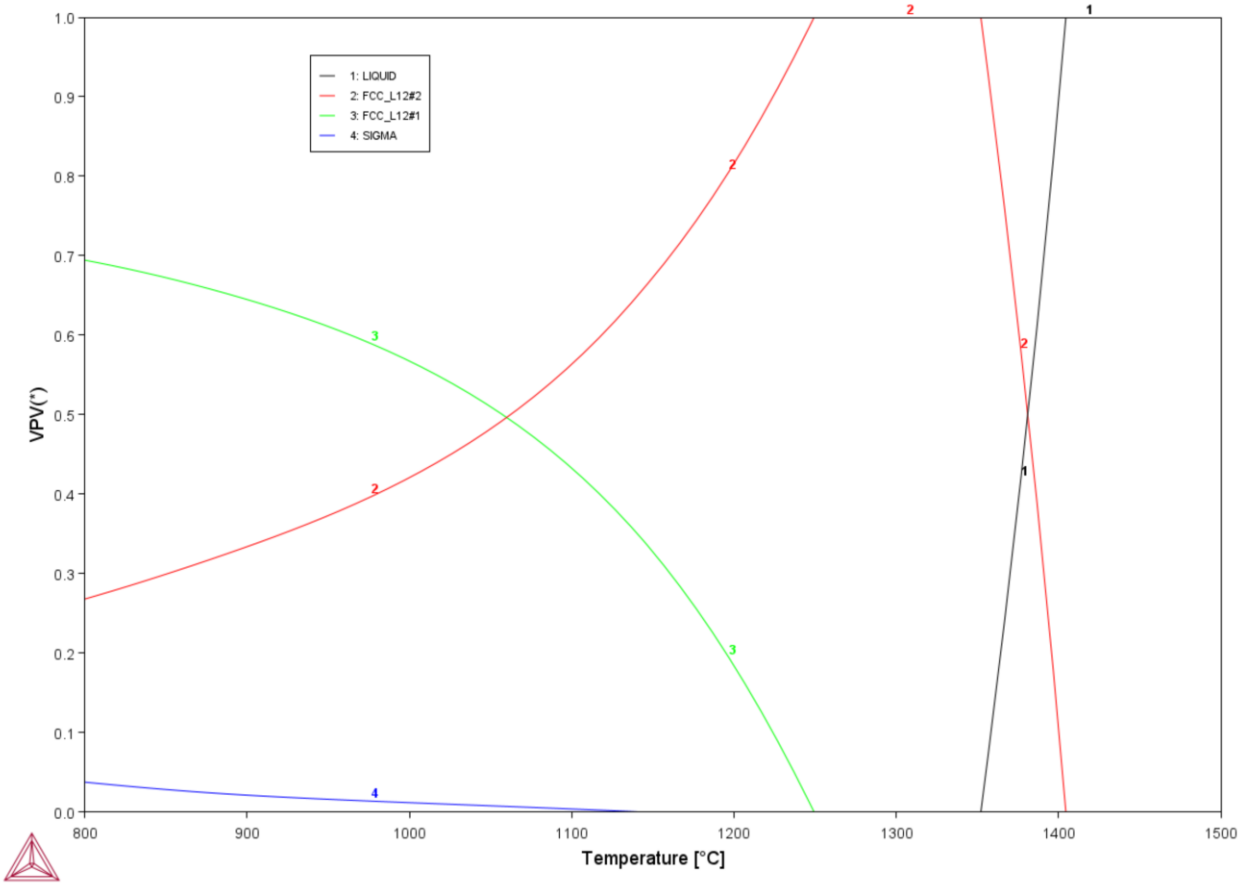
POST:SET_LABEL_CURVE_OPTION

CURVE LABEL OPTION (A, B, C, D, E, F OR N) /N/:F

POST:PLOT_DIAGRAM

POST: MAKE_EXPERIMENTAL_DATAFI

OUTPUT TO SCREEN OR FILE /SCREEN/:FILE



TASK number 3 (Interdendritic composition)

Thermo - Calc 2023b

SYS: SET_LOG_FILE

Heading:

SYS:GOTO_MODULE

MODULE NAME: DATA

TDB_TCFE10:SWITCH_DATABASE

DATABASE NAME /TCFE10/:TCNi10

TDB_TCNI10:DEFINE_ELEMENTS

ELEMENTS:Al Ti Cr Co Ni Mo Ta W Re

TDB_TCNI10:GET_DATA

TDB_TCNI10:GOTO_MODULE

MODULE NAME: POLY 3

POLY: SET_CONDITION

State variable expression: T=1700 p=1e+05 n=1

POLY: SET_CONDITION w(al)=0.0601

..

POLY: SET_CONDITION w(..)=…

POLY: LIST_CONDITIONS

POLY: COMPUTE_EQUILIBRIUM

POLY: LIST_EQUILIBRIUM

OUTPUT TO SCREEN OR FILE /SCREEN/:

Options /VWCS/:

FIRST RESULT (LIQUID)

POLY: SET_AXIS_VARIABLE

Axis number: /1/:1

Condition /NONE/:T

Min value /0/:1000

Max value /1/:1700

Increment /22.5/:10

POLY: STEP_WITH_OPTIONS

Option? /NORMAL/: NORMAL

No initial equilibrium, using default

Step will start from axis value 1700.00

...OK

…. (see next slide)

….

POLY: POST

TASK number 3 (Interdendritic composition)

No initial equilibrium, using default

Step will start from axis value 1700.00

...OK

Phase Region from 1700.00 for:

LIQUID

Global check of adding phase at 1.66050E+03

Calculated 6 equilibria

Phase Region from 1660.50 for:

LIQUID

FCC_L12#1

Global check of removing phase at 1.60805E+03

Calculated 9 equilibria

Phase Region from 1608.05 for:

FCC_L12#1

Global test at 1.53000E+03 .. Back….

Phase Region from 1577.16 for:

FCC_L12#1

FCC_L12#2

Global test at 1.50000E+03 .... OK

Phase Region from 1189.22 for:

FCC_L12#1

FCC_L12#2

SIGMA

Global test at 1.11000E+03 .... O

Phase Region from 1106.45 for:

FCC_L12#1

FCC_L12#2

R_PHASE

SIGMA

Global test at 1.03000E+03 .... OK

Terminating at 1000.00

TASK number 3 (ID)

Thermo - Calc 2023b

SYS: POST

POST:SET_DIAGRAM_AXIS

AXIS (X, Y OR Z) :X

VARIABLE :T-C

POST:SET_DIAGRAM_AXIS

AXIS (X, Y OR Z) :y

VARIABLE :VPV(*)

