Interactions stresses - plastic deformation and phase transformation

Couplages contraintes - déformation plastique et transformation de phases (à l’état solide)

Elisabeth Gautier
Several treatments or fabrication processes involve couplings between stresses and phase transformation

Thermomechanical processing (forging, rolling, cold rolling, HIP...)

Aubert & Duval
Several treatments or fabrication processes involve couplings between stresses and phase transformation.

Thermomechanical processing (forging, rolling, cold rolling, HIP...)

Introduction
Several treatments or fabrication processes involve couplings between stresses and phase transformation

Thermomechanical processing (forging, rolling, cold rolling, HIP...)

\[ T_\beta = 1.43 \quad 930°C \]

TA6V \( \varepsilon = 1.43 \quad 930°C \)
Several treatments or fabrication processes involve couplings between stresses and phase transformation.

Thermomechanical processing (forging, rolling, cold rolling, HIP...)

Optimize the processing route (fine grains structure)

\[ \varepsilon = 0 \text{ ferrite grains } 30 \, \mu m \]
\[ \varepsilon = 1 \text{ ferrite grains } 10-15 \, \mu m \]

Strained at 800°C

Acier Fe 0.16C 1.4Mn
Isothermally transformed at 680°C

Sophie Lacroix
Thèse INPG 2003
Several treatments or fabrication processes involve couplings between stresses and phase transformation

Thermomechanical processing (forging, rolling, cold rolling, HIP…)
Thermal treatments, Welding, FSW, Machining

In use, existence of stresses that modify the microstructure and in consequence the properties (rafting in Ni base superalloys (A. Finel), martensitic transformation of residual austenite)
Several treatments or fabrication processes involve couplings between stresses and phase transformation

- Thermomechanical processing (forging, rolling, cold rolling, HIP...)
- Thermal treatments, Welding, FSW, Machining

In use, existence of stresses that modify the microstructure and in consequence the properties (rafting in Ni base superalloys (A. Finel), martensitic transformation of residual austenite)

Need to understand the interactions between stresses and phase transformation and further model them to optimize properties or processes
Introduction

During phase transformation the new phase is associated with changes in crystal structure

- Same crystal structure: cell parameters
- Change in crystalline structure: transformation strain (taking into account the crystallographic OR)

Iron

BCC

FCC

\[ \Delta V/V \approx 1\% \]

M. Dehmas et col
During phase transformation the new phase is associated with changes in crystal structure

Consequences

Transformation deformation: local deformation source \( d\varepsilon_{\text{tr}} = f(df) \)
consequences on the mechanical behavior (S. Denis)

Elastic/plastic strain are induced (even without external stress field)

Martensitic transformation

In situ HEXDR (volume analysis)
Maraging steel
During phase transformation the new phase is associated with changes in crystal structure

Consequences

Transformation deformation is a deformation source $d\varepsilon^{tr} = f(df)$
Consequences on the mechanical behavior (S. Denis)

Elastic/plastic strain are induced (even without external stress field)
Morphology of the new phase, growth rate, autocatalytic nucleation
“GENESE DES MICROSTRUCTURES et TRANSFORMATION de PHASES”
(A. Deschamps, A. Finel, Ph. Maugis)
During phase transformation the new phase is associated with changes in crystal structure

Consequences

Transformation deformation is a deformation source $d\varepsilon_{tr} = f(df)$
Consequences on the mechanical behavior (S. Denis)

Elastic/plastic strain are induced (even without external stress field)

*With external stresses:*
additional plastic strain during the phase transformation $d\varepsilon_{pt}$ TRIP
modification of morphology of daughter phase
Outline

Influence of plastic strain on phase transformation kinetics

Influence of stress on phase transformation kinetics

Influence of stress on the mechanical behavior during transformation
Influence of stresses/plastic strain on phase transformation

Experimental approach

Transformation is studied in controlled temperature conditions; example in isothermal condition

Thermomechanical tensile machine
Experimental approach

Transformation is studied in controlled temperature conditions example in isothermal condition

Isothermal test under constant load 450°C and 70 MPa

Veaux et col 2001
Influence of stresses/plastic strain on phase transformation

Experimental approach

Transformation is studied in controlled temperature conditions, example in isothermal condition.

