Transformation et comportement des matériaux
Materials behaviour and processing

Residual stresses in processing
Contraintes résiduelles

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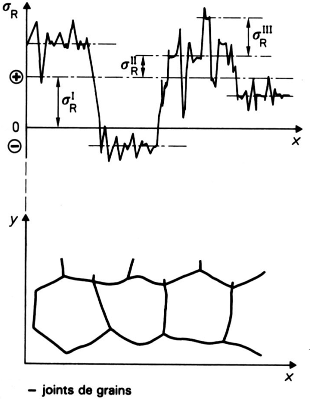
- Origine of strain incompatibility
  - Spherical strain $\underline{\underline{\epsilon}}_s$
    - Expansion liked or not liked to phase transformation : carburizing, surface quenching, coatings,...local plastification is possible
    - precipitation linked to the creation of new phasis : nitriding, carburizing,...
  - Deviatoric strain $\underline{\underline{\epsilon}}_d$
    - Plasticity (mechanical processing) : shot peening, ||galetage, sand blasting,...
  - Deviatoric and spherical strain
    - Plasticity due to a temperature gradient : machining, grounding
- Aim
  - Against tensile stress in operation
  - The origin of strain incompatibility is linked to the microstructure gradient ⇒ mechanical properties gradient (generaly hardening effect)
  - To define surface treatment where mechanical stress state is controled – it is not true every time (machining for exemple)

- Different order of stress
  - Macrocopical scale : engineer scale and continous medium mechanic scale (> some 1/10 of mm)
  - Mesoscopical scale : linked to the heterogneneities (crystal anisotropy, type of phasis) between grains, homogeneous in to the grain (some μm)
  - Microscopical scale : into the grain, on some interriticular length (some nm)
- Residual stress
  - Multiaxial stress
  - Stress in a material = superposition of different order of stress
  - In relation with elastic deformation in the material in order to have total deformation compatible
  - Gradient notion, profile close to the surface for surface treatments of materials
  - **Be careful** : generation of stress can generate the deformation of workpiece (mechanical equilibrum of macroscopical and microscopical stresses)



$$\sigma_R = \sigma_R^{I} + \sigma_R^{II} + \sigma_R^{III}$$

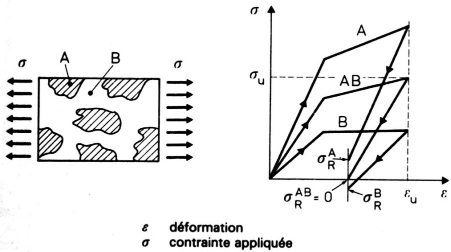
$$\sigma_R^{I} = \left(\frac{\int \sigma_R \, dA}{\int dA}\right)_{\text{plusieurs grains}}$$

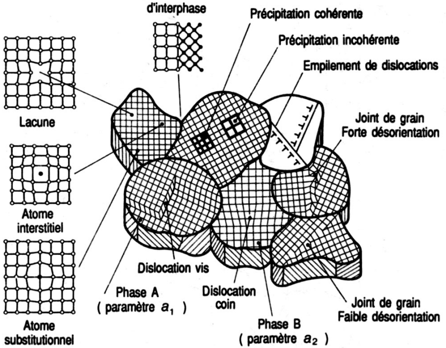
$$\sigma_R^{II} = \left(\frac{\int \sigma_R \, dA}{\int dA}\right)_{\text{un grain}} - \sigma_R^{I}$$

$$\sigma_R^{III} = (\sigma_R - \sigma_R^{I} - \sigma_R^{II})_{\text{un point}}$$

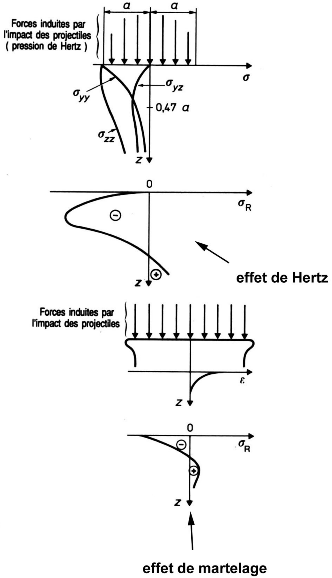
avec dA élément de surface

- Mesoscopical scale (order II) : linked to the heterogeneities between grains and phasis (polyphased materials) and the difference of mechanical behaviour
- Microscopical stress : linked to crystal defects, deformation of crystel network