COLUMN NUMBER /*/:*

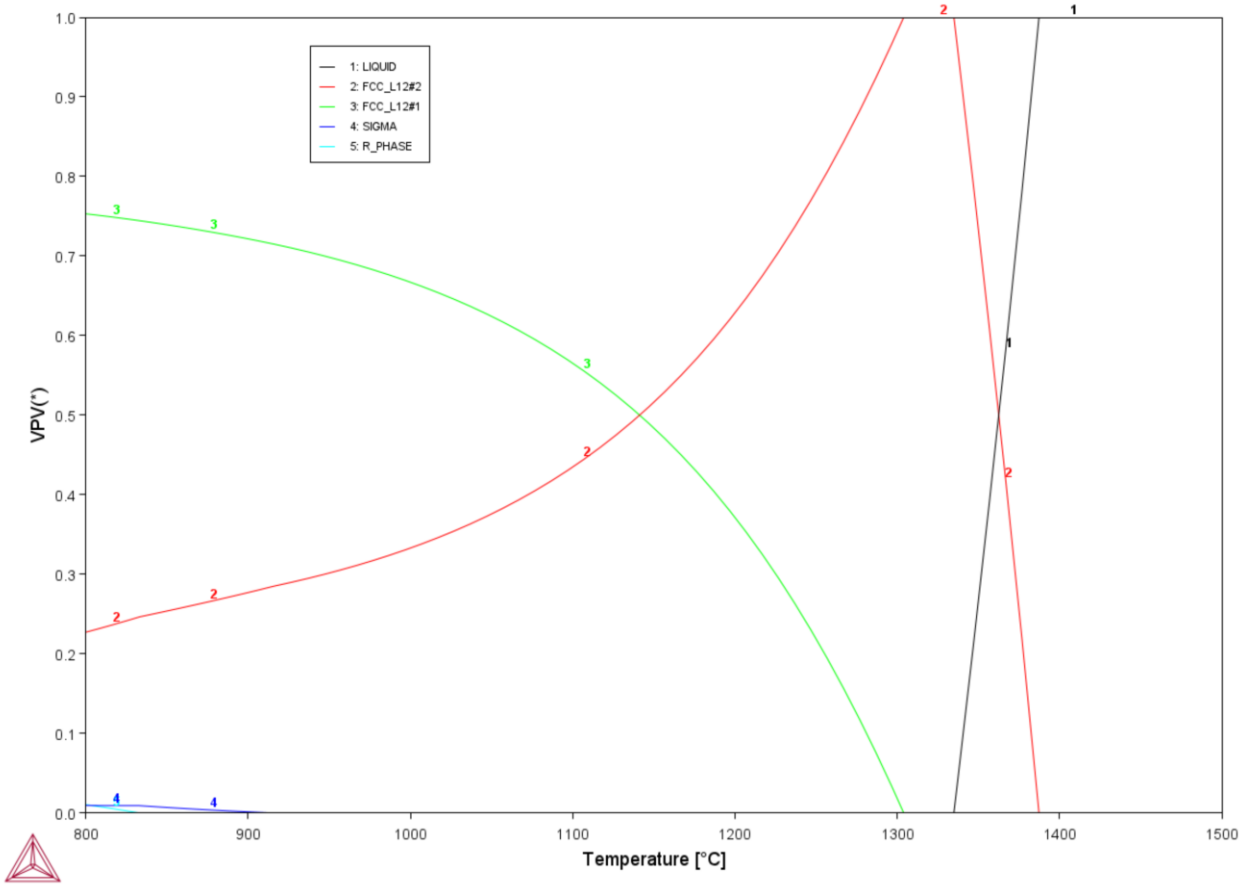
POST:SET_LABEL_CURVE_OPTION

CURVE LABEL OPTION (A, B, C, D, E, F OR N) /N/:F

POST:PLOT_DIAGRAM

POST: MAKE_EXPERIMENTAL_DATAFI

OUTPUT TO SCREEN OR FILE /SCREEN/:FILE



TASK number 3 (Nominal composition)

Thermo - Calc 2023b

SYS: SET_LOG_FILE

Heading:

SYS:GOTO_MODULE

MODULE NAME: DATA

TDB_TCFE10:SWITCH_DATABASE

DATABASE NAME /TCFE10/:TCNi10

TDB_TCNI10:DEFINE_ELEMENTS

ELEMENTS:Al Ti Cr Co Ni Mo Ta W Re

TDB_TCNI10:GET_DATA

TDB_TCNI10:GOTO_MODULE

MODULE NAME: POLY 3

POLY: SET_CONDITION

State variable expression: T=1700 p=1e+05 n=1

POLY: SET_CONDITION w(al)=0.0560

..

POLY: SET_CONDITION w(..)=…

POLY: LIST_CONDITIONS

POLY: COMPUTE_EQUILIBRIUM

POLY: LIST_EQUILIBRIUM

OUTPUT TO SCREEN OR FILE /SCREEN/:

Options /VWCS/:

FIRST RESULT (LIQUID)

POLY: SET_AXIS_VARIABLE

Axis number: /1/:1

Condition /NONE/:T

Min value /0/:1000

Max value /1/:1700

Increment /22.5/:10

POLY: STEP_WITH_OPTIONS

Option? /NORMAL/: NORMAL

No initial equilibrium, using default

Step will start from axis value 1700.00

...OK

…. (see next slide)

….

POLY: POST

TASK number 3 (Nominal composition)

No initial equilibrium, using default

Step will start from axis value 1700.00

...OK

Phase Region from 1700.00 for:

LIQUID

Global check of adding phase at 1.67173E+03

Calculated 5 equilibria

Phase Region from 1671.73 for:

LIQUID

FCC_L12#2

Global check of removing phase at 1.62086E+03

Calculated 8 equilibria

Phase Region from 1620.86 for:

FCC_L12#2

Global test at 1.55000E+03 .... OK

Phase Region from 1532.85 for:

FCC_L12#1

FCC_L12#2

Global test at 1.46000E+03 .... OK

Phase Region from 1206.81 for:

FCC_L12#1

FCC_L12#2

SIGMA

Global test at 1.13000E+03 .... OK

Phase Region from 1020.45 for:

FCC_L12#1

FCC_L12#2

R_PHASE

SIGMA

Terminating at 1000.00

TASK number 3 (Nominal composition)

Thermo - Calc 2023b

SYS: POST

POST:SET_DIAGRAM_AXIS

AXIS (X, Y OR Z) :X

VARIABLE :T-C

POST:SET_DIAGRAM_AXIS

AXIS (X, Y OR Z) :y

VARIABLE :VPV(*)

