11/06/2024

A short introduction to Materials forming

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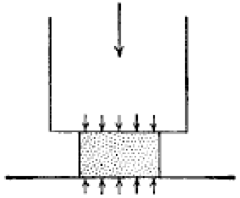
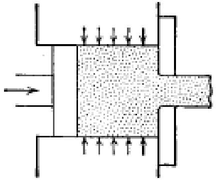
Introduction

Objectives : shape the material and optimize the microstructure ➔ the properties

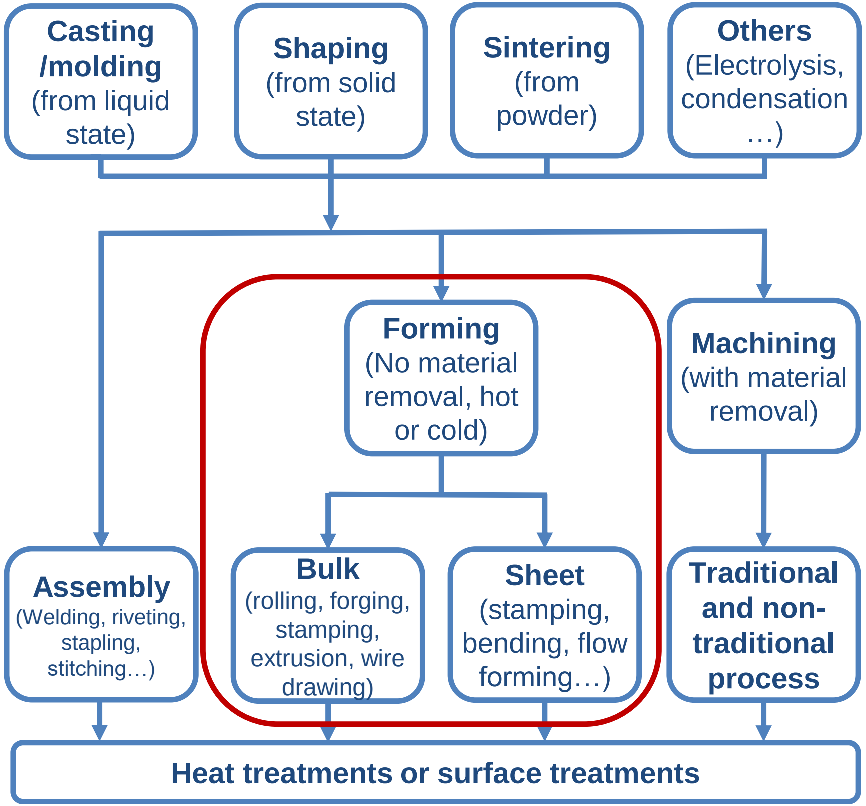


Forging



Extrusion

Stretch forming



Casting /molding (from liquid state)

Shaping (from solid state)

Sintering (from powder)

Others (Electrolysis, condensation …)

Forming (No material removal, hot or cold)

Machining (with material removal)

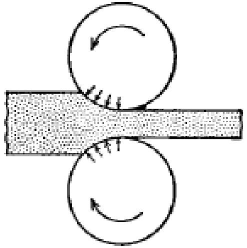
Assembly (Welding, riveting, stapling, stitching…)

Bulk (rolling, forging, stamping, extrusion, wire drawing)

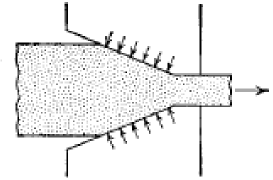
Sheet (stamping, bending, flow forming…)

Traditional and non-traditional process

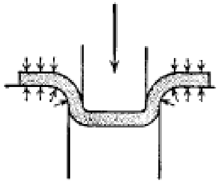
Heat treatments or surface treatments



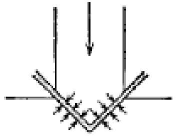
Rolling



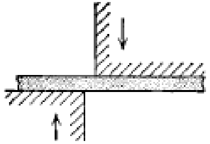
Wire drawing



Deep drawing



Bending



Shearing

Dieter, Mechanical Metallurgy, 3rd edition, 1986

Felder, Mise en forme des métaux, Techniques de l'ingénieur 2015

Introduction

Evolution of various forms of metals and alloys forming processes		
Primitive process	**Date of emergence**	**Modern forms**
Open die forging of hot product	5000 BC	Die forging, drop hammer, mechanical and hydraulic presses, cold/warm/for forging
casting	5000 BC	Pressure die casting in permanent and on-permanent molds, centrifugal castings of tubes, continuous castings of slabs, blooms and billets
Metal sheet forming by hammering, embossing	5000 BC	Stamping, shearing, bending, profiling, heavy sheet metal work, flowforming hydroforming, ironing of tubular products
Wire drawing	First centuries	Multi-passe wire drawing, profiles extrusion
Rolling	XVI century	Rolling in Tandem mill, reversible cage, universal cage, Sendzimir mill, Pilger mill for tubes, Mannesmann piercing mill
Cold extrusion of Pb and soft metals	XIX century	Hot and cold extrusion

Necessity to improve processes, for energy reduction, production cost, more complex geometric shapes and microstructural/properties control

Felder, Mise en forme des métaux, Techniques de l’ingénieur 2015

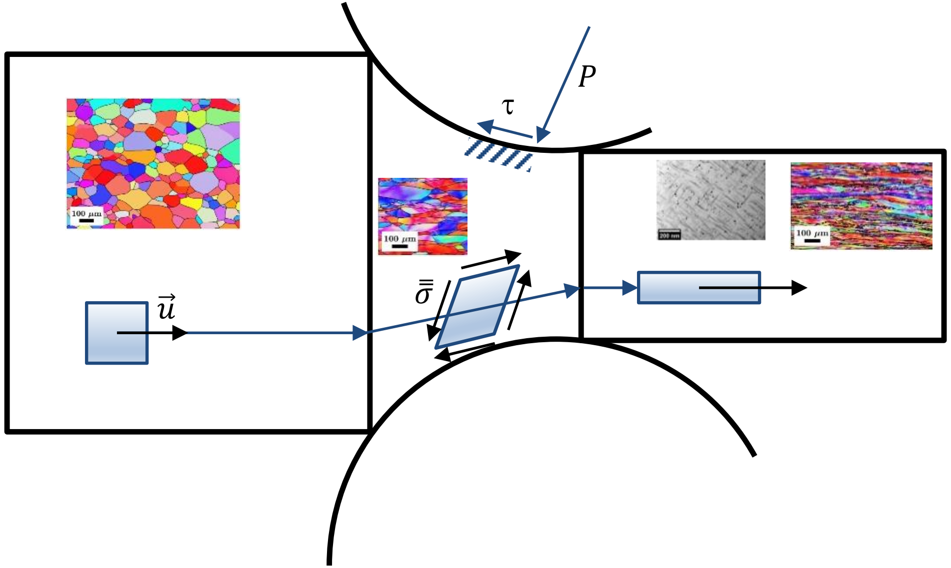
Introduction

Comparison of various processes of hot, warm and cold forming

	Cold ($T/T_M \approx 0.15$)	**Warm** ($T/T_M \approx 0.5$)	**Hot** ($T/T_M \approx 0.7\text{-}0.85$)
Processes	Rolling, forging, stamping, wire drawing, shearing, cutting	Forging, deep drawing	Rolling, forging, stretching, extrusion
Yield strength (steels)	200-1500 MPa	100-500 MPa	50 MPa
Product quality:			
- Dimensional tolerances	High	Average	Weak
- Surface condition	Very good	Good	Very bad
- Microstructure	Strain hardened	Strain hardened	Recovered or recrystallized
Lubrification	Various : emulsions, oils, soaps, soft metals (Sn…), polymers		Difficult: water, oils, graphite grease, glass

Felder, Mise en forme des métaux, Techniques de l'ingénieur 2015

Scientific challenges or a general vision of materials forming



Material flow
Forces involved in the forming process
➔ final shape of the product
Plasticity, ductility, damage …

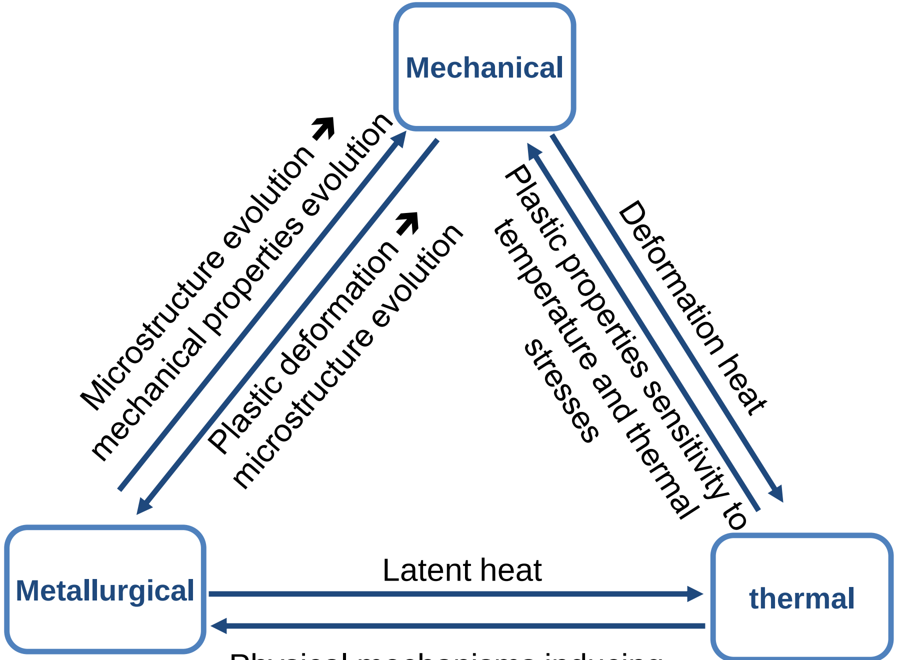
Heat flow
➔T evolution
Adiabatic heating, radiation, convection…

Determines the energies involved in the forming process
➔ various internal and surface defects (cracks, porosities, wrinkles orange peel effect…)
➔ microstructure evolution (phases, grain size and shape, crystallographic texture, dislocations density…)
➔ mechanical properties of the product, residual stresses…

Thermomechanical interactions material – lubricant – tools
➔ surface state
Mechanical stresses (friction shear and contact pressure) and thermal stresses ➔ modifies deformation conditions and tools wear
Lubricant➔ reduces those effects
Tool deformation ➔ alteration of final dimensions
Thermal conduction, friction ➔ T evolution

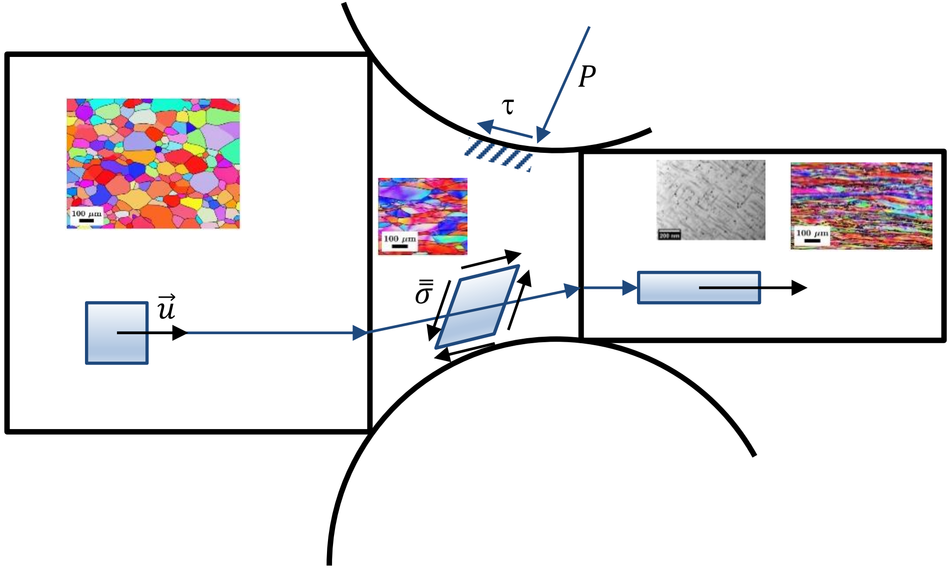
Microstructural evolution
Plasticity, recovery, recrystallization and phase transformation (diffusive and displacive)
➔ Phases (volume fraction, size and shape), grain size and shape, crystallographic texture, dislocations density and sub-structures…),
➔ Mechanical properties of the product, residual stresses…

Main multi-physical interactions during plastic deformation



Physical mechanisms inducing microstructure evolution are highly highly sensitive to temperature

Scientific challenges or a general vision of materials forming



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Material flow : High strains plasticity reminder

Steady or permanent flow if the velocity vector does not depend on time ➔ the deformation zone does not change
Transient state : forging, stamping
Steady state: Rolling, wire drawing
High plastic deformation ➔ plastic flow

Stress tensor (σ_{ij}), strain tensor (σ_{ij}) and strain rate tensor ($\dot{\varepsilon}_{ij}$)

$$\sigma_{ij} = \underline{\underline{\sigma}} = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix}_{(\vec{x_1},\vec{x_2},\vec{x_3})} = \begin{pmatrix} \sigma_I & 0 & 0 \\ 0 & \sigma_{II} & 0 \\ 0 & 0 & \sigma_{III} \end{pmatrix}_{(\vec{1},\vec{2},\vec{3})}$$

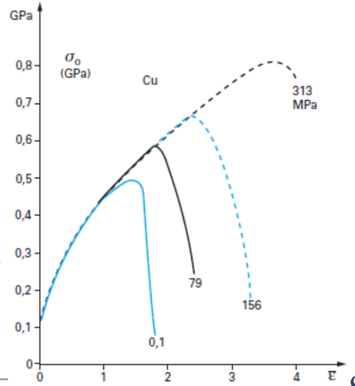
Metallic materials ➔ incompressible, no density evolution
➚ Hydrostatic pressure ➔ increase of material forming capacities

Hydrostatic stress tensor $\underline{\underline{\sigma_S}}$ and Deviatoric stress tensor $\underline{\underline{\sigma_D}}$

$$\begin{cases} \underline{\underline{\sigma}} = \underline{\underline{\sigma_S}} + \underline{\underline{\sigma_D}} \\ tr\left(\underline{\underline{\sigma_D}}\right) = 0 \\ tr\left(\underline{\underline{\sigma_S}}\right) = tr\left(\underline{\underline{\sigma}}\right) = \sigma_{11} + \sigma_{22} + \sigma_{33} \\ \underline{\underline{\sigma_S}} = \frac{1}{3} tr\left(\underline{\underline{\sigma}}\right) \underline{\underline{I}} \\ \underline{\underline{\sigma_D}} = \underline{\underline{\sigma}} - \frac{1}{3} tr\left(\underline{\underline{\sigma}}\right) \underline{\underline{I}} \end{cases}$$

$$\begin{cases} L_1 = tr\left(\underline{\underline{\sigma}}\right) = \sigma_{11} + \sigma_{22} + \sigma_{33} = \sigma_I + \sigma_{II} + \sigma_{III} \\ L_2 = \frac{1}{2}\left(tr^2\left(\underline{\underline{\sigma}}\right) - tr\left(\underline{\underline{\sigma}}^2\right)\right) = \frac{1}{2}\left(\sigma_{ii}\sigma_{jj} - \sigma_{ij}\sigma_{ij}\right) = \sigma_I\sigma_{II} + \sigma_{II}\sigma_{III} + \sigma_{III}\sigma_I \\ L_3 = det\left|\underline{\underline{\sigma}}\right| = \sigma_I\sigma_{II}\sigma_{III} \end{cases}$$

Tension tests under different hydrostatic pressures (Pugh, Sc. Publ. Ltd. London, 1971)



