

La méthode des champs de phase : formulation « classique », coarse-graining, formulation « étroite » et quelques applications.

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## Plan:

- Ist part : introduction (order parameters, Ginzburg-Landau energy...)
- 2nd part : a phase field model by coarse-graining
- 3rd part : the Sharp Phase Field Method



# lère partie :

# Introduction

## Paramètres d'ordre, énergies Ginzburg-Landau, cinétiques...

# Modelling : different scales

### Macroscopic scale

- domains or phases separated by sharp boundaries
- PDE within the domains
- interface tracking
- $\rightarrow$  free-boundary problems

#### Mesoscopic scale

- fields are continuous
- interfaces are diffuse
- → Phase field models

#### Microscopic scale

- atoms are resolved
- two-body (or many-body) forces
- $\rightarrow$  Atomistic models (Dyn. Mol., Monte Carlo...)

#### Top-down regularisation of sharp interfaces

#### Bottom-up :

- coarse-graining
- homogenisation
- statistical physics

## Modelling : different scales

This course :



# **Microstructures and Phase Field simulations**

Rafts in Ni-based Coherency Ni-based Shape memory superalloys loss alloys superalloys Exp.  $= 76^{\circ} + 2^{\circ}$ Cottura et al Geslin et al, Finel et al. Cottura et al. C. R. Phys. (2010) Acta Mat. (2015) APL (2014) **JMPS (2012)**  $\theta = 79^{\circ}$ 

PFM





 $25~\mathrm{nm}$ 



 $2.3~\mu{
m m}$ 

### Order parameters



#### → Primary order parameter :

- phase transition controlled by concentration
- therefore, primary order parameter (OP) will be c(x) : non-linearities of free energy driven by c(x) !

#### → Secondary order parameter :

- if atomic size are different : precipitation generates a strain field  $\epsilon_{ij}(x)$
- $\epsilon_{ij}(x)$  is a "consequence" of c(x): it does not drive the transition
- therefore,  $\epsilon_{ij}(x)$  is a secondary order parameter : no non-linearities on  $\epsilon_{ij}(x)$



## Thermodynamic model

- $\rightarrow$  Primary order parameter is c(x) :
  - Ginzburg-Landau energy on c(x)

$$F_{GL}(\{c(x)\}) = \int d^3x \{ f_L(c(x)) + \frac{1}{2}\lambda \|\nabla c(x)\|^2 \}$$
$$f_L(c) = A(c-c_1)^2(c-c_2)^2$$

- Coefficients A et  $\lambda$  from interface energy and thickness

$$\sigma = \frac{(c_2 - c_1)^3}{3\sqrt{2}} \sqrt{\lambda A}$$
$$\xi = \frac{2\sqrt{2}}{(c_2 - c_1)} \sqrt{\frac{\lambda}{A}}$$

$$c(x) = \frac{c_2 + c_1}{2} + \frac{c_2 - c_1}{2} \tanh(\frac{2x}{\xi})$$





- → Contribution of secondary order parameter, here strain field :
  - atomic size difference is defined by an eigenstrain  $\epsilon^0_{ij}(x)$  :

$$\epsilon_{ij}^0(x) = \epsilon_{ij}^0(c(x) - c_0) \qquad (\text{ex.: } \epsilon_{ij}^0 = \epsilon^0 \delta_{ij})$$

• if  $\epsilon_{ij}(x)$  is the actual strain, elastic energy is given by (linear elasticity) :

$$E_{strain}(\{\epsilon_{ij}(x)\}) = \int d^3x \ \lambda_{ijkl}(x) \left[\epsilon_{ij}(x) - \epsilon_{ij}^0(x)\right] \left[\epsilon_{kl}(x) - \epsilon_{kl}^0(x)\right]$$



### Kinetics

#### Secondary order parameter :

- here, strain field  $\epsilon_{ij}(x)$
- elastic relaxation time << characteristic time for diffusion
- therefore, we suppose that strain field relaxes instantaneously (quasi-static approx.) :

$$E_{strain}^{eq}(\{c(x)\}) = \min_{\{\epsilon_{ij}(x)\}} E_{strain}(\{c(x)\}, \{\epsilon_{ij}(x)\})$$
  
with  
$$E_{strain}(\{c(x)\}, \{\epsilon_{ij}(x)\}) = \int d^3x \ \lambda_{ijkl}(x) \left[\epsilon_{ij}(x) - \epsilon_{ij}^0(c(x))\right] \left[\epsilon_{kl}(x) - \epsilon_{kl}^0(c(x))\right]$$