Tensile test $\dot{\varepsilon} = 10^{-3}$ s$^{-1}$

Veaux et col 2001
Experimental approach

Transformation is studied in controlled temperature conditions.

In situ experiments

SAXS (Deschamps et al Acta 2012)

M. Dehmas et col Mat et Tech. 2009
Influence of stresses/plastic strain on phase transformation

Modifications in transformation kinetics (case of steels)

Plastic strain

Formation of ferrite

Fe 0.164C 1.39Mn
Deformed at 800°C transformed at 700°C

Sophie Lacroix Thèse INPG 2003

Tensile stress

Formation of pearlite

Fe 0.8C
Stress applied at 710°C, transformed at 685°C

E. Gautier Thèse INPL 1985
Influence of stresses/plastic strain on phase transformation

 Modifications in transformation kinetics (Martensitic transformation)

Effect of stress on Ms

Patel et Cohen Acta Met 1953

Effect of uniaxial stress on f (α’)
Maraging steel (HEXRD)

\[ \frac{dM_s}{d\sigma} = 0.25^\circ C/MPa \]

M. Dehmas et col Mat et Tech. 2009
Influence of stresses/plastic strain on phase transformation

Modifications in mechanical behavior (Fe base alloys)

Transformation during cooling under stress

Tensile tests at T> Ms

Collette Thèse INPL 1980

Olson Azrin Met Trans 1978
Influence of plastic strain on phase transformation

Transformation kinetics (isothermal, diffusion controlled) :

\[ f_f = y_{max}(1 - \exp \kappa t^n) \]

\[ f_f = f(N, G, t) \]

? Change in driving force

? Change in nucleation rate

? Change in growth rate
Influence of plastic strain on phase transformation

Transformation kinetics (isothermal, diffusion controlled) :

\[ f_f = y_{\text{max}} (1 - \exp \kappa t^n) \]
\[ f_f = f(N, G, t) \]

? Change in driving force

? Change in nucleation rate

? Change in growth rate

Difference in free energy

\[ N \propto v_0 N_0 \exp \left( -\frac{Q + \Delta G^*}{kT} \right) \]

\[ \Delta G^* \propto A \frac{\gamma^3}{\left( \frac{\Delta G_{m_n}}{V_m} + \Delta G_e \right)^2} \]

\[ G \propto D_B^\alpha \left( \frac{c_B^0 - c_B^{ae}}{c_B^\beta - c_B^{ae}} \right) \frac{1}{R} \]

Growth of spherical precipitate \( \beta \) in \( \alpha \)

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Influence of plastic strain on phase transformation

Change in equilibrium conditions/driving force:

Plastic strain

\[ \text{dislocation density } \rho: \]
Influence of plastic strain on phase transformation

Change in equilibrium conditions/driving force:

Plastic strain

dislocation density $\rho$:

$$W \approx \rho \left( \frac{\mu b^2}{4\pi K} \right) \ln \left( \frac{r}{r_0} \right)$$

Order of magnitude

1 to 10 J.mol$^{-1}$

- $\rho$ dislocation density
- $\mu$ shear modulus
- $b$ half the magnitude of the Burgers vector
- $r$ outer cut-off radius
- $r_0$ inner cut-off radius
- $K$ constant

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Influence of plastic strain on phase transformation

Change in nucleation and growth:
Influence of plastic strain on phase transformation

Large increase in nucleation density; poor effect on growth

Fe 0.164C 1.39Mn
T = 700°C
Quenching after 1 min. holding

Sophie Lacroix Thèse INPG 2003, M. Veron, Y. Bréchet
Influence of plastic strain on phase transformation

