Interactions stresses - plastic deformation and phase transformation

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

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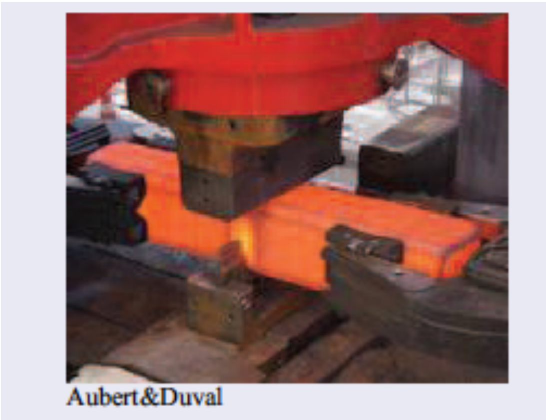
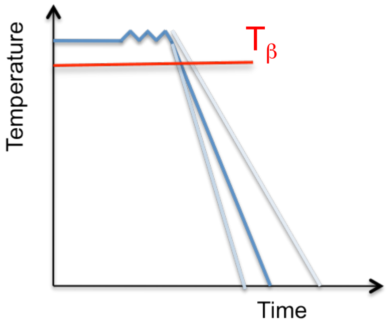
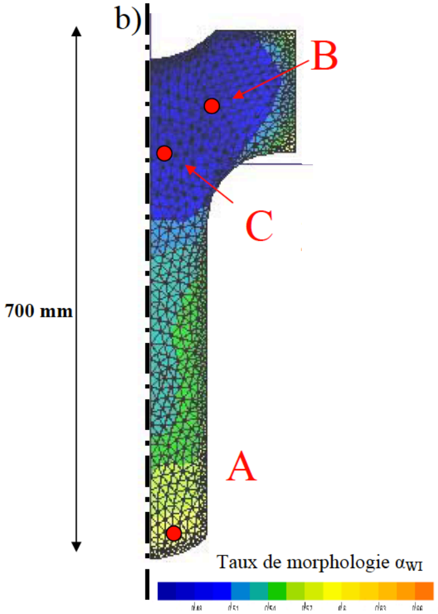
Introduction

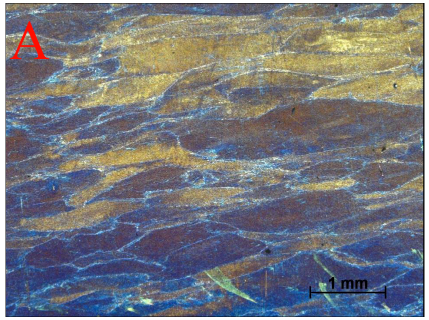
Several treatments or fabrication processes involve couplings between stresses and phase transformation

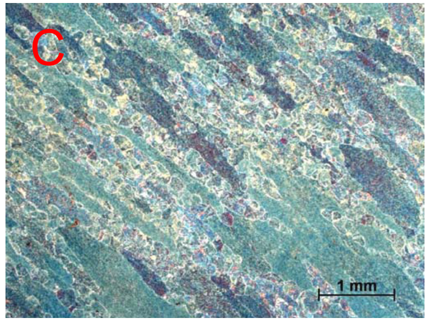
Thermomechanical processing (forging, rolling, cold rolling, HIP…)











J. Teixeira PhD Nancy 2005

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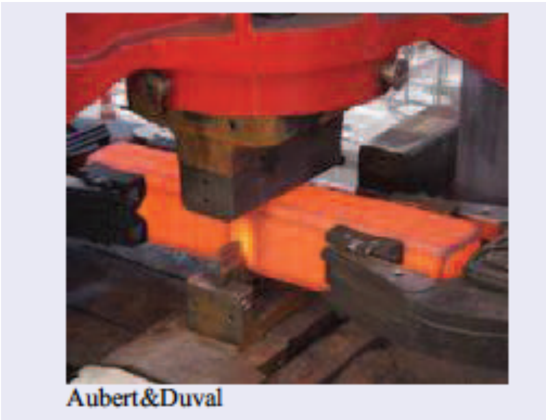

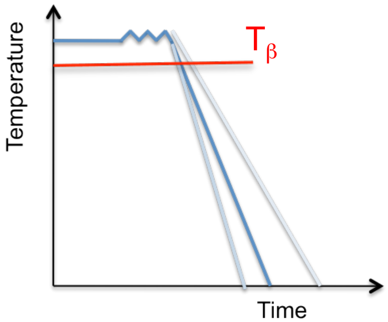

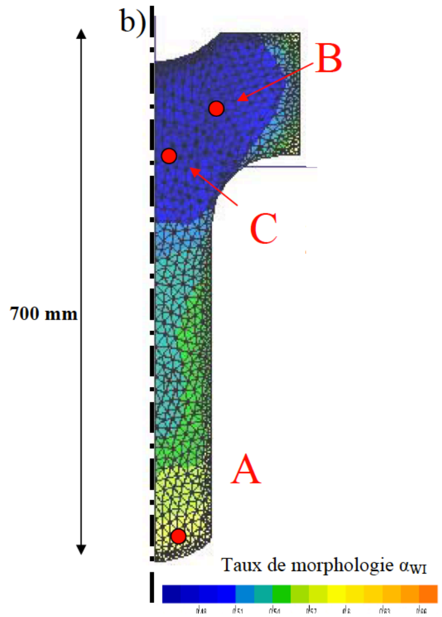

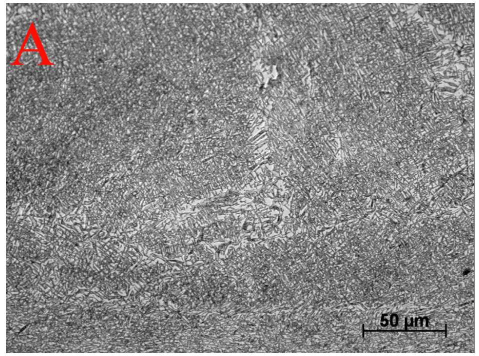

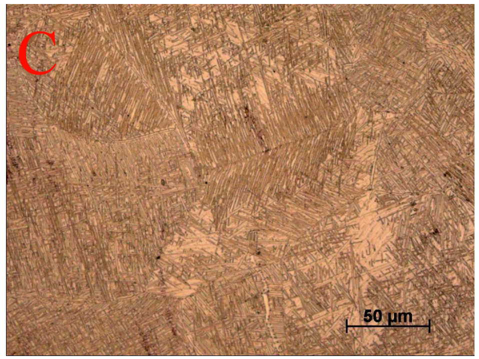

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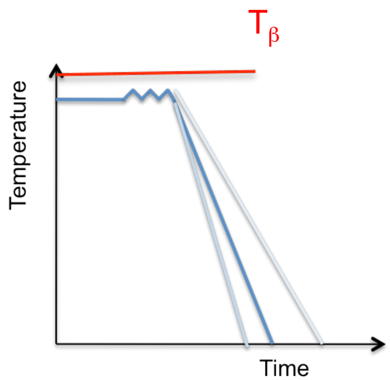
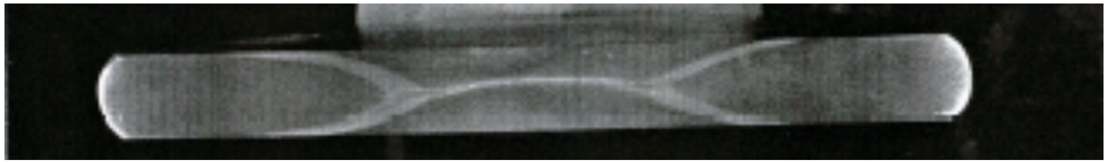
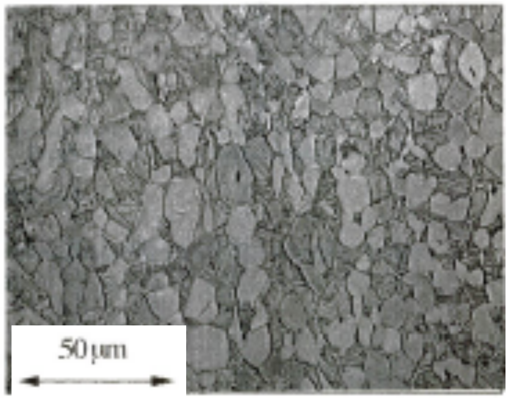
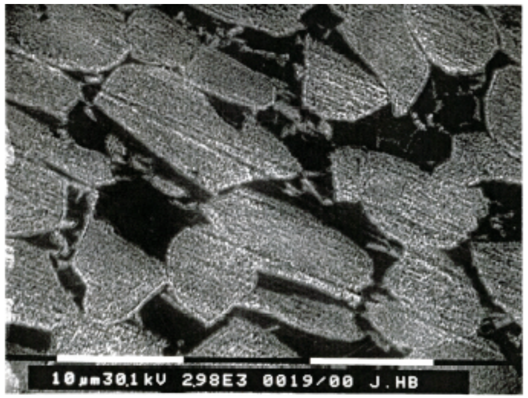
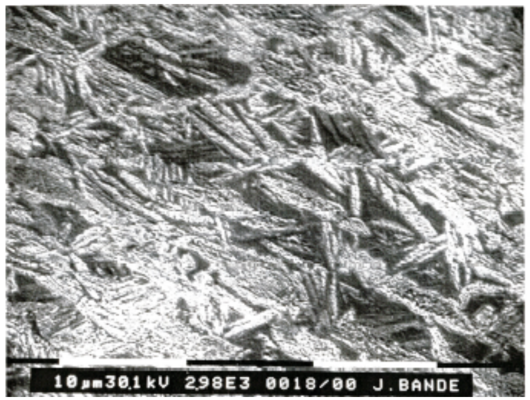




TA6V $\bar{\varepsilon}$ = 1.43 930°C







J.F. Biegun Mémoire CNAM Nancy 1992

Introduction

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

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

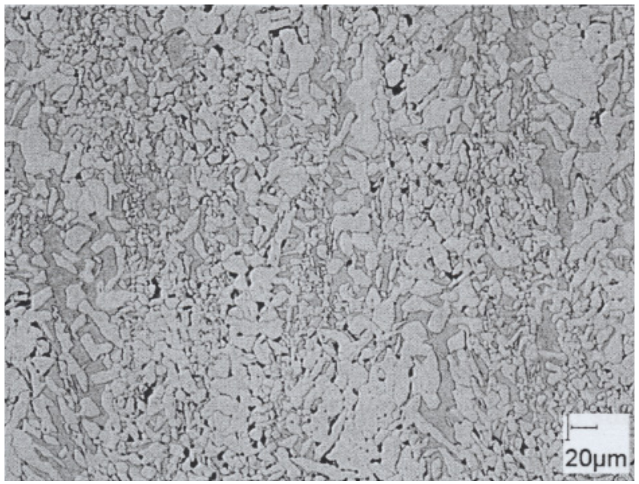
Optimize the processing route (fine grains structure)

$\varepsilon = 0$ ferrite grains 30 μm

Strained at 800°C

➔

$\varepsilon = 1$ ferrite grains 10-15 μm



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

Sophie Lacroix
Thèse INPG 2003

Introduction

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)

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

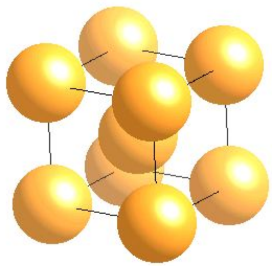
Introduction

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

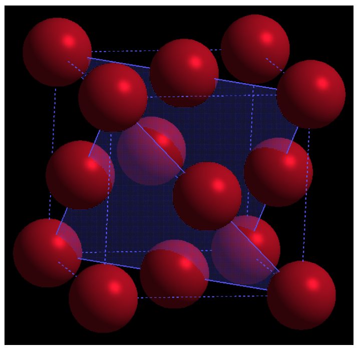
Same crystal structure : cell parameters

Change in crystalline structure: transformation strain (taking into account the crystallographic OR)

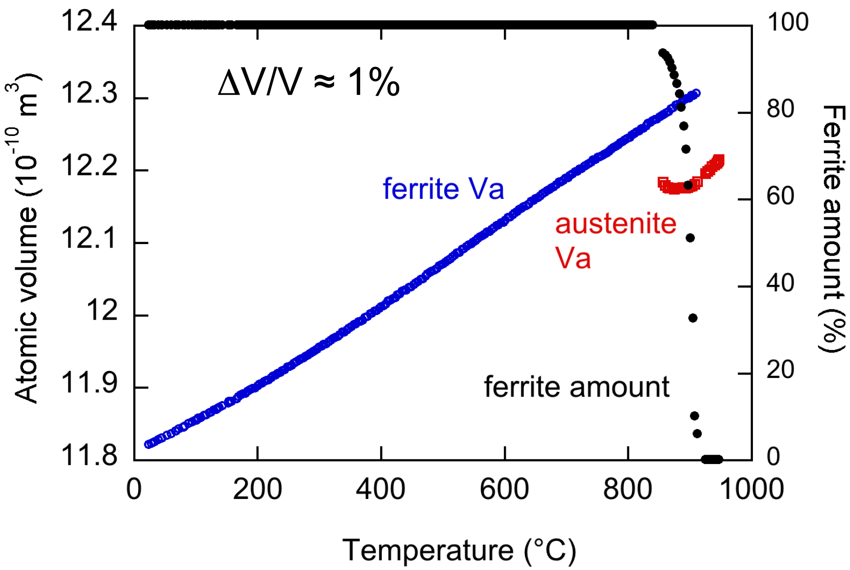
Iron



BCC



FCC



M. Dehmas et col

Introduction

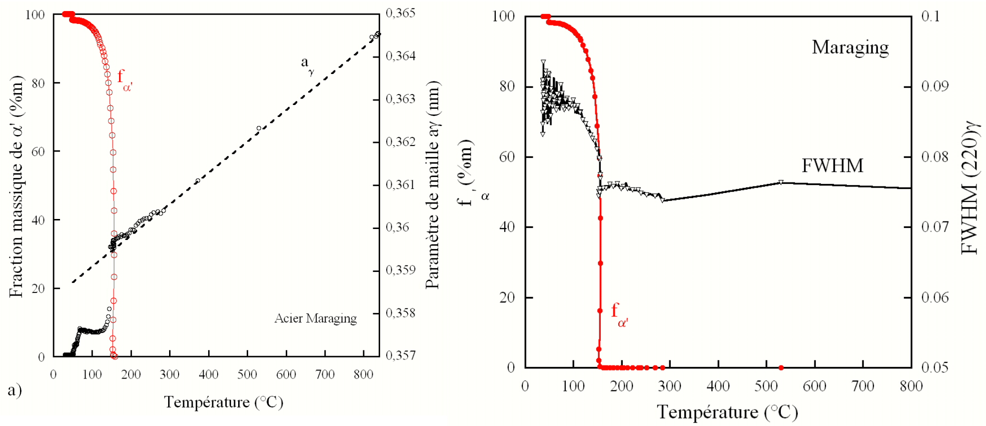
During phase transformation the new phase is associated with changes in crystal structure

Consequences

Transformation deformation : local deformation source $d\varepsilon^{tr} = f(df)$

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

M. Dehmas et col Mat et Tech. 2009

Introduction

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Morphology of the new phase, growth rate, autocatalytic nucleation

"GENESE DES MICROSTRUCTURES et TRANSFORMATON de PHASES"

(A. Deschamps, A. Finel, Ph. Maugis)

Introduction

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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

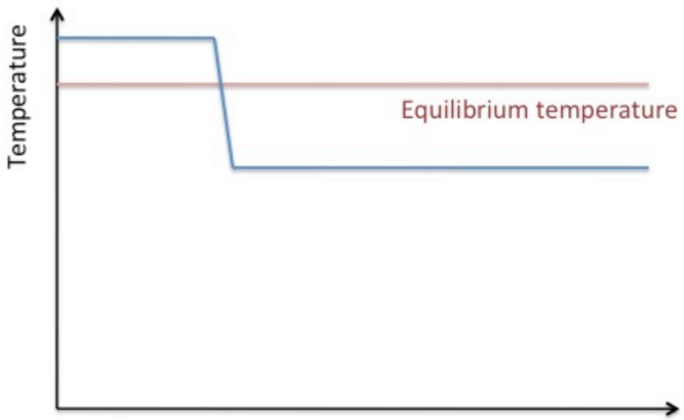
Influence of stress on the mechanical behavior during transformation

Influence of stresses/plastic strain on phase transformation

Experimental approach

Transformation is studied in controlled temperature conditions

example in isothermal condition



Thermomechanical tensile machine

Influence of stresses/plastic strain on phase transformation

Experimental approach

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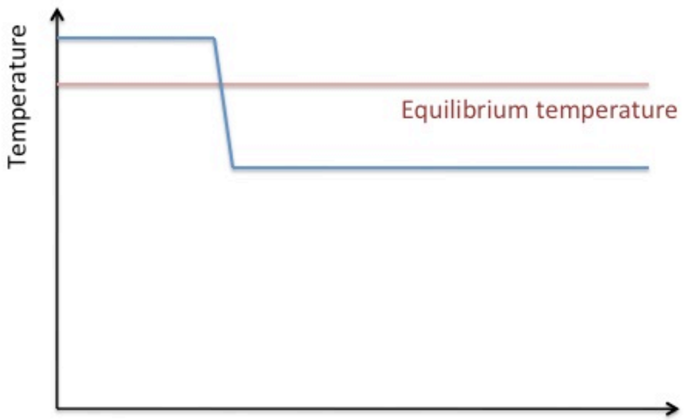
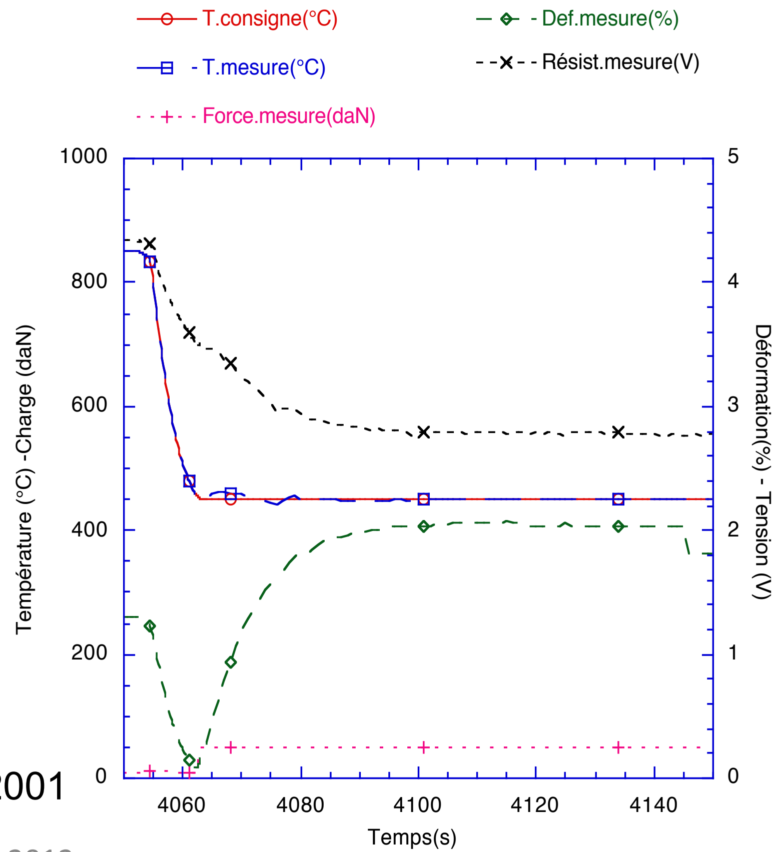