[more precisely : minimise wrt displacement field  $u_i(x)$  with  $\epsilon_{ij}(x) = \frac{1}{2}(\frac{\partial u_i(x)}{\partial x_j} + \frac{\partial u_j(x)}{\partial x_i})$ ]

 $\rightarrow$  Thermodynamics of primary order parameter is given by :

 $F_{tot}(\{c(x)\}) = F_{GL}(\{c(x)\}) + E_{strain}^{eq}(\{c(x)\})$ 

## Kinetics (cont.)

#### Primary order parameter :

• concentration *c*(*x*,*t*) is locally conserved :

$$\frac{\partial c(x,t)}{\partial t} = -\text{div} \ \vec{j}(x,t)$$

• flux is non-zero if the system is out of equilibrium :

$$\vec{j}(x,t) = -M(c(x,t))\nabla\mu(x,t)$$

where  $\ M(c)$  is the mobility and  $\ \mu(x,t)$  the alloy chemical potential

$$\mu(x,t) = \frac{\delta F_{tot}(\{c(x,t)\})}{\delta c(x,t)}$$

• if M does not depend on concentration, we get the Cahn-Hilliard eq. (1958) :

$$\frac{\partial c(x,t)}{\partial t} = M \nabla^2 \frac{\delta F_{tot}(\{c(x,t)\})}{\delta c(x,t)}$$

• Easy to verify that CH eq. guaranties a decrease of total free energy :

$$\frac{dF_{tot}(\{c(x,t)\})}{dt} = \int d^3r \; \frac{\delta F_{tot}(\{c(r,t)\})}{\delta c(x,t)} \; \frac{\partial c(x,t)}{\partial t}$$
$$\leqslant 0$$

## Kinetics (cont.)

### Primary order parameter :

if we need fluctuations to overcome energy barriers (for nucleation...), we add a Langevin noise  $\eta(x,t)$ :

$$\frac{\partial c(x,t)}{\partial t} = M \nabla^2 \frac{\delta F_{GL}(\{c(x,t)\})}{\delta c(x,t)} + \eta(x,t)$$

where the noise term must fulfilled the "fluctuation-dissipation" theorem :

$$<\eta(x,t)>=0$$
  
$$<\eta(x,t)\ \eta(x',t')>=-2kTM\nabla^2\delta(x-x')\ \delta(t-t')$$

in order to recover the correct configurational probabilities when equilibrium is reached :

$$P(\{c(x,t)\}) \sim \exp(-\frac{F_{tot}(\{c(x,t)\})}{kT})$$

 $\rightarrow$  But this procedure is incoherent !!!

## Kinetics (cont.)

#### → The procedure is not well-controlled :

- to add a noise to a predefined non-linear equilibrium free energy is inconsistent (fluctuations modify the equilibrium concentrations)
- fluctuations are needed : they permit to overcome energy barriers that i() result from metastable energies...
- but these metastable energies are not (uniquely) defined by the phase diagram nor by the interface energies...



#### → How to define a "good" phase field theory with fluctuations ?

- we cannot use a macroscopic free energy, i.e. a free energy that is fitted to phase diagrams (such as Calphad free energies)
- concentration fluctuations (generated by a noise term) depend on the free energy density AND on the gradient pre-factor  $\lambda$  and mobility M, which themselves may depend on concentration...

Kinetics and free energy functional must be derived simultaneously by coarse-graining from a lower scale...

(see part 2)

### Order parameters

• A simple example : disorder  $\longrightarrow$  "antiferromagnetic" order



- We need to differentiate the different variants
- Hence, the notion of "long-range" order parameters (OP)
- How to identify the long-range OP's ?

## Order parameters (cont.)

• General method <sup>(1)</sup>: (atomic) concentration wave decomposition



- The symmetry change is controlled by  $\,\eta\,:\,{\rm primary}\;{\rm OP}\,$
- Transition may be associated to a change in  $c_0$ : secondary OP

## Order parameters (cont.)

• Generic situation : inhomogeneous distribution of the variants :



- Order parameter  $\eta(x)$  varies slowly with x, where x is the unit cell coordinate
- Concentration on site (x+u), where u is the relative coordinate inside the unit cell at position x, is written as :

$$c(x+u) = c_0(x) + \eta(x) \exp iq.u$$

where  $c_0(x)$  and  $\eta(x)$  are the "average" concentration and long-range order-parameter in cell "x", respectively.