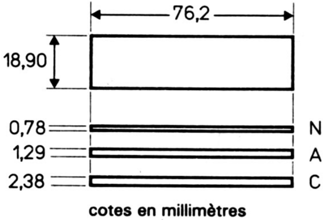


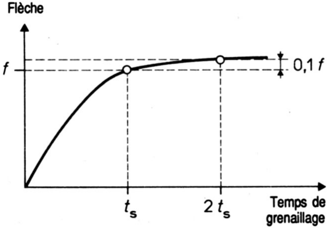


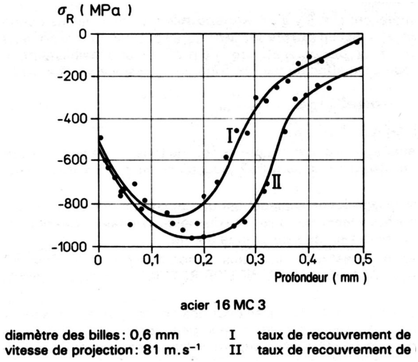
- Plastic deformation close to the surface induce by ball (media) impact
  - Hertz pressure on the substrate
  - In-depth maximal stress (efficient even the hardness of the media is less important than the substract one)
  - Localised plastic deformation between 50 and 700 μm (depend of the parameters)
  - Hammering effect close to the surface (10 to 30 μm) linked to the ball friction, important for ball with high hardness and subtract with low hardness
- Process parameters
  - Media : steel, ceramic, glass
  - Controlled projection speed (between 10 and 90 m/s), projection using turbine or compressed air
  - Known incidence angle (between 70˚ and 85˚)
  - Controlled exposition time - notion of saturation
  - Possibility to shot peen several time with different parameters
- Normalised surface treatment : NF L 06-831, NF L 06-832
- No confusion between shot peening and cleaning using media
- Possibility to make forming for thin parts (*peen forming*)

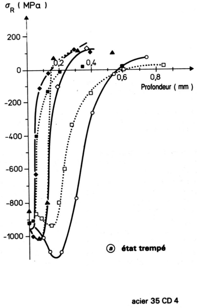


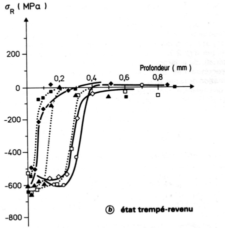
- Almen strip
  - Parallelipedic thin plate in SAE1070 (XC65) steel clamped on tick holder
  - Disposed closed to the shot peened area
  - Deformation of specimen (generated stress effect)
  - Caracterize the shot peening intensity (by ex. F20A)
- Saturation curve
  - Evolution of Almen arc in function of the exposition time
  - Saturation of the Almen strip deformation
  - Known incidence angle (between 70˚ et 85˚)
  - Controlled of the exposition time
  - Saturation time t_s approximatively corresponding to 100% coverage rate (for a X65 type of material)
  - 100% of Almen strip surface has been impacted (optical determination)



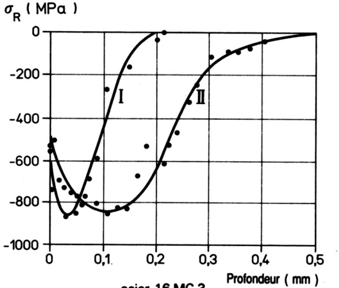








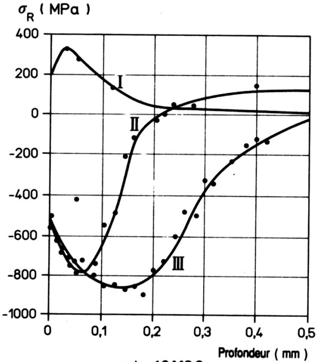
Courbes	Intensités *Almen* (§ 4,1041)	Calibre des billes (§ 4,1043)
■	10 N	S 70
◆	10 N	S 110
▲	10 A	S 110
◇	10 A	S 230
□	6 C	S 230
○	6 C	S 550