Material flow : Stress triaxiality

Steady or permanent flow if the velocity vector v dos not depend on time ➔ the deformation zone does not change
Transient state : forging, stamping
Steady state: Rolling, wire drawing
High plastic deformation ➔ plastic flow

Stress tensor (σ_{ij}), strain tensor (σ_{ij}) and strain rate tensor $(\dot{\varepsilon}_{ij})$

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Stress triaxiality represents the relative degree of hydrostatic pressure

$$\eta = \frac{\frac{1}{3} Tr\left(\underline{\underline{\sigma}}\right)}{\sigma^{VM}{}_{eq}}$$

Materials forming processes are generally under negative triaxiality to increase ductility (forging rolling, extrusion…). For the ones under positive triaxiality (stamping), only small strains can be applied

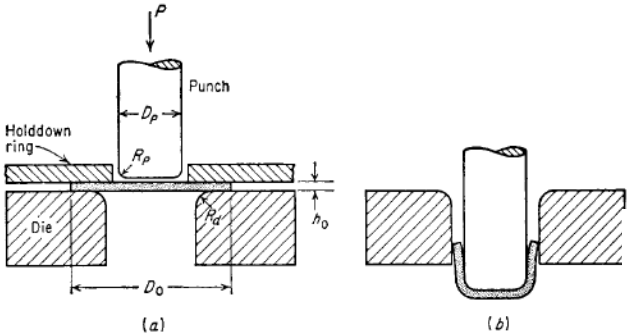
- η = 0 ➔ Pure shear
- η = 0,33 ➔ Uniaxial tension
- η = 0,66 ➔ Equi-biaxial tension
- η = -0,33 ➔ Uniaxial compression
- η = -0,66 ➔ Equi-biaxial compression
- η = - ∞ ➔ Hydrostatic compression

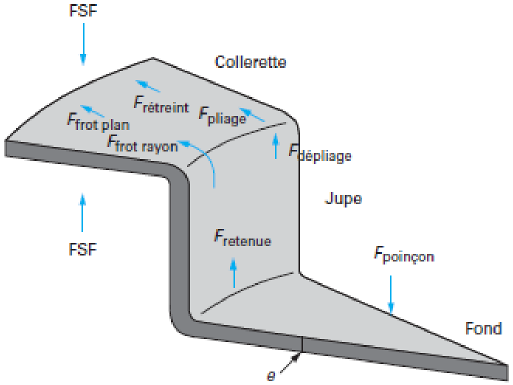
Sheet metal forming (Deep drawing and stamping)

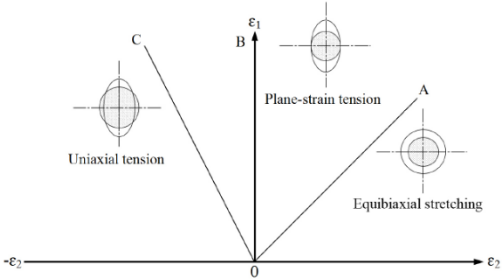
Main deformation mode : Tension ➔ small strain rates

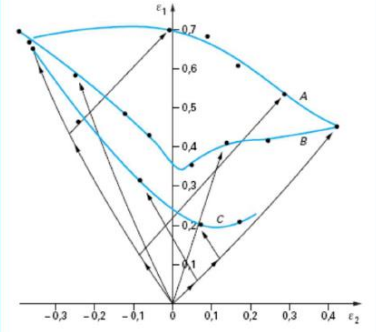
High sensitivity to anisotropy

Because of effect of deformation mode (triaxiality) on ductility, simple tension test is not enough to predict failure





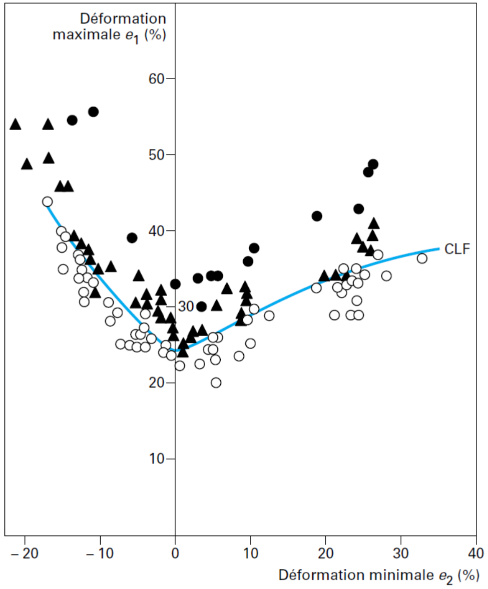




A courbe limite en trajectoire simple

B déformation en rétreint suivie d'une déformation en expansion

C déformation en expansion suivie d'une déformation en rétreint



○ succès ▲ striction ● rupture

Tôle en alliage d'aluminium (nuance 2036 - état T4)

Dieter, Mechanical Metallurgy, 3rd edition, 1986

Col, Technique de l'ingénieur, 2011

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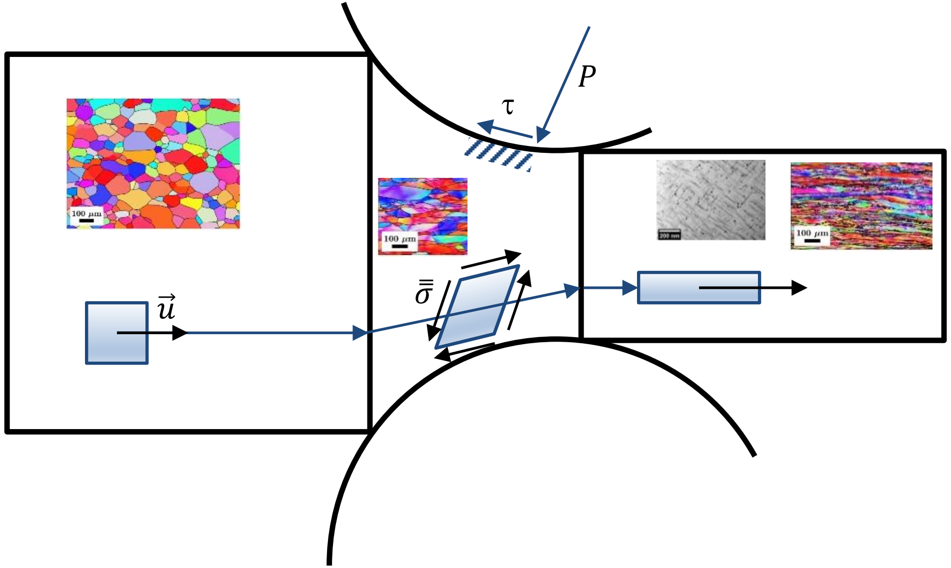

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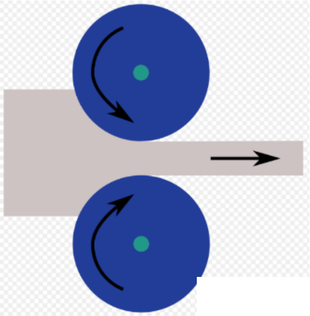
Rolling



Wikipedia, 2

Heavy plates
Strips
Bars
Wire rod
Beams
Rails
Tubes

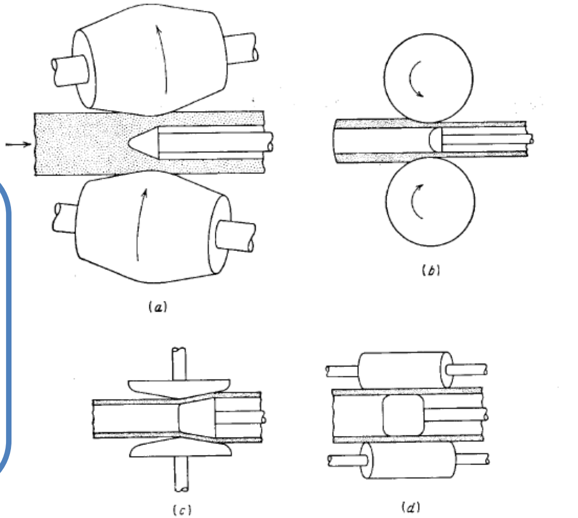
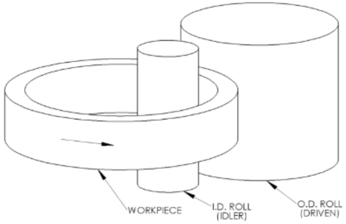
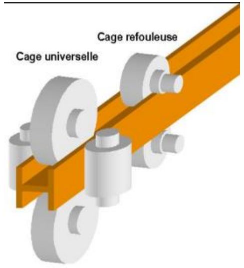


Figure 18-10 (*a*) Mannesmann mill; (*b*) plug rolling mill; (*c*) three-roll piercing mill; (*d*) reeling mill.

Dieter, Mechanical Metallurgy, 3rd edition, 1986



Wikipedia, 2020



Wikipedia, 2020

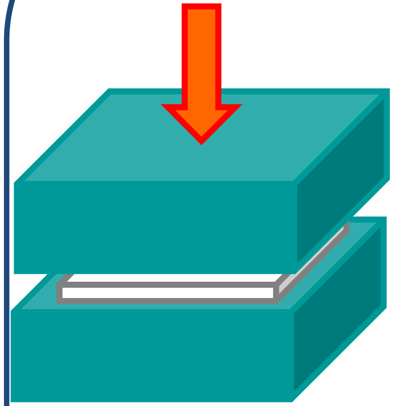
% of total tonnage of uses and processes of semi-finished aluminum alloy products in France

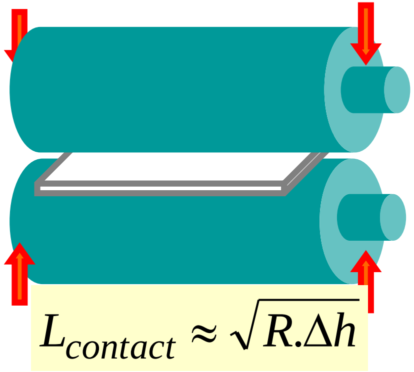
Products	%	Process
Rolled	48.7	Plates casting and hot **rolling**
Bars and profiles	21.2	Billet casting and hot extrusion
Tubes	1	
Thin sheets	7.1	Cold rolling of hot **rolled** sheets
Conductive wires	14.7	Continuous casting – Hot **rolling** – Wire drawing
Wire rod	6	Continuous casting – Hot **rolling**
Poudre	1	

Courtesy of E. Felder

Rolling

Flat products: Rolling vs free forging





$$L_{contact} \approx \sqrt{R.\Delta h}$$

L = 5 m

l = 2 m

σ_0 = 100 MPa

F = 10^9 N = 100 000 T !!

$L_{contact}$ = 120 mm
if R = 500 mm
h 100 → 70 mm

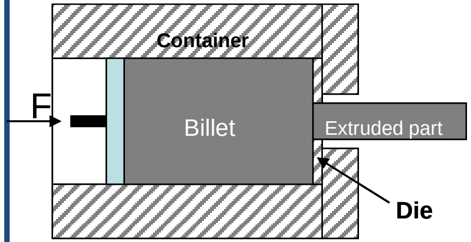
l = 2 m

σ_0 = 100 MPa

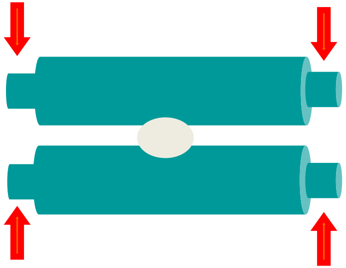
F = 24.10^6N = 2 400 T

Long products: Rolling extrusion

$$F \geq S_0.Ln\frac{S_0}{S_f}.\sigma_0$$



$$F \geq l.L.\sigma_0$$



Φ 100 → Φ 70

F > 56 T

With 2 passes:

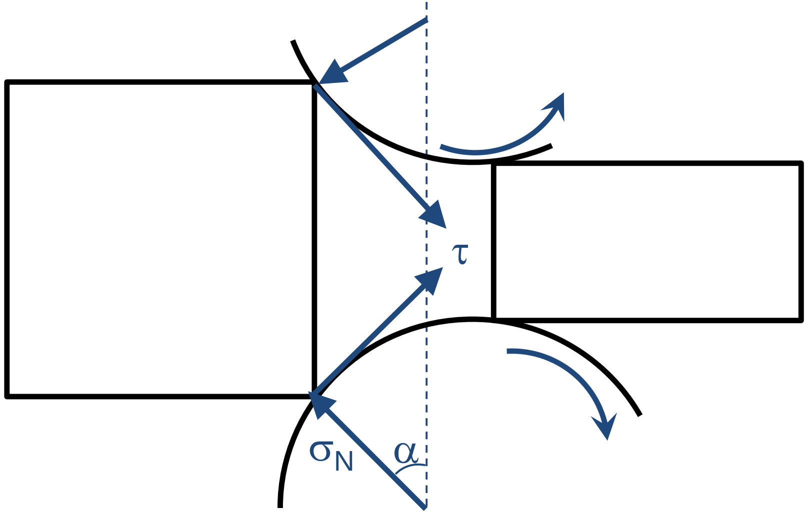
Φ 100
↓
60x110

77 T

110x60
↓
Φ 70

49 T

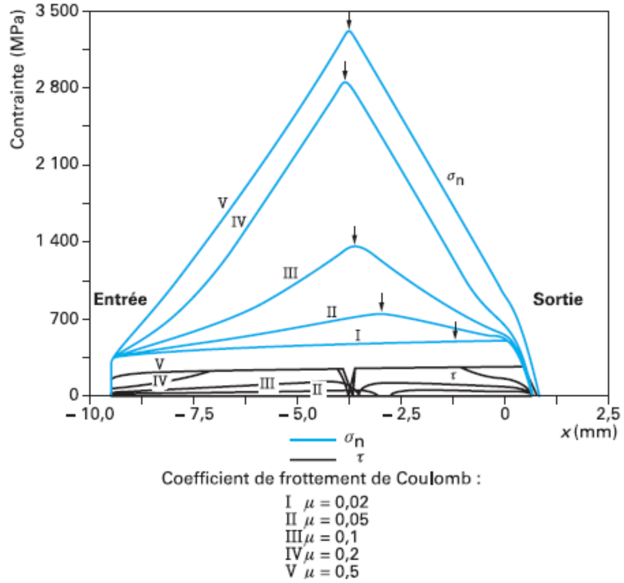
Effect of friction : Case of rolling



$$\tau cos\alpha - \sigma_N sin\alpha \geq 0$$

➔ Friction coefficient $\mu = \dfrac{\tau}{\sigma_N} \geq tan\alpha \approx \sqrt{\dfrac{\Delta h}{R}}$

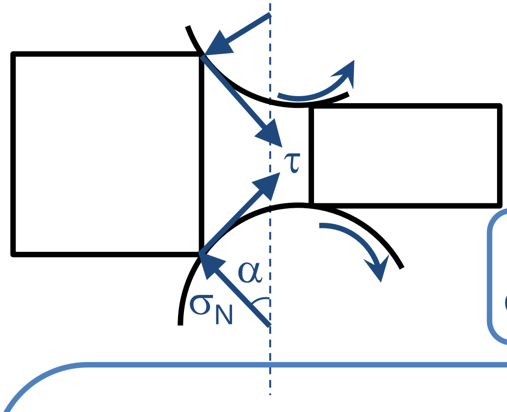
A minimal amount of friction is necessary so the sheet can advance



↗ Reduction and /or ↗ friction ➔ ↗ Load
➔ ↗ Tools deformation
➔ ↘ Geometrical precision
➔ ↗ Tools degradation (wear for example)