Plastic deformation: nucleation at GBs Titanium alloy (Ti17, transformed at 800°C)

M. Salib, J. Teixeira, L. Germain PhD in progress Ti17 (5Al, 5Mo, 3Cr, 2Sn, 2 Zr)
Influence of plastic strain on phase transformation

Change in heterogeneous nucleation site nature, density:

- variation of GB surface (grain deformation)
- new GB: recrystallisation (dynamic and metadynamic))
- defects (deformation bands, twin)
- Increase in dislocations density

Change in nucleation barrier:

- “Structure” of GB: serrations, formation of TJs
- Nucleation on dislocation

Change in diffusion/growth process:

- Diffusion along dislocations (precipitation)
- Change in local equilibrium at the moving interface
- Possible segregation of solutes
- Defects (vacancies)
Influence of plastic strain on phase transformation

Change in heterogeneous nucleation site nature, density:

- variation of GB surface (grain deformation)
- new GB: recrystallisation (dynamic and metadynamic)
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- Possible segregation of solutes

Modelling: Necessity to take into account N and G // deformation microstructure
Influence of plastic strain on phase transformation

Deformation of the single parent phase previous to transformation

Modelling:

Ferrite formation (S. Lacroix INPG 2003)

Transformation $\beta \rightarrow \alpha$ Titanium alloys (J. Teixeira INPL 2005, 2008)
Influence of plastic strain on phase transformation

Deformation in a two phase domain

- Deformation partitioning
- Changes in equilibrium conditions (stored elastic energy)
- Heat release

Changes in the microstructure during the deformation
amount and composition of the phases
possible dissolution due to Gibbs Thomson effect
possible dissolution or morphology change due to elastic stored energy
Influence of plastic strain on phase transformation

Deformation in a two phase domain

Amount of $\alpha$ phase versus time during adiabatic heating and further cooling for 3 different effective diffusion

B. Appolaire HDR 2010
Influence of plastic strain on phase transformation

Deformation in a two phase domain

Effect of grain size on its dissolution during adiabatic heating

B. Appolaire HDR 2010
Influence of plastic strain on phase transformation

Deformation in a two phase domain

Effect of nodular size grain on its dissolution during adiabatic heating

B. Appolaire HDR 2010

In progress:
Prediction of morphology changes using phase field: dynamic evolution from orange to lemons

B. Appolaire MMM 2012
Influence of stresses on phase transformation

Influence of uniaxial stress
Case of martensitic transformation

Collette thèse INPL 1980
Olson Azrin Met Trans 1978
Influence of stresses on phase transformation

Martensitic transformation

a nano/micro scale:

Arrangements of self-organized domains (Bain variants) leading to a plate with a given habit plane and OR to which can be associated a deformation tensor (mean shear strain $\gamma_0$, volume variation $\varepsilon_0$)

\[
\varepsilon_{\text{tr}}^{\alpha} = \begin{bmatrix}
0 & \gamma_0/2 \\
\gamma_0/2 & \varepsilon_0
\end{bmatrix}
\]

$\varepsilon_0$ : volume variation
$\gamma_0$ : macroscopic shear

For steels
$\gamma_0 = 0.2$
$\varepsilon_0 = 0.03$

Formation of the plate:
Interface energy, Elastic energy (deformation energy)

Fe-Ni-C Alloy
X.M. Zhang

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Influence of stresses on phase transformation

Martensitic transformation

a nano/micro scale:

Arrangements of self-organized domains (Bain variants) leading to a plate with a given habit plane and OR to which can be associated a deformation tensor (mean shear strain $\gamma_0$, volume variation $\varepsilon_0$)

In the parent grain and the polycrystal

stresses are partially relaxed by formation of self-accommodated plates - in order to accommodate the “macroscopic” shear strain ($\gamma_0$)
Influence of stresses on phase transformation

Martensite transformation

at $T = Ms$, without applied stress

$$V_M \Delta G_{ch}^{P-M} = S_M \gamma_{P/M} + V_M E_{el}$$
Influence of stresses on phase transformation