COLUMN NUMBER /*/:*

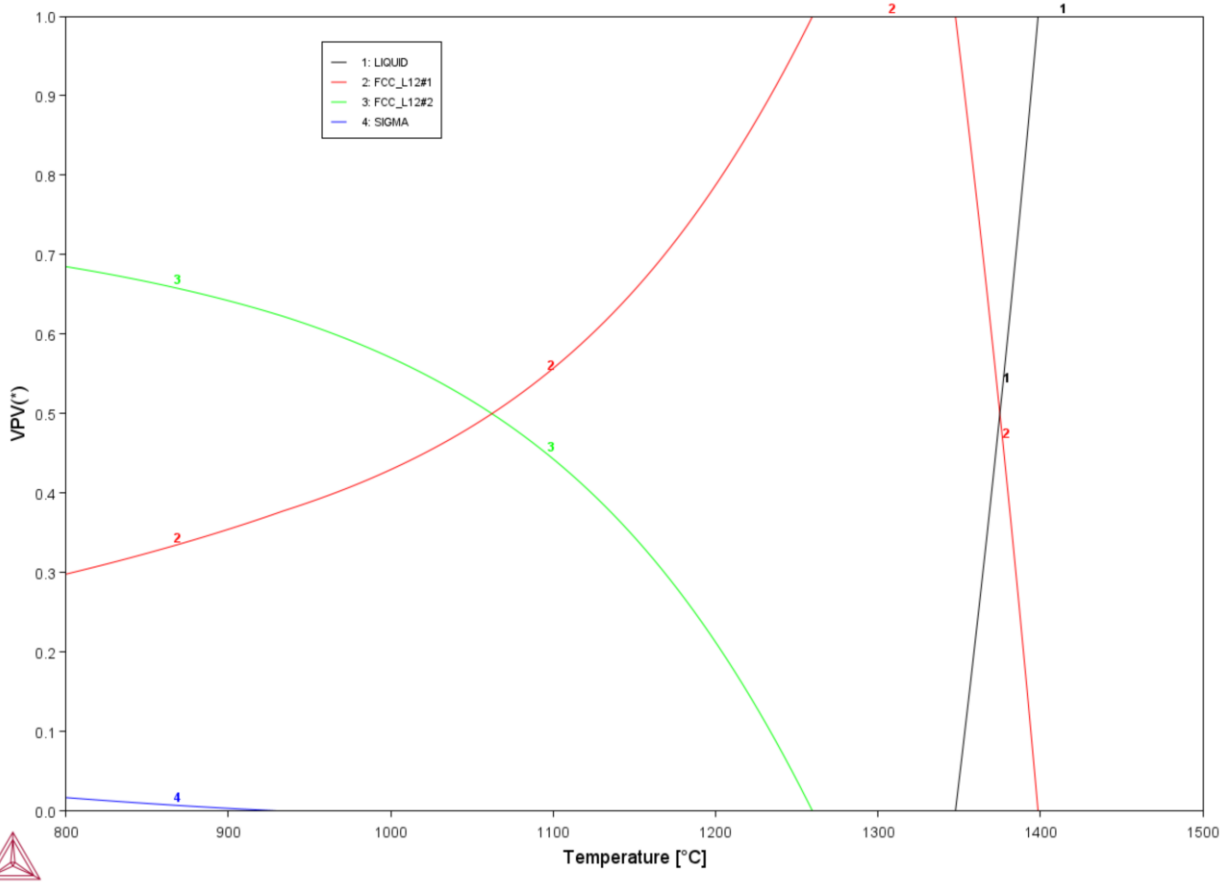
POST:SET_LABEL_CURVE_OPTION

CURVE LABEL OPTION (A, B, C, D, E, F OR N) /N/:F

POST:PLOT_DIAGRAM

POST: MAKE_EXPERIMENTAL_DATAFI

OUTPUT TO SCREEN OR FILE /SCREEN/:FILE



Exercise Nr.3

Characteristic temperatures calculated via Thermo-Calc

Equilibrium calculations for CMSX-4 (nominal, DC and ID)

a. Determination of the main transformation temperatures of the different phases that coexist in equilibrium conditions and calculation of the processing-window temperature for this alloy.
b. Representation of the evolution of amount of phases with temperature.

T in Kelvin	Liquidus	Solidus	γ´ solvus	Sigma	R_Phase
Interdendritic	1660.50	1608.05	-	1189.22	1106.45
Dendrite core	1677.70	1625.29	1522.54	1417.93	-
Nominal	1671.73	1620.86	1532.85	1206.81	-

Exercise Nr.3

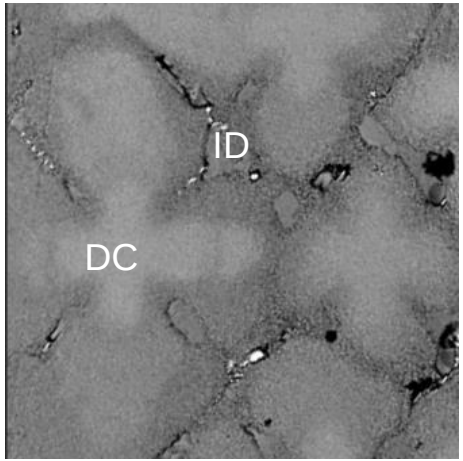
Characteristic temperatures calculated via Thermo-Calc

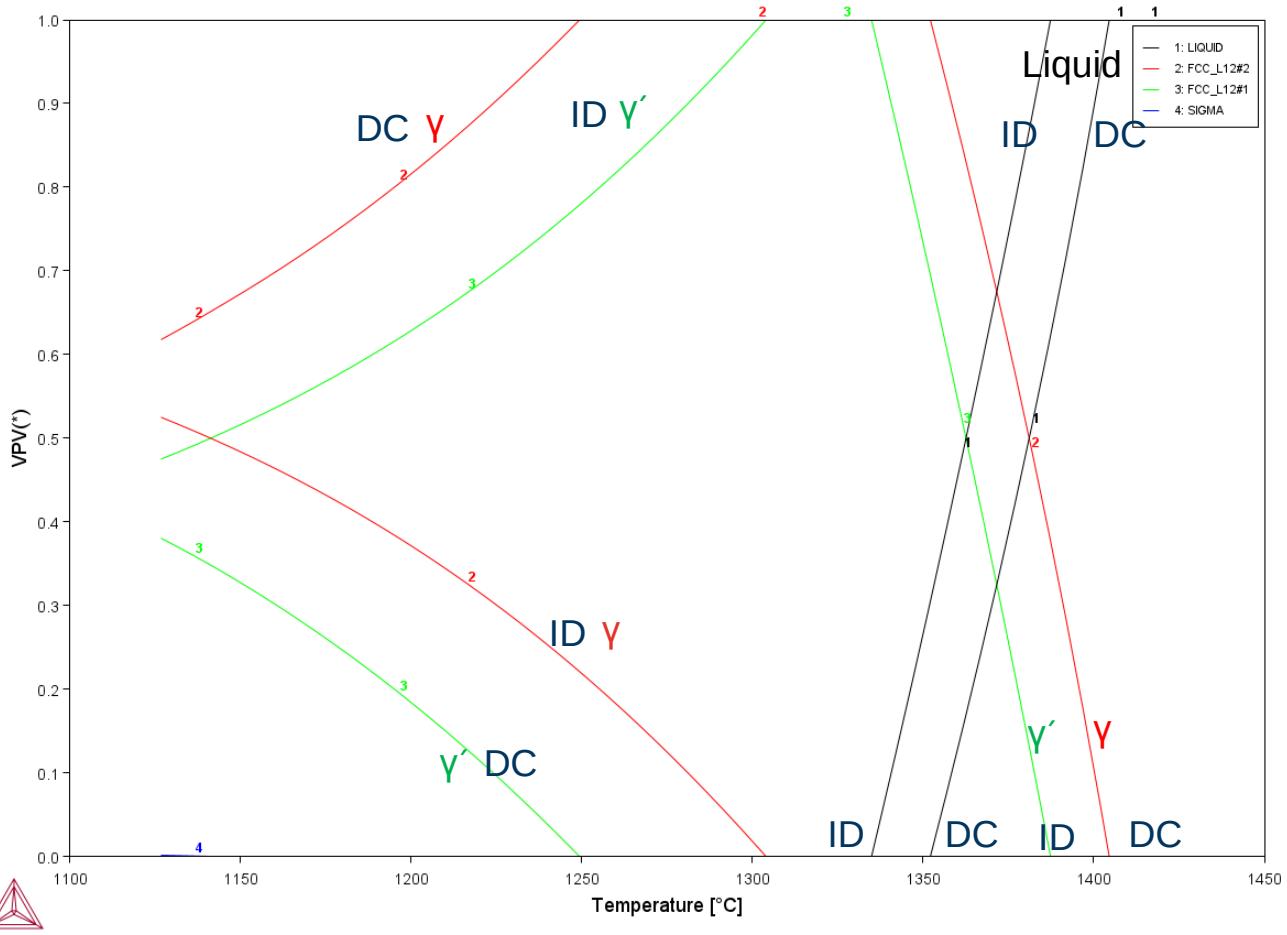
Equilibrium calculations for CMSX-4 (nominal, DC and ID)

a. Determination of the main transformation temperatures of the different phases that coexist in equilibrium conditions and calculation of the processing-window temperature for this alloy.
b. Representation of the evolution of amount of phases with temperature.