Montmitonnet, Technique de l'ingénieur, 2016

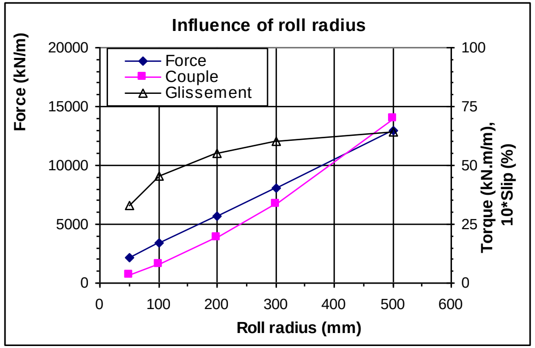
Effect of friction : Case of rolling



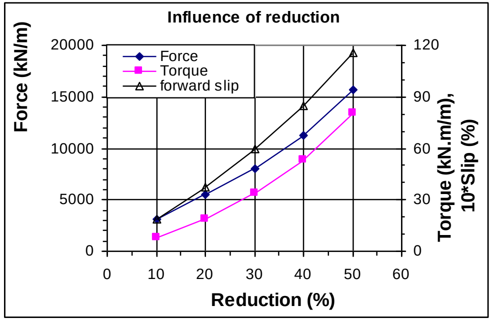
$$\tau cos\alpha - \sigma_N sin\alpha \geq 0$$

➔ Friction coefficient $\mu = \frac{\tau}{\sigma_N} \geq tan\alpha \approx \sqrt{\frac{\Delta h}{R}}$

Small rollers for limited forces ➔ may fail to entrain the strip and may not be rigid enough



$$E = 210\,GPa, \quad = 0.3$$
$$\sigma(MPa) = 300(1 + 50\bar{\varepsilon})^{0.1}$$
$$\mu = 0.1$$
$$R = 300mm$$



Example:

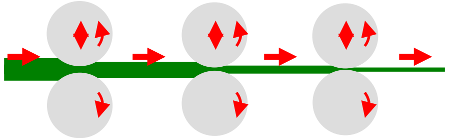
$$\sigma_y = 100MPa$$
$$R = 500mm$$
$$V = 1.2m/s$$
$$h = w = 400mm$$
$$25\%\ reduction \rightarrow \Delta h = 100mm$$

$$L_{contact} \approx \sqrt{R \times \Delta h} \approx 220mm$$
$$F \approx \sigma_y \times w \times L_{contact} \approx 8.8 \times 10^6 N = 880\ T$$
$$P \approx 10^7 W = 13000HP$$
$$Torque = \frac{P}{\omega} = 2.5 \times 10^6 N.m$$

$\mu > 0.5$

Only moderate reductions are possible

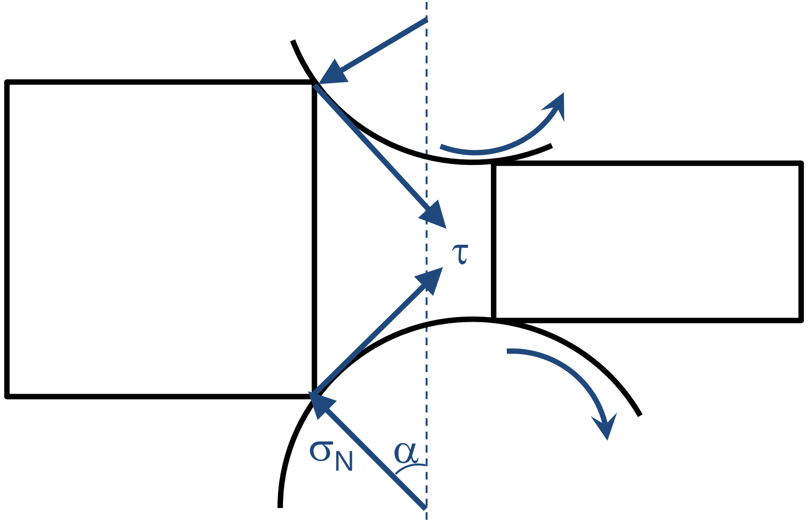
➔ ↗ number of passes



Multi-stand mill, single stand reversing mill, tandem mill

Courtesy of P. Montmitonnet

Effect of friction : Case of rolling

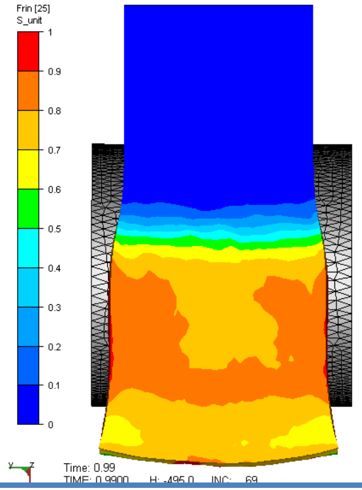


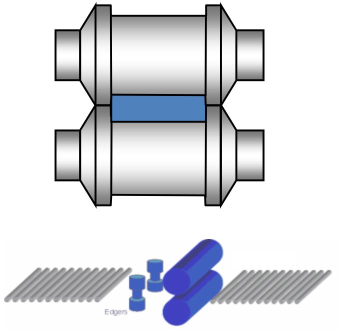
$$\tau cos\alpha - \sigma_N sin\alpha \geq 0$$

➔ Friction coefficient $\mu = \frac{\tau}{\sigma_N} \geq tan\alpha \approx \sqrt{\frac{\Delta h}{R}}$

Tribological condition: Minimum friction

Competition during the flow :
Compromise between geometric tolerance and acceptable forces

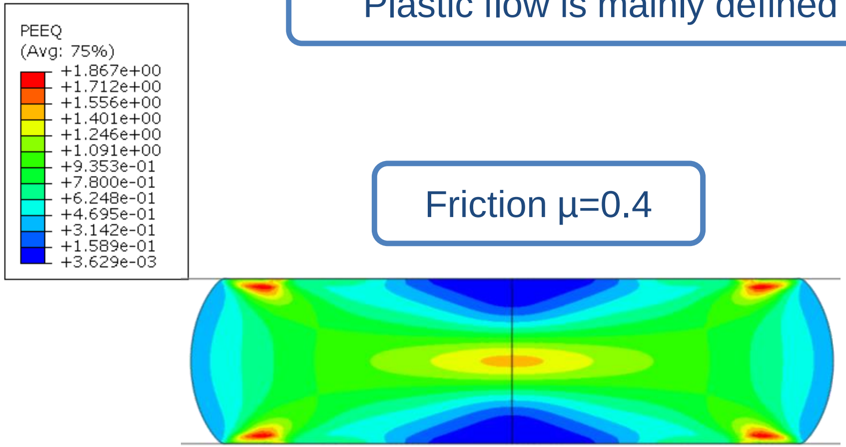




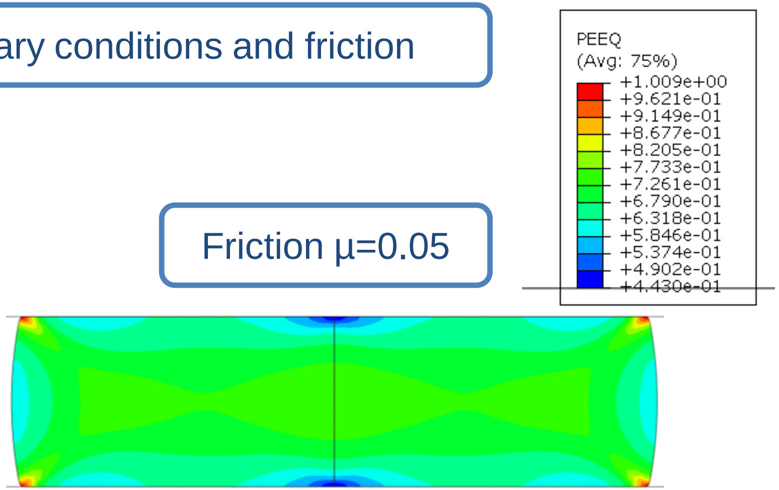
Lateral flow depends on anisotropy, friction and dimensions (Width W, bite length L and thickness H)
↗ W/H (flat) ➔ ↘ lateral flow (spread)
For W/L >>1 (flat): ↗ friction ➔ ↘ spread
For W/L ≈ 1 (long): ↗ friction ➔ ↗ spread

Effect of friction on flow : Case of rolling

Plastic flow is mainly defined by boundary conditions and friction



Friction μ=0.4



Friction μ=0.05

↗ friction → ↗ shear in the contact region → ↗ plastic heterogeneity in terms of plastic deformation and deformation mode

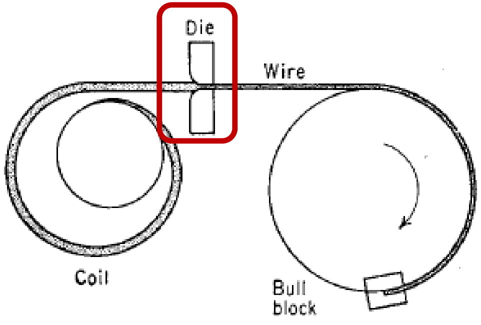
→ may induce some macroscopic defects
→ will induce microstructural heterogeneities and probably some properties heterogeneities

Effect of friction: Case wire drawing

Hot rolling for wire until $D \approx 5mm$ then Wire drawing for $D < 5mm$

Series of cold operation followed by heat treatment to regain ductility (recovery and recrystallization)

Friction has an extreme importance



Dieter, Mechanical Metallurgy, 3rd edition, 1986

A : Die (diamond or carbides : CW, CCo)

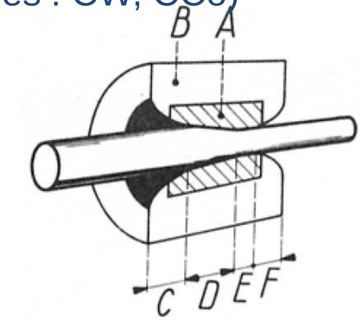
B: Steel casing

C: Bell radius

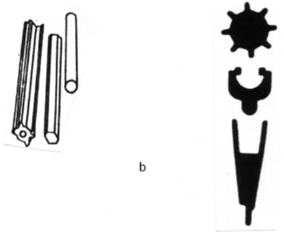
D: Entrance angle

E: Land

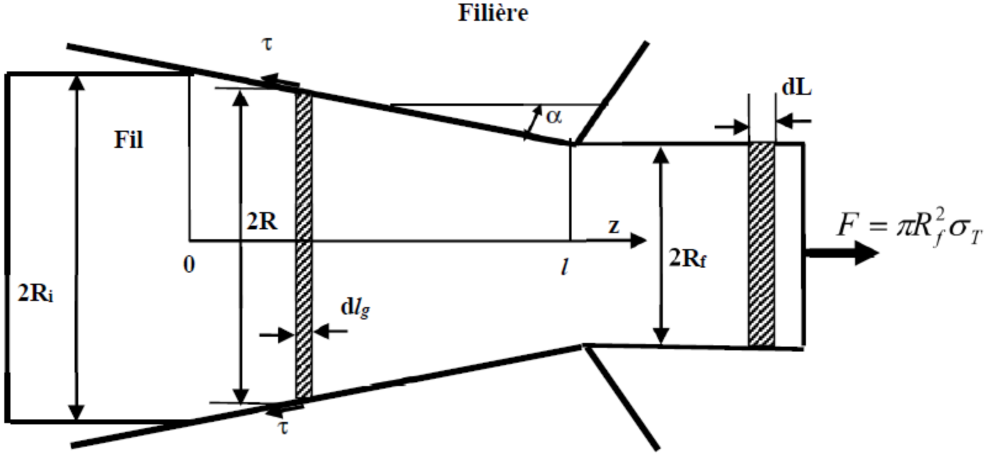
F: Back relief



Complex geometries

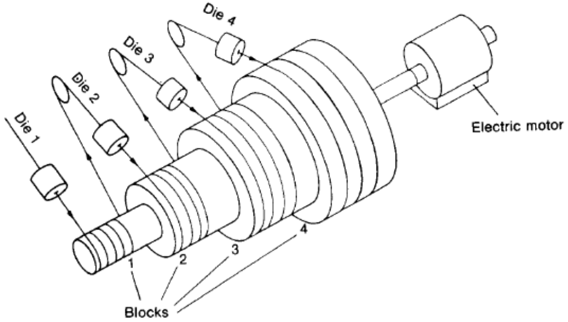


Effect of friction: Case wire drawing



Wire drawing force

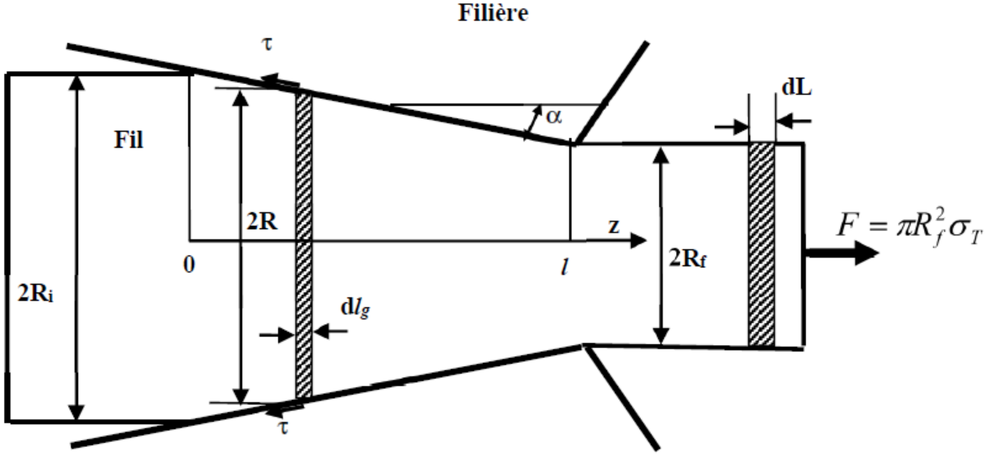
$$F = \pi R_f^2 \sigma_0 \left(1 + \frac{\bar{m}}{\sqrt{3}} cot\alpha\right) ln\left(\frac{R_i^2}{R_f^2}\right)$$



Dieter, Mechanical Metallurgy, 3rd edition, 1986

- ↗ Diameter reduction➔ ↗ Force
- ↗ Friction ➔ ↗ Force (α small ≈ 6° so cotα is high ≈ 9,5)
- To avoid that the operation transforms into a tensile test (negative triaxiality leading to damage) $\sigma_T = F/\left(\pi R^2{}_f\right) < \sigma_0$
  - ➔ The reduction should be smaller than a given value, the highest is the friction, the smallest is this value and the smallest is the reduction
  - ➔ Reduction is generally $1-(R_f / R_i)^2 < 30\%$

Effect of friction: Case wire drawing



Wire drawing force: $F = \pi R_f^2 \sigma_0 \left(1 + \frac{\bar{m}}{\sqrt{3}} cot\alpha\right) ln\left(\frac{R_i^2}{R_f^2}\right)$

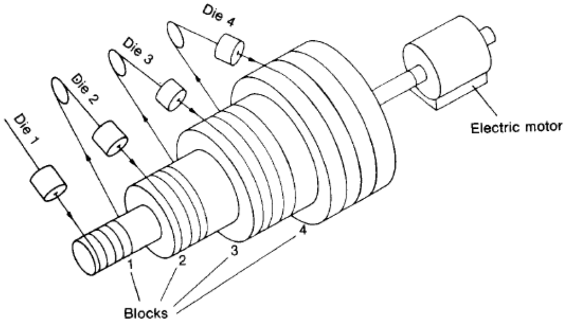
Angle $\alpha \approx \left[\frac{\bar{m}}{0.77\sqrt{3}} ln\left(\frac{R_i^2}{R_f^2}\right)\right]^{1/2}$