Martensite transformation

With an applied stress:

Additional Work $U'$ associated with the transformation

$$V_M \Delta G_{P-M}^c + V_M [\sigma][\varepsilon^{ir}] = S_M \gamma^{P/M} + V_M E_{el}$$

$$\Delta M_s = \frac{U'}{-\Delta S^{P-M}} = \frac{[\sigma][\varepsilon^{ir}]}{-\Delta S^{P-M}}$$

Assuming $\gamma_0$ constant

$$U' = (\sigma_n \varepsilon_0 + \tau \gamma_0) V$$

$\sigma_n$ and $\tau$ are the normal stress to the habit plane and the shear stress in the habit plane, respectively.

$U'$ function of plate orientation

For maximal value of $U'$
Influence of stresses on phase transformation

Martensite transformation

Polycrystal:

\[ \Delta M_s = \sigma \left[ \gamma_0 \sin 2\theta \cos \alpha \pm \varepsilon_0 (1 + \cos 2\theta) \right] \frac{1}{2} \frac{1}{-(\Delta S_{ch}^{\gamma\rightarrow\alpha})} \]

+ tensile
- compression

U’max: \( \text{tg} 2\theta = \frac{\gamma_0}{\varepsilon_0} \)

\( \theta \) angle between \( \sigma \) and plate orientation
\( \alpha \) angle between shear direction and maximal shear direction

*Patel Cohen 1953*
Influence of stresses on phase transformation

Martensite transformation

Polycrystal:

$$\Delta M_s = \sigma \left[ \gamma_0 \sin 2\theta \cos \alpha \pm \varepsilon_0 (1 + \cos 2\theta) \right] \times \frac{1}{2} \left( -(\Delta S_{ch}^{\gamma \rightarrow \alpha}) \right)$$

Patel Cohen 1953

+ tensile
- compression

$$U'_{\text{max}} : \tan 2\theta = \pm \gamma_0 / \varepsilon_0$$

$\theta$ angle between $\sigma$ and plate orientation
$\alpha$ angle between shear direction and maximal shear direction

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Influence of stresses on phase transformation

Martensite transformation (in steels)

Orientation of following plates: driven by the local stress state

0 MPa

285 MPa

600 MPa
Influence of stresses on phase transformation

Transformation can be mechanically induced at $T > M_s$
Influence of stresses on phase transformation

Evolution with temperature of the critical stress for the onset of martensitic transformation
Influence of stresses on phase transformation

For $T > M_s^\alpha$ Plastic strain before transformation

New nucleation sites (Lecroisey, Pineau 1972)
Deformation bands, twins bands
$\varepsilon$ Martensite previous to $\alpha'$

Lecroisey Thèse 1975
Influence of stresses on phase transformation

For $T > M_s^\alpha$, Plastic strain before transformation

New nucleation sites (Lecroisey, Pineau 1972)
Deformation bands, twins bands new nucleation site
$\varepsilon$ Martensite previous to $\alpha'$

Martensite formed under stress
Change in plate morphology (Zhang et col Acta Metal 1989)
Change in twin distribution (Roitburd, Pankova)

Zhang et al Acta 1989
Influence of stresses on phase transformation

EBSD scanning on thermal martensite
G. Miyamoto et al Acta Mat. 2009

Fe30Ni0.4C

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Influence of stresses on phase transformation

EBSD scanning on thermal martensite
G. Miyamoto et al Acta Mat. 2009

Fe30Ni
Influence of stresses on phase transformation

For \( T > M_s^\alpha \) Plastic strain before transformation

New nucleation sites (Lecroisey, Pineau 1972)
Deformation bands, twins bands new nucleation site
\( \varepsilon \) Martensite previous to \( \alpha' \)

Accommodation of \( \varepsilon^{tr} \) by slip (change in “deformation” energy)
Martensite formed under stress
Change in plate morphology (Zhang et col Acta metal 1989)
Change in twin distribution (Pankova Roitburd), dislocations