acier 16 MC 3

taux de recouvrement : 100 %
vitesse de projection : 53 m.s^{-1}

I diamètre des billes de 0,3 mm
II diamètre des billes de 0,6 mm

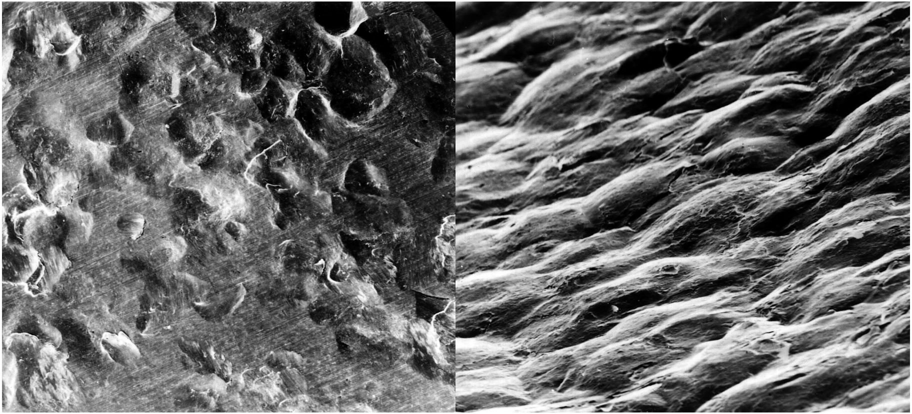


acier 16 MC 3

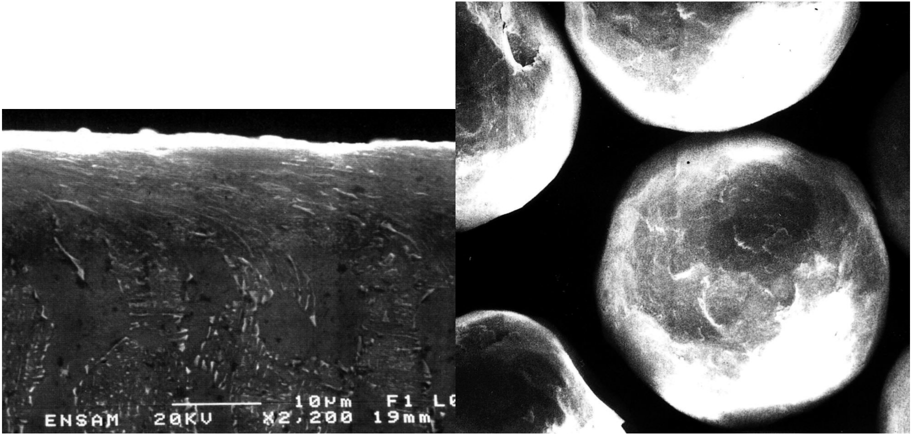
diamètre des billes : 0,6 mm
taux de recouvrement : 100 %

I pas de grenaillage
II vitesse de projection de 23 m.s^{-1}
III vitesse de projection de 81 m.s^{-1}

- Surface plastic deformation ⇒ roughness modification
- Avantages : elimination of machining stripes, homogeneity of roughness anisotropy
- Inconvenient : creation of microcracks, important damage of the surface



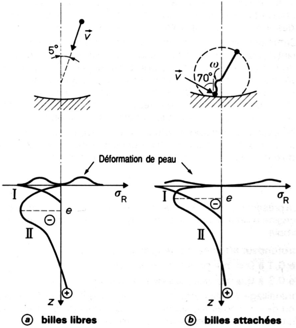
Shot peening effect on workpiece (TiAl6V4)