Plastic strain $\bar{\varepsilon} = 2ln(R_i/R_f) + 0.77\alpha$

- ↗ friction ➔ ↗ α_{opt}
- For a reduction r = 30% and a friction coefficient $\overline{m} = 0{,}1$

  ➔ α_{opt}= 9,3° ➔ consistent with experimental observations

  ➔ $\overline{\varepsilon} = 0{,}48$



Dieter, Mechanical Metallurgy, 3rd edition, 1986

Effect of friction

Effect of Friction:

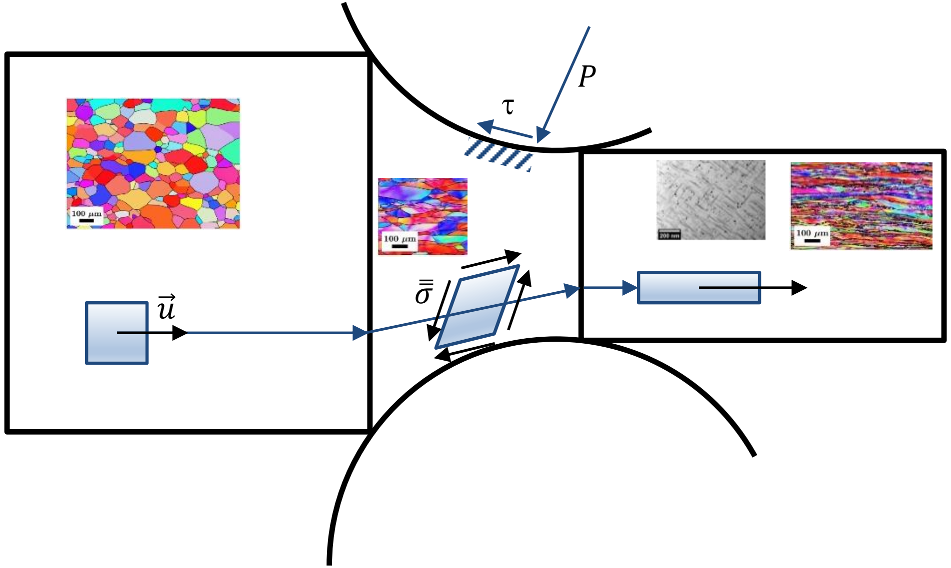
- unavoidable during materials forming
- Increases the necessary forces and torques ➔ increases stresses on tools
- Increases temperature and Wear
- Modifies plastic flow by adding shear components ➔ heterogeneous flow
- Heterogeneity of plastic flow and temperature ➔ heterogeneous microstructure and properties

Friction depends on :

- The nature of the materials in contact : Workpiece, tool
- The surface state of these materials: roughness, surface treatments…
- The lubricant: chemical neture, viscosity, quantity…
- Contact conditions, temperature,, sliding speed, normal stress…

Tribology consist in controlling friction and wear using lubrication and surface coatings

Scientific challenges or a general vision of materials forming



Material flow
Forces involved in the forming process
➔ final shape of the product
Plasticity, ductility, damage …

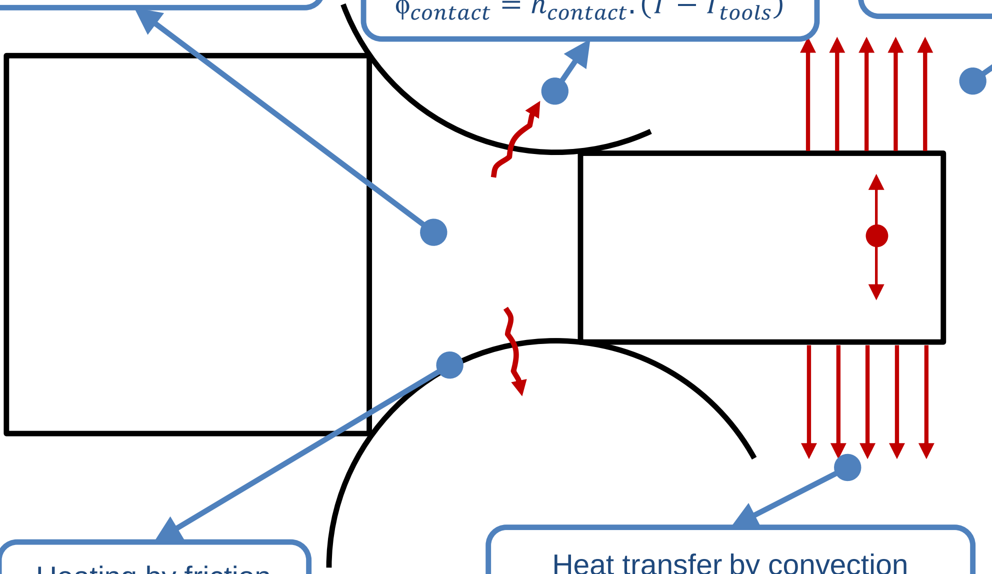
Heat flow
➔T evolution
Adiabatic heating, radiation, convection…

Determines the energies involved in the forming process
➔ various internal and surface defects (cracks, porosities, wrinkles orange peel effect…)
➔ microstructure evolution (phases, grain size and shape, crystallographic texture, dislocations density…)
➔ mechanical properties of the product, residual stresses…

Thermomechanical interactions material – lubricant – tools
➔ surface state
Mechanical stresses (friction shear and contact pressure) and thermal stresses ➔ modifies deformation conditions and tools wear
Lubricant➔ reduces those effects
Tool deformation ➔ alteration of final dimensions
Thermal conduction, friction ➔ T evolution

Microstructural evolution
Plasticity, recovery, recrystallization and phase transformation (diffusive and displacive)
➔ Phases (volume fraction, size and shape), grain size and shape, crystallographic texture, dislocations density and sub-structures…),
➔ Mechanical properties of the product, residual stresses…

Heat flow: Rolling case



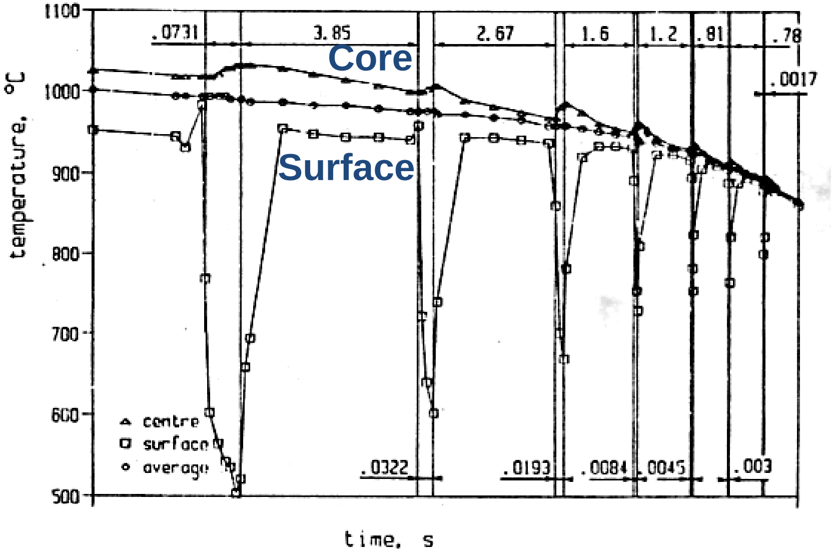
Thermoplastic effect
$\dot{Q}_{plastique} = \beta.\sigma_0.\dot{\bar{\varepsilon}}$

Heat transfer towards the tools
$\phi_{contact} = h_{contact}.(T - T_{tools})$

Heat transfer by radiation
$\phi_{radiation} = \varepsilon_{emmissivity}.\sigma_{stefan}.(T^4 - T^4{}_{\infty})$

Heating by friction
$\dot{Q}_{friction} = \tau \cdot \Delta v =$

Heat transfer by convection
$\phi_{convection} = h_{convection}.(T - T_{\infty})$



Generally, 5-10°C per pass in hot rolling
Up to 100°C per pass in cold rolling by

Courtesy of P. Montmitonnet

Materials forming : Cold vs Hot, general considerations

Advantages of hot forming:

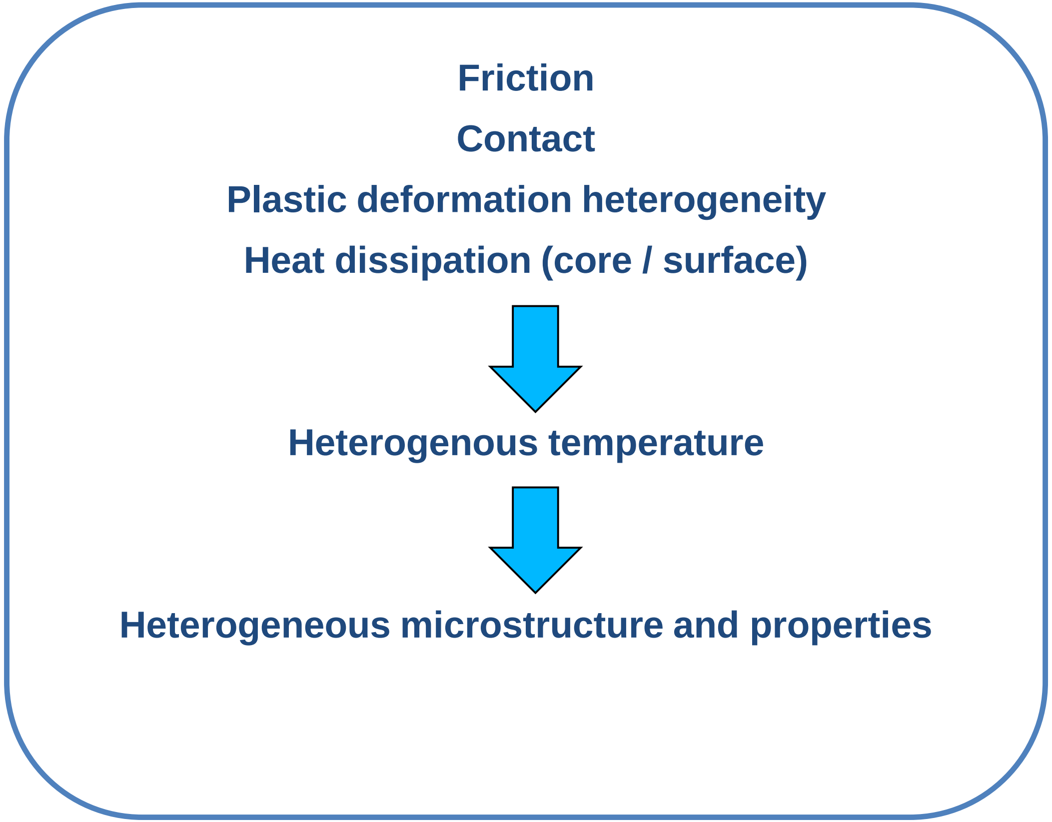
- ➘ hardness ➔ ➘ necessary Forces ➔ ➚ workpiece dimensions
- ➚ ductility ➔ ➚ plastic strains and reductions
- Activation of recovery and recrystallisation ➔ renew of the microstructure and ➚ ductility

Advantages of cold forming:

- Work hardening ➔ ➚ mechanical resistance of final piece
- Higher geometrical precisions
- Better surface (no oxides for ex.)

Courtesy of P. Montmitonnet

Heat flow



Friction

Contact

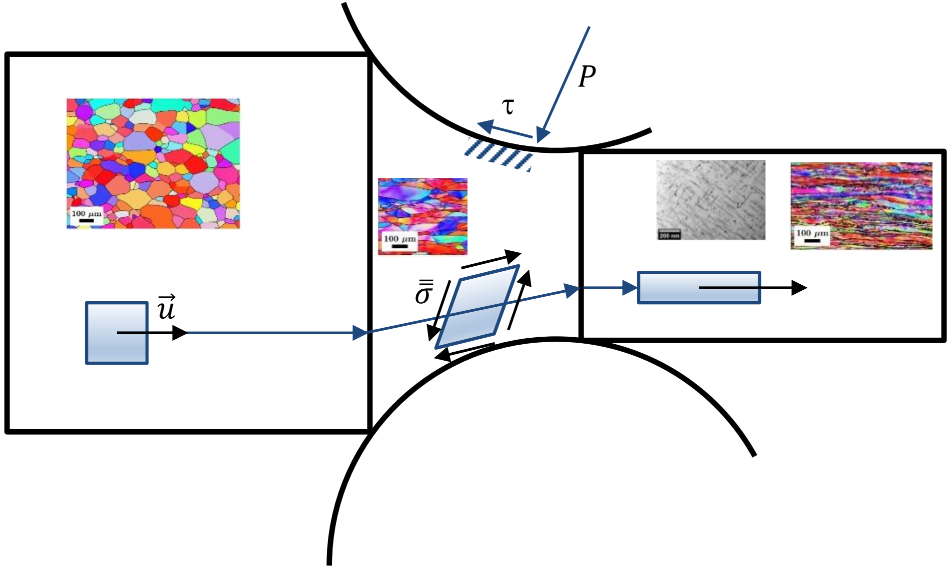
Plastic deformation heterogeneity

Heat dissipation (core / surface)

Heterogenous temperature

Heterogeneous microstructure and properties

Scientific challenges or a general vision of materials forming



Material flow
Forces involved in the forming process
➔ final shape of the product
Plasticity, ductility, damage …

Heat flow
➔T evolution
Adiabatic heating, radiation, convection…

Determines the energies involved in the forming process
➔ various internal and surface defects (cracks, porosities, wrinkles orange peel effect…)
➔ microstructure evolution (phases, grain size and shape, crystallographic texture, dislocations density…)
➔ mechanical properties of the product, residual stresses…

Thermomechanical interactions material – lubricant – tools
➔ surface state
Mechanical stresses (friction shear and contact pressure) and thermal stresses ➔ modifies deformation conditions and tools wear
Lubricant➔ reduces those effects
Tool deformation ➔ alteration of final dimensions
Thermal conduction, friction ➔ T evolution

Microstructural evolution
Plasticity, recovery, recrystallization and phase transformation (diffusive and displacive)
➔ Phases (volume fraction, size and shape), grain size and shape, crystallographic texture, dislocations density and sub-structures…),
➔ Mechanical properties of the product, residual stresses…

Microstructure evolution during material forming

Plasticity + temperature

Plasticity : dislocation slip, Twinning induced plasticity and Transformation induced plasticity

➔ ↗ of dislocation density, texture evolution, twin boundaries and phases volume fraction

Recovery and recrystallization

➔ ↘ of dislocation density, evolution of texture, grain size and grains shape

Phase transformation

➔ Modifies the phase volume fraction

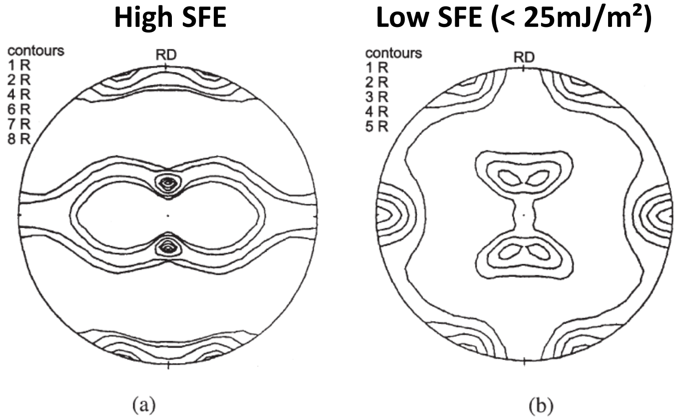
All those mechanisms are coupled

Microstructure evolution: Deformation texture

Deformation textures

Deformation occurs on the most favorably oriented slip ➔ Preferred orientation during plastic deformation

➔ Deformation texture



High SFE

Low SFE (< 25mJ/m²)

(a)

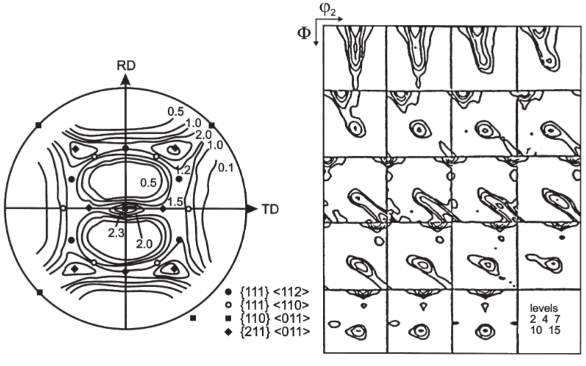
(b)

Fig. 3.1. 111 Pole figures of 95% cold rolled fcc metals; (a) copper; (b) 70:30 brass, (Hirsch and Lücke 1988a).