Isothermal test under constant load 450°C and 70 MPa



Veaux et col 2001

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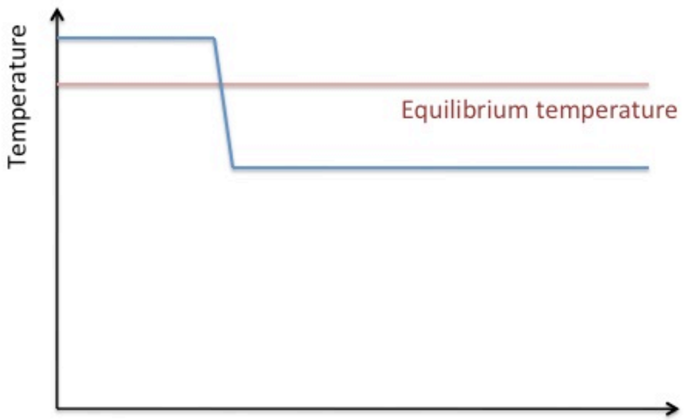
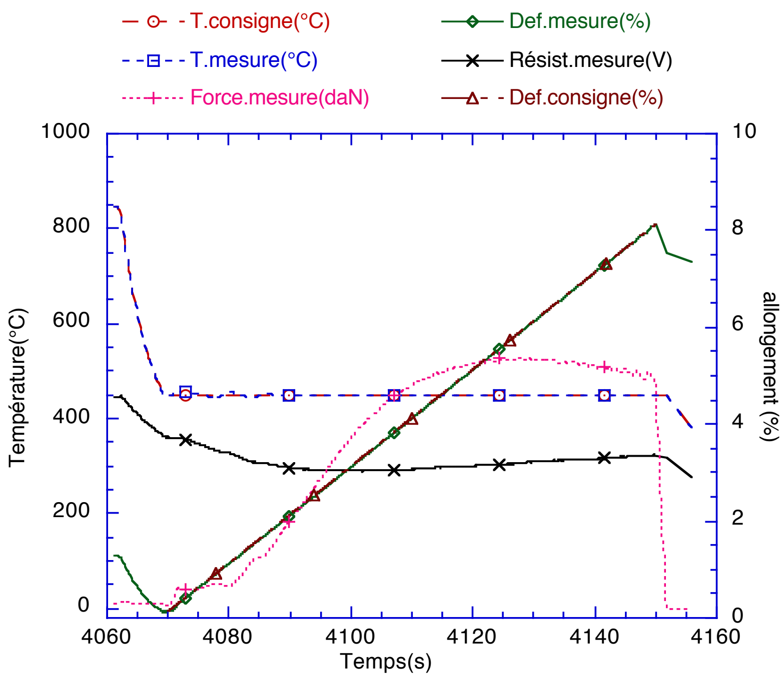


Tensile test $\dot{\varepsilon}$ 10^{-3} s^{-1}



Veaux et col 2001

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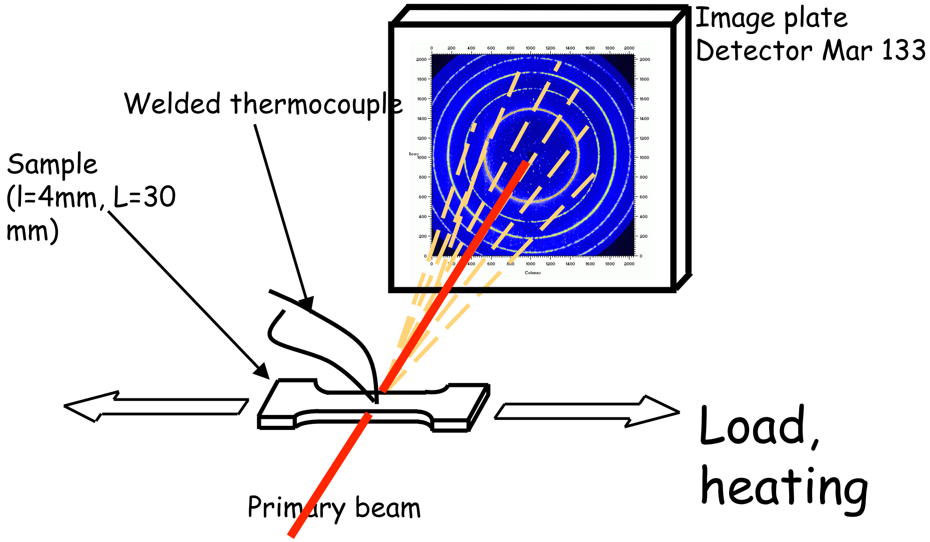
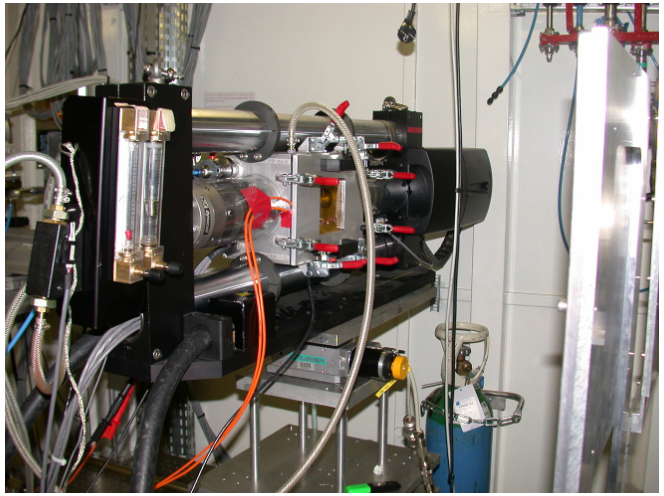


M. Dehmas et col Mat et Tech. 2009

In situ experiments

HEXRD (Dehmas et al Mat Tech. 2009, S. Berveiller et al Acta 2011)

SAXS (Deschamps et al Acta 2012)

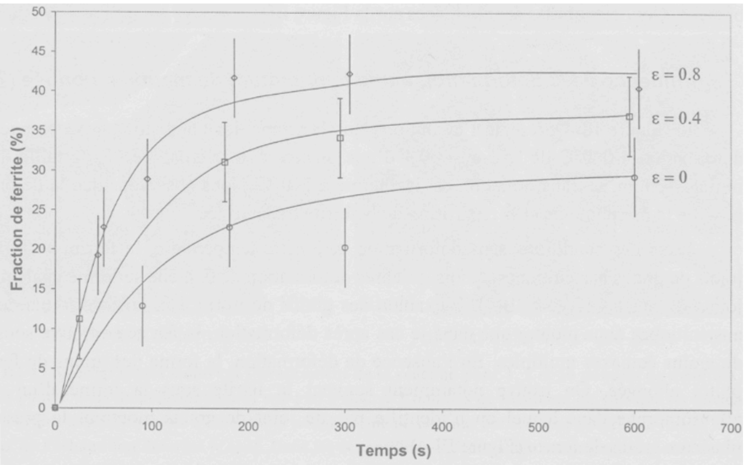


ETMT (Fame 38)

Influence of stresses/plastic strain on phase transformation

Modifications in transformation kinetics (case of steels)

Plastic strain

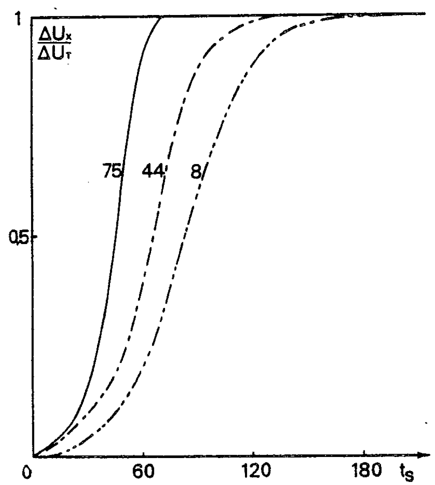


Formation of ferrite

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

Sophie Lacroix Thèse INPG 2003

Tensile stress



Formation of pearlite

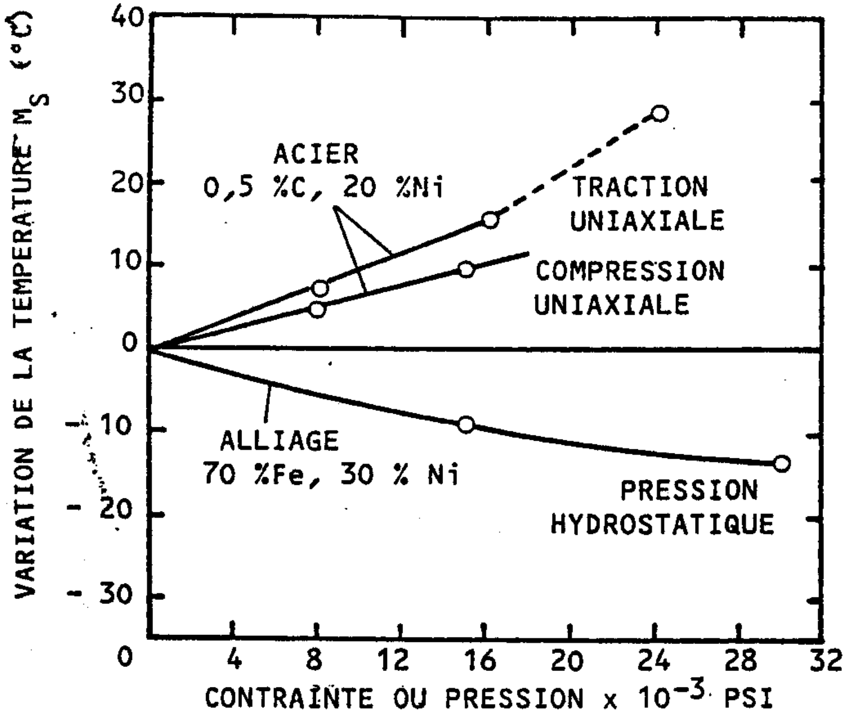
Fe 0.8C
Stress applied at 710°C, transformed at 685°C

E. Gautier Thèse INPL 1985

Influence of stresses/plastic strain on phase transformation

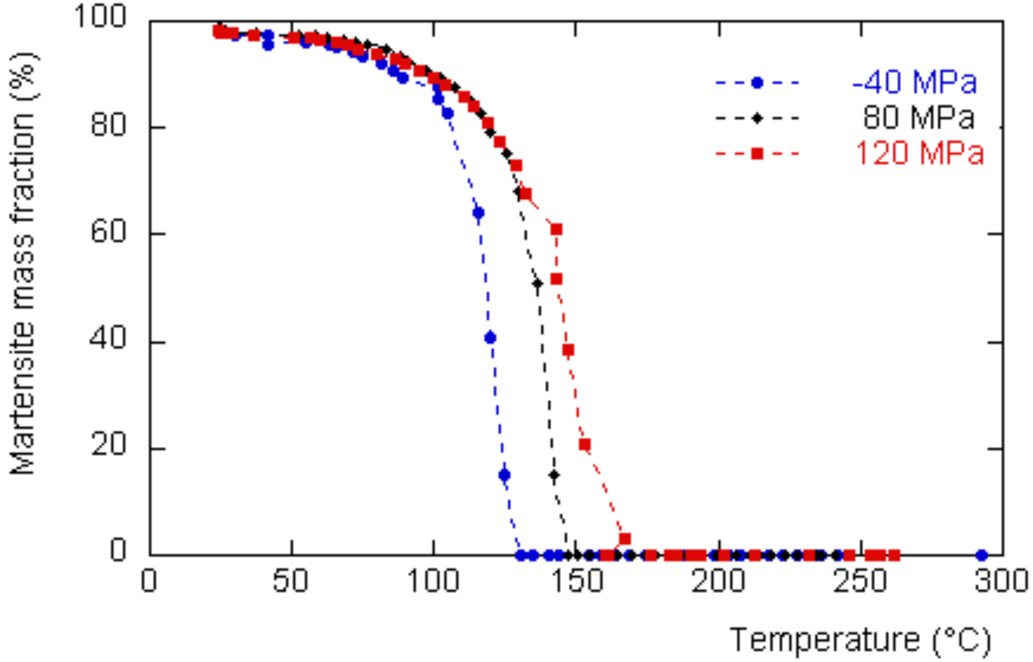
Modifications in transformation kinetics (Martensitic transformation)

Effect of stress on Ms



Patel et Cohen Acta Met 1953

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



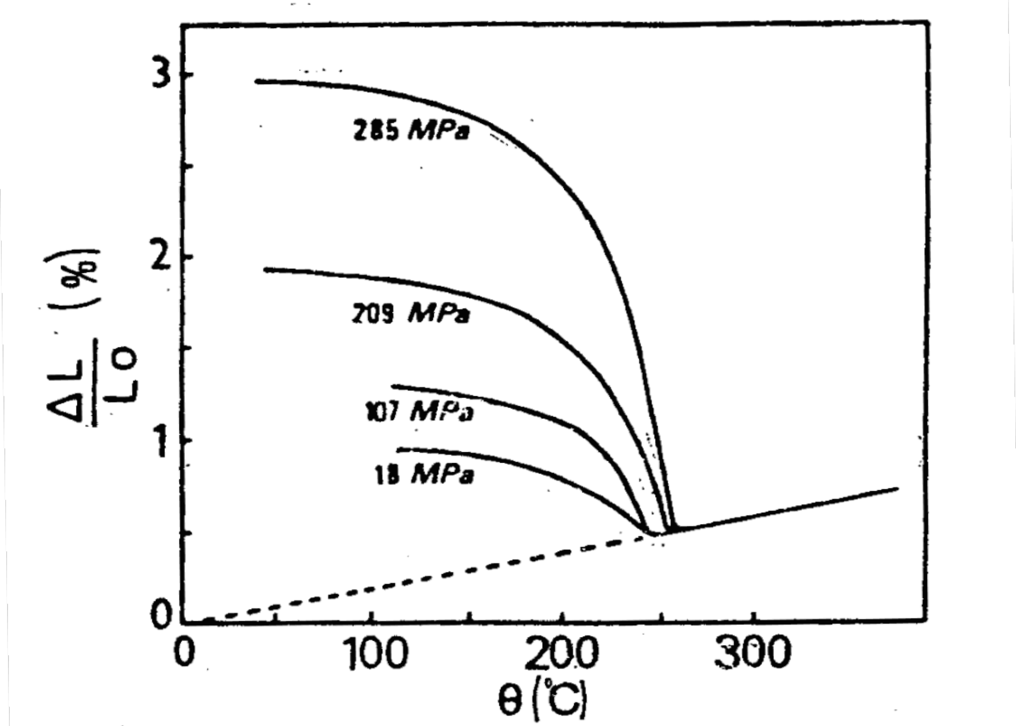
dMs/dσ = 0.25°C/MPa

M. Dehmas et col Mat et Tech. 2009

Influence of stresses/plastic strain on phase transformation

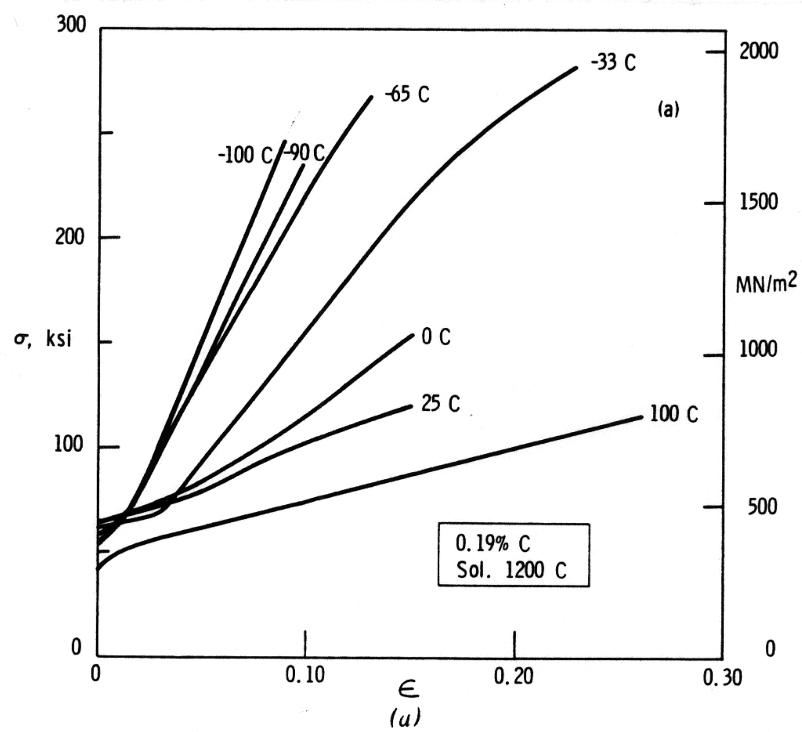
Modifications in mechanical behavior (Fe base alloys)

Transformation during cooling under stress



Collette Thèse INPL 1980

Tensile tests at T> Ms



Olson Azrin Met Trans 1978

Influence of plastic strain on phase transformation

Transformation kinetics (isothermal, diffusion controlled) :

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

$f_f = f\ (N, G, t)$

? Change in driving force

? Change in nucleation rate

? Change in growth rate

Influence of plastic strain on phase transformation

Transformation kinetics (isothermal, diffusion controlled) :

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

$f_f = f\,(N, G, t)$

? Change in driving force

Difference in free energy

? Change in nucleation rate

$$\dot{N} \propto \nu_0 \, N_0 \exp\left(-\frac{Q + \Delta G^*}{kT} \right)$$

$$\Delta G^* \propto A \frac{\gamma^3}{\left(\frac{\Delta Gm_n}{Vm} + \Delta G_e\right)^2}$$

? Change in growth rate

$$G \propto D_B^\alpha \frac{(c_B^0 - c_B^{\alpha e})}{(c_B^\beta - c_B^{\alpha e})} \frac{1}{R}$$

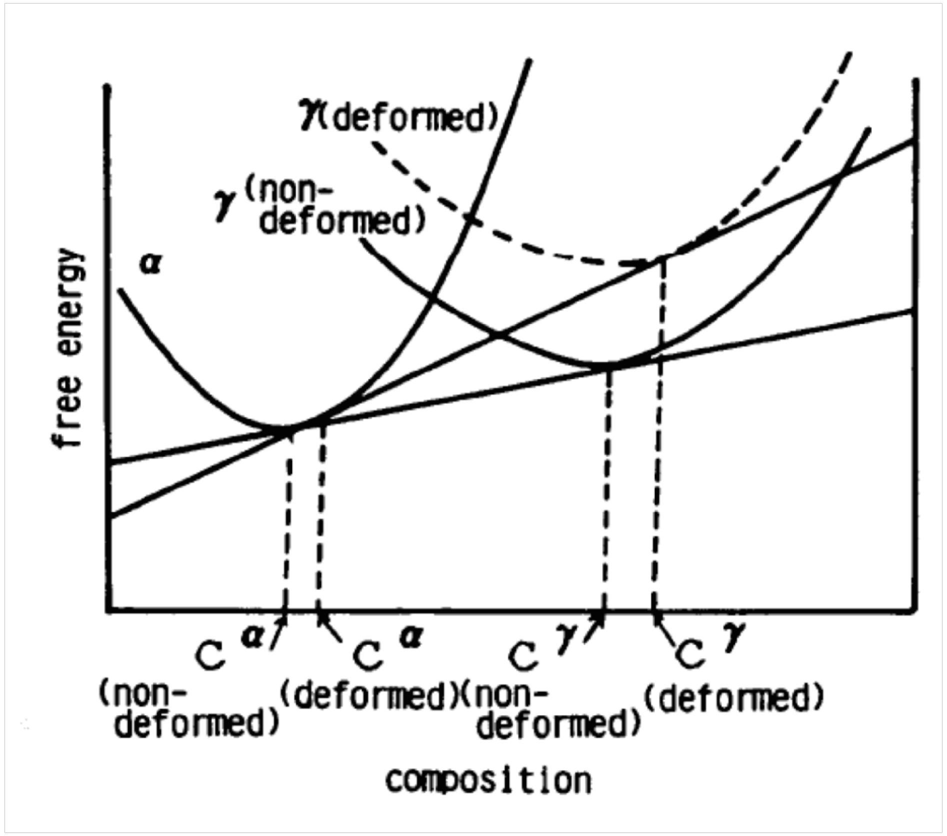
Growth of spherical precipitate β in α

Influence of plastic strain on phase transformation

Change in equilibrium conditions/driving force:

Plastic strain

dislocation density ρ:



Influence of plastic strain on phase transformation

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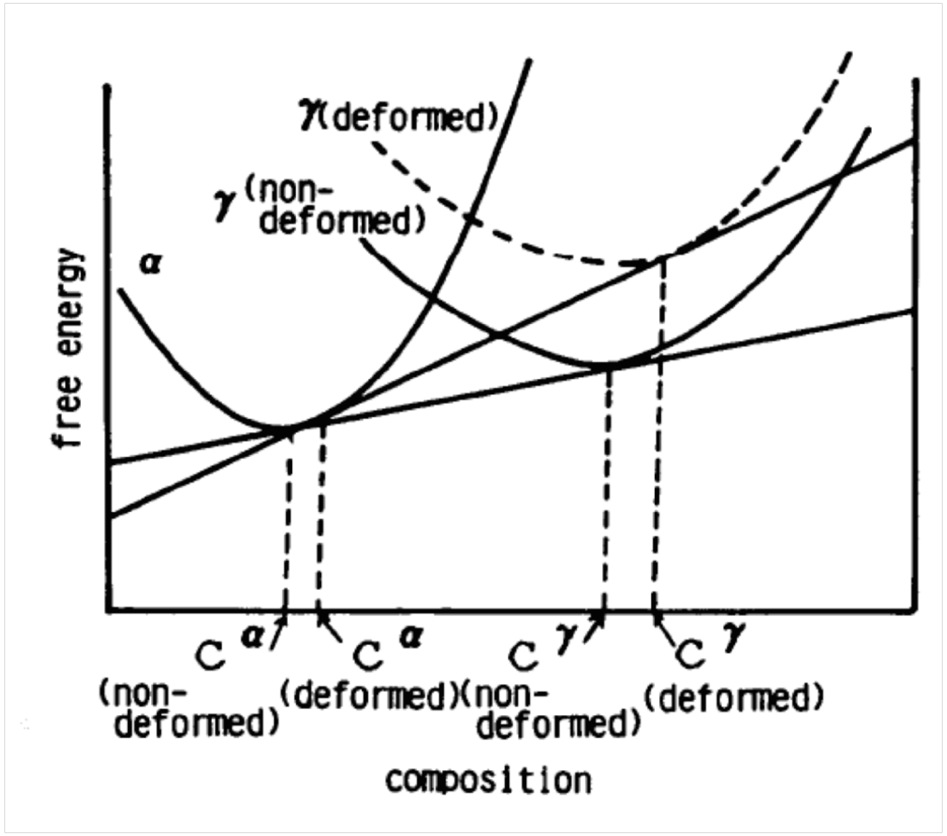


dislocation density ρ:

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

ρ dislocation density
μ shear modulus
r outer cut-off radius
r_0 inner cut off radius
K constant

Order of magnitude

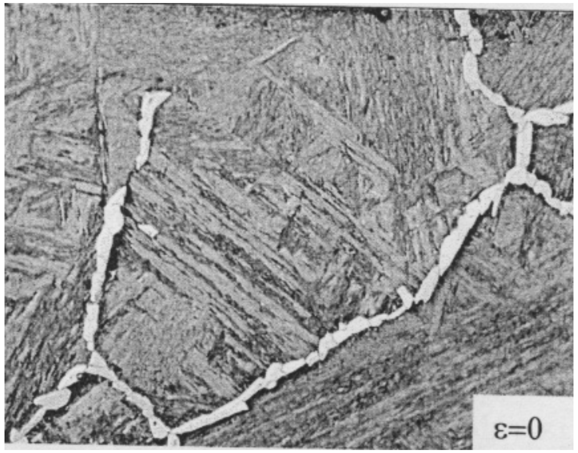
1 to 10 $J.mol^{-1}$

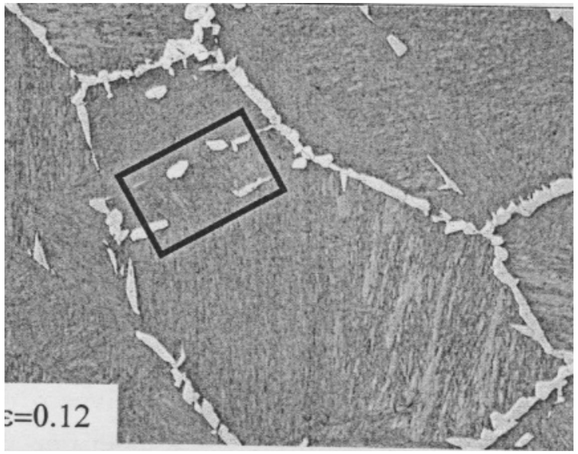
Influence of plastic strain on phase transformation

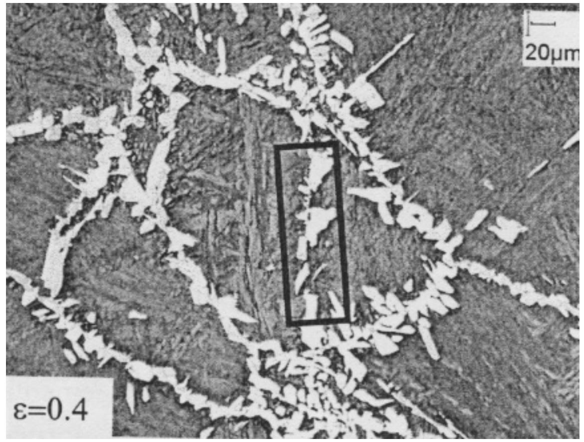
Change in nucleation and growth:

Influence of plastic strain on phase transformation

Large increase in nucleation density ; poor effect on growth



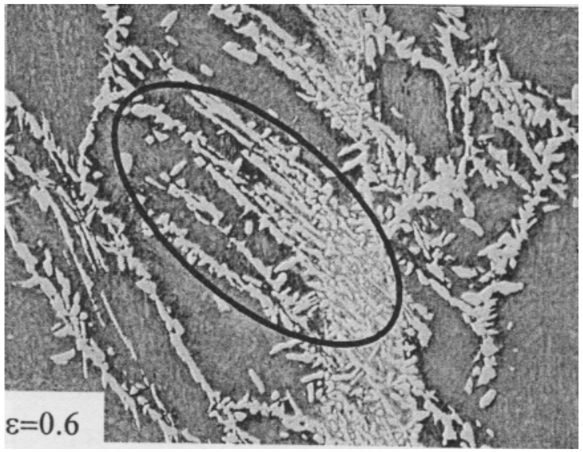


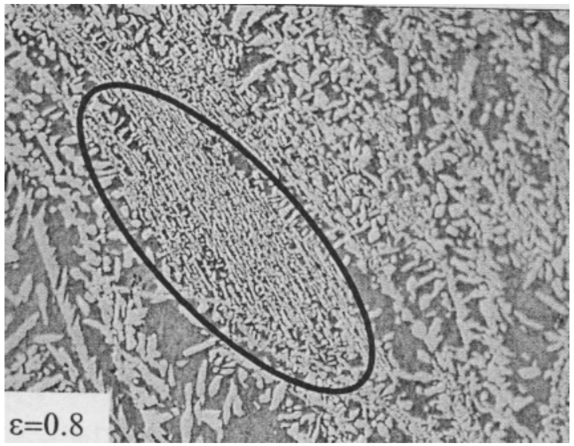


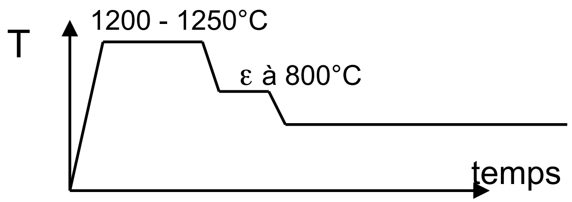
Fe 0.164C 1.39Mn

T = 700°C

Quenching after 1 min. holding



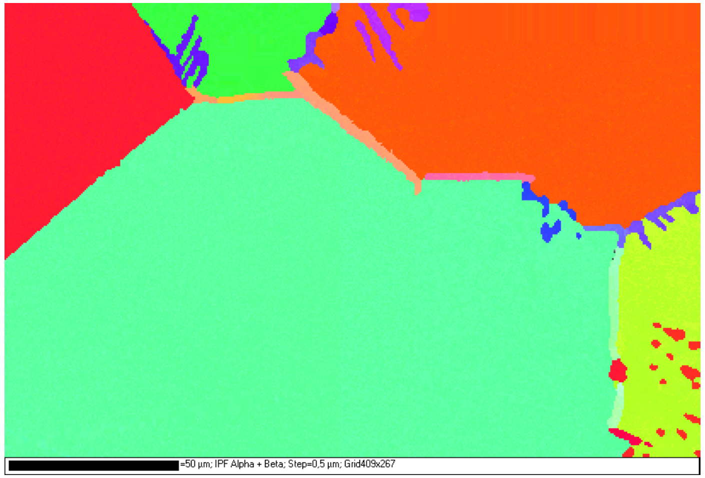




Sophie Lacroix Thèse INPG 2003, M. Veron, Y. Bréchet

Influence of plastic strain on phase transformation

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

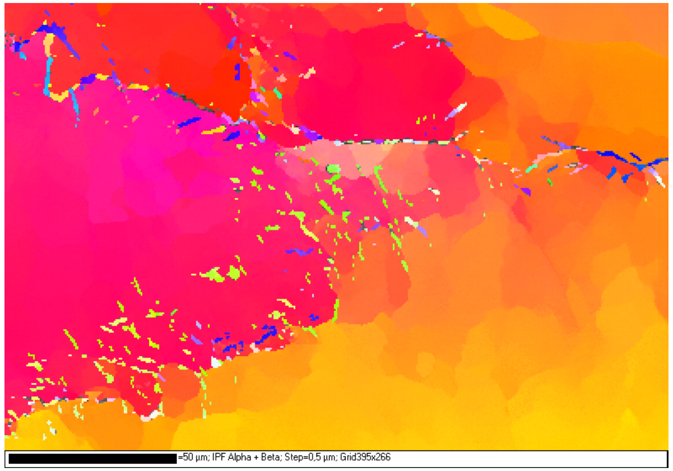


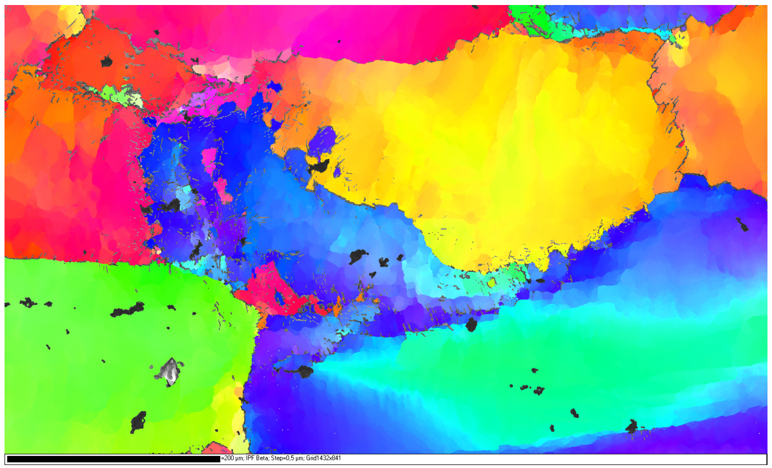
←

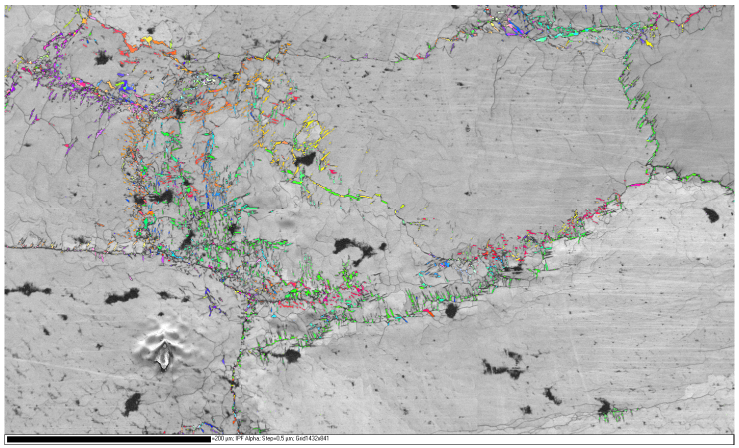
ε = 0
3600s holding

ε = 20%, 800°C
700s holding

↙ ↘ →



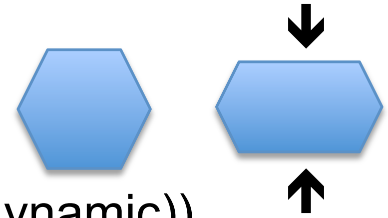




M. Salib, J. Teixeira, L. Germain PhD in progress Ti17 (5Al, 5Mo, 3Cr, 2Sn, 2 Zr)

Influence of plastic strain on phase transformation

Change in heterogeneous nucleation site nature, density:



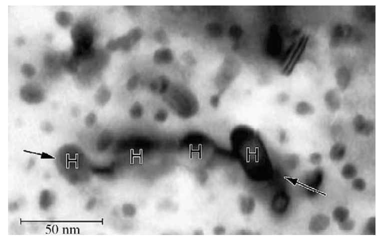
↗↗

- variation of GB surface (grain deformation)
- new GB: recristallisation (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



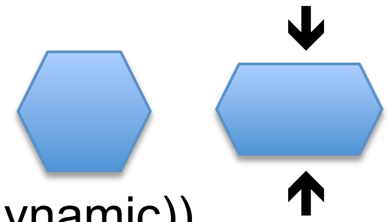
Embury, Deschamps, Bréchet Scripta Mat 2003

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:



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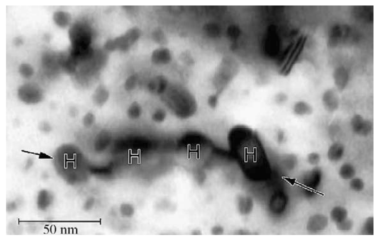

Embury, Deschamps, Bréchet Scripta Mat 2003

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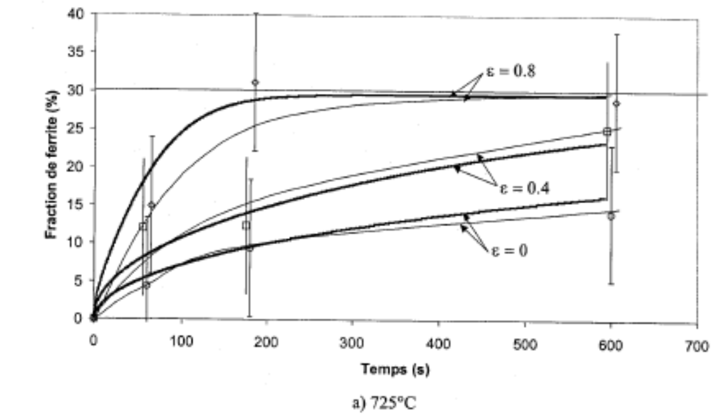
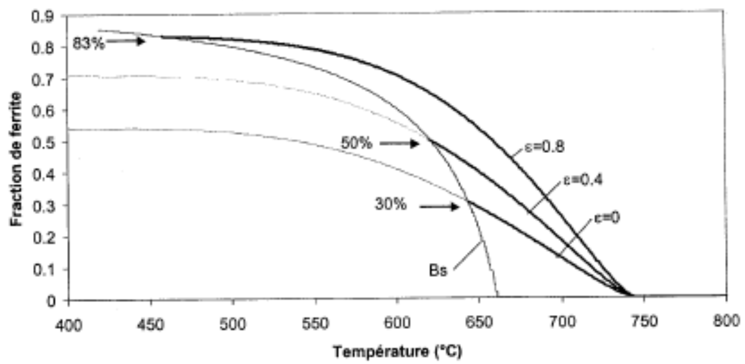
Modelling: Necessity to take into account N and G // deformation microstructure

Influence of plastic strain on phase transformation

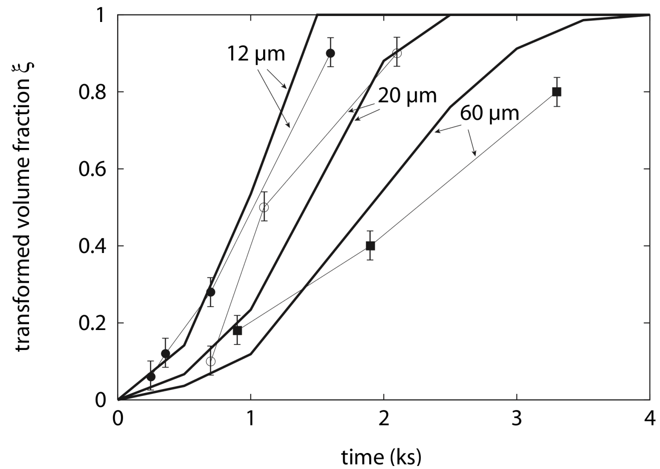
Deformation of the single parent phase previous to transformation

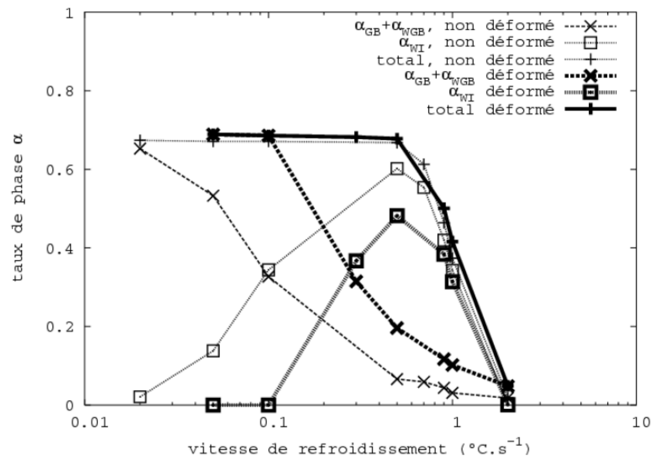
Modelling:





Ferrite formation (S. Lacroix INPG 2003)

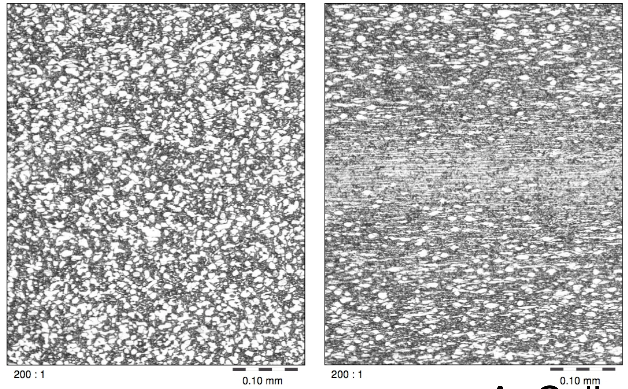




Transformation β –> α Titanium alloys (J. Teixeira INPL 2005, 2008)