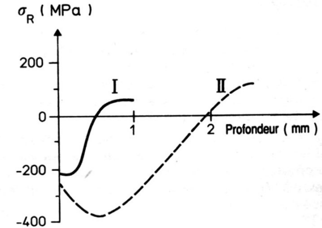
Effect of shot peening on the surface of workpiece (TiAl6V4) and on the media (BA300)

- Process evolution : ultrasonic shot peening
  - US transductor allowing to move media with large diameter
  - Recovery, sorts, no wear of media
  - Affected depth by large stress field
  - Reduction of harmenning effect in order to obtain superficial nanostructure of material (improvement of use properties)
- Applications
  - Aeronautic : tubine blade (machining stripes), powerschaft, ...
  - Automotive : spring,...
  - Nuclear : tube of steam generators,...
  - ...
- More information
  - *The Shootpeener*, american revue of this process

- Surface deformation using percussion gun (harmenning) or media in rotation (rotopeening)
- No recuperation system for the media
- Local use : inner of the tube (rotopeening), thin plate (peen forming)



- ● bille
- surface du matériau
- e point de Hertz ou point de cisaillement maximal
- $\vec{v}$ vitesse de la bille
- z profondeur sous la surface
- ω vitesse angulaire
- I contrainte résiduelle due au frottement
- II contrainte résiduelle due à la pression de Hertz

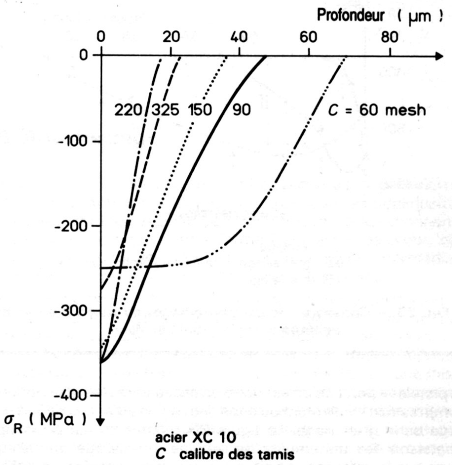


taux de recouvrement 200 %
acier Z2 CN 18-10

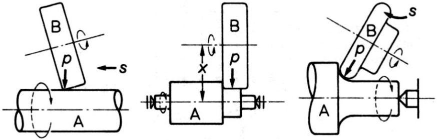
I après grenaillage à billes libres avec calibre de billes de 0,6 mm et intensité *Almen* 10 A

II après martelage avec pistolet à percussion à 6 coups par seconde et par carré de 5 × 5 cm² et intensité *Almen* 12 A

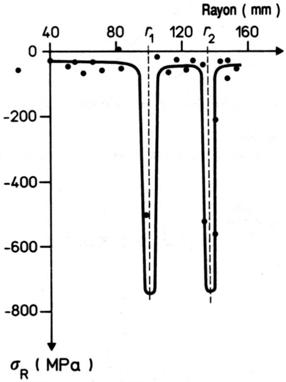
- Non cotrolled media (size, form,...) with low dimension (10-100 μm) in silica, alumina,...
- Use : decaping, cleaning
- It is not a mechanical surface treatment



- Use of roller in order to apply a surface deformation
- Application : fillets in crankpin / crankshaft

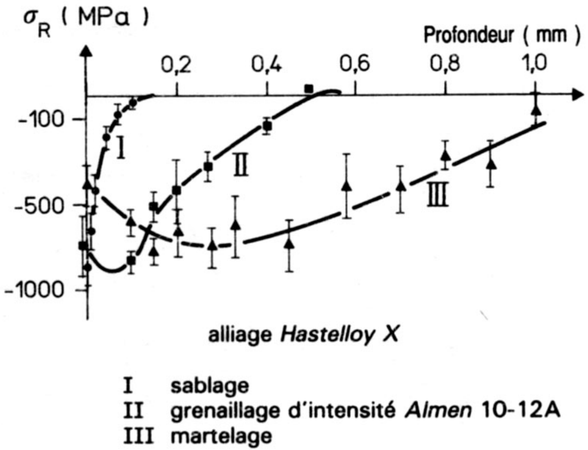


A	pièce	*s*	avance
B	galet	*x*	écartement des axes suivant le diamètre de la pièce à réaliser
p	pression		