FCC

Depends on the alloy and the deformation conditions

Abundant literature on rolling texture



(a)

(b)

Fig. 3.9. Rolling texture of 90% cold rolled low carbon steel; (a) 200 pole figure (Hutchinson 1984); (b) ODF (Lücke and Hölscher 1991).

BCC

Humphreys and Hatherly, Elsevier, 2nd edition, 2004

Microstructure evolution: Deformation texture

Factors influencing deformation textures

SFE and purity level

Texture of the initial state

Deformation conditions

Rolling: Theoretically plane deformation➔ uniform texture in the thickness

Rolling geometry and friction ➔ Texture gradient in the thickness

➘ D roller, ➘ reduction per pass, ➚ thickness of the sheet ➔ ➚ texture gradient in the thickness

➚ Friction ➔ ➚ texture gradients

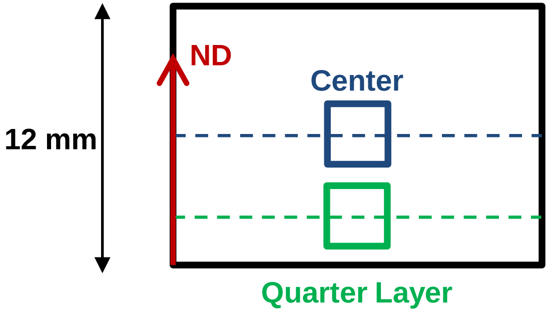
Deformation temperature

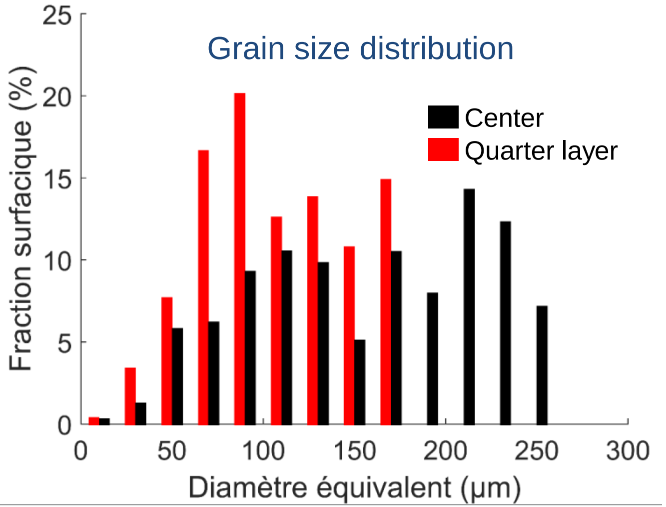
Grain size

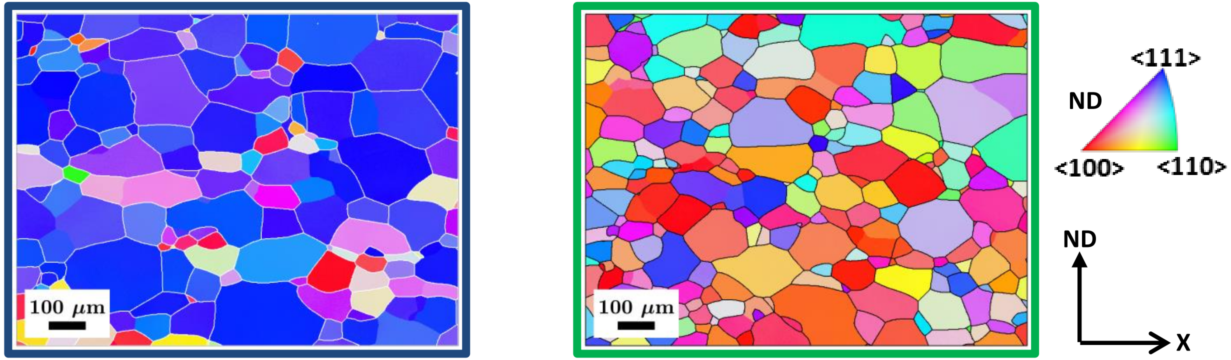
Second phase particles

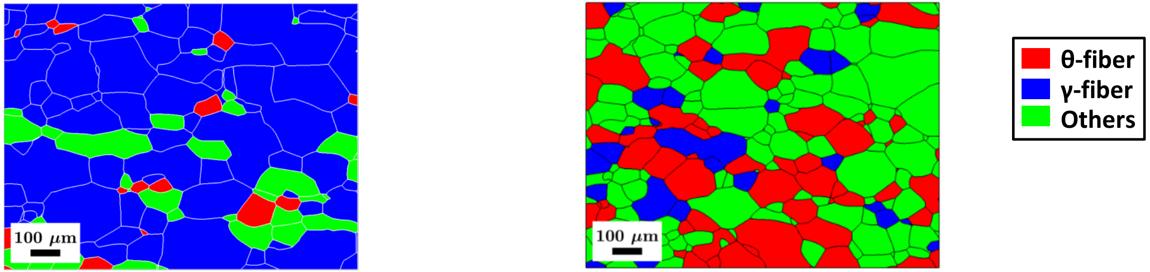
Microstructure evolution: Plasticity

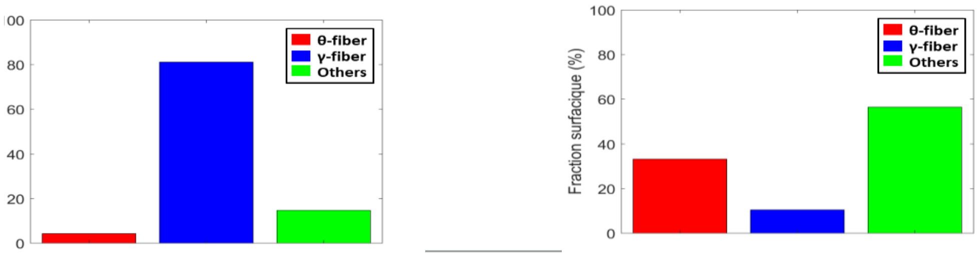
Pure Tantalum BCC




Grain size distribution



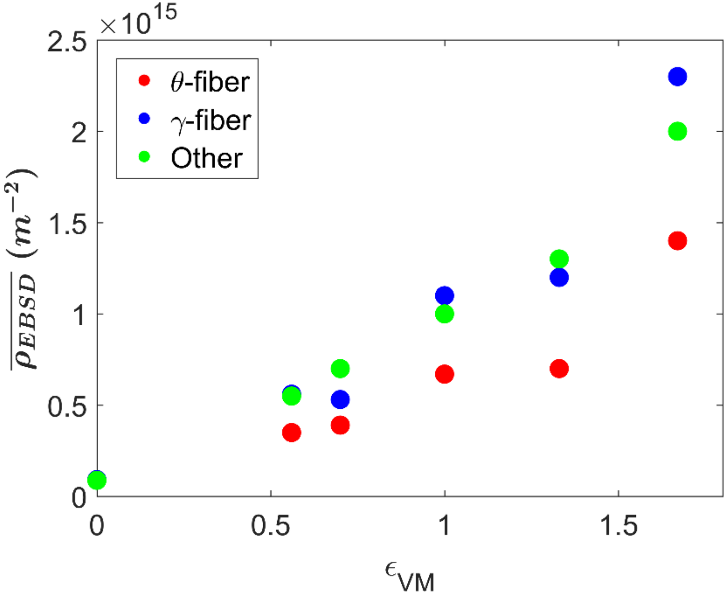




Baton et al., Materials Characterization 2021

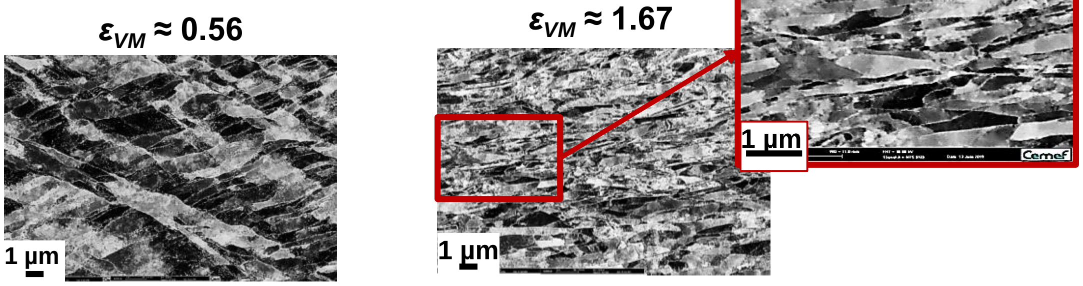
Microstructure evolution: Plasticity

Anisotropic behavior: dislocation content after cold deformation

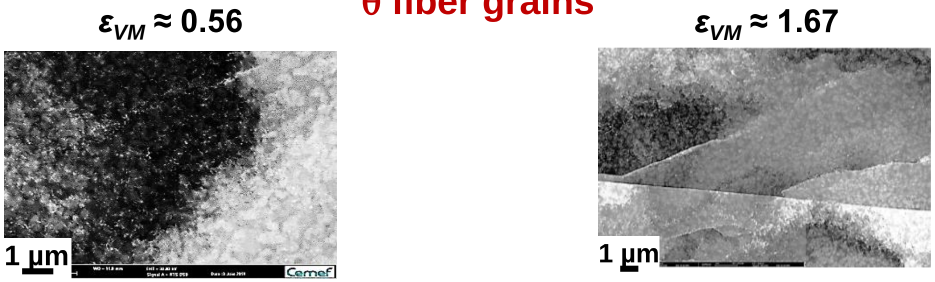


Higher dislocation density in γ fiber grains

γ fiber grains



θ fiber grains

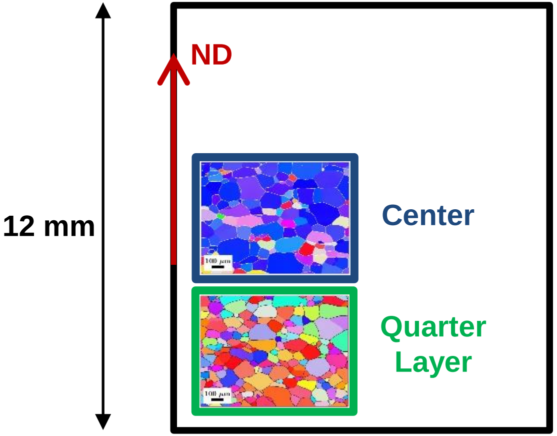


Spatial distribution of dislocation affected by crystal orientation (sub-boundaries)

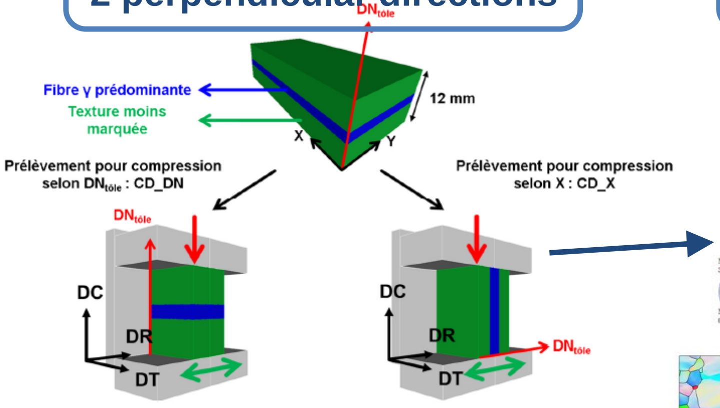
Baton et al., Materials Characterization 2021

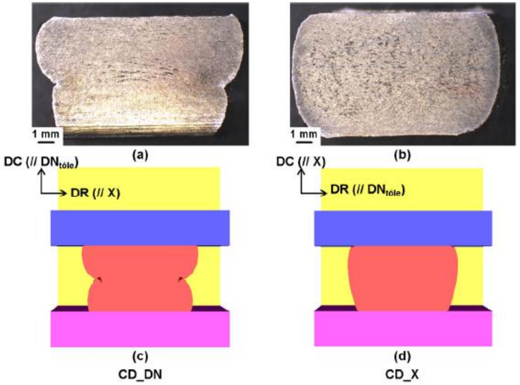
Microstructure evolution: Plasticity

Pure Tantalum BCC

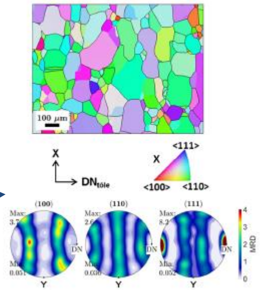


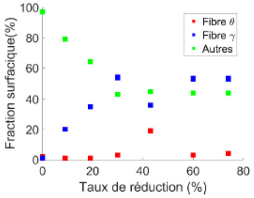
Chanel Die compression in 2 perpendicular directions

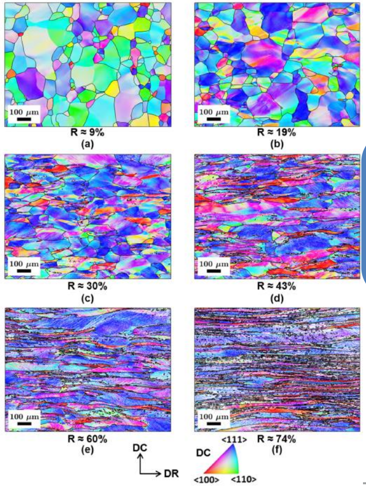




Texture evolution during channel die compression







γ Fiber is very stable in BCC materials

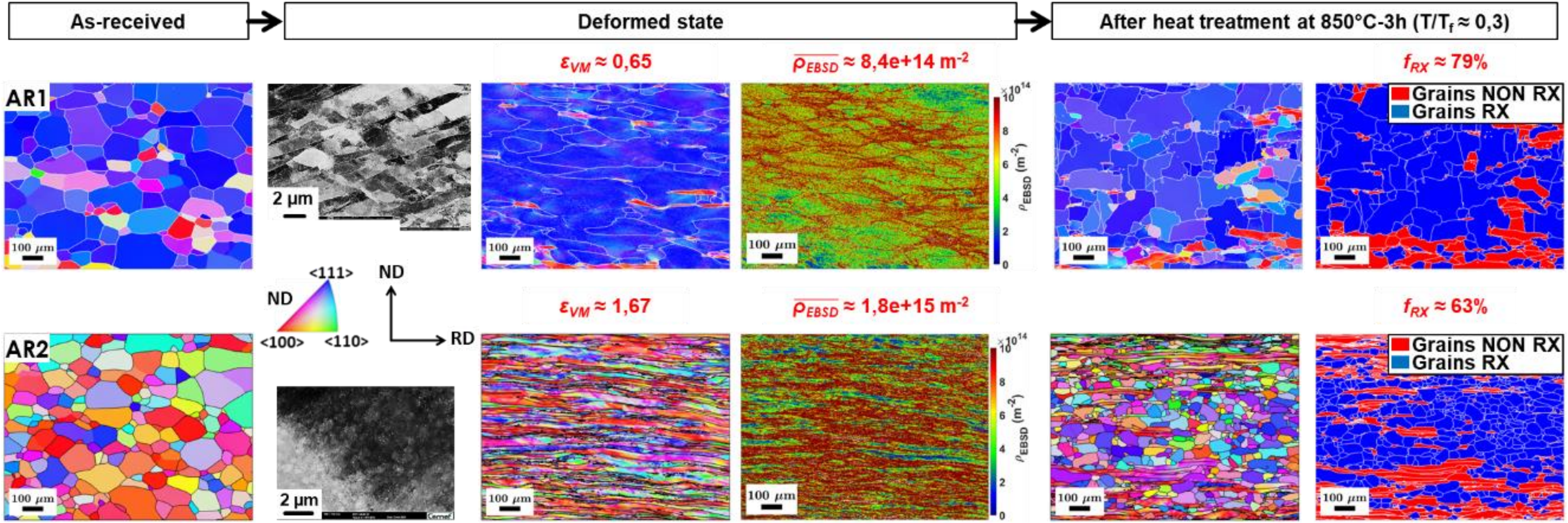
➔ High mechanical resistance and small plastic deformations (not necessarily smaller dislocation density)

Very "fast" γ Fiber formation

Baton, PhD, Mines Paris, 2021

Microstructure evolution: Plasticity and recrystallization

What does this heterogenous plastic deformation implies?