T in °C	Liquidus	Solidus	γ´ solvus	Sigma	R_Phase
Interdendritic	1387.35	1334.9	-	916.07	833.3
Dendrite core	1404.55	1352.14	1249.39	1144.78	-
Nominal	1398.58	1347.71	1259.7	933.66	-

Exercise Nr.3





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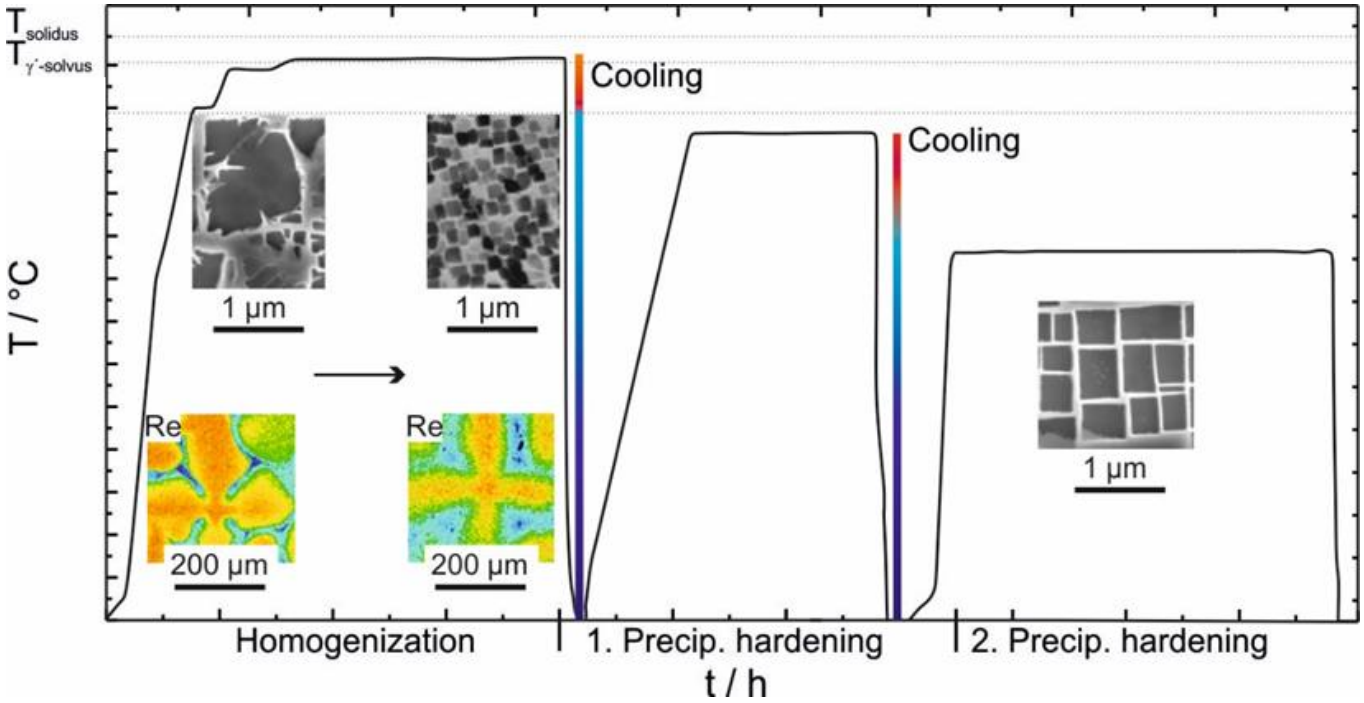
Important !

Conventional processing route



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Important !

Conventional processing route

- Objective:

  - (Macroscopically) homogeneous element distribution

  - Uniform fine γ‘- precipitates within the γ-matrix (γ-channels)

- How?:

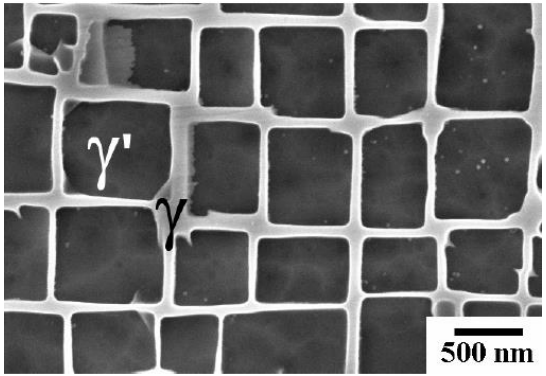
  - **Solution and homogenization of the γ- field**