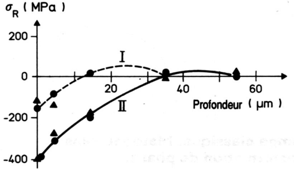


Dimensions de la scie circulaire :

diamètre 350 mm
hauteur des dents 30 mm
pas des dents 1,75 mm
rayons galetés : r_1 = 101 mm
r_2 = 137 mm


σ_R (MPa)
Profondeur (mm)
0,2
0,4
0,6
0,8
1,0
-100
-500
-1000
I
II
III
alliage *Hastelloy X*
I sablage
II grenaillage d'intensité *Almen* 10-12A
III martelage

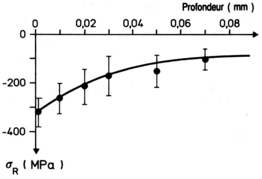
- Obtention of better roughness
- Eliminate of machining stripes
- Generation of compressive residual stress
- Low affected depth



● contraintes parallèles aux stries de polissage
▲ contraintes perpendiculaires aux stries de polissage

acier XC 48

I diamètre de SiC 8 µm
II diamètre de SiC 50 µm



alliage *Hastelloy X*

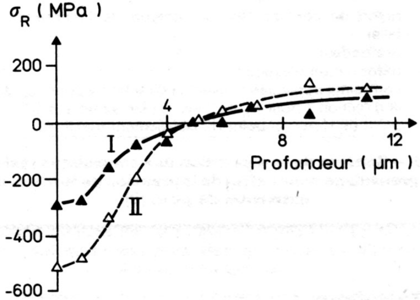
Surface	Avant tonnelage			Après tonnelage		
	σ_R^L MPa	σ_R^T MPa	$b(2\theta)$ °	σ_R^L MPa	σ_R^T MPa	$b(2\theta)$ °
rectifiée *Ra* = 1 µm	+ 65 (± 30)	– 190 (± 30)	2,70	– 350 (± 25)	– 350 (± 25)	2,75
Fraisée *Ra* = 3,2 µm	– 155 (± 70)	+ 90 (± 35)	3,40	– 245 (± 55)	– 5 (± 20)	3,70

Ra rugosité apparente
b largeur de corde (§ 6,223) des pics de diffraction
σ_R^L contrainte résiduelle longitudinale
σ_R^T contrainte résiduelle transversale
θ angle de Bragg (§ 6,223)

- Self-hooping [1]
  - Presure higher to the use pressure in the case of thick tube
  - Creation of plastic deformation for the interior of the tube
  - Application : cannon tubes
- Preconformage
  - Used when loading is well known
  - Palstic deformation in order to stabilize yield stress of material
  - Application : plate spring, helicoidal spring, torsion bar, cylinder under pressure
- Schock waves
  - By explosion or by creating a confined plasma using laser beam (10^9 W.cm^2 during 100 ns)
  - Schock waves $\Rightarrow$ plastic deformation
  - Great depth : 2 to 4 mm
  - No significative modification to the roughness

1. auto-frettage

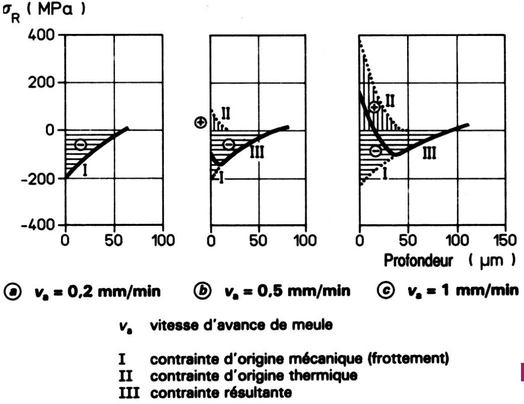
- Mechanical and thermal aspect
- Anisotropy of the stresses (grinding transverse direction ≠ longitudial direction)
- Low affected depth
- Important influance of cooling liquid (be careful to grinding burn)
- Compressive and tension stress state (if temperature effect is important)