## Thermodynamic model

- Transition controlled by primary order parameter  $\,\eta(x)$
- Therefore, the non-linearity in the Landau free energy must be controlled by  $\eta(x)$
- Landau energy must be invariant if we exchange the 2 variants
  - → if we have a 2nd order transition (continuous transition between disorder and order) :

$$f_{GL}(\eta) = a(T)\frac{\eta^2}{2} + b\frac{\eta^4}{4} + \frac{\lambda}{2}||\nabla\eta||^2$$
  
with  
$$a(T) = A(T - T_c)$$
$$A > 0$$
$$b > 0$$







## Thermodynamic model

- Transition controlled by primary order parameter  $\eta(\boldsymbol{x})$
- Therefore, the non-linearity in the Landau free energy must be controlled by  $\eta(\boldsymbol{x})$
- Landau energy must be invariant if we exchange the 2 variants
  - → if we have a lst order transition (coexistence between disorder and order) :

$$f_{GL}(\eta) = a(T)\frac{\eta^2}{2} - b\frac{\eta^4}{4} + d\frac{\eta^6}{6} + \frac{\lambda}{2}||\nabla\eta||^2$$
with
$$a(T) = A(T - T_0)$$

$$A > 0$$

$$b > 0$$

$$d > 0$$

 $\rightarrow$  if we have a 1st order transition with a concentration change :

$$f_{GL}(\eta, c) = a(c - c_0)^2 + (c_1 - c)\frac{\eta^2}{2} - b\frac{\eta^4}{4} + d\frac{\eta^6}{6} + \frac{\lambda}{2}||\nabla\eta||^2 + \frac{\beta}{2}||\nabla c||^2$$







### **Kinetics**

• Concentration is conserved  $\rightarrow$  Cahn-Hilliard eq. (with noise) :

$$\frac{\partial c(x,t)}{\partial t} = M \nabla^2 \frac{\partial f_{GL}(\{c(x,t)\})}{\partial c(x,t)} + \xi(x,t)$$

• Order parameter  $\eta(x)$  is not conserved  $\longrightarrow$  Allen-Cahn eq. (with noise) :

$$\frac{\partial \eta(x,t)}{\partial t} = -L \frac{\partial f_{GL}(\{c(x,t)\})}{\partial \eta(x,t)} + \zeta(x,t)$$

with the "fluctuation-dissipation" theorem for the noise terms :

$$<\xi(x,t) > = 0$$
  

$$<\xi(x,t) \ \xi(x',t') > = -2kTM\nabla^2\delta(x-x') \ \delta(t-t')$$
  

$$<\zeta(x,t) > = 0$$
  

$$<\zeta(x,t) \ \zeta(x',t') > = 2kTL\delta(x-x') \ \delta(t-t')$$
  

$$<\xi(x,t) \ \zeta(x',t') > = <\xi(x,t) > <\zeta(x',t') > = 0$$

# A more complexe ordering transition : superalloys $\gamma-\gamma'$

### Order parameters



 $FCC(\gamma) \to L1_2(\gamma')$ 





- FCC lattice may be decomposed into 4 simple cubic lattices
- In L12, 1 among these 4 SC lattices is (essentially) occupied by the minority atomic species (○) and the 3 others by the majority atomic species (●)
- Therefore,  $L1_2$  phase may display 4 different variants (with the same concentration), each of which can be obtained from each of the other three by a translation of type  $\langle \frac{1}{2} \frac{1}{2} 0 \rangle$ :



• We need long-range order parameters to differentiate these 4 variants

# A more complexe ordering transition : superalloys $\gamma-\gamma'$

### Order parameters



#### 

• Ex : I single homogeneous  $L1_2$  variant :

 $c(x) = c_0 + \eta_1 \exp(-iq_1 \cdot x) + \eta_2 \exp(-iq_2 \cdot x) + \eta_3 \exp(-iq_3 \cdot x)$ with  $q_1 = [100] \quad q_2 = [010] \quad q_3 = [001]$ 