Influence of plastic strain on phase transformation

Deformation in a two phase domain



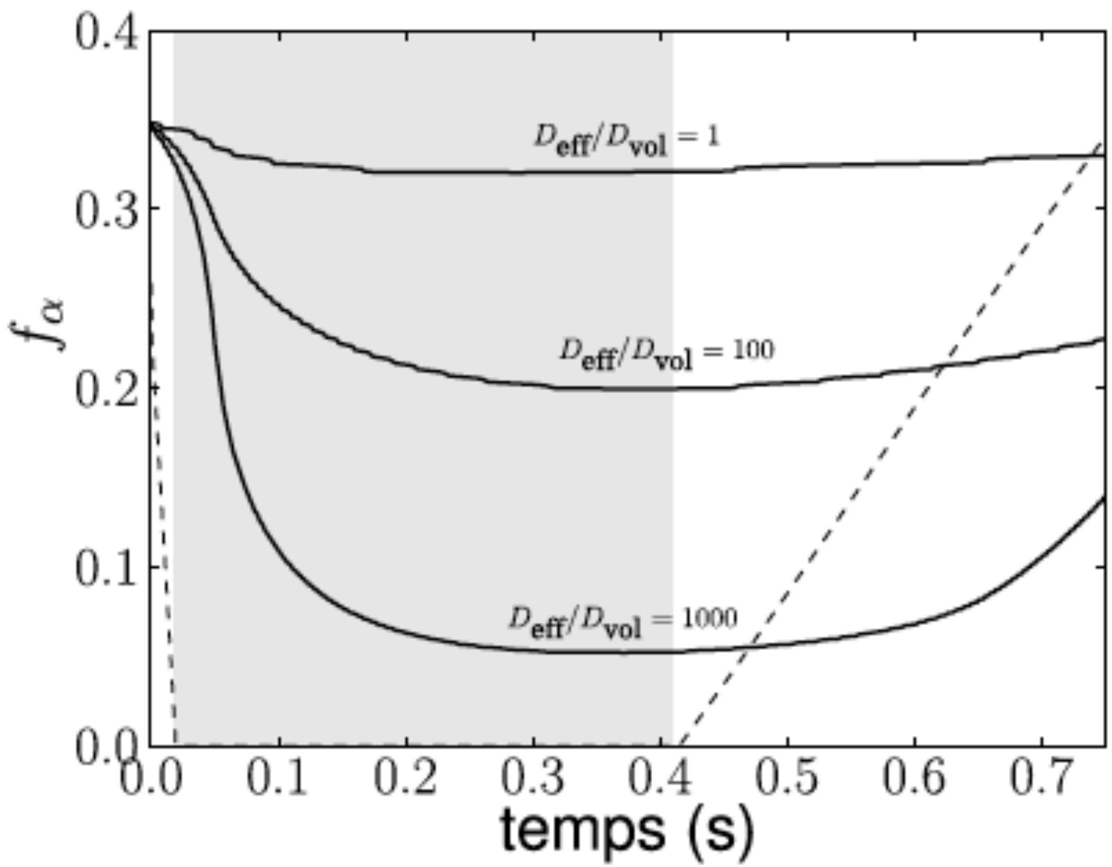
A. Colin St Etienne
TA6V4

- 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

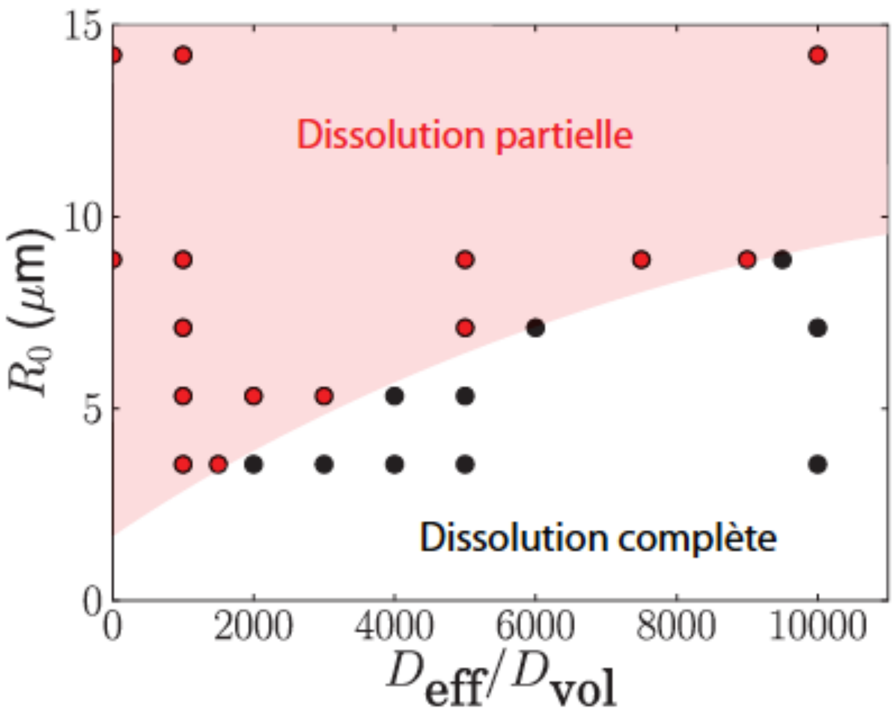


Amount of α phase versus time during adiabatic heating and further cooling for 3 different effective diffusion

B. Appolaire HDR 2010

Influence of plastic strain on phase transformation

Deformation in a two phase domain

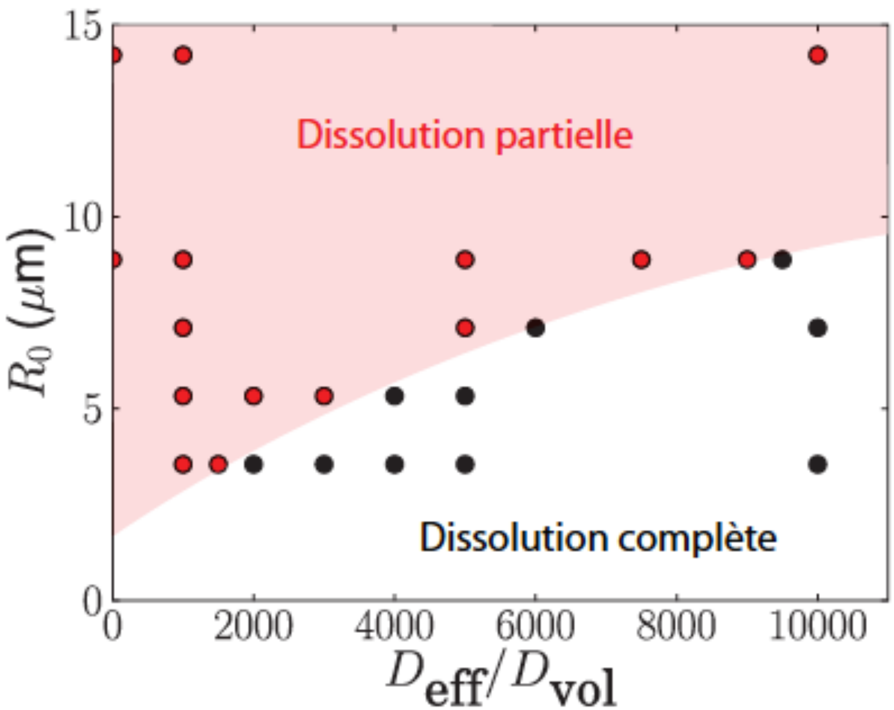


Effect of grain size on its dissolution during adiabatic heating

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

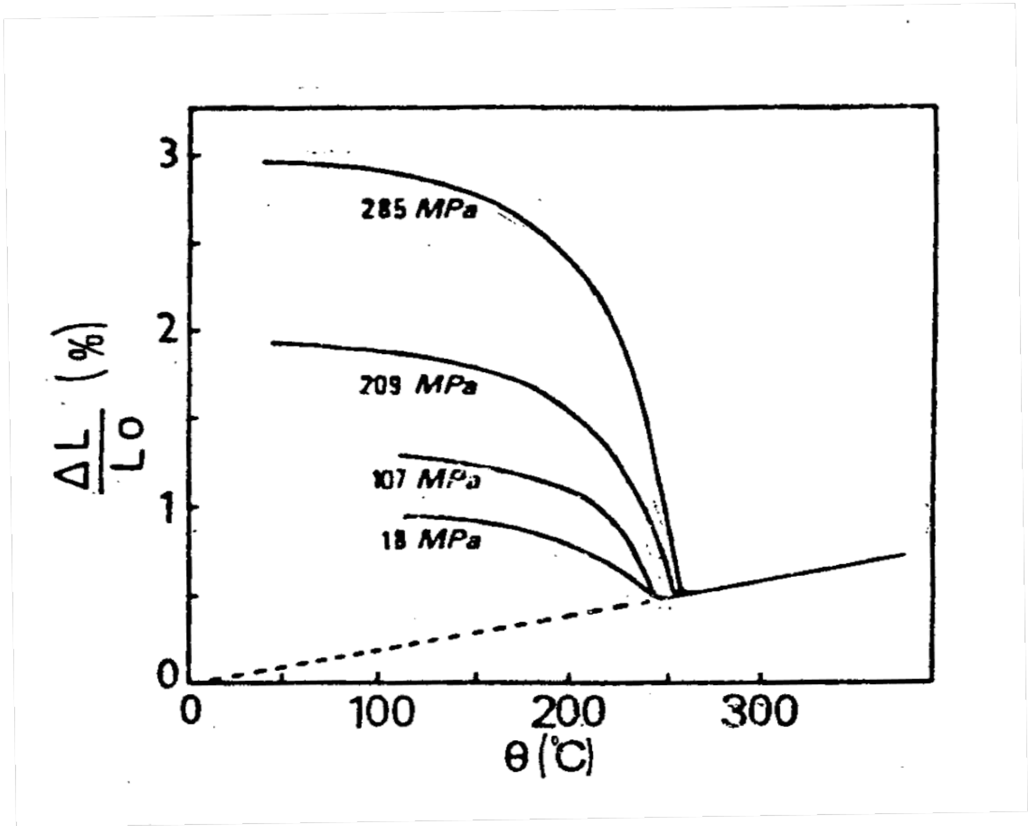
B. Appolaire HDR 2010

In progress :

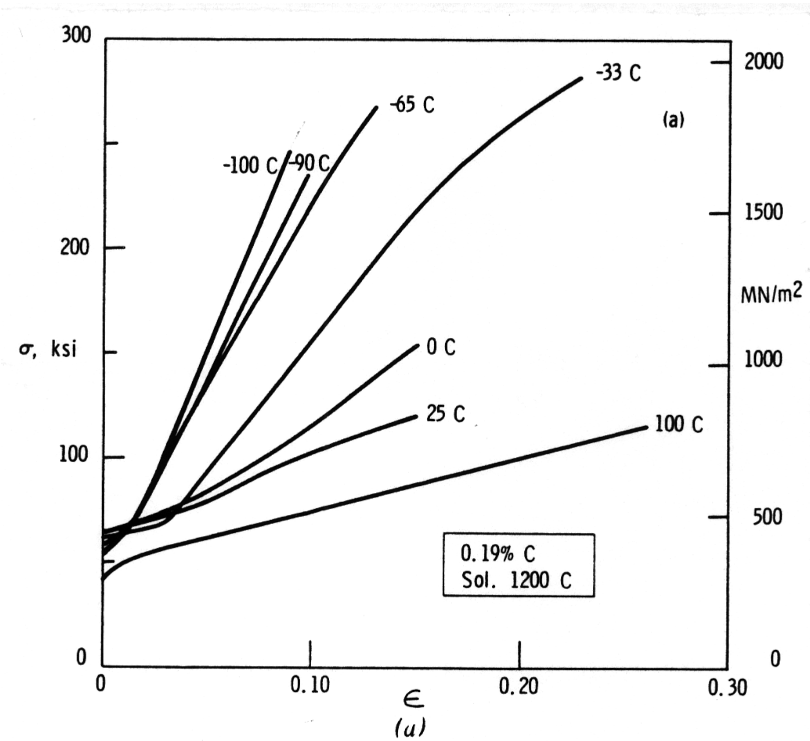
Prediction of morphology changes using phase field : dynamic evolution from orange to lemons ***B. Appolaire MMM 2012***

Influence of stresses on phase transformation

Influence of uniaxial stress
Case of martensitic transformation



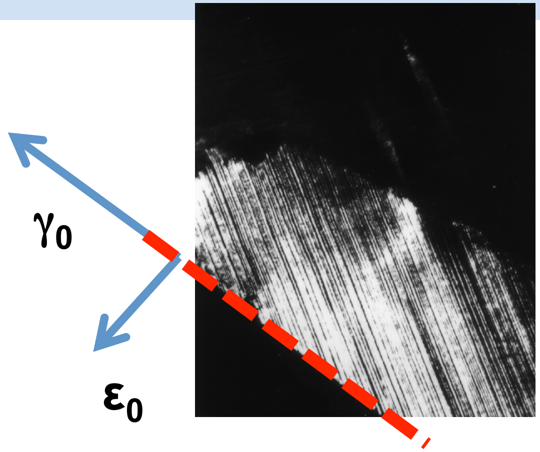
Collette thèse INPL 1980



Olson Azrin Met Trans 1978

Influence of stresses on phase transformation

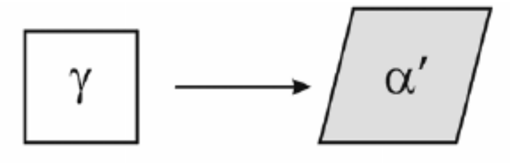
Martensitic transformation



Fe-Ni-C Alloy
X.M. Zhang

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 γ_0, volume variation ε_0)



$$\varepsilon^{tr}_{\underline{d,\,n}} = \begin{bmatrix} 0 & \gamma_0/2 \\ \gamma_0/2 & \varepsilon_0 \end{bmatrix}$$

ε_0 : volume variation
γ_0 : macroscopic shear

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

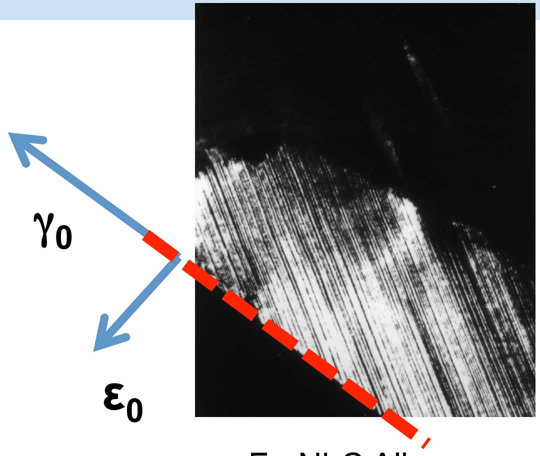
Formation of the plate :
Interface energy, Elastic energy (deformation energy)

Influence of stresses on phase transformation

Martensitic transformation

a nano/micro scale :

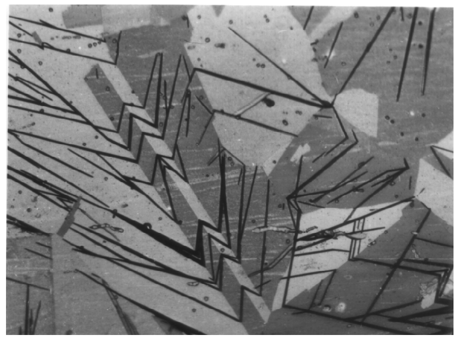
Arrangements of self-organized domains (Bain variants) leading to a plate with a given habit plane and OR to which can be associated a deformation tensor (mean shear strain γ_0, volume variation ε_0)



Fe-Ni-C Alloy
X.M. Zhang

In the parent grain and the polycrystal

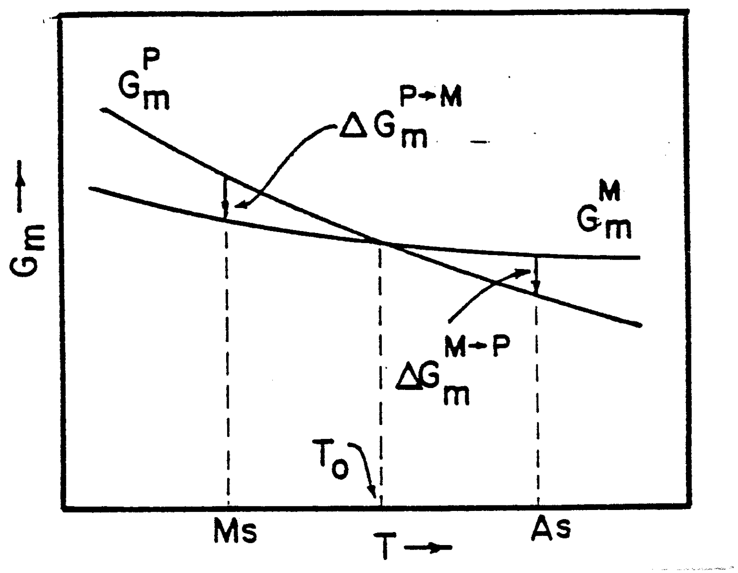
stresses are partially relaxed by formation of self-accommodated plates - in order to accommodate the "macroscopic" shear strain (γ_0)



Fe-Ni-C Alloy
J.S. Zhang

Influence of stresses on phase transformation

Martensite transformation

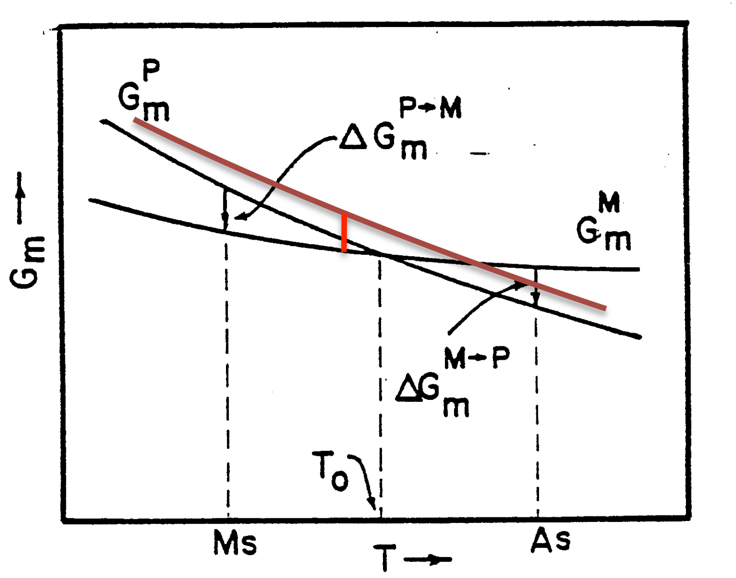


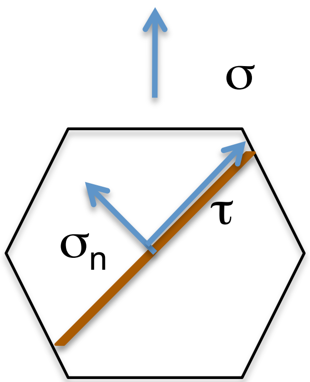
at T = Ms, without applied stress

$$V_M \Delta G_{ch}^{P-M} = S_M \gamma^{P/M} + V_M E_{el}$$

Influence of stresses on phase transformation

Martensite transformation





With an applied stress:

Additional Work U' associated with the transformation

$$V_M \Delta G_{ch}^{P\_M} + \underbrace{V_M [\sigma][\varepsilon^{tr}]}_{U'} = S_M \gamma^{P/M} + V_M E_{el}$$

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

Assuming γ_0 constant

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

σ_n and τ are the normal stress to the habit plane and the shear stress in the habit plane, respectively.