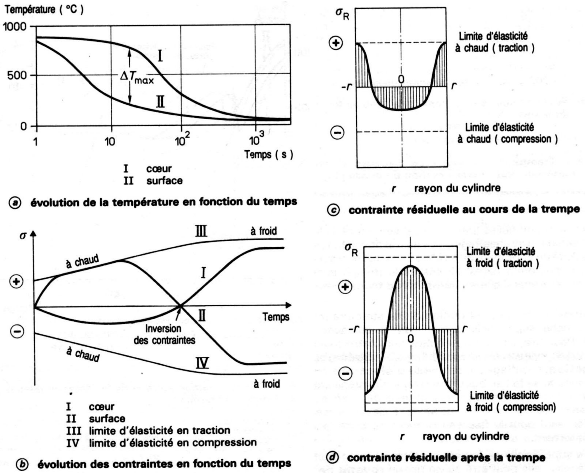
acier 100 C 6

I contrainte résiduelle parallèle aux stries de rectification
II contrainte résiduelle perpendiculaire aux stries de rectification

- Mechanical and thermal qspect
- Anisotropy of the stresses (machining transverse direction ≠ longitudinal direction)
- Important influence of machining parameters (cutting depth,...)
- Residual stresses use is fundamental today (surface integrity)
- Can be considered like a surface treatment if the machining parameters are fixed and the effects well known



- Free stress deformation of dilation (temperature gradient) ⇒ plastic deformation ⇒ residual stresses
- Temperature effects
- Possibility of shrinkage cracks creation by local plastification of the material (yield stress)



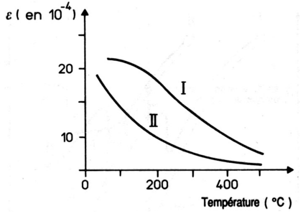
ⓐ évolution de la température en fonction du temps

ⓑ évolution des contraintes en fonction du temps

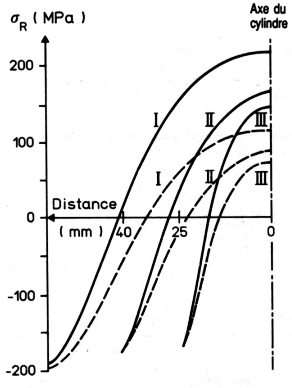
ⓒ contrainte résiduelle au cours de la trempe

ⓓ contrainte résiduelle après la trempe

- Geometry effect
- Material effect



ε déformation élastique maximale
I alliage d'aluminium 7075
II alliage d'aluminium 2014

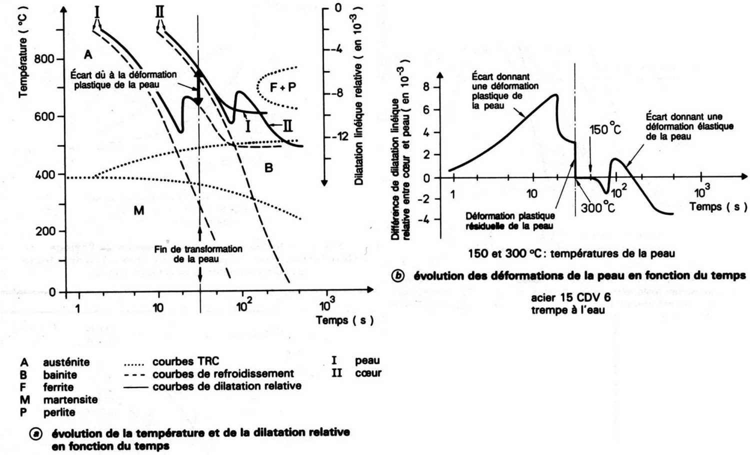


alliage d'aluminium 7075
trempe à l'eau à 20 °C depuis 467 °C

– – – contraintes résiduelles circonférentielles
——— contraintes résiduelles longitudinales
r rayon du cylindre plein