    => Dissolution of the γ‘

    => Homogenization by diffusion

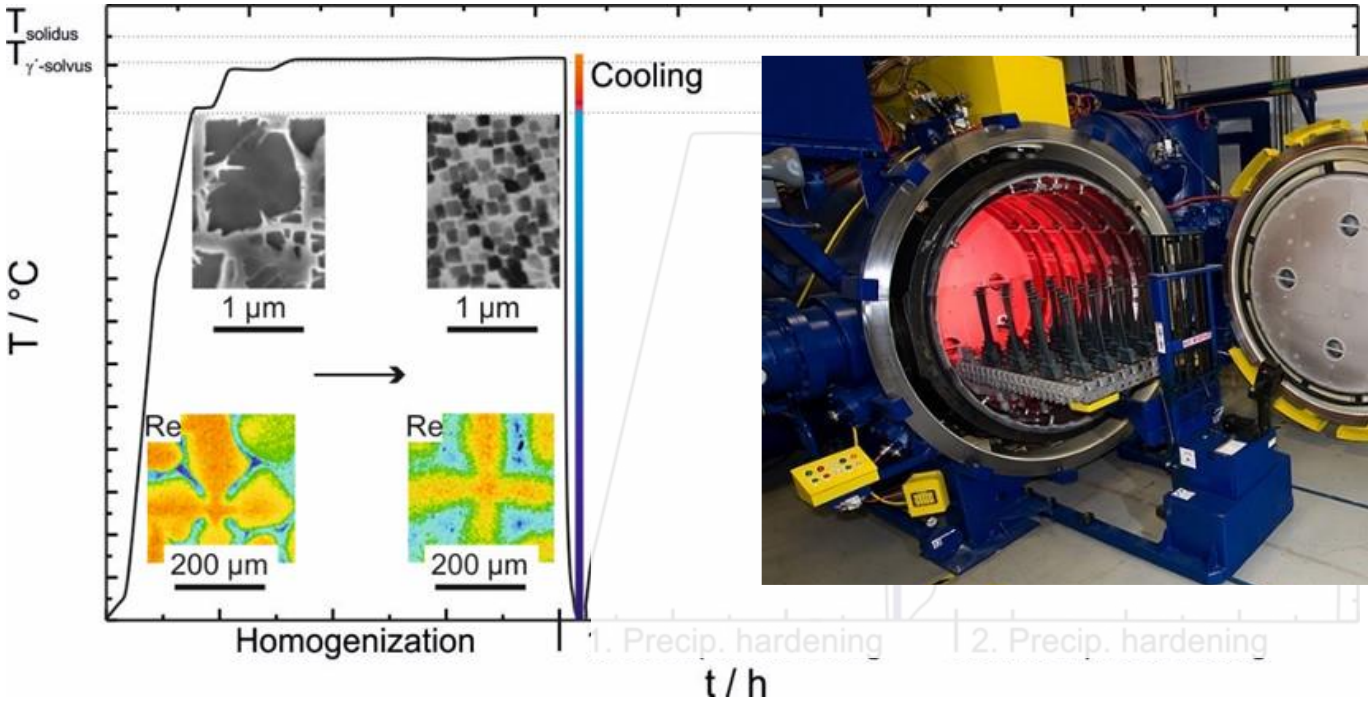
    Fast cooling / Quenching

  - **Precipitation hardening / Aging**

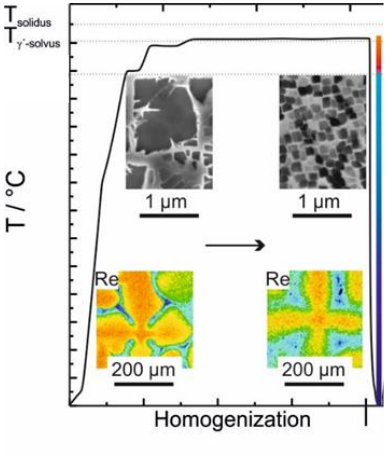


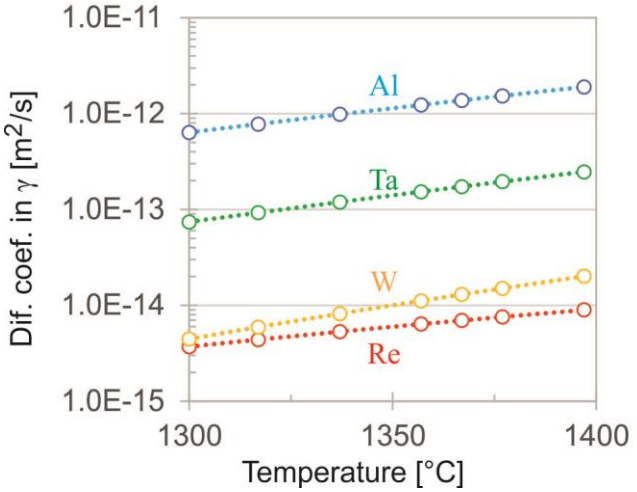
Conventional processing route

- Very long heat-treatments (€€€)
- Increase of porosity (Kirkendall)



Conventional processing route

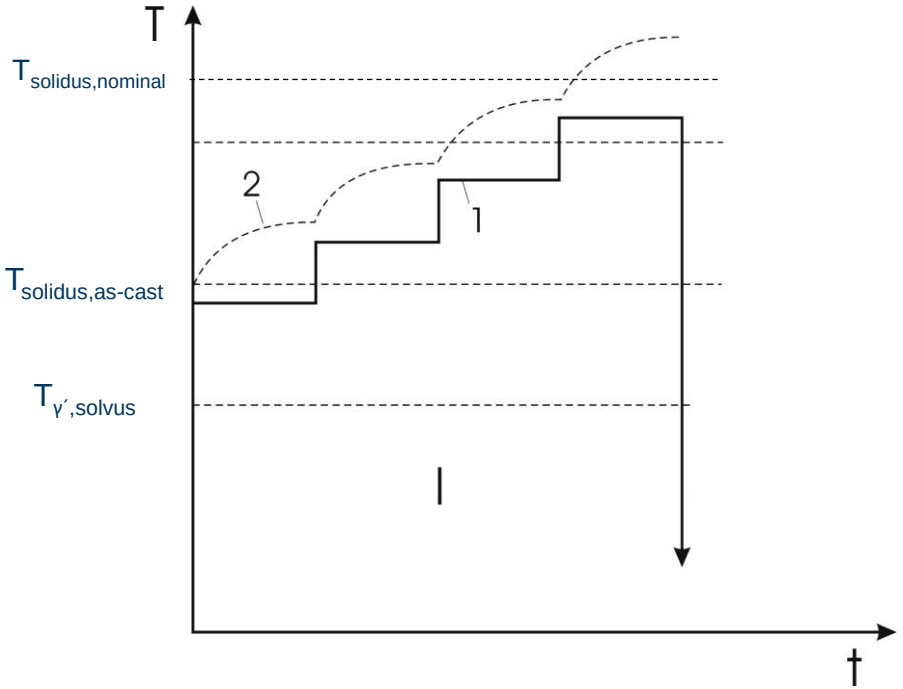




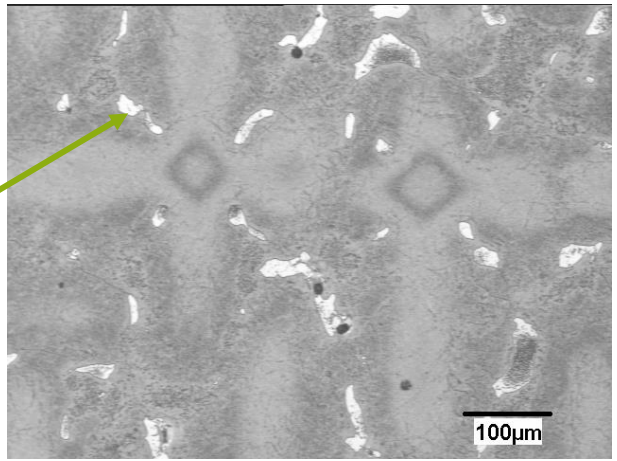
- Very long heat-teatments (€€€)
- Increase of porosity (Kirkendall)
- Deterioration of mech. properties

Complex SXs are no longer attractive for the aeronautical sector despte their potential

Solution annealing “Stepwise”

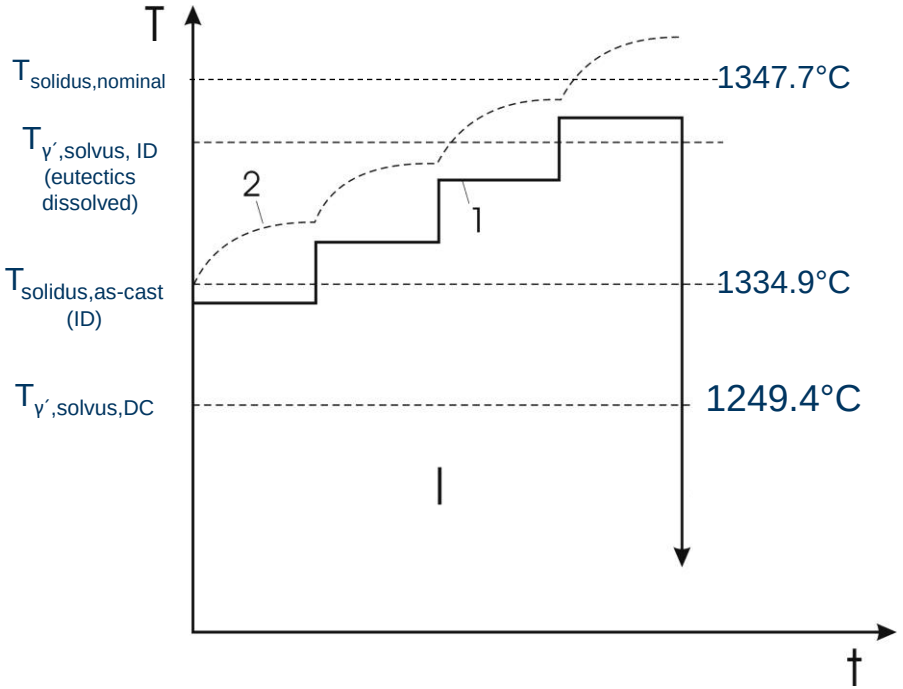


„incipient melting“



- Strong segregation lead to locally different $T_{solidus}$
- Sometimes $T_{solidus,lokal} < T_{\gamma'\text{-solvus,global}}$

Solution annealing “Stepwise”



T in °C	Solidus	γ´ solvus
Interdendritic	1334.9	-
Dendrite core	1352.14	1249.39
Nominal	1347.71	1259.7

- Strong segregation lead to locally different $T_{solidus}$
- Sometimes $T_{solidus,lokal} < T_{\gamma'\text{-solvus,ID}}$

Exercise Nr.4

Interdiffusion coefficients in γ - phase

a. Calculation of interdiffusion coefficients of the alloying elements in the γ - phase at 1300°C.

b. Which alloying element determines the duration of the solution annealing heat treatment? Which alloying element will be the first to homogenize?