Decrease in nucleation barrier

Modification in growth
Influence of stresses on phase transformation
Mechanical behavior

Stress triggers plates orientation

Resulting transformation strain in the stress direction
Maximal value of 0.08 for polycrystal (Magee 1966)

Stress > austenite yield stress favors accommodation by slip

Less self accommodation
Changes in plate morphology:
  Plastic strain in austenite and product phase

Transformation plasticity (Gautier 1995)
Influence of stresses on phase transformation
Mechanical behavior

Tensile test at different temperatures

Kinetics of martensite formation

Formation of martensite
Strengthening effect
Deformation source (ductility)

TRIP steel 0.19% C (Olson, Azrin Met Trans 1978)
Influence of stresses on phase transformation
Mechanical behavior

Improvement of toughness and ductility

I. Tamura

Fe-19Cr-11Ni

Fe-24Mn-0.26C

0.2% proof stress

Tensile strength

Elongation

Test temperature (°C)

Improvement of toughness and ductility

I. Tamura

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Influence of stresses on phase transformation
Mechanical behavior

Mechanical behavior of TRIP 600 steel

(Berrahmoune et al Mat Scien Eng 2004)

Complex behavior: several micromechanical approaches to model kinetics triggered by stress and strain associated behavior
Influence of stresses on phase transformation
Mechanical behavior

Mechanical behavior of TRIP 600 steel

(Berramoune et al Mat Scien Eng 2004)

Complex behavior: micromechanical approaches to model kinetics triggered by stress and strain associated behavior

Improvements of properties: TRIP multiphase steels

P. Jacques  Current opinions in solid state and Mat Science 2004
Influence of stresses on phase transformation

SMA alloys single cristal: one single variant formed under stress

Plate orientation

Cu-Zn-Al

Patoor (1995, 2006), cliché S. Dominiak
Influence of stresses on phase transformation

Polycristal

Cu-Zn-Al transformé sous contrainte de traction

Thermomechanical behavior law: Patoor et al
Challenges

Transformation kinetics:
- Necessity to take into account the nucleation and growth processes to describe the coupling between stresses and transformations
- Growth under concurrent straining (growth rate/deformation rate)
- Competitive processes: deformation/recovery/recrystallisation/phase transformations (precipitation)

Associated mechanical behavior
- Several successful micromechanical approaches
- Correlations at lower scales
- Local stress fields due to transformation history (transformation of residual austenite)

Design
- New alloy chemistry and processing routes (Cf Bainitic TRIP steels)
- TRIP and TWIP in titanium alloys (Laheurte et col Marteleur et col Scripta Mat 2012)
- Composite
Références

in situ grands instruments


Influence de la déformation plastique
Y. Desalos, A. le Bon, R. Lombry 24ieme Colloque Métallurgie Saclay 1981, P 137. Ed. INSTN CEA Saclay


E. Gautier, A. Simon Analysis of the kinetics of pearlitic transformation under stress or after plastic deformation, PTM 87, International Conference Phase Transformations '87 University of Cambridge 6-10 July 1987, The Institute of Metals, Ed. G.W. LORIMER, p 451


J.D. Embury, A. Deschamps, Y. Brechet The interaction of plasticity and diffusion controlled precipitation reactions, Scripta Materialia, 49, 2003, pp 927-932

S. Lacroix, Aspects cinétiques et microstructuraux du couplage entre déformation à l’état austénitique et transformation ferritique dans les aciers au carbone Thèse de doctorat Institut National Polytechnique de Grenoble 2003

J. da Costa Teixeira Etude expérimentale et calcul des évolutions microstructurales au cours des traitements thermiques post - forgeage dans l’alliage de titane Ti 17 Thèse de doctorat Institut National Polytechnique de Lorraine 2005


Comportement mécanique et changement de phases (sans cisaillement)