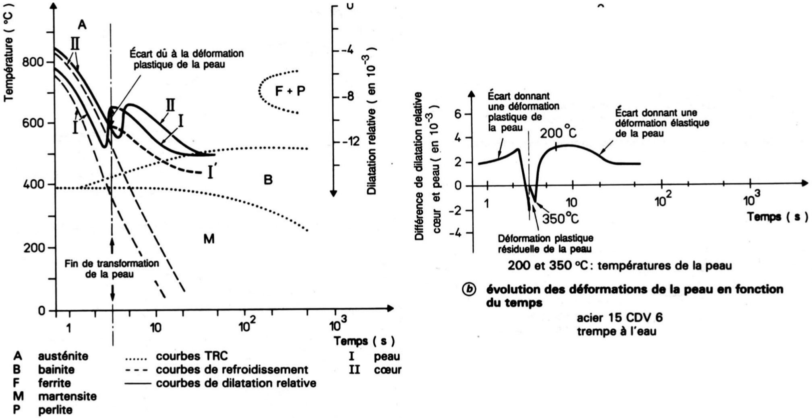
I r = 60 mm
II r = 40 mm
III r = 25 mm

- Stress free deformation dur to phase transformation (austinte ⇒ martensite) : volume deformation ⇒ residual stresses
- Application : stell (special grade)



Superficial quenching with phase transformation – 100 mm diameter cylinder

- Size effect of part

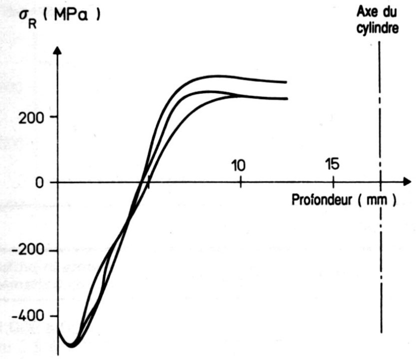


ⓐ **évolution de la température et de la dilatation relative en fonction du temps**

ⓑ **évolution des déformations de la peau en fonction du temps**

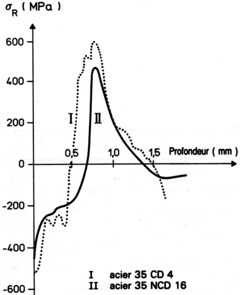
Trempe Superficial quenching with phase transformation – 10 mm diameter cylinder

- Creation of Foucault current with an inductor
- Metallic material
- Simple geometry of parts
- Application : cranshaft, sawtooth

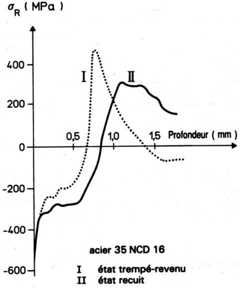


acier XC 42
cylindre de diamètre 36 mm (3 éprouvettes)
induction moyenne fréquence

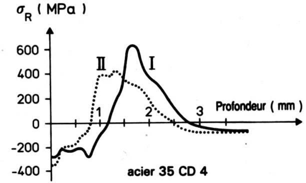
- Heating using high energy beam
- Application very localized
- **Be carrefull** : tensile residual stress in subsurface (metallurgical effect)



ⓐ influence de la nuance



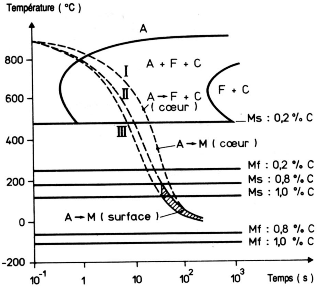
ⓑ influence de l'état initial



vitesse du faisceau d'électrons 0,6 m.min^{-1}
tension 50 kV

I intensité 80 mA
II intensité 60 mA

- Carbon content increasing of the material ($T \geq A_{C3}$) ⇒ law carbon steels
- Quenching ⇒ austinito-martisentic transformation ⇒ volume variation