Exercise Nr.4

Thermo - Calc 2023b

SYS: SET_LOG_FILE

Heading:

SYS:GOTO_MODULE

MODULE NAME: DATA

TDB_TCFE10:SWITCH_DATABASE

DATABASE NAME /TCFE10/:TCNi10

TDB_TCNI10:DEFINE_SPECIES

SPECIES:Ni Co Cr Al Mo Ti Re W Ta

TDB_TCNI10:GET_DATA

TDB_TCNI10:APPEND

DATABASE NAME /TCNI10/:MOBNi5

APP:DEFINE_SYSTEM

ELEMENTS:Ni Co Cr Al Mo Ti Re W Ta

APP:GET_DATA

TDB_TCNI10:GOTO_MODULE

MODULE NAME: POLY 3

POLY: SET_CONDITION

State variable expression: T=1573.15 p=1e+05 n=1

POLY: SET_CONDITION w(al)=0.0560

..

POLY: SET_CONDITION w(..)=…

POLY: LIST_CONDITIONS

POLY: COMPUTE_EQUILIBRIUM

POLY: LIST_EQUILIBRIUM

OUTPUT TO SCREEN OR FILE /SCREEN/:

Options /VWCS/:

POLY: show-val DT(FCC_L12,Ti)

DT(FCC_L12,TI)=1.1864672E-13

Exercise Nr.4

DT(FCC_L12,TI)=1.1864672E-13 **[m²/s]**

DT(FCC_L12,AL)=3.1910091E-13

DT(FCC_L12,TA)=6.0495126E-14

DT(FCC_L12,W)=1.0794955E-14

DT(FCC_L12,RE)=2.1409152E-15

DT(FCC_L12,MO)=5.7555214E-14

DT(FCC_L12,CR)=1.9909263E-13

DT(FCC_L12,CO)=8.6006041E-14

DT(FCC_L12,NI)=2.8196456E-14

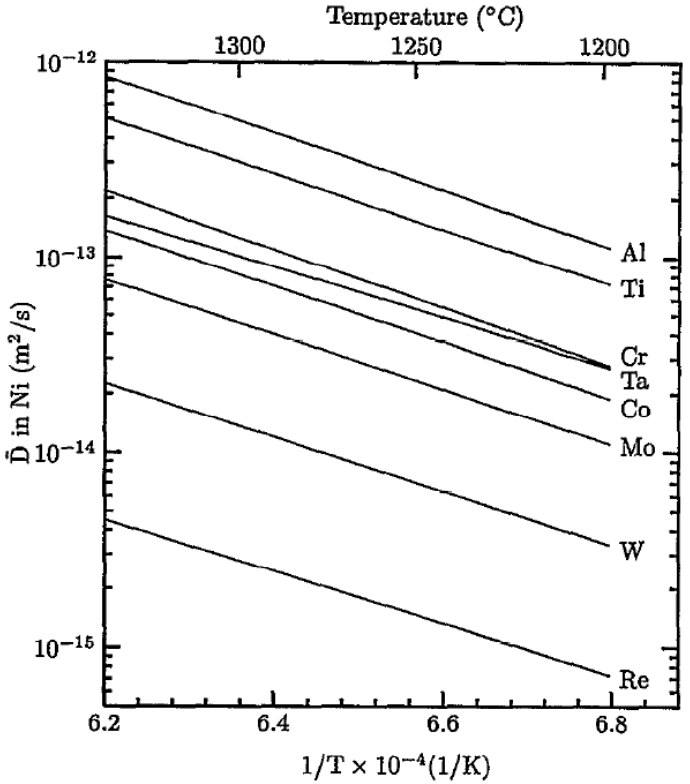
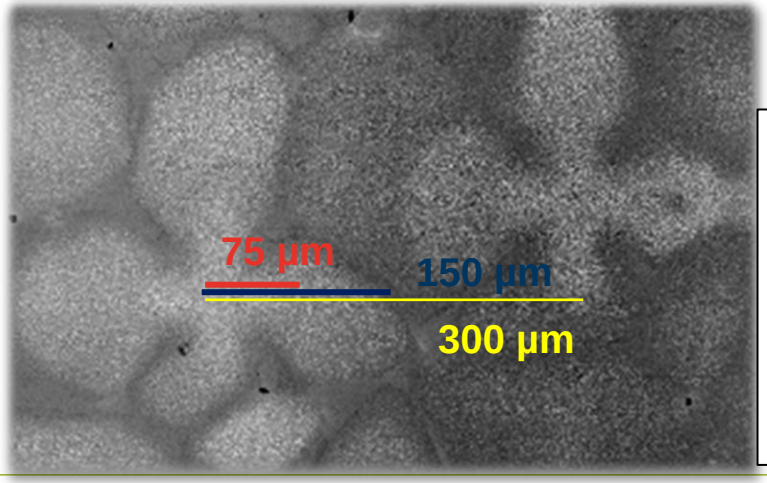


Figure 1: Variation of the interdiffusion coefficient in pure nickel of various elements pertinent to the superalloys, as a function of inverse temperature.

Exercise Nr.4

Assumption: Homogenization is reached when the diffusion length, d_{diff}, equals one half of the dendrite arm spacing i.e., the distance between maximum and minimum of the element concentration.
Hint: You've already measured the distance. Take a closer look onto the units of D.

D is the diffusion coefficient of a solute in free solution. The diffusion coefficient determines the time it takes a solute to diffuse a given distance in a medium. D has the units of area/time (typically cm^2/s). Its value is unique for each solute and must be determined empirically.



DT(FCC_L12,RE)=2.14 E-15

Units of D: [m²/s] = (Distance)²/t

t = (Distance)^2/D

Distance = PDS/4 = 75 µm = 7.5 E-5 m = 0.000075 m

t = (0.000075)^2 / 2.14 E-15 = 2.63E+6 s = 730,6 h > 30,44 days

Exercise Nr.5

Simulation of the solution annealing heat treatment by using DICTRA. For this task, the composition of the simplified alloy listed in Table 1 will be used.

a. Isothermal homogenization heat treatments at 1400°C. Homogenization time = 1h. Width of the region = 150 µm

b. For each isothermal heat treatment, graphical representation of the homogenization profiles for the different homogenization steps.

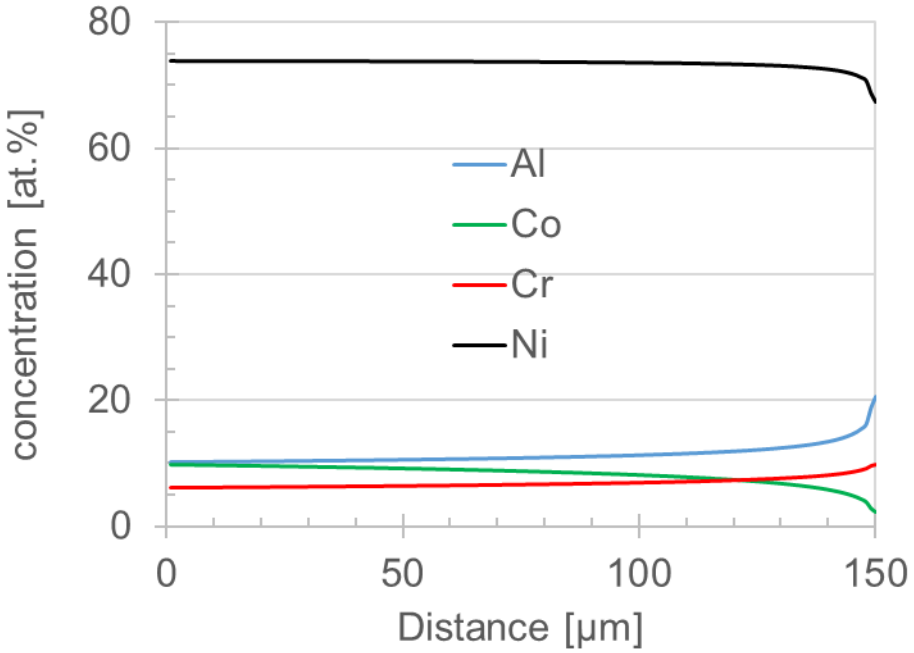
c. Calculation of the time necessary to achieve homogenization at different temperatures.