- order parameters  $\eta_i$  represent the amplitude of the wave with q-vector  $q_i$
- order parameters for each of the 4 variants :

variant 1:  $(\eta_1, \eta_2, \eta_3) \sim (111)$ variant 2:  $(\eta_1, \eta_2, \eta_3) \sim (1\overline{1}\overline{1})$ variant 3:  $(\eta_1, \eta_2, \eta_3) \sim (\overline{1}\overline{1}1)$ variant 4:  $(\eta_1, \eta_2, \eta_3) \sim (\overline{1}1\overline{1})$ 

## Order parameters (cont.)

 $\rightarrow$  General method : concentration wave decomposition (cont.)

• generic situation : inhomogeneous distribution of 4 variants



- order parameters varie slowly with R, where R is the unit cell (fcc cube) coordinate
- concentration on site of coordinate R+r, where r is the relative coordinate inside the unit cell, may be written as :

$$c(R+r) = c_0(R) + \eta_1(R) \exp(-iq_1 r) + \eta_2(R) \exp(-iq_2 r) + \eta_3(R \exp(-iq_3 r)) + \eta_3(R$$

• where  $c_0(R)$  and  $\eta_i(R)$  are the "average" concentration and order parameters in cell R.

# Ordering transition : superalloys $\gamma - \gamma'$

## Landau free energy

- Transition is controlled by the long-range order parameters  $\eta_i(R)$ , which play the rôle of primary order parameters
- Thus, we look for a non-linear Landau function al(iR)
- This functional must be invariant w.r.t. symmetry operations that leave the FCC lattice invariant, i.e. symmetry operations that belong to the FCC space group.

Example : exchanges between the variants by translations of type  $\frac{1}{2} < 110 > :$ 



- FCC symmetry operations lead to change the sign of two order parameters or to permute them
- look for polynomial components that are invariant w.r.t. these operations
- ... and stop the expansion to the lowest order compatible with the existence of a transition...

# Ordering transition : superalloys $\gamma - \gamma'$

## Landau free energy (cont.)

• Here we get :

$$\begin{array}{rcl} \eta_1 + \eta_2 + \eta_3 : & no \\ \eta_1^2 + \eta_2^2 + \eta_3^3 : & yes \\ \eta_1\eta_2 + \eta_2\eta_3 + \eta_3\eta_1 : & no \\ & \eta_1\eta_2\eta_3 : & yes \\ \eta_1^2\eta_2 + \eta_1\eta_2^2 + \dots : & no \\ & \eta_1^4 + \eta_2^4 + \eta_3^4 : & yes \end{array}$$

• Thus, the "minimal" Ginzburg-Landau energy density has the following form :

$$f_{GL} = \frac{A}{2}(c-c_0)^2 + \frac{B}{2}(c'-c)(\frac{\eta_1^2 + \eta_2^2 + \eta_3^2}{3}) - C\eta_1\eta_2\eta_3 + \frac{D}{4}(\frac{\eta_1^4 + \eta_2^4 + \eta_3^4}{3}) + \frac{\lambda}{2} ||\nabla c(x,t)||^2 + \frac{\beta_i}{2} ||\nabla \eta_i(x,t)||^2$$

# Ordering transition : superalloys $\gamma - \gamma'$

### **Kinetics**

• Concentration is conserved  $\rightarrow$  Cahn-Hilliard eq. (with noise) :

$$\frac{\partial c(x,t)}{\partial t} = M \nabla^2 \frac{\partial f_{GL}(\{c(x,t)\})}{\partial c(x,t)} + \xi(x,t)$$

• Order parameter  $\eta(x)$  is not conserved  $\longrightarrow$  Allen-Cahn eq. (with noise) :

$$\frac{\partial \eta_i(x,t)}{\partial t} = -L \frac{\partial f_{GL}(\{c(x,t)\})}{\partial \eta_i(x,t)} + \zeta_i(x,t) \qquad i = 1 \text{ to } 4$$

with the "fluctuation-dissipation" theorem for the noise terms :