U' function of plate orientation

M_s^σ For maximal value of U'

Influence of stresses on phase transformation

Martensite transformation

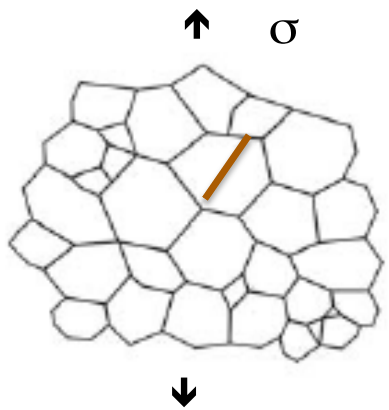
Polycristal:

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

+ tensile
- compression

Patel Cohen 1953

U'max : $tg2\theta = \pm\gamma_0/\varepsilon_0$



θ angle between σ and plate orientation
α angle between shear direction and maximal shear direction

Influence of stresses on phase transformation

Martensite transformation

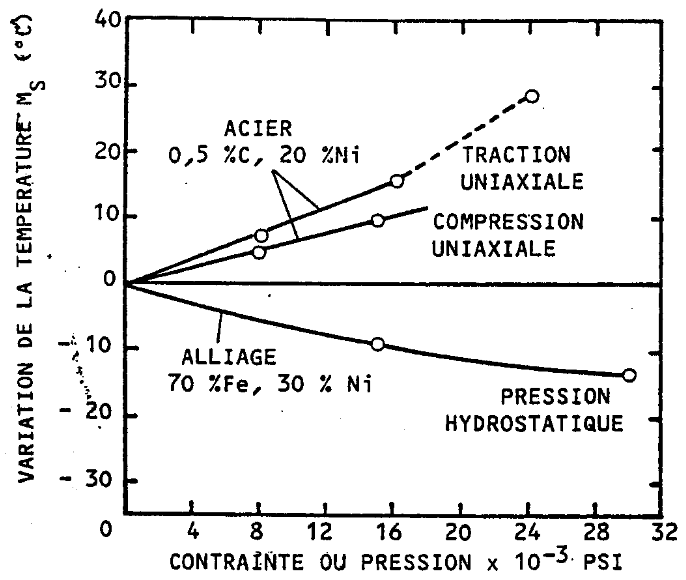
Polycristal:

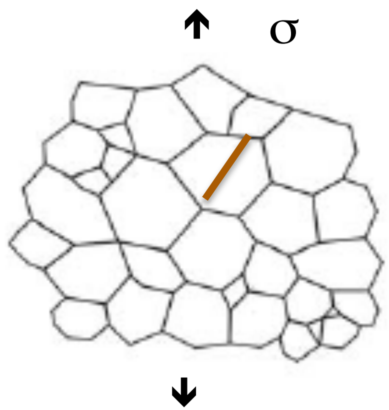
$$\Delta M_s = \sigma \frac{[\gamma_0 \sin 2\theta \cos\alpha \pm \varepsilon_0 (1+\cos 2\theta)]}{2} * \frac{1}{(-(\Delta S_{ch}^{\gamma\rightarrow\alpha'}))}$$

+ tensile
- compression

Patel Cohen 1953

U'max : $tg2\theta = \pm\gamma_0/\varepsilon_0$



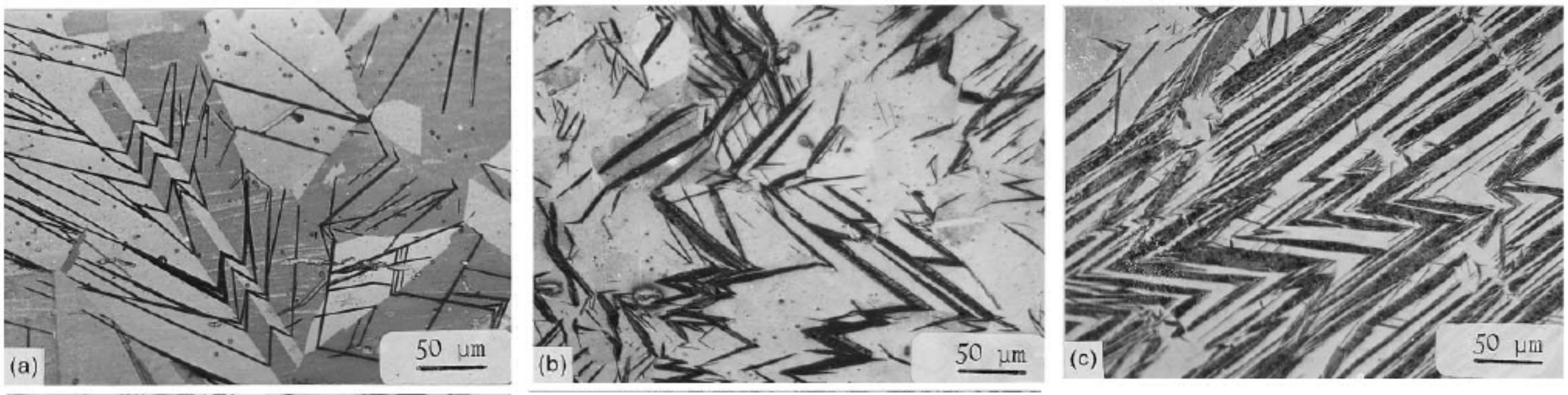


θ angle between σ and plate orientation
α angle between shear direction and maximal shear direction

Influence of stresses on phase transformation

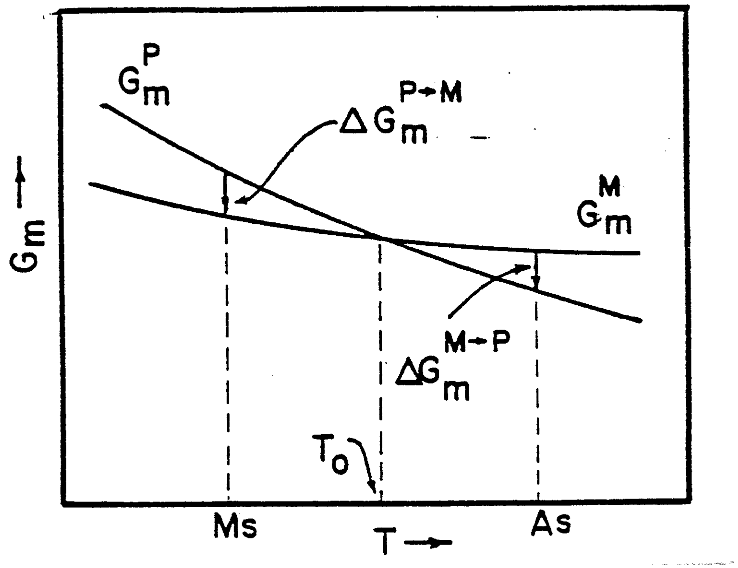
Martensite transformation (in steels)

Orientation of following plates: driven by the local stress state



0 MPa 285 MPa 600 MPa

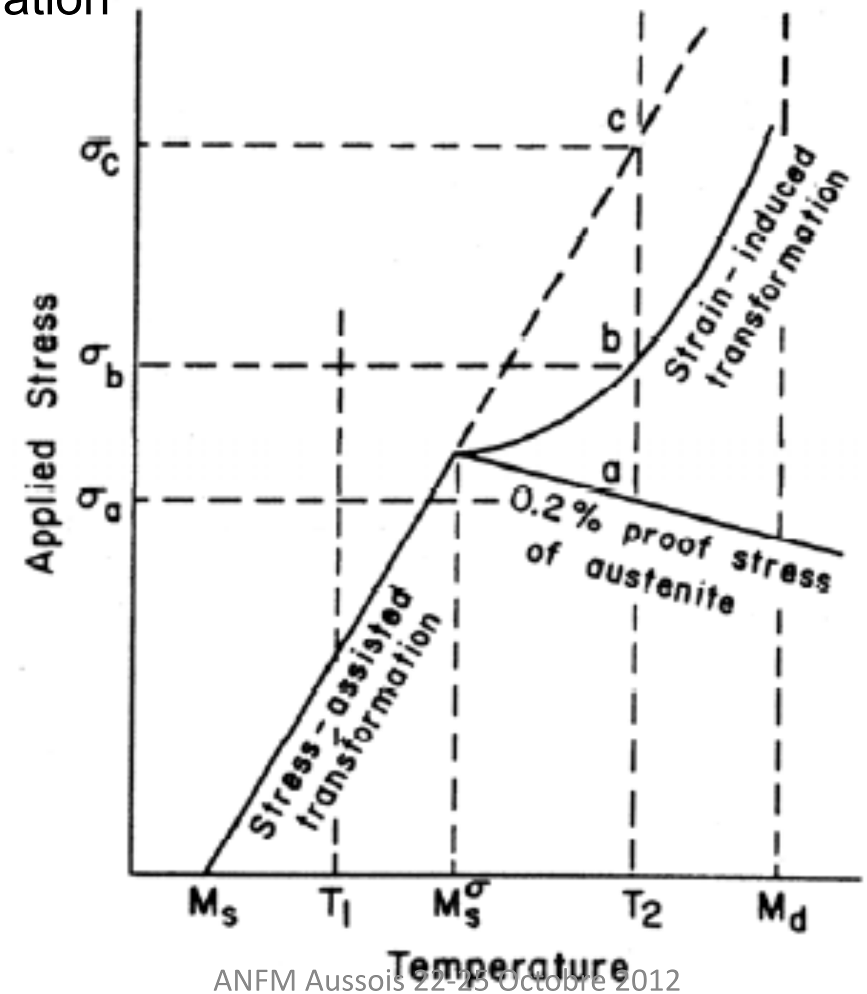
Influence of stresses on phase transformation



Transformation can be mechanically induced at T > Ms

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^{σ} Plastic strain before transformation

New nucleation sites (Lecroisey, Pineau 1972)

Deformation bands, twins bands

ε Martensite previous to α'

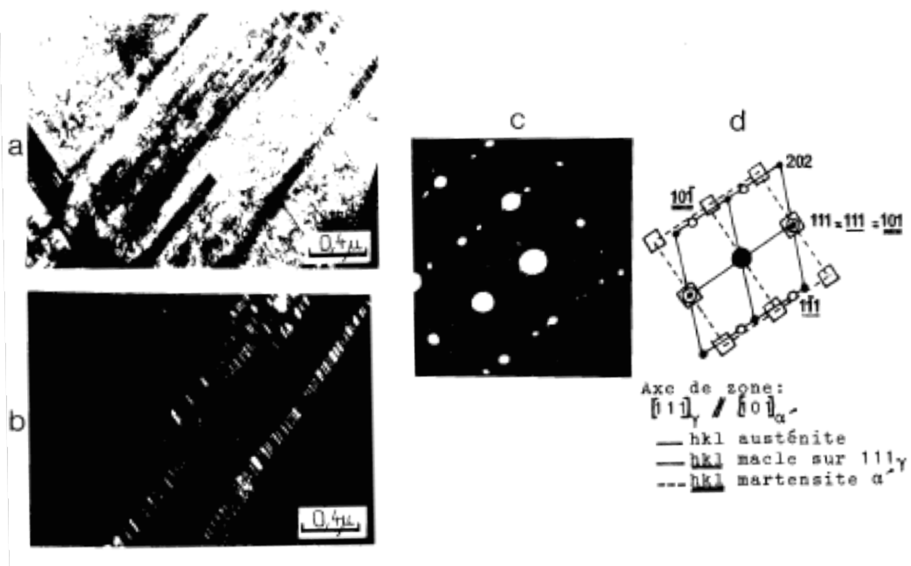


FIG.52- Structures de déformation. Alliage 16-11C:0°C,20%. Lattes de martensite α' et macles de déformation dans l'austénite. (a) champ clair, (b) champ sombre, g=(10$\bar{1}$)α',(c) cliché de diffraction (d) interprétation.

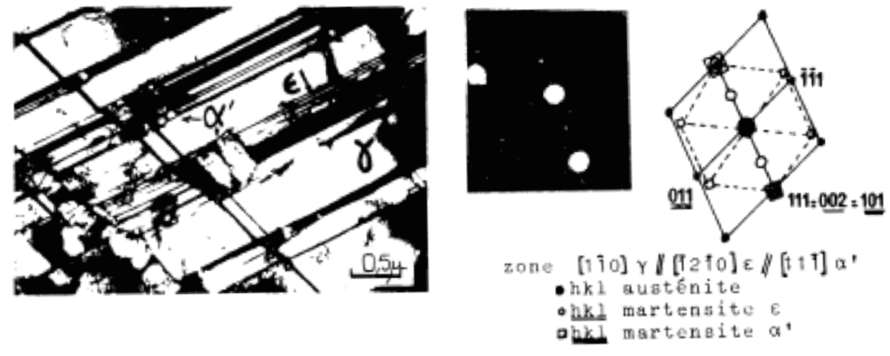


FIG.49- Structures de déformation. Alliage 16-11 C :-196°C,10% Martensites α' et ε.Orientation voisine de KS.

Lecroisey Thèse 1975

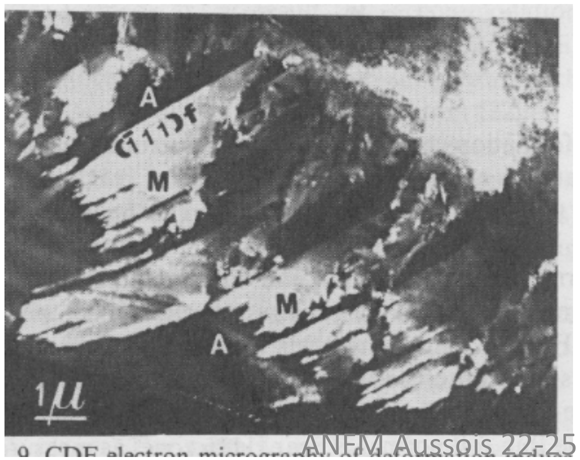
Influence of stresses on phase transformation

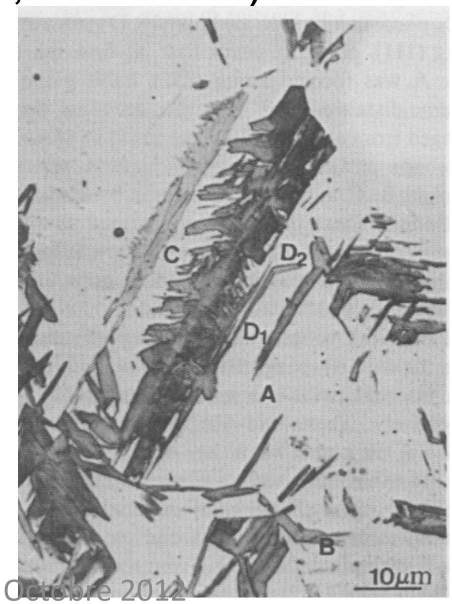
For T > M_s^σ Plastic strain before transformation

New nucleation sites (Lecroisey, Pineau 1972)
Deformation bands, twins bands new nucleation site
ε Martensite previous to α'

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

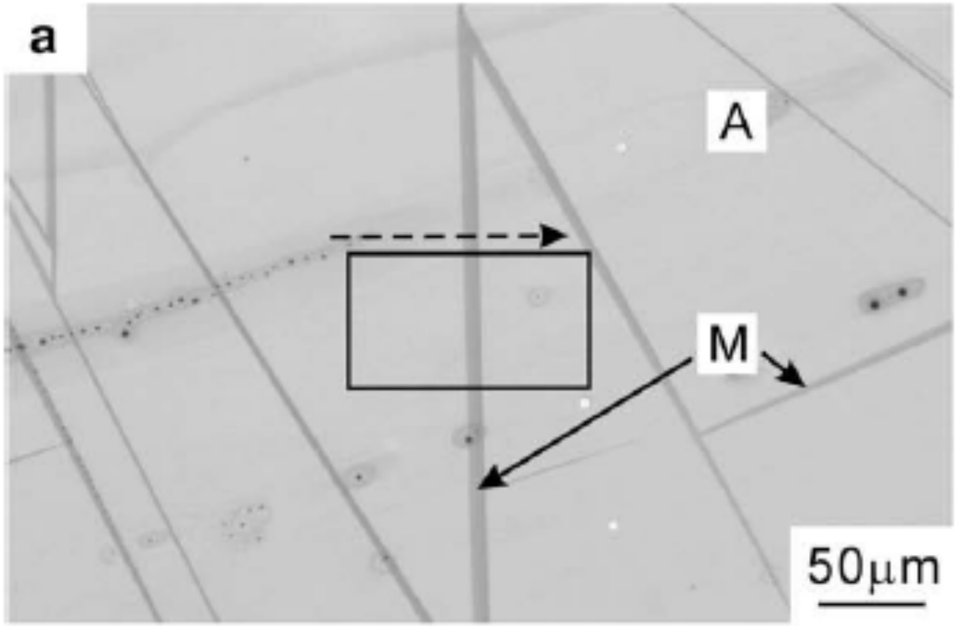
Zhang et al Acta 1989

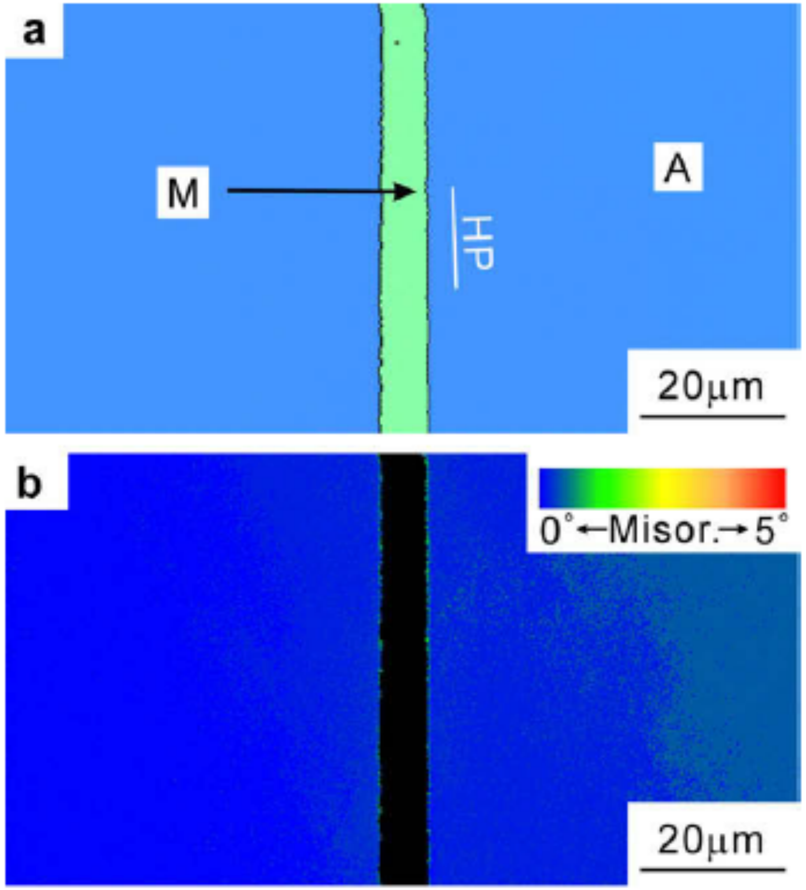




Influence of stresses on phase transformation

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

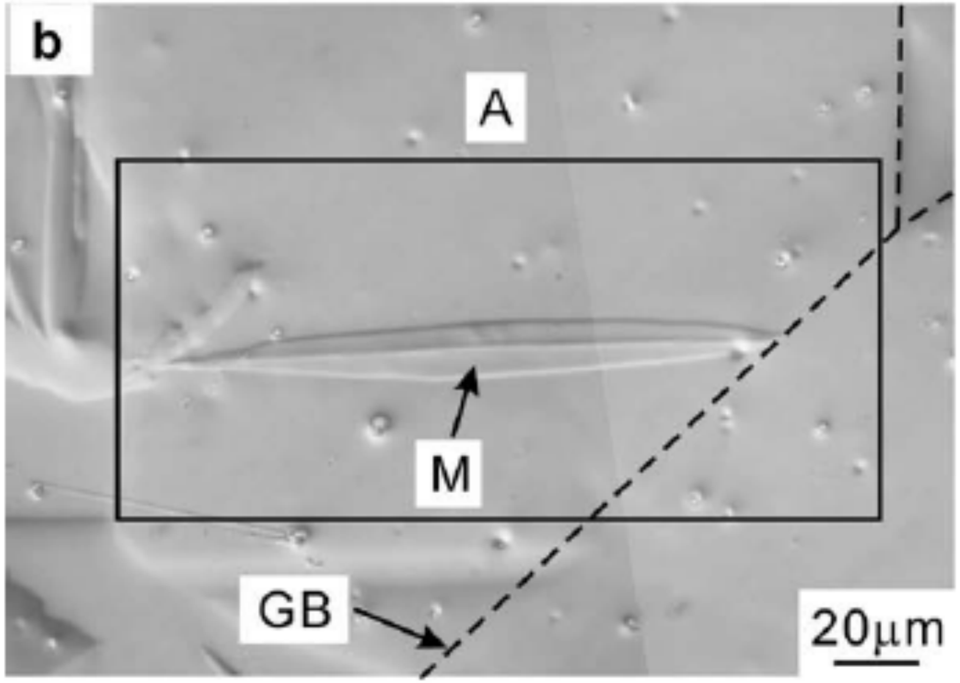


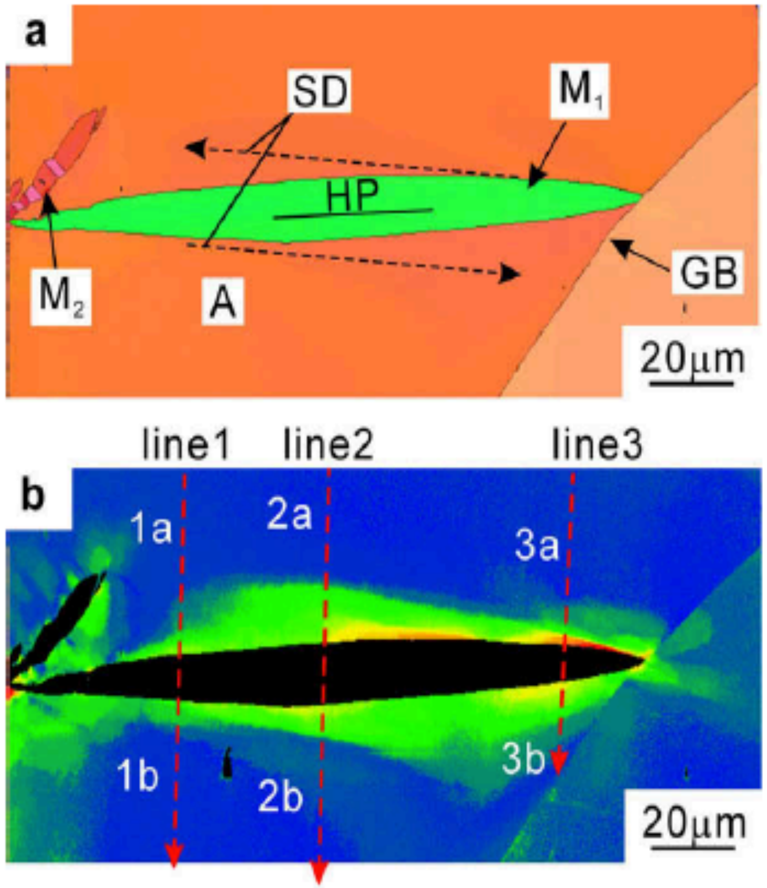


Fe30Ni0.4C

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^{σ} Plastic strain before transformation