Table 1. Nominal chemical compositions in wt.% of the two alloys used in the exercise: a complex single crystal Ni base superalloy, CMSX-4, and a simplified alloy, S4_alloy.

	Cr	Co	Mo	W	Ta	Ti	Al	Hf	Re	Ni
CMSX-4	6.5	9	0.6	6	6.5	1	5.6	0.1	3	Bal
S4_alloy	6.5	9	-	-	-	-	5.6	-	-	Bal

Exercise Nr.5

Initial segregation profile:



(HOMOGENIZATION 1400 °C = 1673.15 K)

Exercise Nr.5

Thermo - Calc 2023b

SYS: SET_LOG_FILE

Heading:

SYS:GOTO_MODULE

MODULE NAME: DATA

TDB_TCFE10:SWITCH_DATABASE

DATABASE NAME /TCFE10/:TCNi10

TDB_TCNI10: DEFINE_SYSTEM

ELEMENTS:Ni Co Cr Al

TDB_TCNI10: REJECT PHASES *

TDB_TCNI10: RESTORE PHASES FCC_L12

TDB_TCNI10: GET

TDB_TCNI10:APPEND

DATABASE NAME /TCNI10/:MOBNi5

… DEFINE_SYSTEM

…. Ni Co Cr Al

…. REJECT PHASES *

… RESTORE PHASES FCC_L12

… GET

TDB_TCNI10: :GOTO_MODULE

MODULE NAME: DICTRA_MONITOR

DIC> INPUT_SCHEIL_PROFILE → TXT file

ENTER WIDTH OF REGION /1/:150e-6

PHASE NAME:fcc_l12#1

SHOULD MORE PHASES BE ENTERED IN THE REGION /NO/:n

DIC> SET_CONDITION

GLOBAL OR BOUNDARY CONDITION /GLOBAL/:glob

VARIABLE :T

LOW TIME LIMIT /0/:0

T(TIME,X)=1673.15;

HIGH TIME LIMIT /*/:*

ANY MORE RANGES /N/:N

DIC>SET_SIMULATION_TIME

END TIME FOR INTEGRATION /.1/:3600

AUTOMATIC TIMESTEP CONTROL /YES/:y

MAX TIMESTEP DURING INTEGRATION /360/:360

INITIAL TIMESTEP : /1E-07/:

SMALLEST ACCEPTABLE TIMESTEP : /1E-07/:

DIC>SAVE_WORKSPACES

DIC>SET_INTERACTIVE

DIC>SIMULATE_REACTION

(HOMOGENIZATION 1400 °C = 1673.15 K)

Exercise Nr.5

Thermo - Calc 2023b

Post

s-p-c

time

0,60,600,1800,3600

label-curv

y

s-d-a

x

distance

global

s-d-a

y

w-p(FCC_L12#1)

al

plot

make

file

s-d-a

y

w-p(FCC_L12#1)

co

plot

make

file

s-d-a

y

w-p(FCC_L12#1)

cr

plot

make

file

s-d-a

y

w-p(FCC_L12#1)

ni

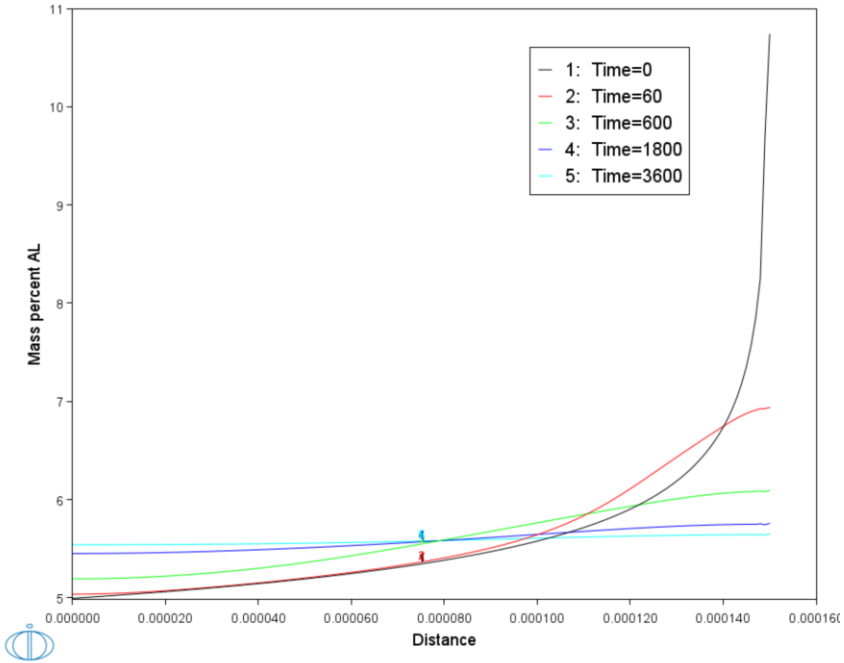
Plot

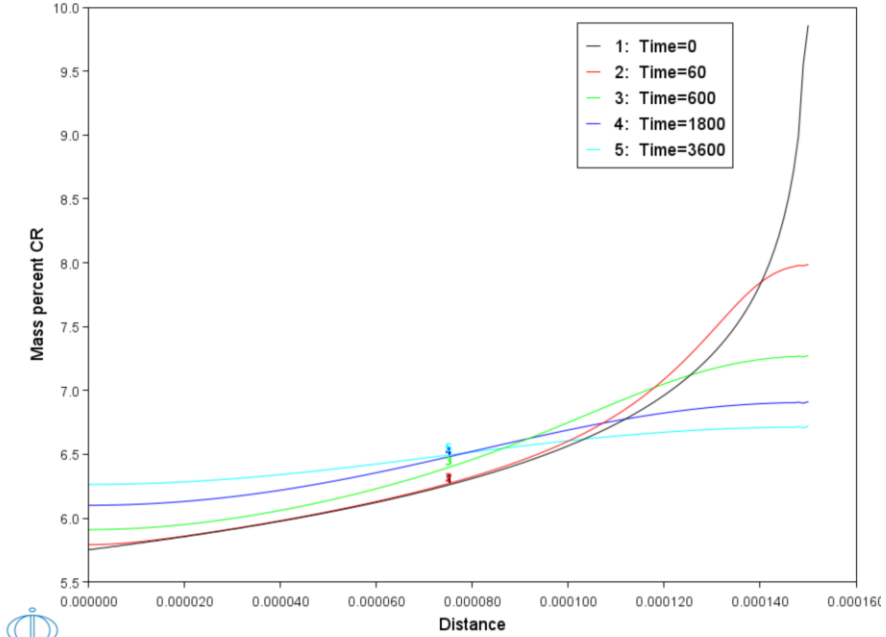
make

file

(HOMOGENIZATION 1400 °C = 1673.15 K)