Different static recrystallization behavior ➔ different final microstructures

Baton et al., Int. J. of Refractory Metal and hard alloys, 2022

Moussa et al., 2022

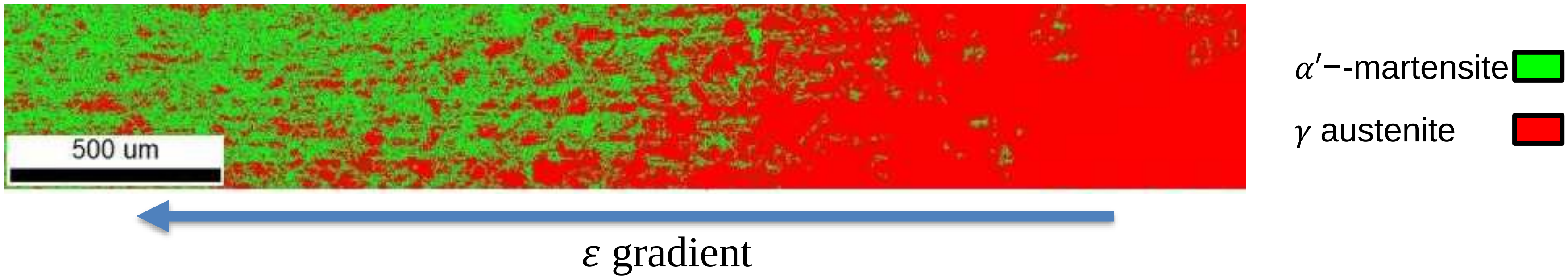
Microstructure evolution: TRIP Plasticity

TRIP effect and forming conditions

Plasticity : dislocation slip, Twinning induced plasticity and Transformation induced plasticity

In austenitic stainless steel with low Ni content like 304L (9-11%) Plastic deformation can induce by shearing the transformation

Austenite γ (FCC) ➔ ε martensite (HCP) or α' martensite (body centered tetragonal ~BCC)



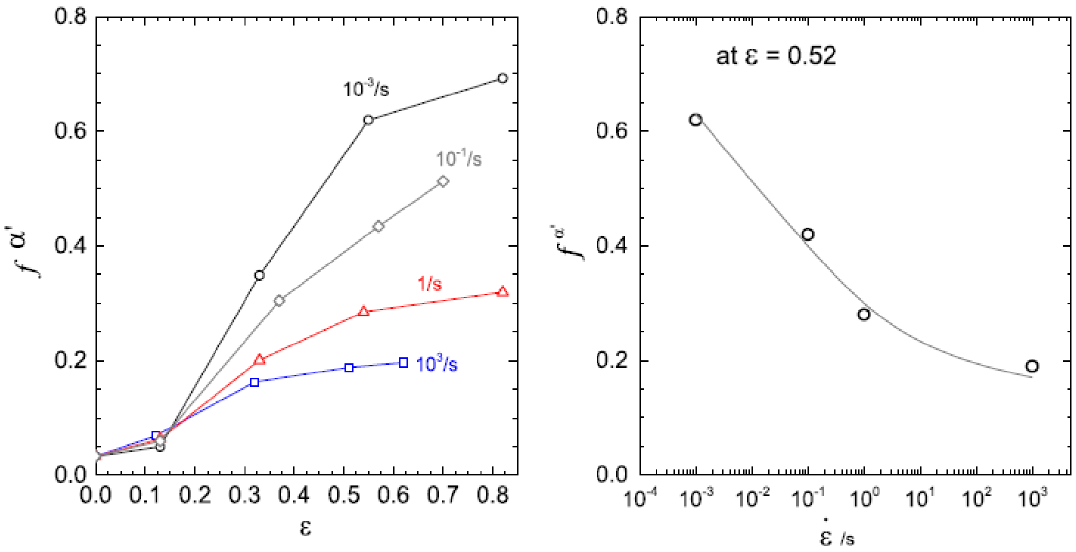
The amount of α' martensite increases with strain

Berahmand et al, Micron, 2021

Microstructure evolution: TRIP Plasticity

TRIP effect and forming conditions

How to control it?



High strain rate forming processes may be a solution

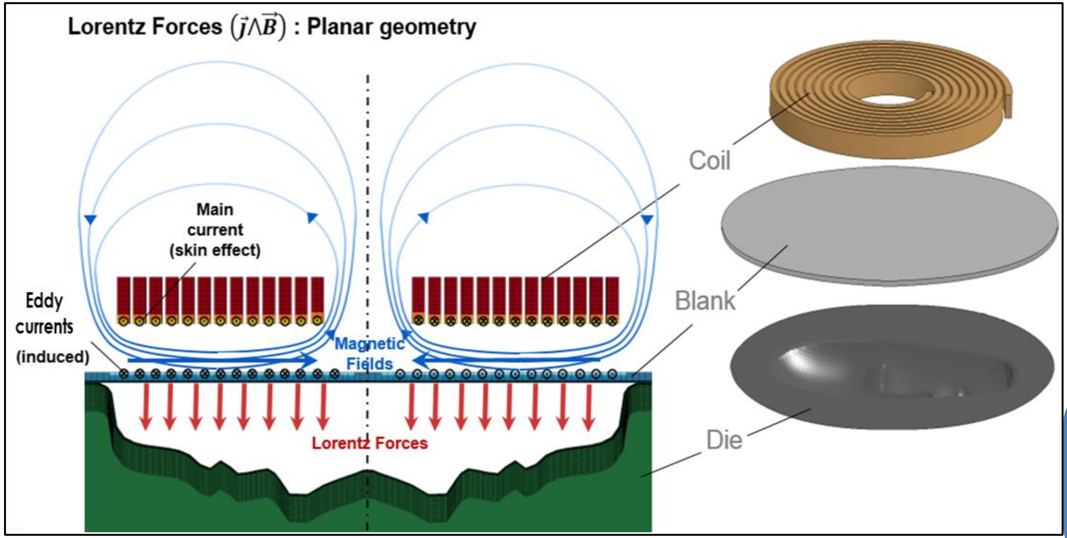
↗ strain rate, ↗ T → ↘ TRIP effect and the amount of α' martensite

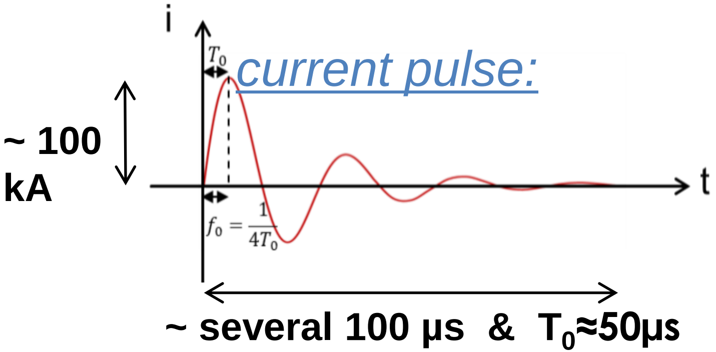
Chen et al, Acta Materialia, 2011

Microstructure evolution: TRIP Plasticity

Magnetic Pulse Forming (MPF)

High-speed forming process that consists of generating a strong magnetic field, which rapidly changes when it passes through the coil ➔ this changing induces Eddy currents which generates its own magnetic field to oppose the original one ➔ the interaction between the two magnetic fields creates Lorentz forces that deform the metallic material



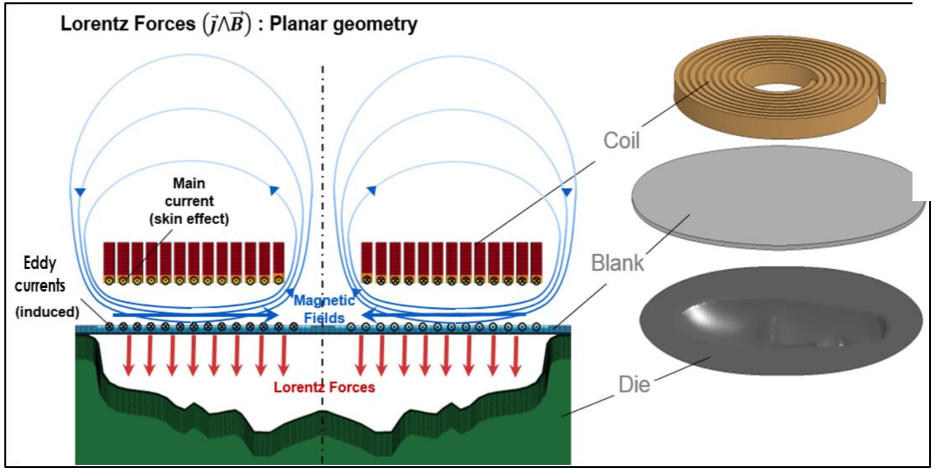


Particularities: No contact, reduces springback and very high strain rate (~$10^3 s^{-1}$)

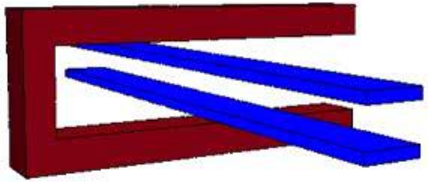
Courtesy of F. Bay

Microstructure evolution: TRIP Plasticity

Magnetic Pulse Forming (MPF)



Opportunities for cold welding

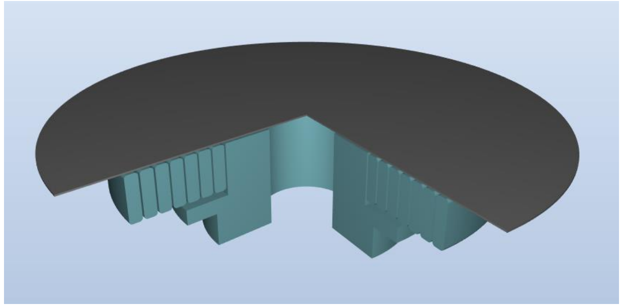


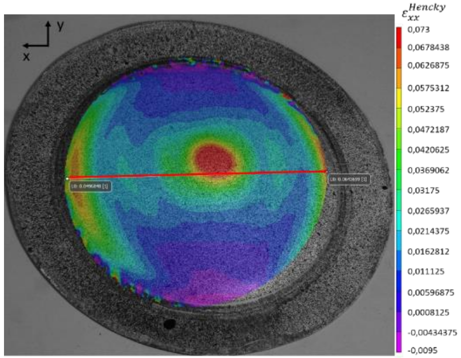
Zittel, a historical reveiw of high speed metal forming, 2010

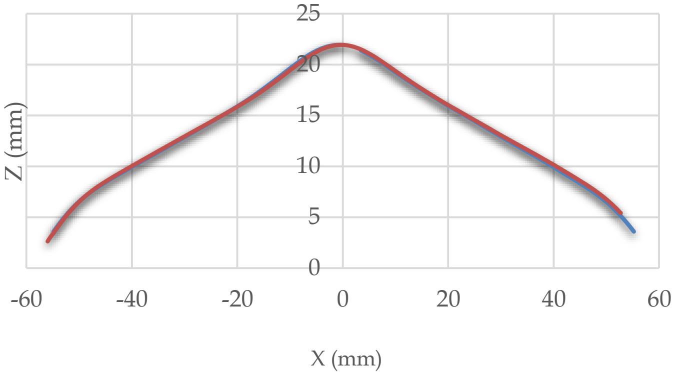
Courtesy of F. Bay

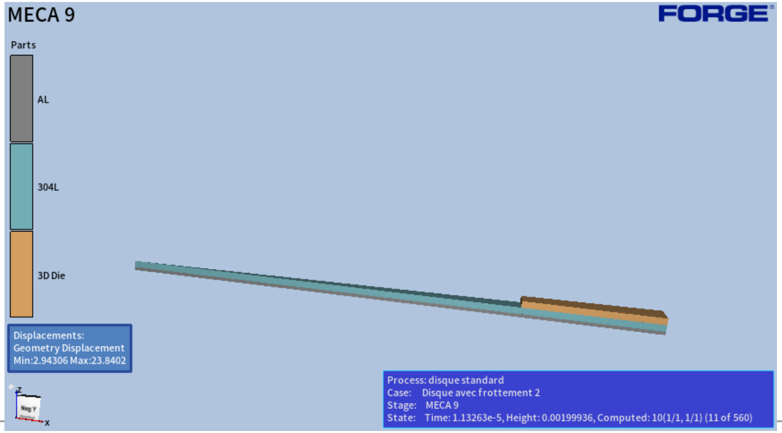
Microstructure evolution: TRIP Plasticity

Magnetic Pulse Forming (MPF) application on 304L steel to reduce TRIP effect









Displacements:
Geometry Displacement
Min:2.94306 Max:23.8402

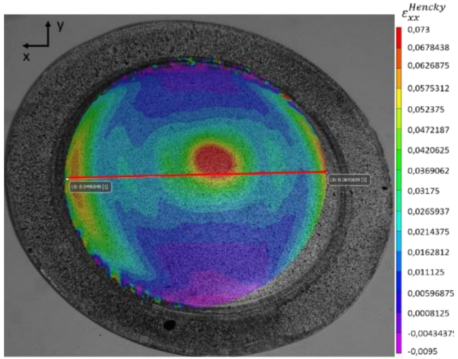
Process: disque standard
Case: Disque avec frottement 2
Stage: MECA 9
State: Time: 1.13263e-5, Height: 0.00199936, Computed: 10(1/1, 1/1) (11 of 560)

$$\dot{\varepsilon} \approx 10^4 s^{-1}$$

Ramon, Mapmod Thesis, Mines Paris, 2021

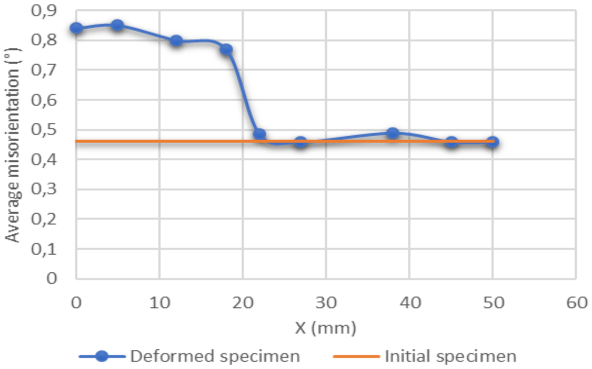
Microstructure evolution: TRIP Plasticity