Influence des contraintes sur les transformation de phases

F. Lecroisey, A. Pineau Met Trans 3, 1972, 387
F. Lecroisey Transformations martensitiques induites par déformation plastique dans le système Fe-Ni-Cr-C Thèse Université Nancy I, 1971
Lois de comportement : AMF – Transformation à caractère displacif


F. Marketz, F.D. Fischer A micromechanical study on the coupling effect between microplastic deformation and martensitic transformation Computational Materials Science, Volume 3, Issue 2, November 1994, Pages 307-325
M. Cherkaoui, M. Berveiller, X. Lemoine Couplings between plasticity and martensitic phase transformation: overall behavior of polycrystalline TRIP steels International Journal of Plasticity, 16, 2000, pp 1215-1241

Design quelques exemples
P. Jacques Transformation induced plasticity for high strength formable steels Current opinions in solid state and Mat Science 8 2004 pp 259-265.
Contraintes élastiques générées par les changements de phases

Et papiers J. Eshelby
Influence of stresses on phase transformation

Effect of hydrostatic pressure

CCT diagram
E. Schmidtmann et col (Trait. Therm. 1977)

J.E. Hilliard (Trans. Met. Soc. AIME 1963)
Influence of stresses on phase transformation

Change in equilibrium conditions/driving force:

**Hydrostatic pressure**

\[
G_m^\gamma = U_m^\gamma - TS_m^\gamma + PV_m^\gamma \\
G_m^\alpha = U_m^\alpha - TS_m^\alpha + PV_m^\alpha
\]

Variations in equilibrium temperature and solubility limits

For low P variations (\(V_m\) incompressible):

\[
\frac{dT_e}{dP} \approx \frac{T_e(V_m^\gamma - V_m^\alpha)}{(H_m^\gamma - H_m^\alpha)}
\]

Clausius Clapeyron

Pure iron: \(T_e^{\alpha/\gamma} = 912^\circ\text{C}\)

\(V_m^\alpha = 7.384 \times 10^{-6} \text{ m}^3\text{.mol}^{-1}\)

\(V_m^\gamma = 7.300 \times 10^{-6} \text{ m}^3\text{.mol}^{-1}\)

\(H_m^\alpha = 33.582 \text{ kJ.mol}^{-1}\)

\(H_m^\gamma = 34.594 \text{ kJ.mol}^{-1}\)
Influence of stresses on phase transformation

Effect of hydrostatic pressure
Change in equilibrium conditions/driving force:

Modification of equilibrium temperatures and solubility limits

\[ T_{\alpha/\gamma} = 912^\circ C \]
\[ P = 1 \text{ bar} \]

\[ T_{\alpha/\gamma} = 720^\circ C \]
\[ P = 35 \text{ kbar} \]
Influence of stresses on phase transformation
Mechanical behavior

SMA Alloys Influence of crystalline orientation

Stress induced transformation

Stress strain curves for different grain orientation

Deformation associated with transformation is dependant on the grain orientation

(Horikawa et al. 1988)
Influence of stresses on phase transformation

Fe-25Ni-0.66C

0 MPa

600 MPa
Influence of stresses on phase transformation
Mechanical behavior

Bainitic transformation under stress

Modification in transformation kinetics

Additional plastic strain during transformation: transformation plasticity

Change in morphology of daughter phase

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Influence of stresses on phase transformation

Bainite formed at 350°C

0 MPa
Length 1-3µm Width 0.2µm

128 MPa
Length 10µm Width 0.3 – 0.9µm
Influence of phase transformation on mechanical properties

Multiphase components

At T:
Mechanical properties are function of the amount, morphology, spatial distribution of phases

TTT diagram for AA 7010 alloy Godard PhD 1998

Tensile tests after different holding at T

Godard PhD INPL 1998
Influence of phase transformation on mechanical properties

Mechanical properties are function of the amount, morphology, spatial distribution of phases (Al base alloy)