Exercise Nr.5





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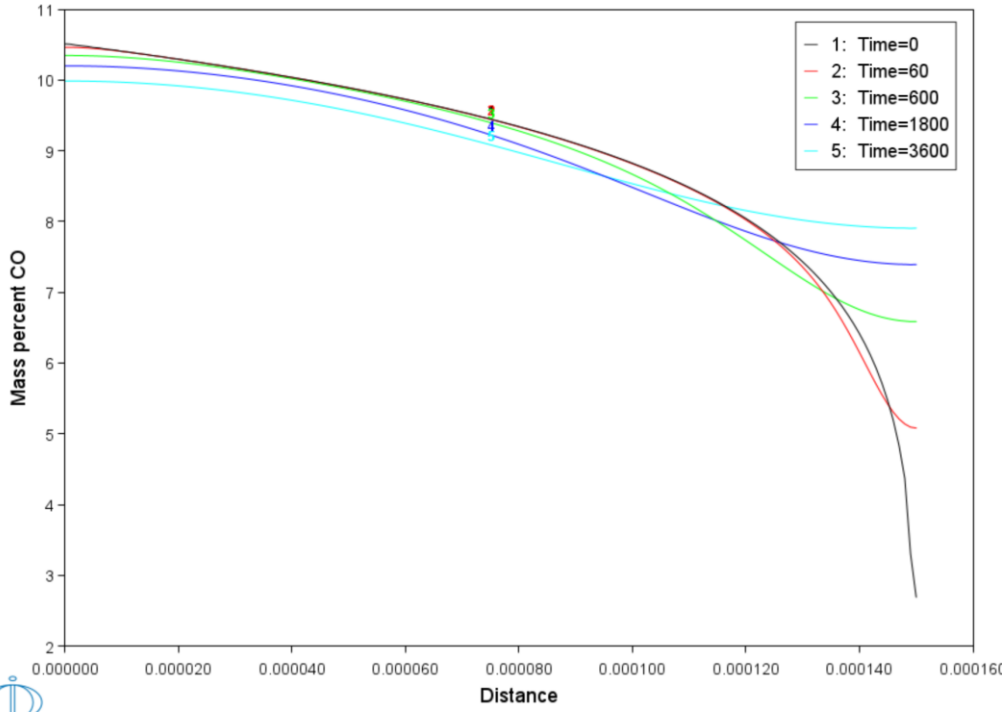
(HOMOGENIZATION 1400 °C = 1673.15 K)

Exercise Nr.5



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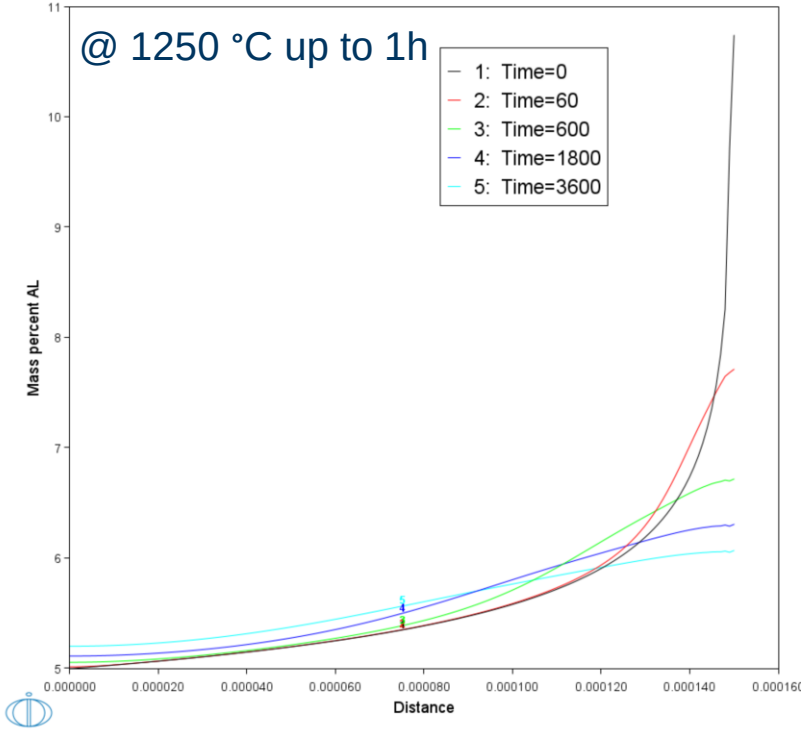
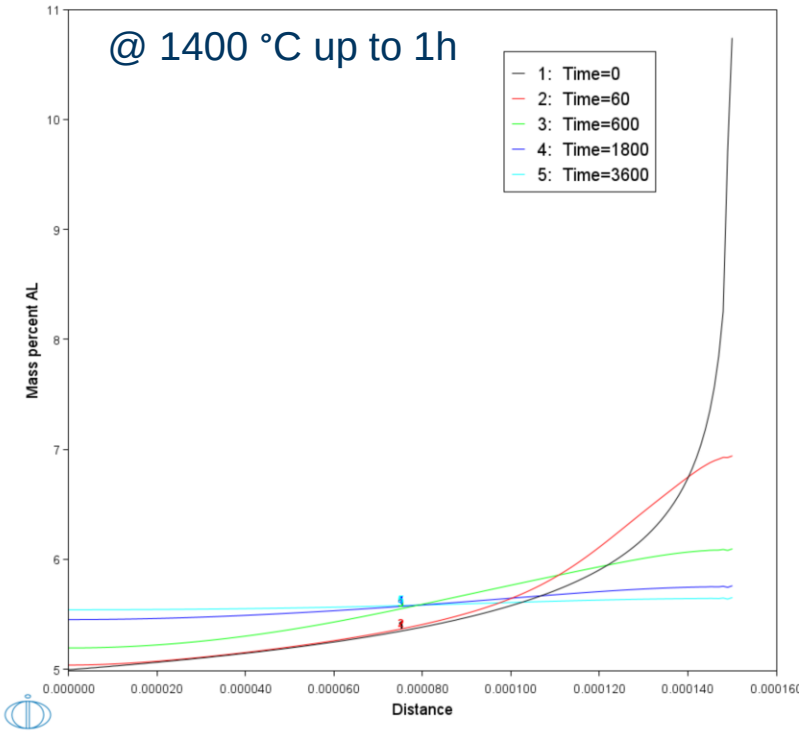
Exercise Nr.5

Diagrams: Al





Überprüfungsfragen

1. Welchen Belastungen müssen Superlegierungen standhalten können und durch welche legierungstechnischen Maßnahmen wird dies sichergestellt?
2. Wie wird im Feinguss die Erstarrung als Einkristall erreicht? Wodurch wird die Kristallorientierung beeinflusst?
3. Welche Gussparameter beeinflussen das Erstarrungsgefüge?
4. Nennen Sie die typischen Legierungselemente einkristalliner Ni-basis Superlegierungen der 2. Generation. Was ist der Grund für die inhomogene Elementverteilung?
5. Warum liegt eine kubische bzw. würfelförmige Morphologie der γ´-Phase vor?
6. Wie ist die Porosität mit Blick auf die mechanischen Eigenschaften zu beurteilen?
7. Erklären Sie mit einem Schema den Verlauf (Temperatur vs. Zeit) der Wärmebehandlung von einer Nickelbasis Superlegierung nach der Erstarrung.
8. Warum ist das Lösungsglühen von Superlegierungen nötig? Was ist das größte Risiko dieser Wärmebehandlung?
9. Welchen Einfluss hat die Abkühlgeschwindigkeit vom Lösungsglühen?

Literature

- Reed, RC (2008) The Superalloys: Fundamentals and Applications. Cambridge University Press, Cambridge.
- R. Burgel (2006) Handbuch Hochtemperatur-Werkstofftechnik: Grundlagen, Werkstoffbeanspruchungen, Hochtemperaturlegierungen. Vieweg+Teubner Verlag.
- Lechner C, Seume J (2010) Stationare Gasturbinen. Springer, Berlin & Heidelberg.
- Parsa AB et. al (2015) Advanced Scale Bridging Microstructure Analysis of Single Crystal Ni-Base Superalloys. Adv. Eng. Mater. 17(2):216–230.
- Ruttert B, Meid C, Mujica Roncery L, Lopez-Galilea I, Bartsch M, Theisen W (2018) Effect of porosity and eutectics on the high-temperature low-cycle fatigue performance of a nickel-base single-crystal superalloy. Scripta Mater. 155:139–143.

Thank you for your attention !

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