New nucleation sites (Lecroisey, Pineau 1972)

Deformation bands, twins bands new nucleation site

ε Martensite previous to α'

Accommodation of ε^{tr} by slip (change in "deformation" energy)

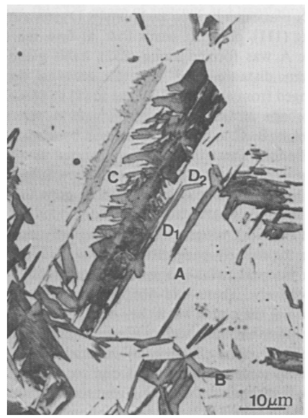
Martensite formed under stress

Change in plate morphology (Zhang et col Acta metal 1989)

Change in twin distribution (Pankova Roitburd), dislocations

Decrease in nucleation barrier

Modification in growth

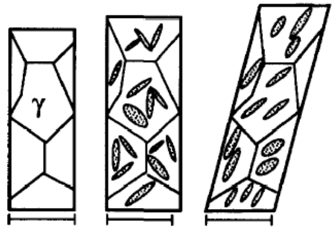


Influence of stresses on phase transformation
Mechanical behavior

Stress triggers plates orientation

Resulting transformation strain in the stress direction

Maximal value of 0.08 for polycrystal (Magee 1966)

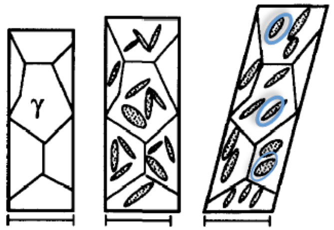


Stress > austenite yield stress favors accommodation by slip

Less self accommodation

Changes in plate morphology :

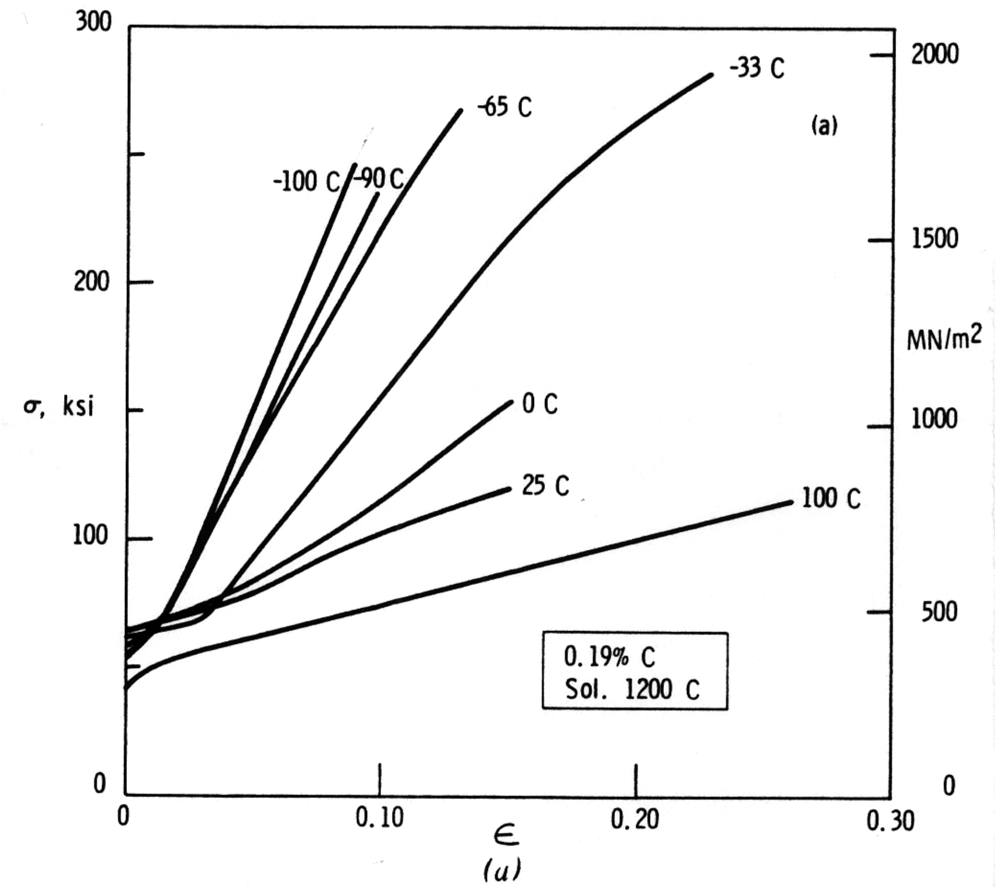
Plastic strain in austenite and product phase



Transformation plasticity (Gautier 1995)

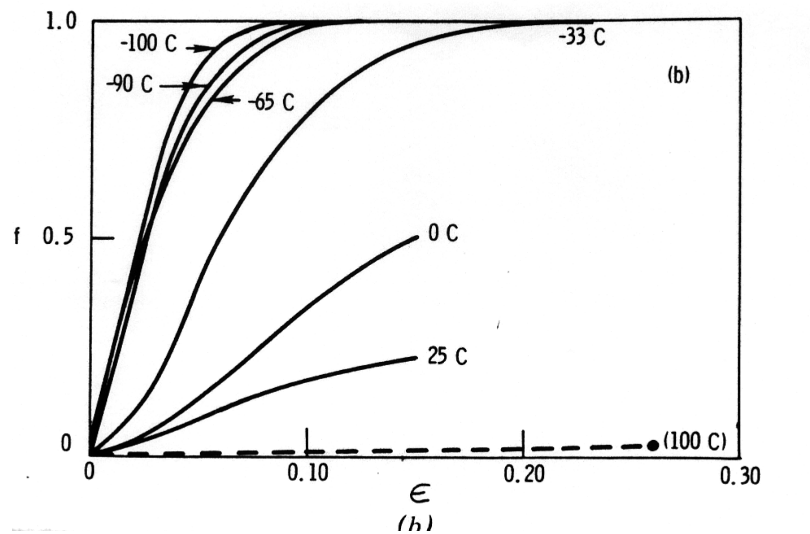
Influence of stresses on phase transformation
Mechanical behavior

Tensile test at different temperatures



TRIP steel 0,19%C (Olson, Azrin Met Trans 1978)

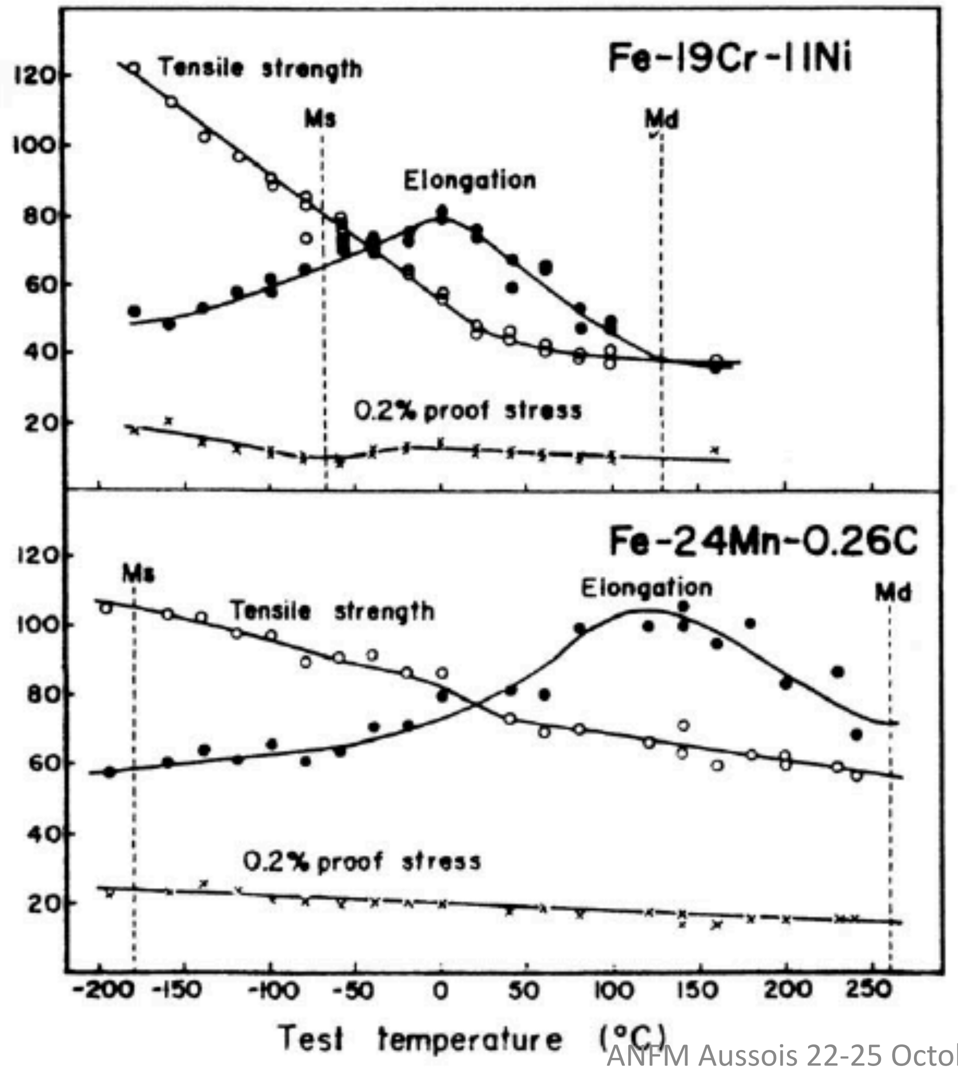
Kinetics of martensite formation



Formation of martensite
Strengthening effect

Deformation source (ductility)

Influence of stresses on phase transformation
Mechanical behavior

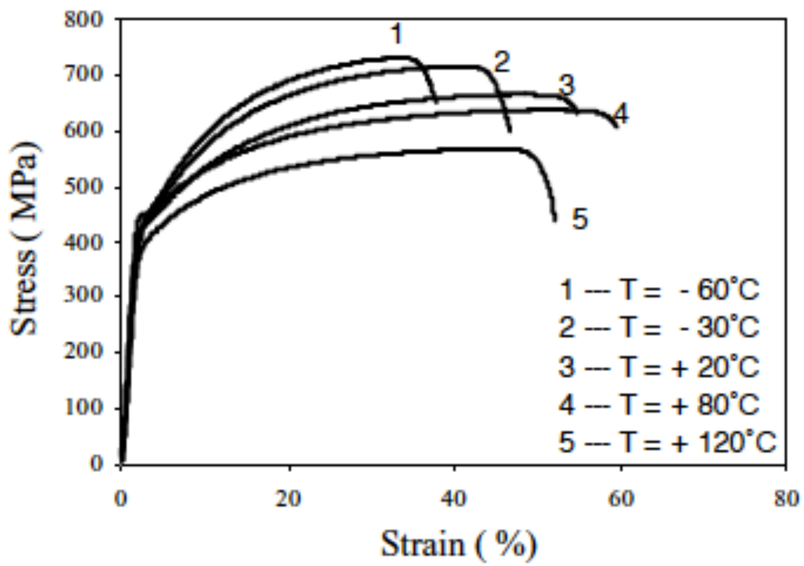


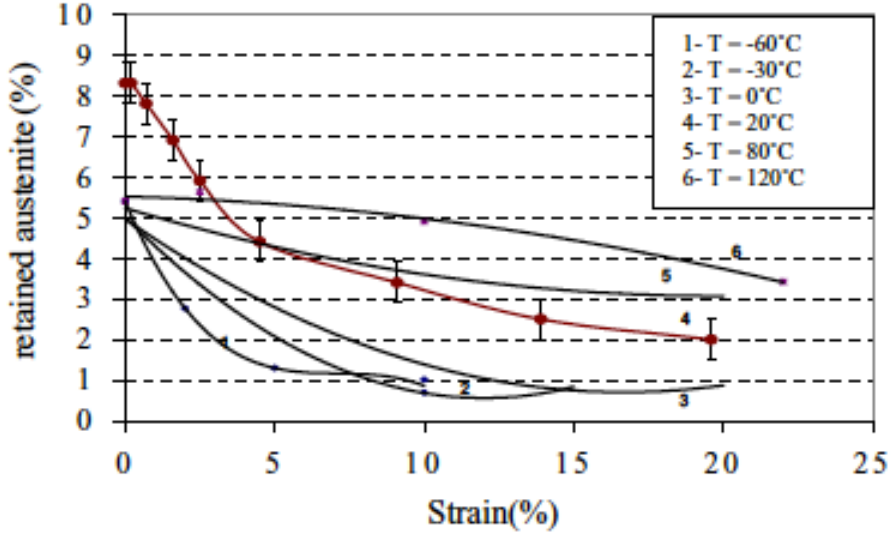
Improvement of toughness and ductility

I. Tamura

Influence of stresses on phase transformation
Mechanical behavior

Mechanical behavior of TRIP 600 steel



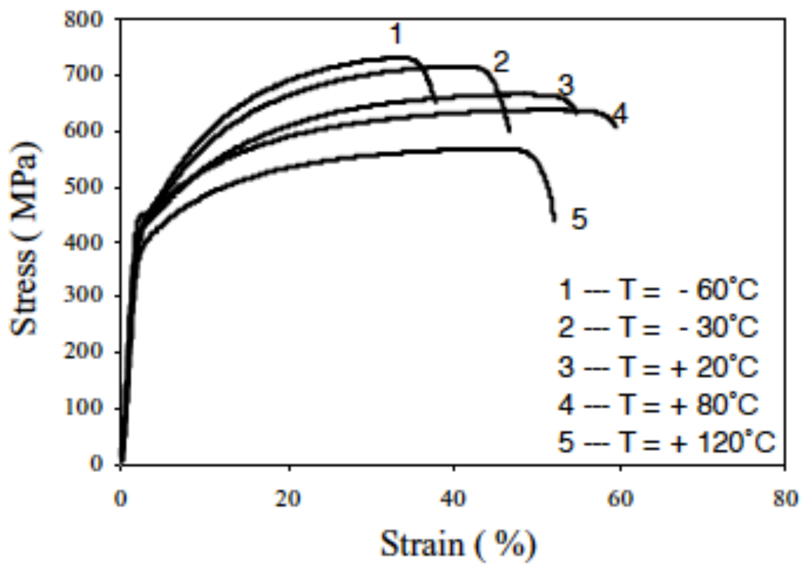


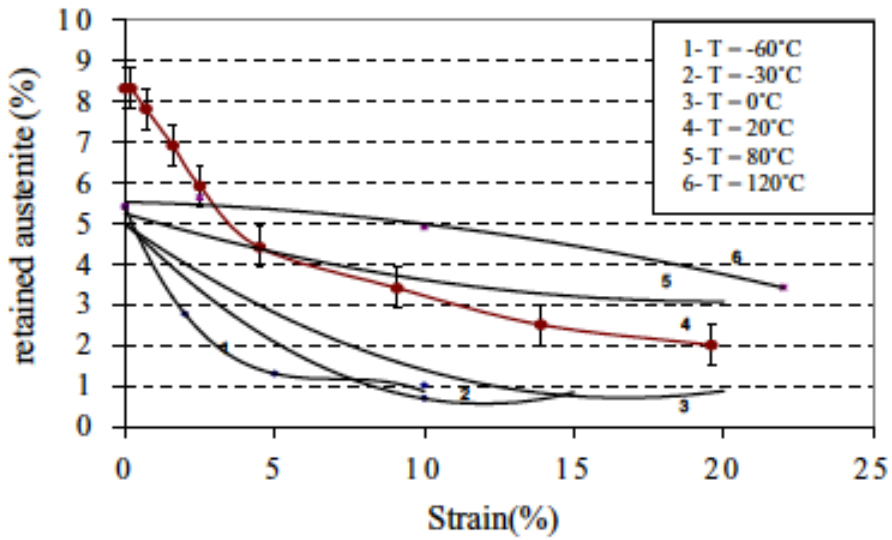
(Berrahmoune et al Mat Scien Eng 2004)

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)

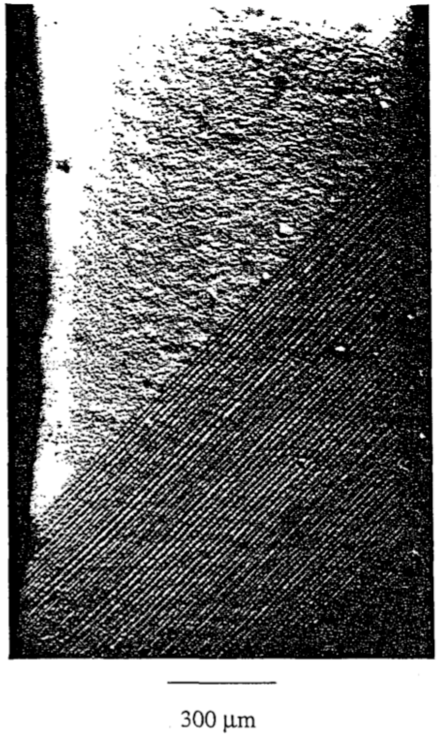
Complex behavior: micromechanical approaches to model
kinetics triggered by stress and strain
associated behavior

→ Improvements of properties: TRIP multiphase steels
P. Jacques Current opinions in solid state and Mat Science 2004

Influence of stresses on phase transformation

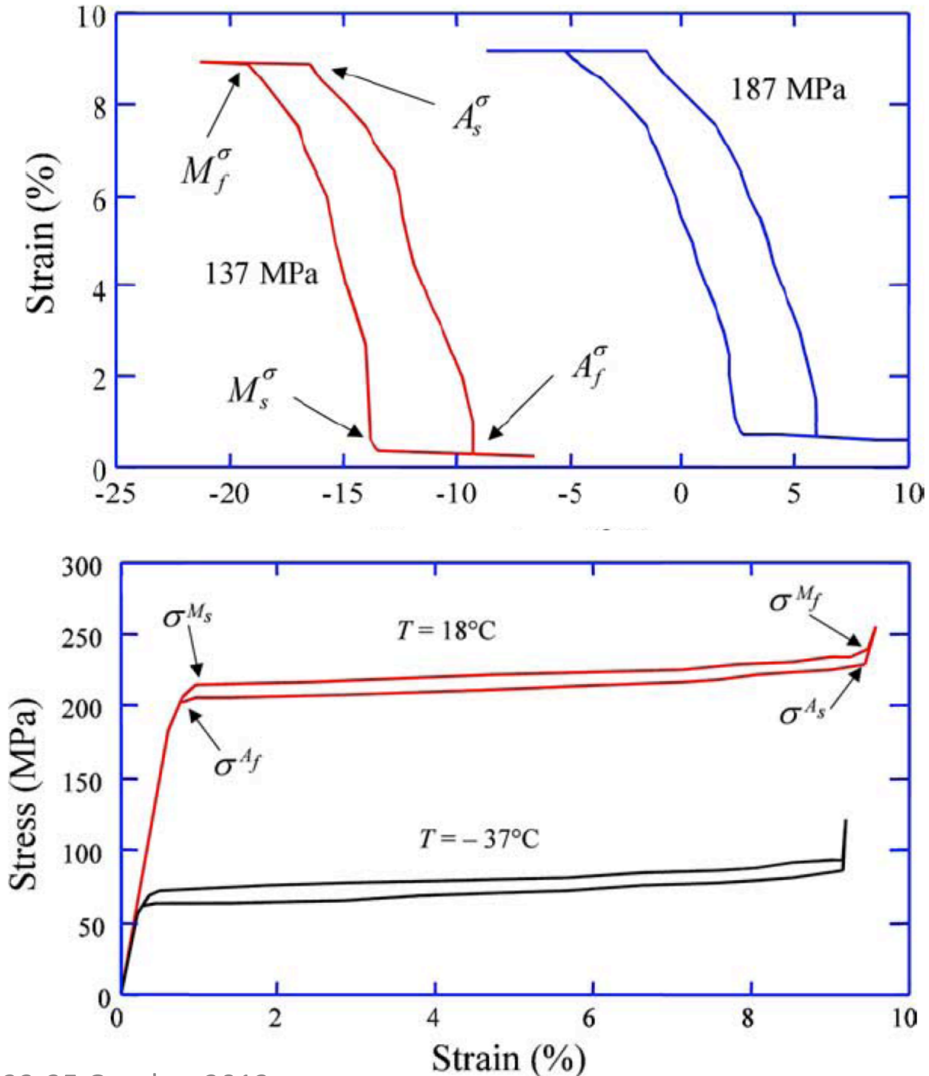
SMA alloys single cristal : one single variant formed under stress