Tensile tests at 300°C after various holding times

Godard PhD INPL 1998
Coupling yield stress with precipitation

Variation of yield stress at 300° versus holding times

Godard PhD INPL 1998
Coupling yield stress with precipitation

\[ \sigma(T) = \sigma_0(T) + \left[ \sum_i a_i(T) X_i \right]^n \]

\[ \Delta\sigma = \left[ a_{eq} X_{Mg}^{ss} \right]^{2/3} \left\{ 1 - \left[ 1 - \frac{\Delta X_{Mg}}{X_{Mg}} \right]^{2/3} \right\} \]

\[ n = 2/3 \]
Rôle des dislocations sur la germination

Effet de l’énergie de cœur

\[ E_c = \alpha \mu b^2 \]

\[ \Delta G = 4\pi \gamma R^2 - \frac{4}{3} \pi R^3 \Delta G_v - 2R E_c \]

\[ \Delta G^* = \frac{16\pi \gamma^3}{3\Delta G_v^2} - \frac{4\gamma \alpha \mu b^2}{\Delta G_v} \]

Ex : Al-2,35%Mg-6,1%Zn

- \( \Delta G_n = 7750 \text{ J.mol}^{-1} \)
- \( \Delta G_v = 7,75 \times 10^8 \text{ J.m}^{-3} \)
- \( \Delta G_{\text{hom}}^* = 2,232 \times 10^{-19} \text{ J} \)
- \( \Delta G_{\text{disl}}^* = 8,71 \times 10^{-21} \text{ J} \)

160°C \( \alpha \rightarrow \text{MgZn}_2 \)

\( \mu = 25,4 \text{ GPa} \)

\( b = 0,286 \text{ nm} \)

\( \alpha = 0,1 \)

\( Y = 200 \text{ mJ.m}^{-2} \)

Modèles plus détaillés

- prise en compte du champ élastique (forme du germe critique, position par rapport à la dislocation).
- nature de la dislocation (coin, vis, mixte).
Rôle des dislocations sur la diffusion

**Effet sur le coefficient de diffusion en volume**

Accélération de la diffusion dans les dislocations

Energie d’activation de la diffusion de 40 à 70 % de celle dans le volume

Ex : Dutta et al. (Acta 2001)

Diffusion du Nb dans l’austénite à 950°C

\[ D_0 = 1,4 \times 10^{-4} \text{ m}^2\text{s}^{-1} \]
\[ Q = 270 \text{ kJ.mol}^{-1} \] dans le volume \( \Rightarrow \]
\[ D_{\text{vol}} = 4,1 \times 10^{-16} \text{ m}^2\text{s}^{-1} \]
\[ Q = 210 \text{ kJ.mol}^{-1} \] dans les dislocations \( \Rightarrow \]
\[ D_{\text{disl}} = 1,5 \times 10^{-13} \text{ m}^2\text{s}^{-1} \] rapport ~ 370

\[ D_{\text{eff}} = D_{\text{disl}} \cdot \pi R^2 \rho + D_{\text{vol}} \cdot (1 - \pi R^2 \rho) \]

Avec \( R_{\text{core}} = 5 \times 10^{-10} \text{ m} \)
\( \rho = 10^{15} \text{ m.m}^{-3} \)
\( D_{\text{eff}} = 5,28 \times 10^{-16} \text{ m}^2\text{s}^{-1} \)
\( \rho = 10^{16} \text{ m.m}^{-3} \)
\( D_{\text{eff}} = 1,59 \times 10^{-15} \text{ m}^2\text{s}^{-1} \)
Influence of stresses/plastic strain on phase transformation

Modifications in transformation kinetics (case of steels, on cooling)

Hydrostatic pressure

Plastic strain

ε = 0.35 at 750°C

CCT diagram (Fe base alloy)
E. Schmidtmann et col (Trait. Therm. 1977)

Fe0.25C1CrMo transformed on cooling

Y. Desalos et col Colloque Métallurgie Saclay (1981)