Magnetic Pulse Forming (MPF) application on 304L steel to reduce TRIP effect

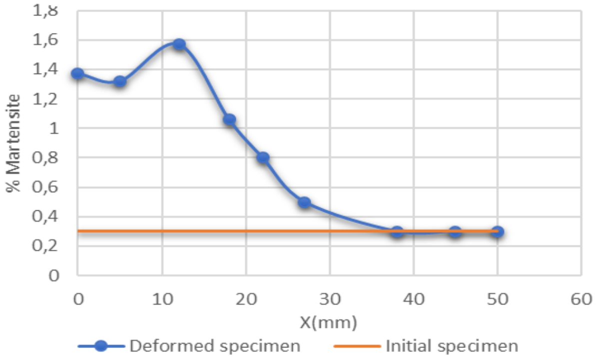


Early stages of transformation

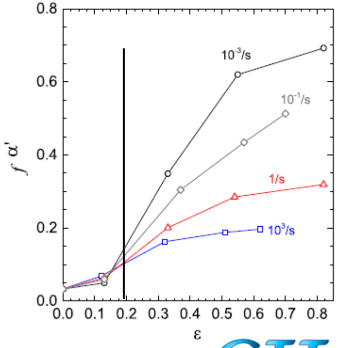
Intragranular disorientations ~ dislocation density



% of martensite



Compared to literature for similar plastic strains, smaller amount of martensite is obtained (1.5% vs 5%)



Ramon, Mapmod Thesis, Mines Paris 2021

Microstructure evolution: thermally activated mechanisms

Dynamic recrystallization occurs during hot deformation

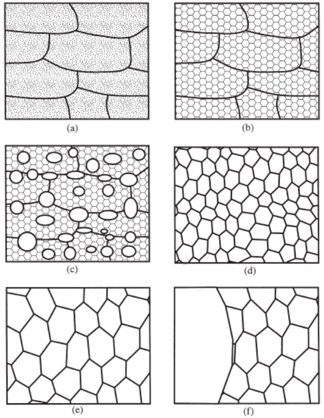
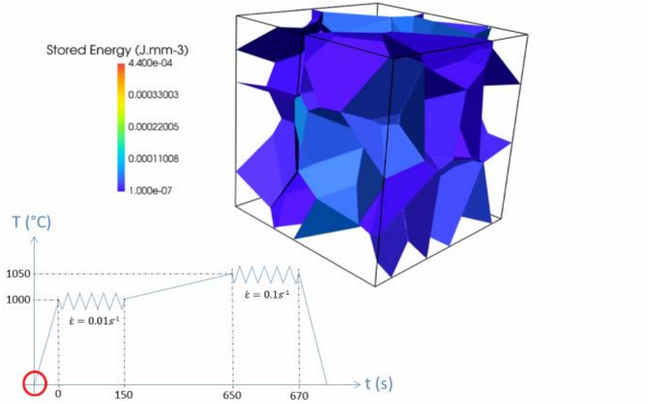


Fig. 1.1. Schematic diagram of the main annealing processes; (a) Deformed state, (b) Recovered, (c) Partially recrystallized, (d) Fully recrystallized, (e) Grain growth and (f) Abnormal grain growth.

Humphreys et Hatherly, Recrystallization and related annealing phenomena, 2nd edition, 2004.



Maire PhD, Mines Paris, 2018

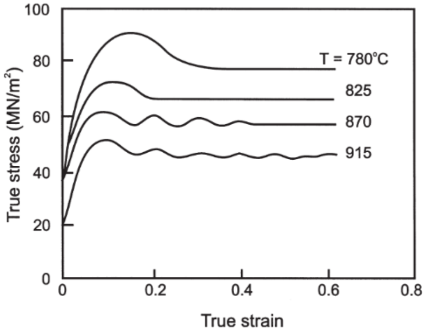
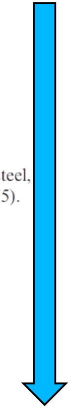
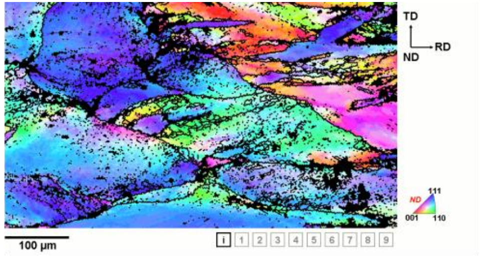


Fig. 13.12. The effect of temperature on the stress-strain curves for 0.68%C steel, deformed in axisymmetric compression, $\dot{\varepsilon} = 1.3 \times 10^{-3}\ s^{-1}$, (Petkovic et al. 1975).



High T
low $\dot{\varepsilon}$
High SFE

Low T
high $\dot{\varepsilon}$
High SFE



Kerisit, PhD Mines Paris, 2012

Highly sensitive to T and $\dot{\varepsilon}$

Defines the final grain size

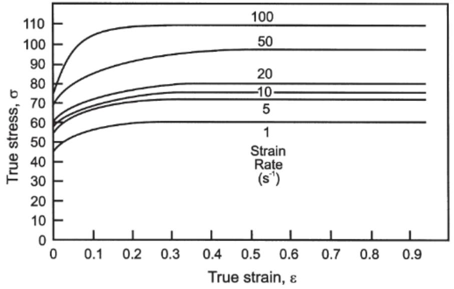
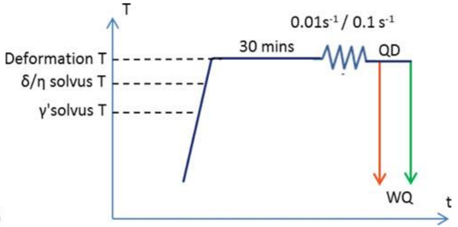
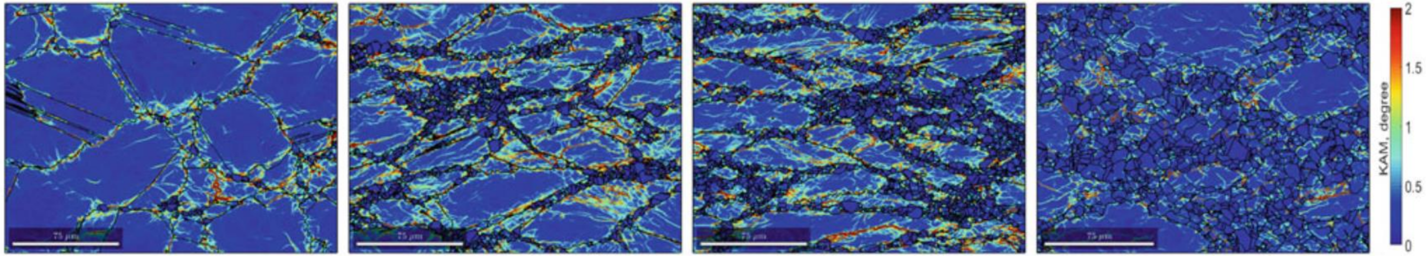


Fig. 13.1. Stress-strain curves for Al–1%Mg at 400°C, (Puchi et al. 1988).

Microstructure evolution: thermally activated mechanisms

Dynamic recrystallization occurs during hot deformation: Application to VDM780 Nickel base superalloy



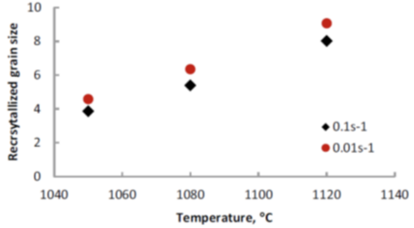


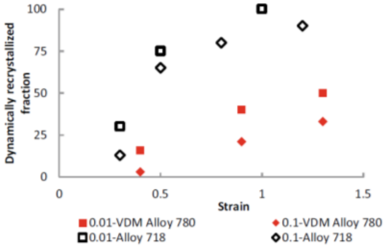
(a) $\varepsilon = 0.4$ at $0.1\ s^{-1}$
$f_r = 3\ \%$ $D_r = 5\ \mu m$

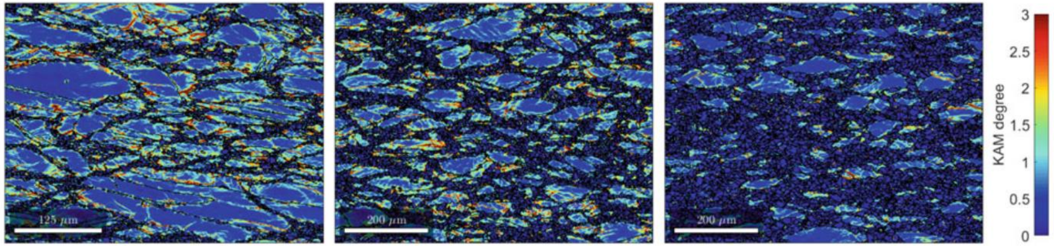
(b) $\varepsilon = 0.9$ at $0.1\ s^{-1}$
$f_r = 21\ \%$ $D_r = 5\ \mu m$

(c) $\varepsilon = 1.3$ at $0.1\ s^{-1}$
$f_r = 33\ \%$ $D_r = 4\ \mu m$

(d) $\varepsilon = 1.3$ at $0.01\ s^{-1}$
$f_r = 50\ \%$ $D_r = 6\ \mu m$







(a) T = 1050 °C

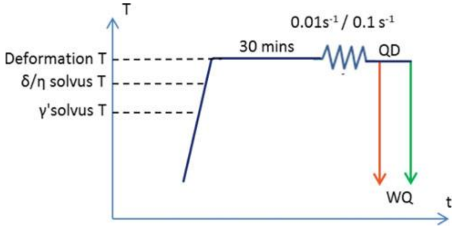
(b) T = 1080 °C

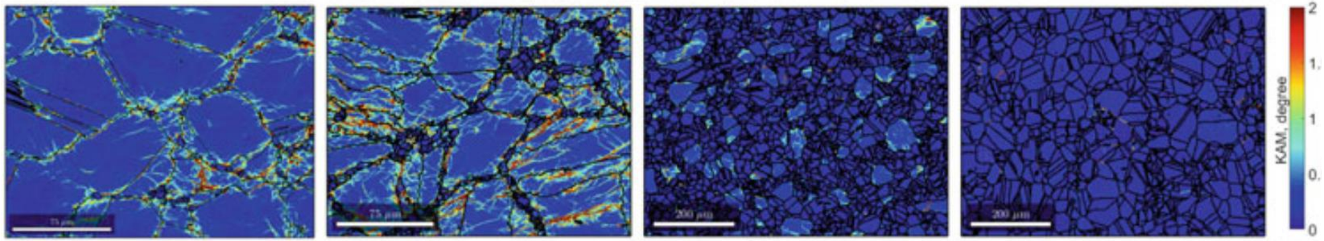
(c) T = 1120 °C

Sharma et al., Met Trans, 2020

Microstructure evolution: thermally activated mechanisms

Post dynamic recrystallization occurs after dynamic recrystallization (Meta or static recrystallization): Application to VDM780 Nickel base superalloy

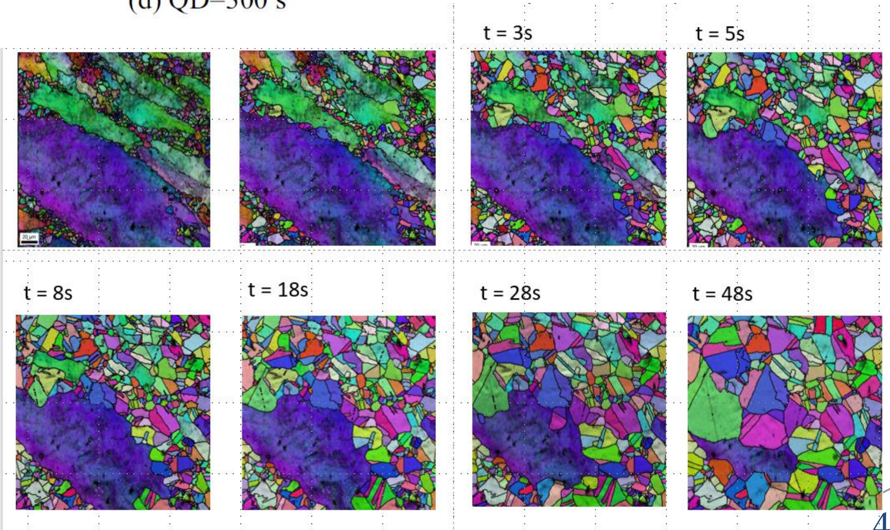




(a) QD=3 s (b) QD=6 s (c) QD=30 s (d) QD=300 s

Sharma et al., Met Trans, 2020

Very fast post dynamic recrystallization in unstable transient partially recrystallized microstructures



Zouari, PhD Mines Paris, 2015

Microstructure evolution: thermally activated mechanisms

Heterogeneous thermo-mechanical conditions ➔ heterogeneous microstructure:

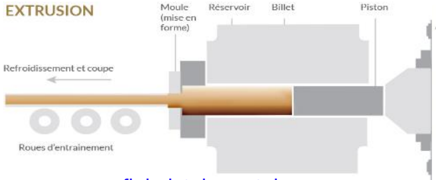
Application to Extrusion of Inconel 718

Difficulties:

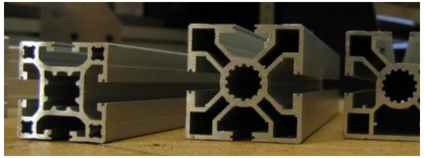
- Tool design difficulties
- Tool manufacturing cost
- Time required for die development through successive rials (including simulations) to achieve dimensional tolerances and to eliminate various geometric defects
- Die Lifespan
- Tool kinematics
- Tool – material contact conditions

Advantages:

- Material savings
- Hot or cold, solid or hollow parts
- Robust tools and powerful presses
- High geometric accuracy without machining
- Satisfactory surface finish
- Work hardened material

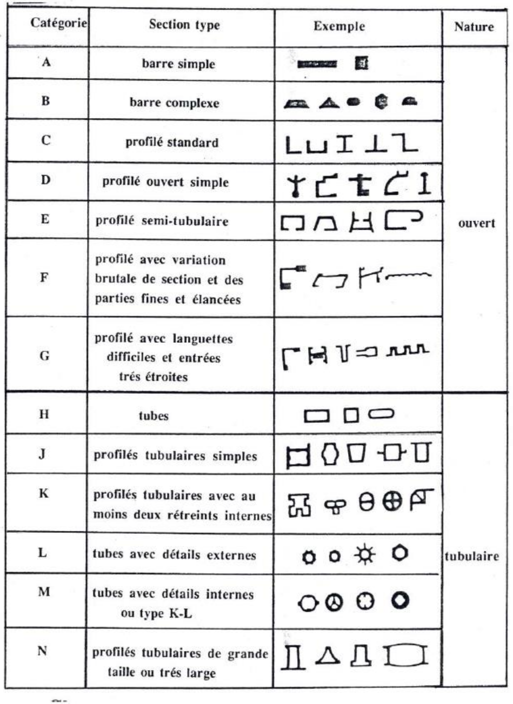


www.finkelstein-metals.com



Wikipedia, Extrusion, 2020

Courtesy of E. Felder



Catégorie	Section type	Exemple	Nature
A	barre simple		ouvert
B	barre complexe		
C	profilé standard		
D	profilé ouvert simple		
E	profilé semi-tubulaire		
F	profilé avec variation brutale de section et des parties fines et élancées		
G	profilé avec languettes difficiles et entrées trés étroites		
H	tubes		tubulaire
J	profilés tubulaires simples		
K	profilés tubulaires avec au moins deux rétreints internes		
L	tubes avec détails externes		
M	tubes avec détails internes ou type K-L		
N	profilés tubulaires de grande taille ou trés large		