Plate orientation



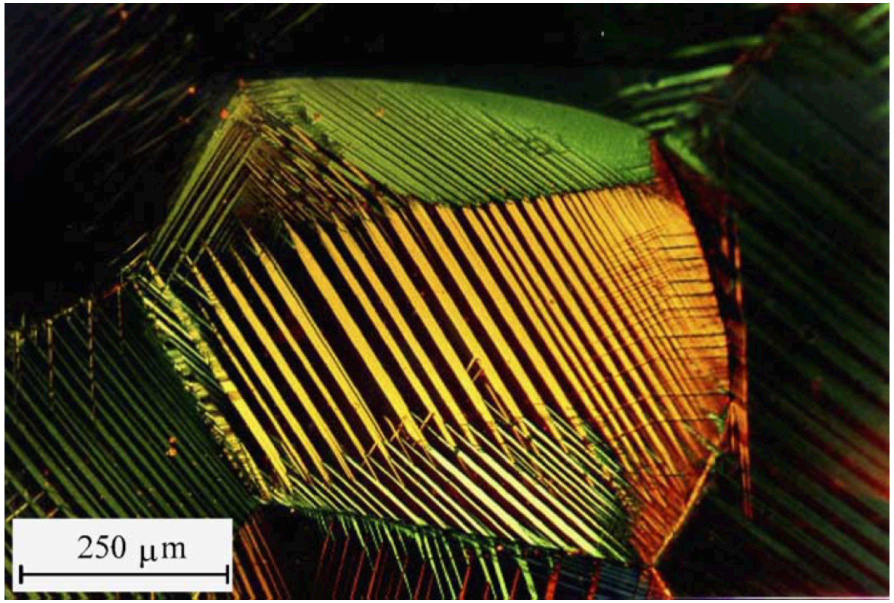
Cu-Zn-Al

Patoor (1995, 2006), cliché S. Dominiak

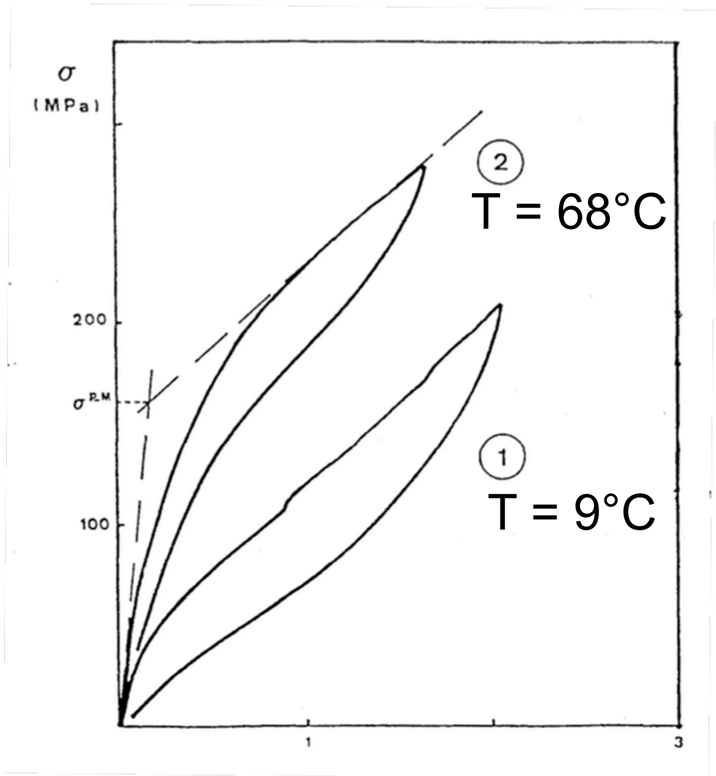


Influence of stresses on phase transformation

Polycristal



Cu-Zn-Al transformé sous contrainte de traction
(E. Patoor, cliché A. Eberhardt 1995, 2006)



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/recristallisation/ phase transformations (precipitation)

Cu-Cd precipitation
Sulonen

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

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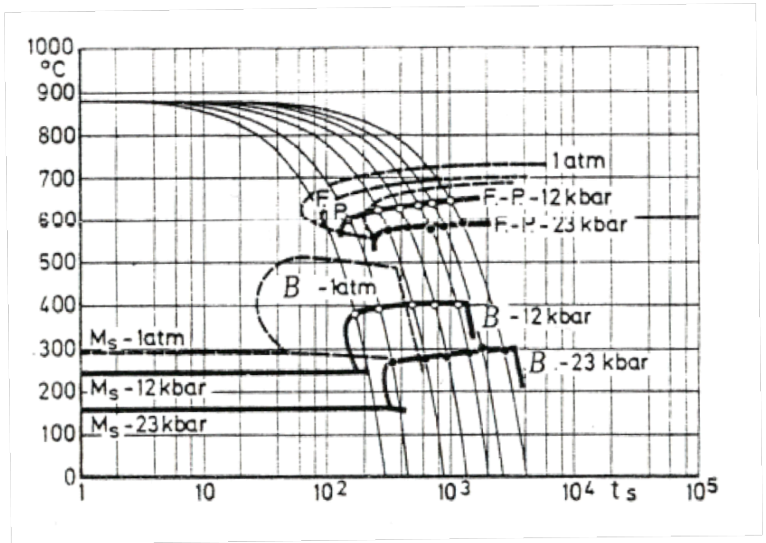
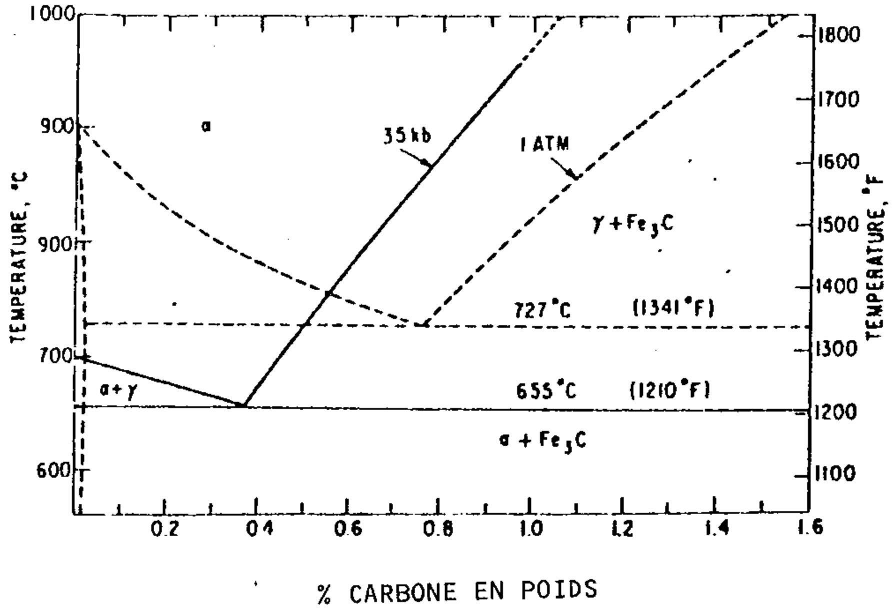
Influence of stresses on phase transformation

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

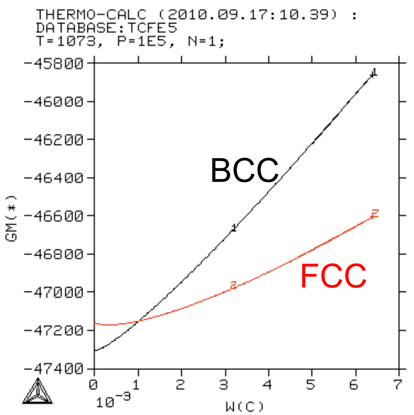
$$G_m^{\gamma} = U_m^{\gamma} - TS_m^{\gamma} + PV_m^{\gamma}$$

$$G_m^{\alpha} = U_m^{\alpha} - TS_m^{\alpha} + PV_m^{\alpha}$$

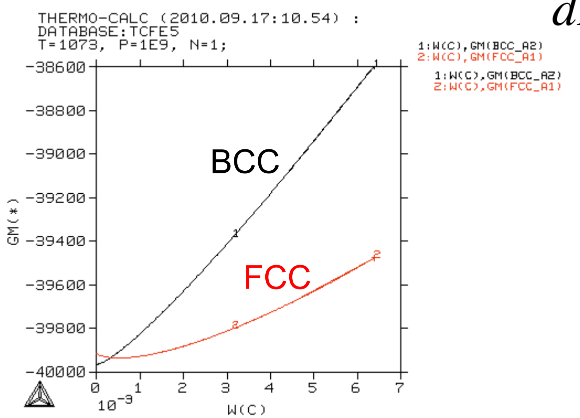
Variations in equilibrium temperature and solubility limits

For low P variations (V_m incompressible):

$$\frac{dTe}{dP} \approx \frac{Te(V_m^{\gamma} - V_m^{\alpha})}{(H_m^{\gamma} - H_m^{\alpha})}$$ Clausius Clapeyron



P = 10^5Pa



P = 10^9Pa

Fe - C 1073K

Pure iron: $T_e^{\alpha/\gamma}$ = 912°C

V_m^{α} = 7.384 10^{-6} $m^3.mol^{-1}$

V_m^{γ} = 7.300 10^{-6} $m^3.mol^{-1}$

H_m^{α} = 33.582 $kJ.mol^{-1}$

H_m^{γ} = 34.594 $kJ.mol^{-1}$

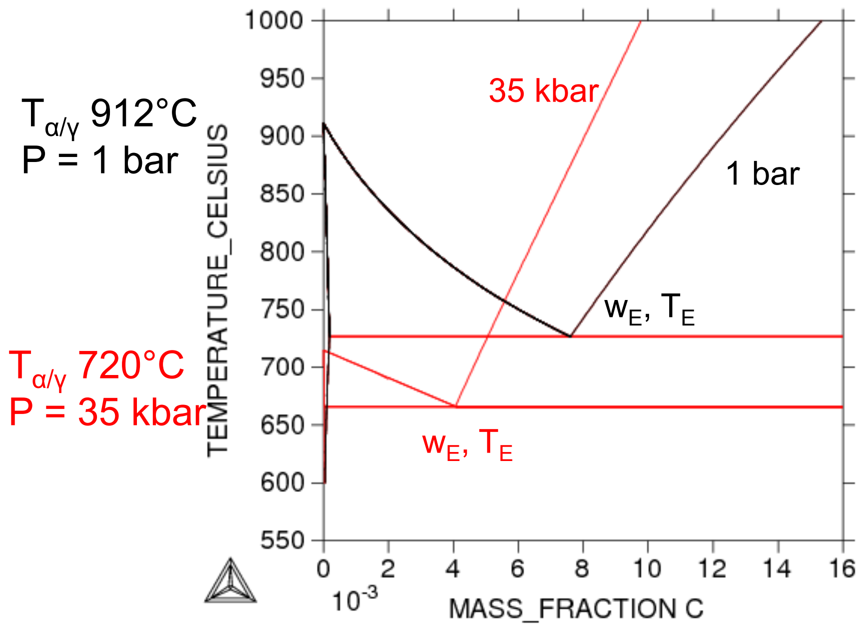
$$\frac{dTe}{dP} \approx 9°C/(100\,MPa = 1kbar)$$

Influence of stresses on phase transformation

Effect of hydrostatic pressure

Change in equilibrium conditions/driving force:

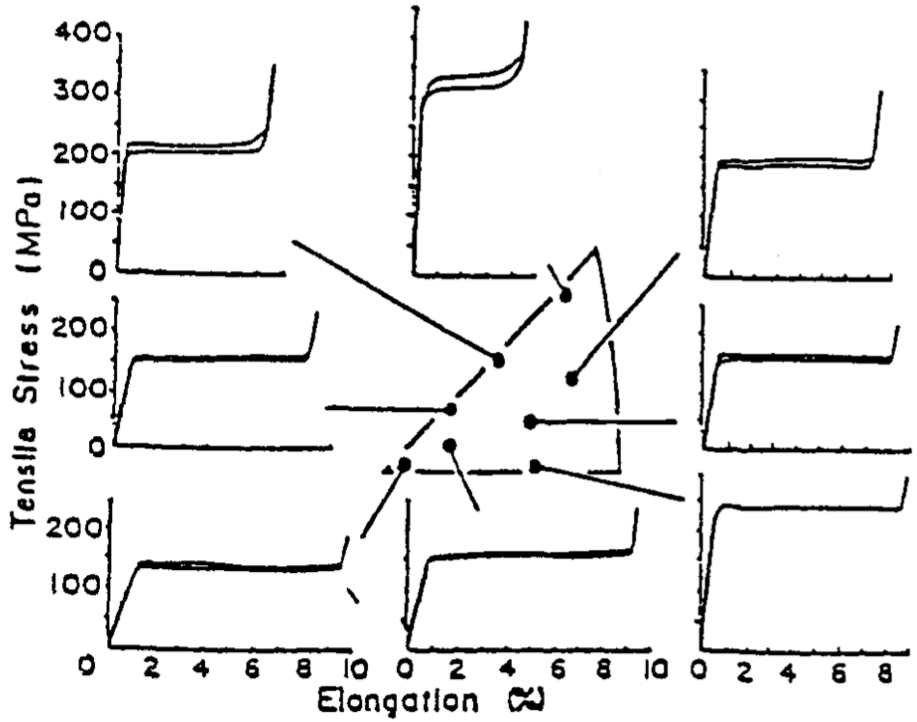
Modification of equilibrium temperatures and solubility limits



Thermocalc
Base données TCFe5
J. Teixeira

Influence of stresses on phase transformation
Mechanical behavior

SMA Alloys Influence of cristalline orientation



Stress induced transformation

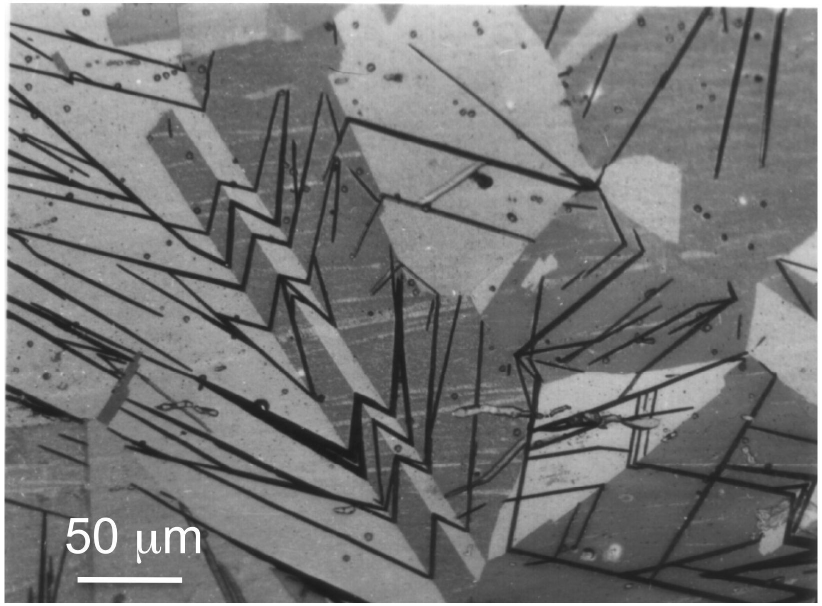
Stress strain curves for different grain orientation

Deformation associated with transformation is dependant on the grain orientation

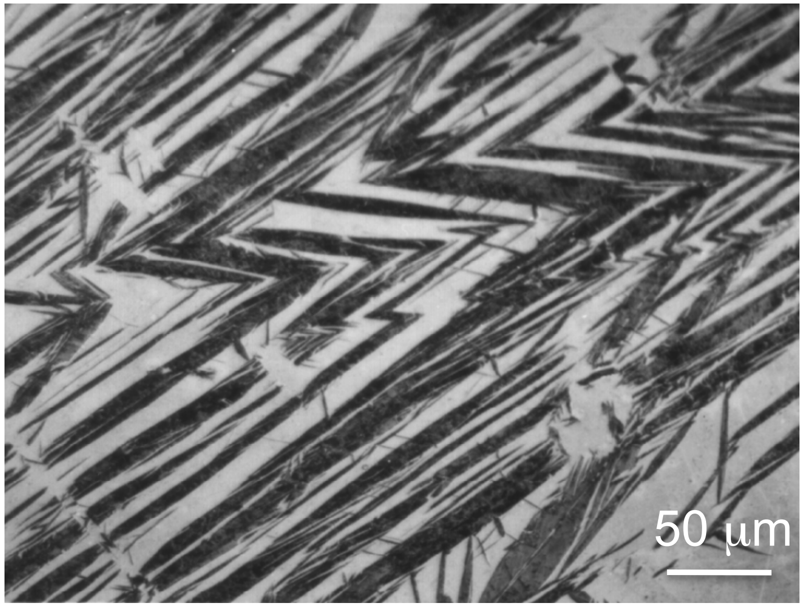
(Horikawa et al. 1988)