$$<\xi(x,t) > = 0$$
  

$$<\xi(x,t) \ \xi(x',t') > = -2kTM\nabla^{2}\delta(x-x') \ \delta(t-t')$$
  

$$<\zeta_{i}(x,t) > = 0$$
  

$$<\zeta_{i}(x,t) \ \zeta_{i}(x',t') > = 2kTL\delta(x-x') \ \delta(t-t')$$
  

$$<\xi(x,t) \ \zeta_{i}(x',t') > = <\xi(x,t) > <\zeta_{i}(x',t') >$$
  

$$<\zeta_{i}(x,t) \ \zeta_{j}(x',t') > = <\zeta_{i}(x,t) > <\zeta_{j}(x',t') > = 0 \qquad i \neq$$

j

# Application I : a simple phase separating system (segregation)

- Primary order parameter : concentration c(x)
- Ginzburg-Landau energy on c(x) :

$$F_{GL}(\{c(x)\}) = \int d^3x \{ f_L(c(x)) + \frac{1}{2}\lambda \|\nabla c(x)\|^2 \}$$
$$f_L(c) = A(c-c_1)^2 (c-c_2)^2$$

• atomic size difference is defined by an eigenstrain :

$$\epsilon_{ij}^0(x) = \epsilon_{ij}^0(c(x) - c_0) \qquad (\text{ex.: } \epsilon_{ij}^0 = \frac{\Delta a}{a}\delta_{ij})$$

• elastic energy (linear elasticity) :

$$E_{strain}(\{\epsilon_{ij}(x), c(x)\}) = \int d^3x \ \lambda_{ijkl}(x) \ [\epsilon_{ij}(x) - \epsilon_{ij}^0(x)] \ [\epsilon_{kl}(x) - \epsilon_{kl}^0(x)]$$



- local stress :

$$\sigma_{ij}(r) = \frac{\delta E_{strain}(\{\epsilon_{ij}(x), c(x)\})}{\delta \epsilon_{ij}(r)} = \lambda_{ijkl}(x) \left(\epsilon_{kl}(r) - \epsilon_{kl}^0(r)\right)$$

- mechanical equilibrium :

- if homogeneous elasticity :

 $f_i(r) = \frac{\partial \sigma_{ij}(r)}{\partial x_j} = 0$ 

$$\lambda_{ijkl} \frac{\partial \epsilon_{kl}(r)}{\partial x_j} = \lambda_{ijkl} \frac{\partial \epsilon_{kl}^0(r)}{\partial x_j}$$

+ 
$$\epsilon_{kl}^{0}(r)$$
 -  $r$  •  $\delta\epsilon_{kl}(r) \sim \frac{1}{r^3}$ 

- residual strain energy : two-body forces

$$E_{strain}^{eq}(\{c(x)\}) = \frac{V}{2} \sum_{q \neq 0} B(q) ||c(q)||^2$$

$$B(q) = \lambda_{ijkl} \epsilon^0_{ij} \epsilon^0_{kl} - q_i \sigma^0_{ij} G_{jl}(q) \sigma^0_{lm} q_m$$

$$G_{ik}^{-1}(q) = \lambda_{ijkl}^0 \, q_j q_l$$

# Application I : a simple phase separating system (segregation)

• total energy :

### $F_{tot}(\{c(x)\}) = F_{GL}(\{c(x)\}) + E_{strain}^{eq}(\{c(x)\})$

- kinetics : concentration is conserved  $\longrightarrow$  Cahn-Hilliard equation :

$$\frac{\partial c(x,t)}{\partial t} = M \nabla^2 \frac{\delta F_{tot}(\{c(x,t)\})}{\delta c(x,t)}$$

- material parameters :
  - phase diagram :  $c_1 = 0.05$   $c_2 = 0.95$
  - interface energy :  $\sigma = 10 \ {\rm mJm}^{-2}$
  - size effects :  $\Delta a/a = 0.0028$
- simulation :
  - 256x256, grid spacing :  $d=4.3~\mathrm{nm}$

elastic constants matrix (GPA)  $C_{11} = 255$   $C_{12} = 205$  $C_{44} = 70$ 

- precipitates (GPa)  $C_{11} = 355$  $C_{12} = 115$
- $C_{44} = 70$



no size effect



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#### → Ginzburg-Landau free energy

Boussinot, Le Bouar, Finel, Acta Mat., 2010

$$F_{GL}(\{c\},\{\eta_i\}) = \int dV \left( f_{hom}(\{c\},\{\eta_i\}) + \frac{\lambda}{2} \mid \nabla c \mid^2 + \frac{\beta}{2} \mid \nabla \eta_i \mid^2 \right)$$