Courtesy of E. Felder

Microstructure evolution: thermally activated mechanisms

Heterogenous plastic flow associated with heterogeneous microstructure ➔ Defects

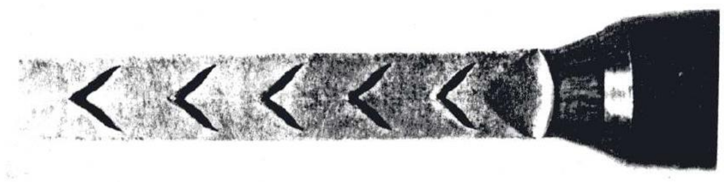
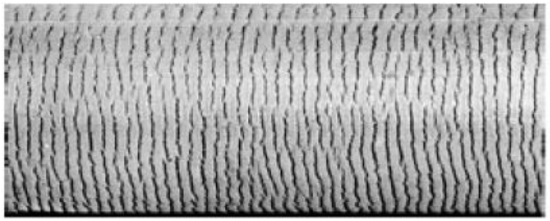


Figure 32 : Défauts internes (chevrons) sur barres d'acier filées à froid (*Central bursting defect*)

Cracks in the core and at the surface

a) Filage avant



a) Vitesse ou température faible

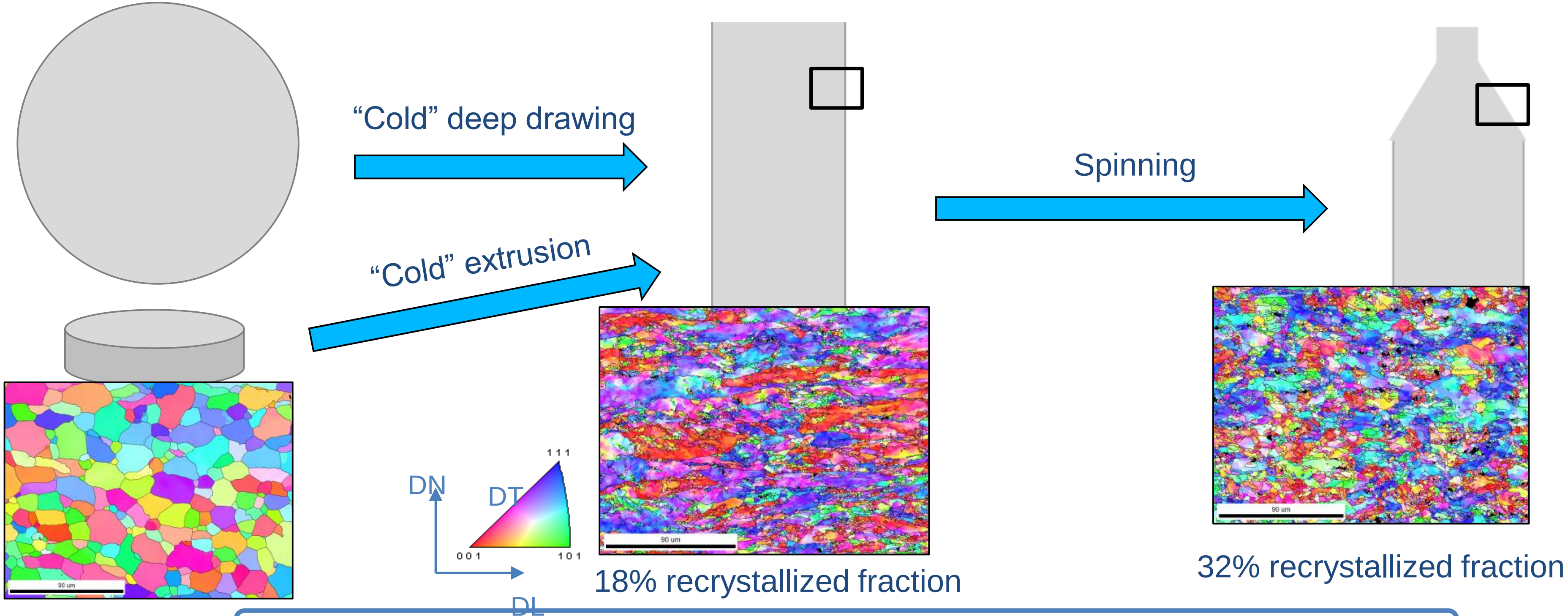
b) Vitesse ou température élevée

Courtesy of E. Felder

Microstructure evolution: thermally activated mechanisms

Thermally activated mechanisms during hot forming? What about cold forming?

Application to deep drawing, extrusion and spinning of aluminum alloy 1050



18% recrystallized fraction

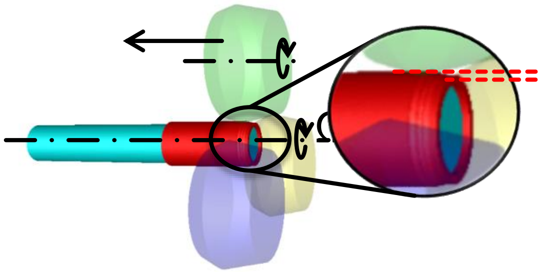
32% recrystallized fraction

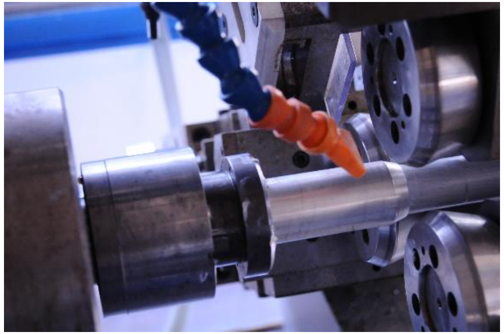
Thermally activated mechanisms can be activated during “cold” forming

Microstructure evolution: thermally activated mechanisms

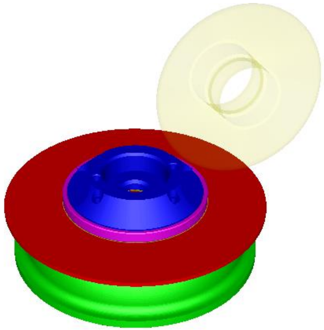
Thermally activated mechanisms during hot forming? What about cold forming?

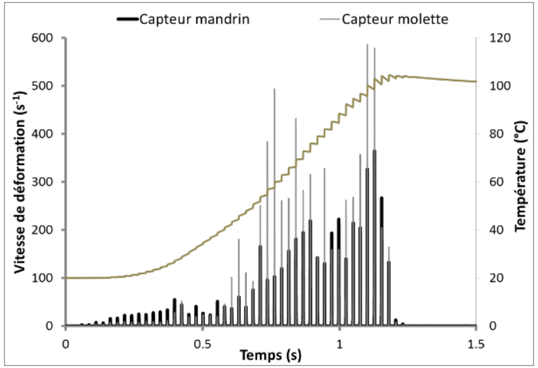
Application to flowforming of Inconel 718





Courtesy of P.O. Bouchard





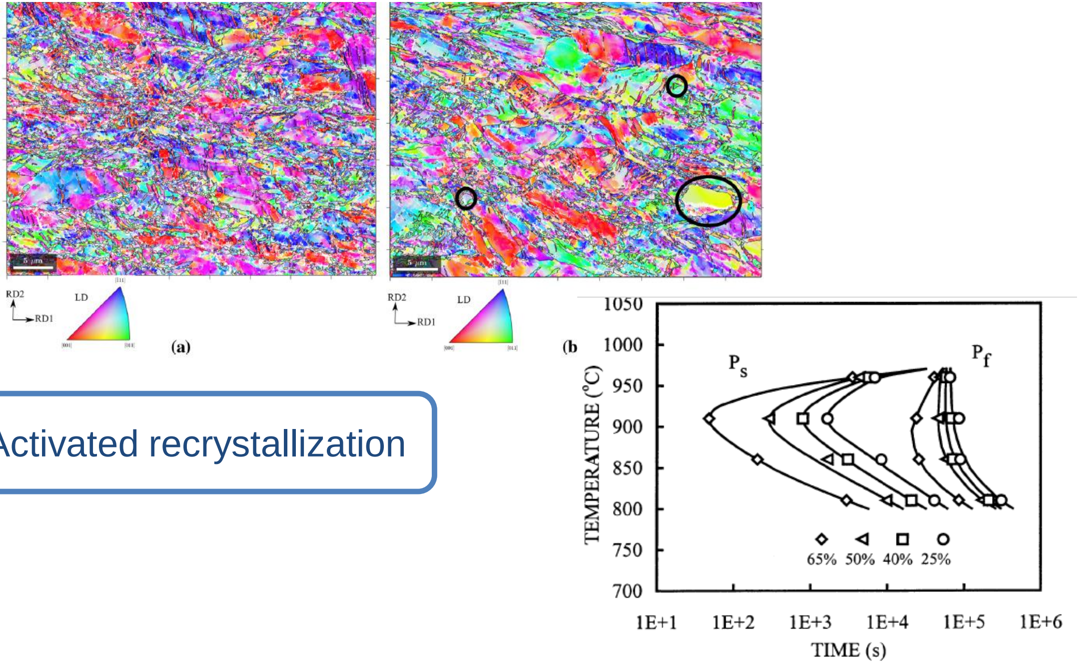
Vidal, PhD, Mines Paris, 2019

- Very high speed incremental deformation
- Mainly compressive triaxiality
- Very high strains (up to 8) and strain rates (up to 100s^{-1})

Microstructure evolution: thermally activated mechanisms

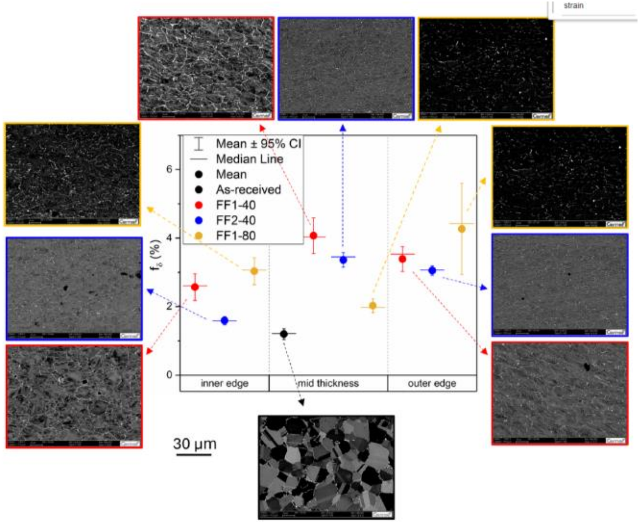
Thermally activated mechanisms during hot forming? What about cold forming?

Application to flowforming of Inconel 718



Activated recrystallization

Liu et al., Met. Trans, 1997



Activated δ phase transformation

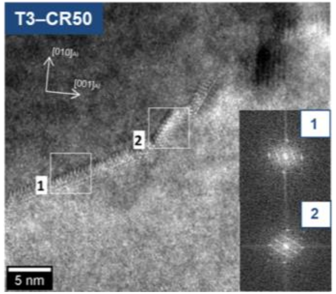
In addition to activating of thermally activated mechanisms, the kinetics are extremely accelerated

Moussa et al. Met. Trans, 2024

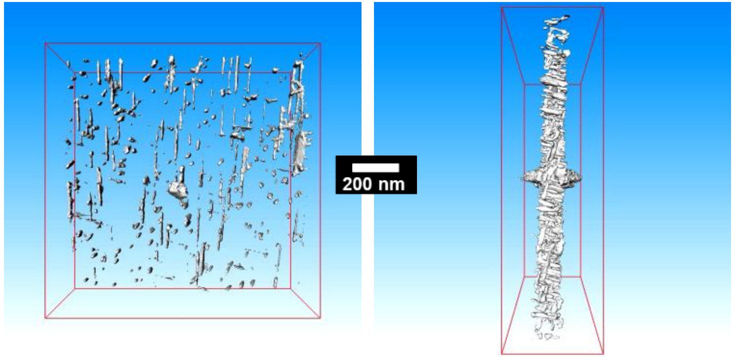
Microstructure evolution: thermally activated mechanisms

interactions between several physical mechanism

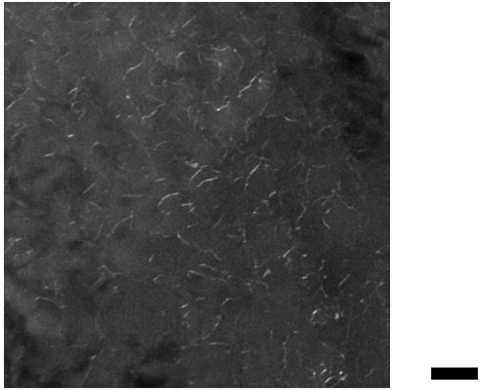
Application to AA 2024 coupling between plasticity and precipitation



S phase precipitation on dislocation lines: Heterogeneous precipitation



Homogeneous distribution of precipitates



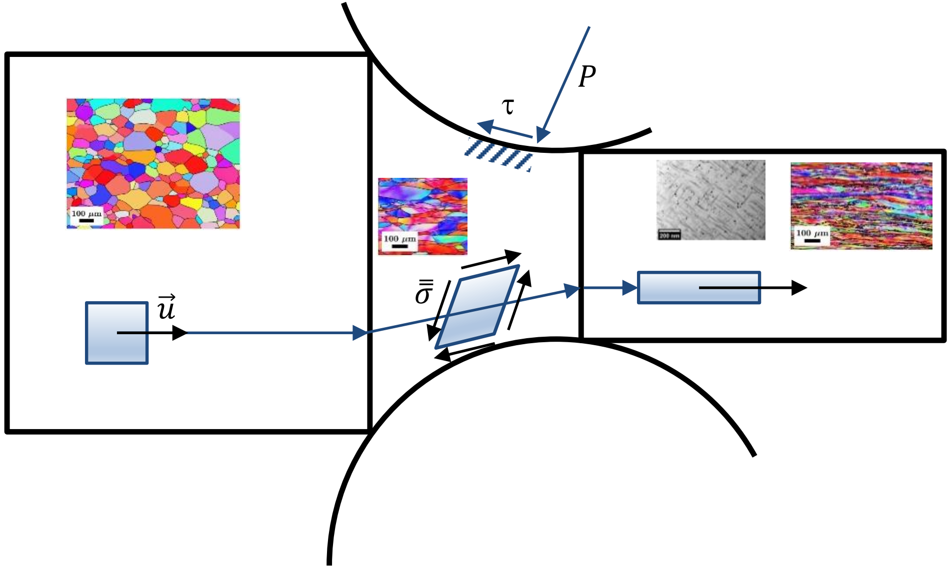
Nucleation, growth and coalescence on dislocation lines

All the physical mechanisms interacts, with increasing the materials forming complexity, understating and modelling microstructural evolutions increases ➔ Future challenges

Irmer et al., J. Alloys and Compounds, 2023

Irmer et al., MRS communications, 2024

Scientific challenges or a general vision of materials forming



Material flow
Forces involved in the forming process
➔ final shape of the product
Plasticity, ductility, damage …

Heat flow
➔T evolution
Adiabatic heating, radiation, convection…

Determines the energies involved in the forming process
➔ various internal and surface defects (cracks, porosities, wrinkles orange peel effect…)
➔ microstructure evolution (phases, grain size and shape, crystallographic texture, dislocations density…)
➔ mechanical properties of the product, residual stresses…

Thermomechanical interactions material – lubricant – tools
➔ surface state
Mechanical stresses (friction shear and contact pressure) and thermal stresses ➔ modifies deformation conditions and tools wear
Lubricant➔ reduces those effects
Tool deformation ➔ alteration of final dimensions
Thermal conduction, friction ➔ T evolution

Microstructural evolution
Plasticity, recovery, recrystallization and phase transformation (diffusive and displacive)
➔ Phases (volume fraction, size and shape), grain size and shape, crystallographic texture, dislocations density and sub-structures…),
➔ Mechanical properties of the product, residual stresses…

Thank you for your attention

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