Influence of stresses on phase transformation

Fe-25Ni-0.66C



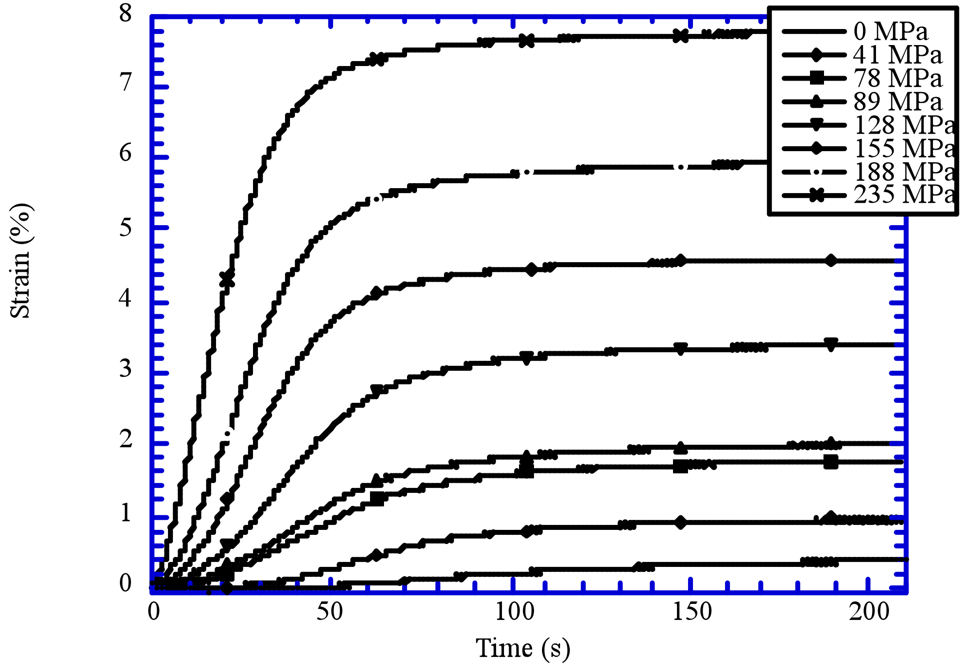
0 MPa



600 MPa

Influence of stresses on phase transformation
Mechanical behavior

Bainitic transformation under stress



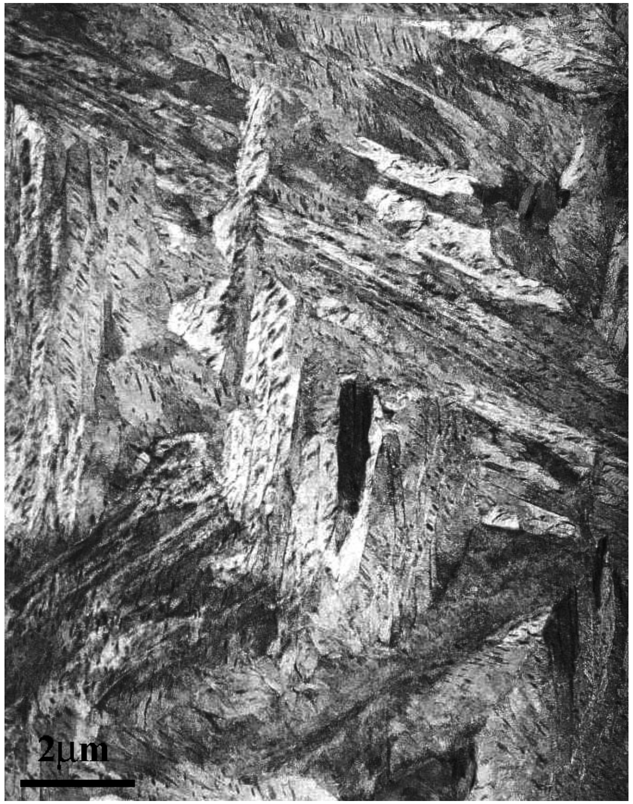
Modification in transformation kinetics

Additional plastic strain during transformation : transformation plasticity

Change in morphology of daughter phase

Influence of stresses on phase transformation

Bainite formed at 350°C



0 MPa

Length 1-3μm Width 0,2μm

128 MPa

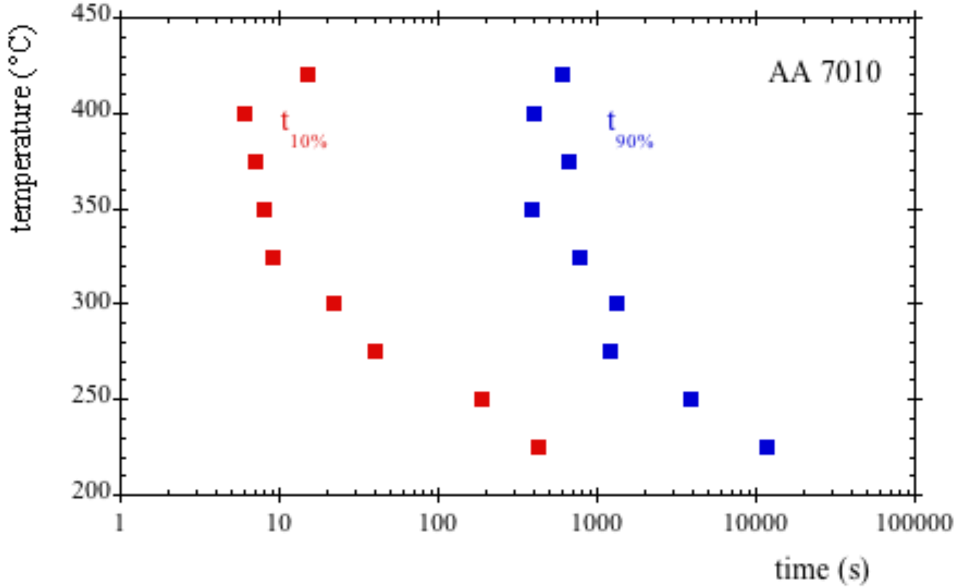
Length 10μm Width 0.3 – 0.9μm

Influence of phase transformation on mechanical properties

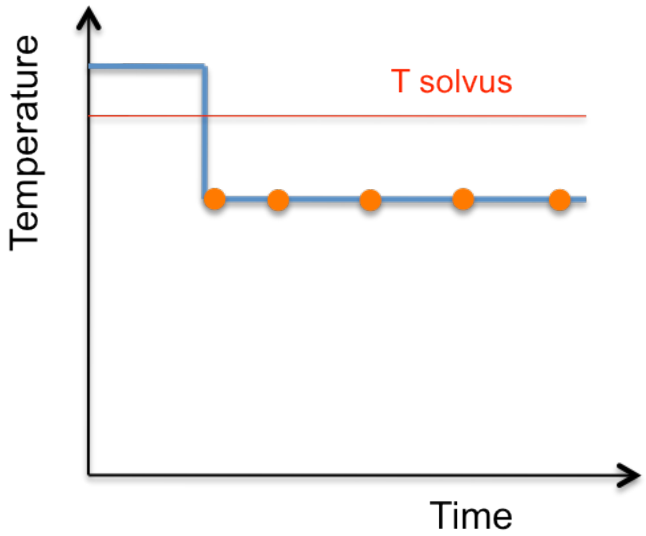
Multiphase components

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

TTT diagram for AA 7010 alloy Godard PhD 1998



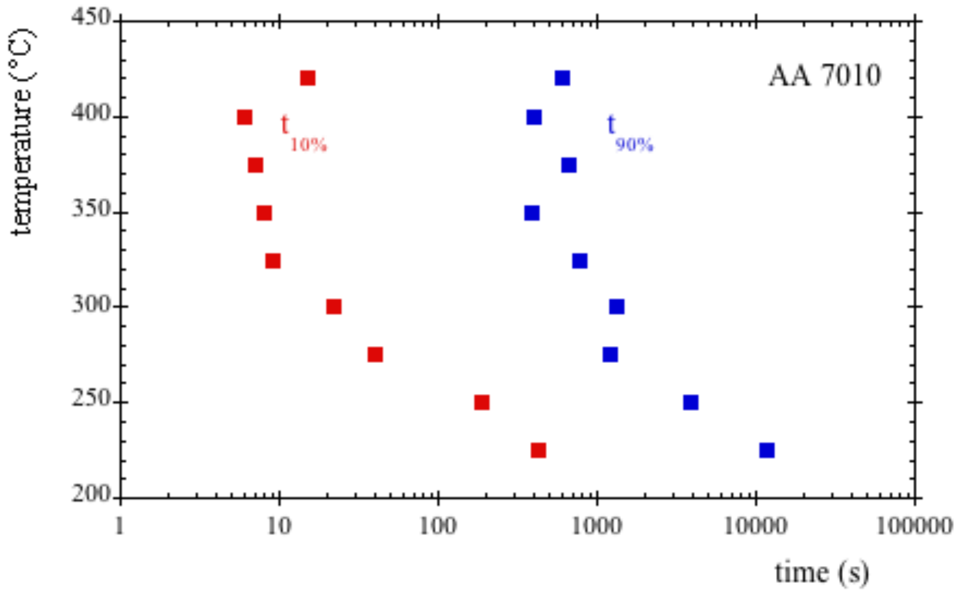
Tensile tests after different holding at T



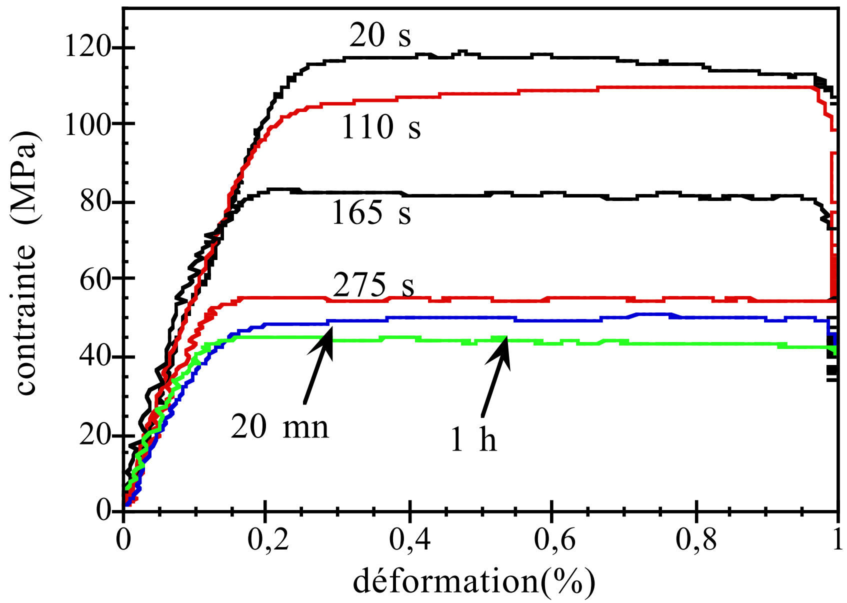
Godard PhD INPL 1998

Influence of phase transformation on mechanical properties

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



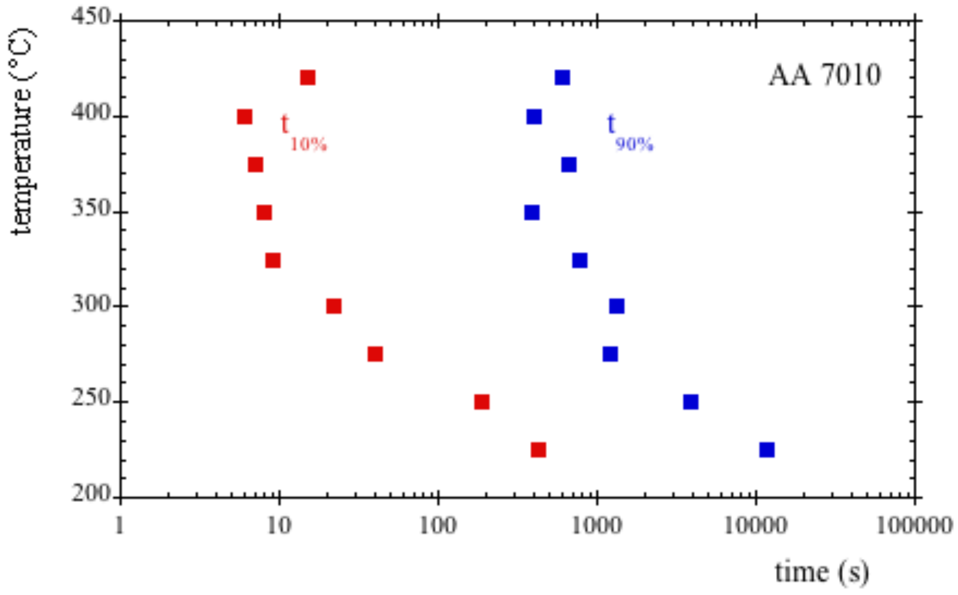
AA 7010 300°C ($10^{-3}s^{-1}$)

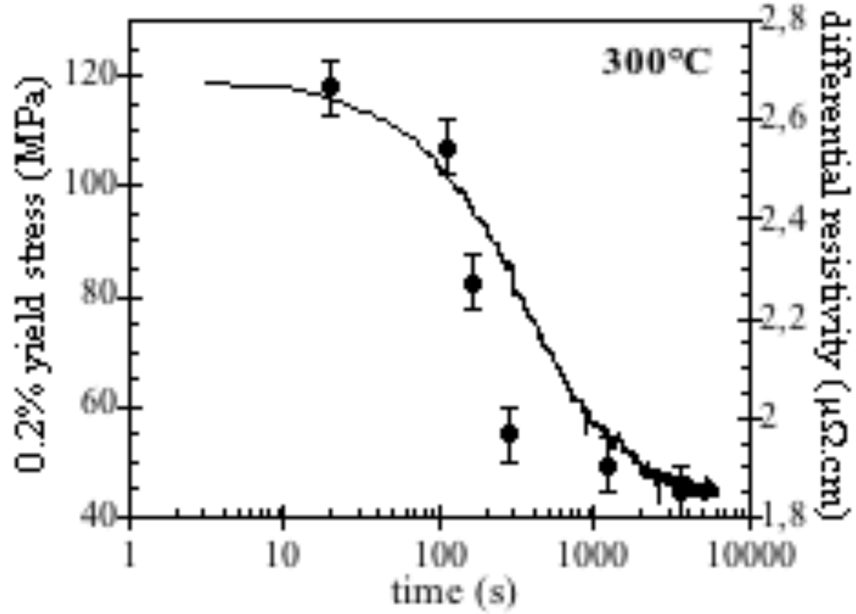


Tensile tests at 300°C after various holding times

Godard PhD INPL 1998

Coupling yield stress with precipitation





Variation of yield stress at 300°versus holding times

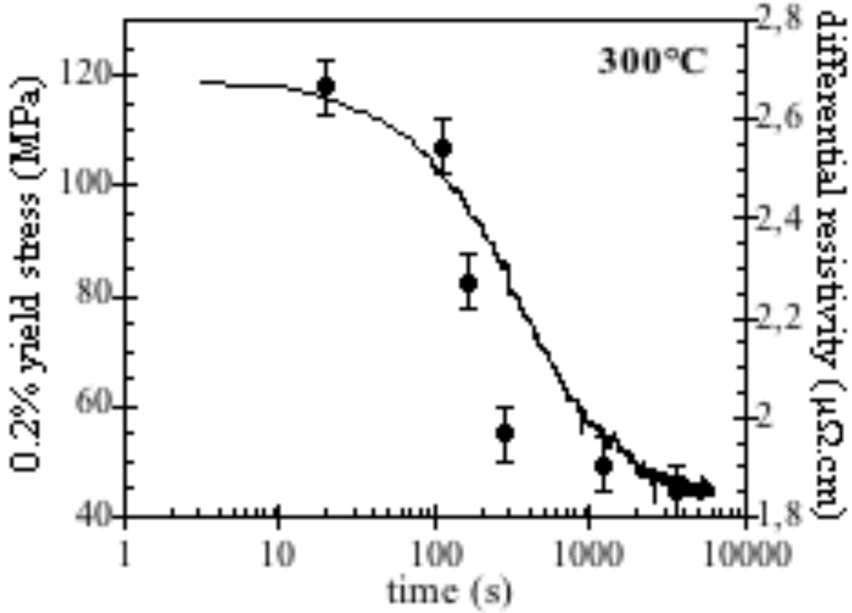
Godard PhD INPL 1998

Coupling yield stress with precipitation

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

n = 2/3

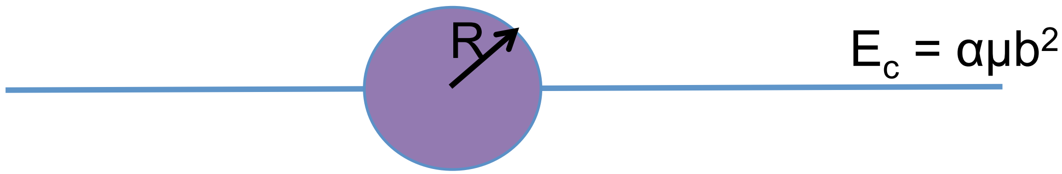
$$\Delta\sigma = \left[a_{eq} X_{Mg}^{sso}\right]^{2/3} \left\{1 - \left[1 - \frac{\Delta X_{Mg}}{X_{Mg}^{sso}}\right]^{2/3}\right\}$$



Godard PhD INPL 1998

Rôle des dislocations sur la germination

Effet de l'énergie de cœur



$$\Delta G = 4\pi\gamma R^2 - \frac{4}{3}\pi R^3 \Delta G_v - 2RE_C$$

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

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

160°C $\alpha \rightarrow MgZn_2$

μ = 25,4 GPa
b = 0,286 nm
α = 0,1
Y = 200 mJ.m^{-2}

ΔG_n = 7750 J.mol^{-1} ΔG_v = 7,75 10^{8} J.m^{-3}

ΔG^*_{hom} = 2,232 10^{-19} J

ΔG^*_{disl} = 8,71 10^{-21} J

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

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

$$D_{eff} = D_{disl} \cdot \pi R_{core}^2 \rho + D_{vol} \cdot (1 - \pi R_{core}^2 \rho)$$

Avec $R_{core} = 5\ 10^{-10}\ m$ $\rho = 10^{15}\ m.m^{-3}$ $D_{eff} = 5{,}28\ 10^{-16}\ m^2.s^{-1}$

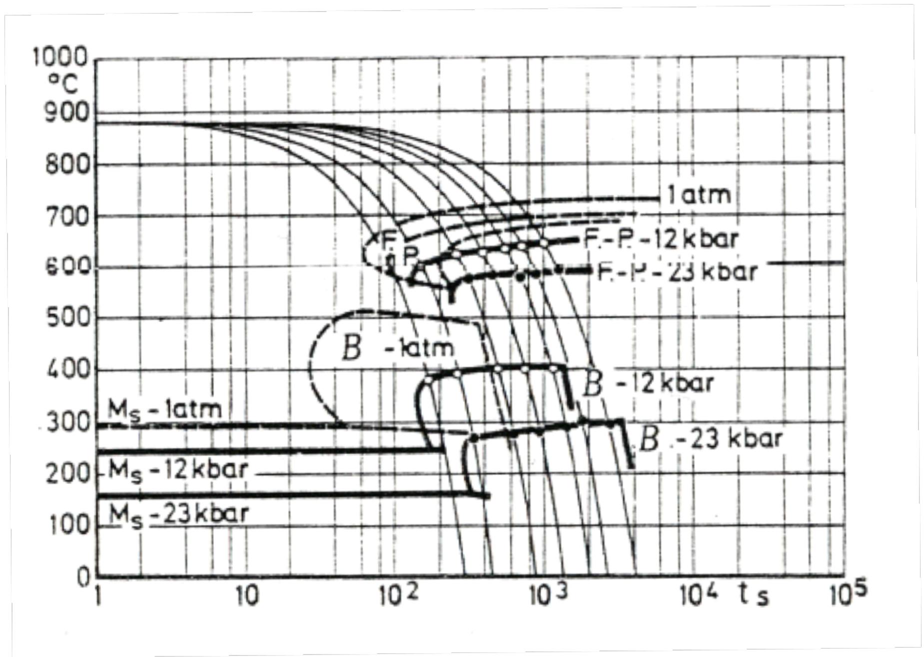
$\rho = 10^{16}\ m.m^{-3}$ $D_{eff} = 1{,}59\ 10^{-15}\ m^2.s^{-1}$

75

Influence of stresses/plastic strain on phase transformation

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

Hydrostatic pressure

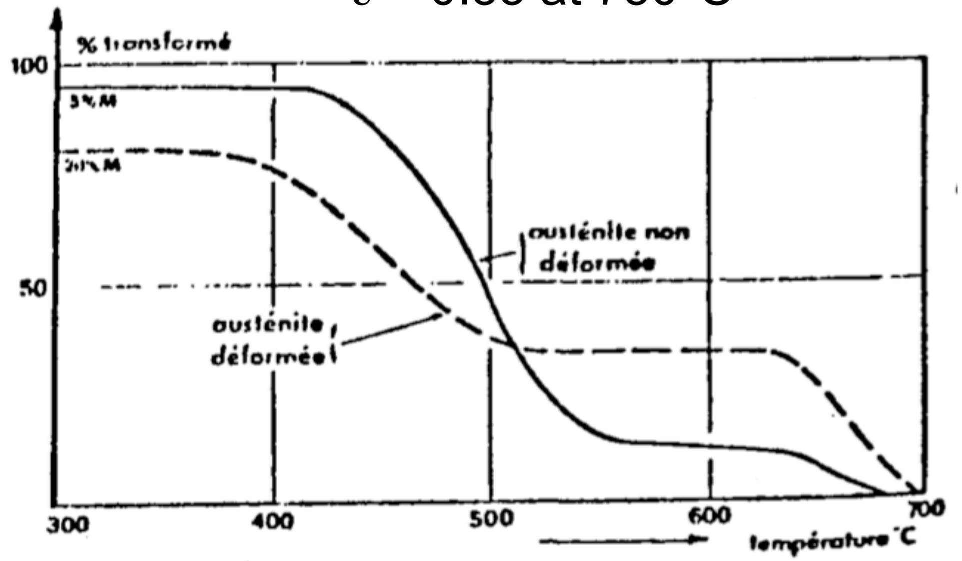


CCT diagram (Fe base alloy)

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

Plastic strain

ε = 0.35 at 750°C



Fe0.25C1CrMo transformed on cooling

Y. Desalos et col Colloque Métallurgie Saclay (1981)