Landau potential :

$$f_{homo}(\{c\},\{\eta_i\}) = \frac{A}{2} \left( c - c_1 \right)^2 + \frac{B}{2} \left( c_2 - c \right) \left( \frac{\eta_1^2 + \eta_2^2 + \eta_3^2}{3} \right) - C_{\text{sma}\_\text{LT2\_MeW\_ny,mb}} + \frac{D}{4} \left( \frac{\eta_1^4 + \eta_2^4 + \eta_3^4}{3} \right) + C_{\text{sma}\_\text{LT2\_MeW\_ny,mb}} + \frac{D}{4} \left( \frac{\eta_1^4 + \eta_2^4 + \eta_3^4}{3} \right) + C_{\text{sma}\_\text{LT2\_MeW\_ny,mb}} + \frac{D}{4} \left( \frac{\eta_1^4 + \eta_2^4 + \eta_3^4}{3} \right) + C_{\text{sma}\_\text{LT2\_MeW\_ny,mb}} + \frac{D}{4} \left( \frac{\eta_1^4 + \eta_2^4 + \eta_3^4}{3} \right) + C_{\text{sma}\_\text{LT2\_MeW\_ny,mb}} + C_{\text{sma}\_mp} + C_{\text{sma$$



→ Kinetics of "chemical fields" :



conserved field (Cahn-Hilliard) non-conserved field (Allen-Cahn)  $\frac{\partial c(r,t)}{\partial t} = M \nabla^2 \frac{\delta F}{\delta c}$  $\frac{\partial \eta_i(r,t)}{\partial t} = -\Gamma \frac{\delta \tilde{F}_{04}}{\delta n \cdot \log t}$ 

### → Formation of a cuboïdal microstructure :

M. Cottura, Y. Le Bouar, A. Finel, B. Appolaire, K. Ammar, S. Forest, JMPS, 2012

2

- no plasticity
- stress-free condition
- misfit :  $\delta = 2(a_{\gamma'} a_{\gamma})/(a_{\gamma'} + a_{\gamma}) = -0.1\%$
- simulation box :
  - 512x512
  - grid spacing : 4.4 nm



Importance of  $\Delta C$  in AM1 superalloys

Cottura, Le Bouar, Appolaire, Finel Acta Mat., 2015

3D

- Lattice misfit :  $\delta = 2(a_{\gamma'} a_{\gamma})/(a_{\gamma'} + a_{\gamma}) = -0.1\%$
- Different  $\Delta C'$  values (6.8<sup>3</sup>  $\mu$ m<sup>3</sup> with 512<sup>3</sup> nodes d = 13.3 nm)



-  $\Delta C' = 0 - 17\%$ : big precipitates presenting a irregular shape + elongated precipitates

-  $\Delta C' = 50\%$  : qualitative agreement !

Formation of a bimodal microstructure by "double quenching"

 $1 \ \mu m$ 

![](_page_29_Picture_3.jpeg)

Boussinot, Finel, Le Bouar, Acta Mat., 2009

![](_page_29_Figure_5.jpeg)

Chellman et al (1989)

#### Influence of external stress with elastic inhomogeneity

• External stress has an influence on the microstructure only if elastic constants of  $\gamma$  and  $\gamma'$  differ !

elastic constants matrix  $\gamma$  (GPA) precipitates  $\gamma'$  (GPa)

| $C_{11}$ | = | 190 | $C_{11}$ | = | 210 |
|----------|---|-----|----------|---|-----|
| $C_{12}$ | = | 138 | $C_{12}$ | = | 150 |
| $C_{44}$ | = | 110 | $C_{44}$ | = | 124 |

- interface energy :  $\sigma = 5 \text{ mJm}^{-2}$ 

misfit : 
$$\delta = 2(a_{\gamma'}-a_{\gamma})/(a_{\gamma'}+a_{\gamma})=0.37\%$$

Boussinot, Le Bouar, Finel,

Acta Mat., 2010

Uniaxial compression 600 MPa along [100] : formation of plate-like precipitates perpendicular to the loading axis

Uniaxial tension 600 MPa along [100] : formation of rod-like precipitates along the loading axis

[001]

256 nm

![](_page_30_Figure_10.jpeg)

#### 3