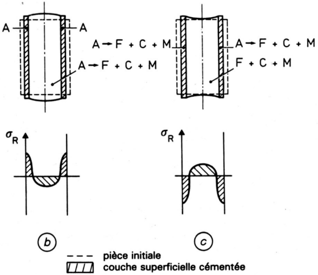


acier XC 18

- - - courbes de refroidissement
—— courbes TRC

A austénite
C cémentite
F ferrite
M martensite
Mf température de fin de transformation martensitique
Ms température de début de transformation martensitique
I refroidissement du cœur
II refroidissement de la sous-couche superficielle
III refroidissement de la surface extérieure

ⓐ **évolution de la température en fonction du temps et transformations de l'austénite.**



ⓑ **contraintes résiduelles après transformation A → F + C + M du cœur**

ⓒ **contraintes résiduelles résultant de la transformation A → F + C + M en surface (état final)**

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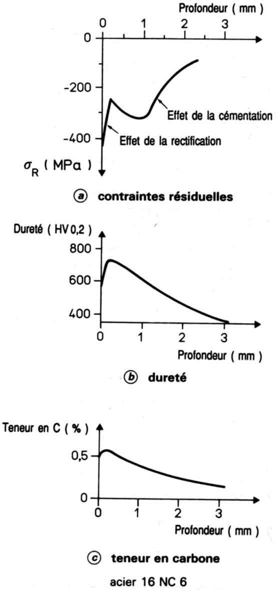
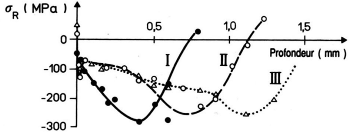
- Increasing of surface hardness
- Affected depth arround 1 mm
- Problem due to the non transformed austenite (in generaly it is good for mechanical behaviour)
- Be carrefull to the deformation of the parts during quenching (quenching under pression)
- Decarburising during tempered treatment (indispensable)



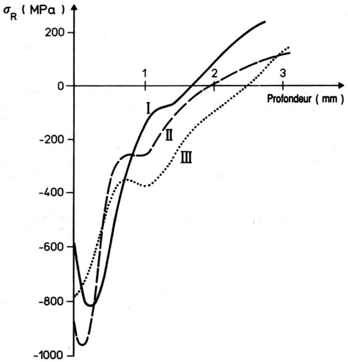
- Carbon medium
  - Solid
  - Gazeous (hydrocarbur – CH_4)
  - Liquid
  - Ionic (in development)
- Transformation is fonction of material composition
- Special grades developed (0,1% to 0,2% of carbon)



cémentation gazeuse
température de trempe 840 °C

I épaisseur cémentée 0,4 mm
II épaisseur cémentée 0,8 mm
III épaisseur cémentée 1,2 mm

ⓐ **acier 16 NC 6** (d'après Tournier)



cémentation solide
température de trempe 880 °C

I épaisseur cémentée 0,2 mm
II épaisseur cémentée 0,4 mm
III épaisseur cémentée 0,8 mm

ⓑ **acier XC 18** (d'après Koch)

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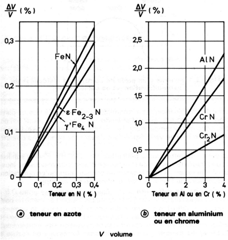
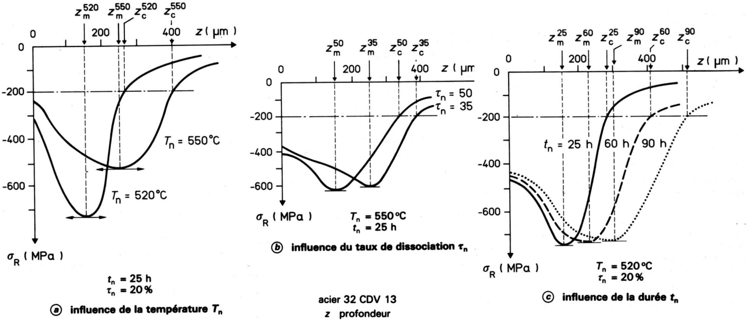
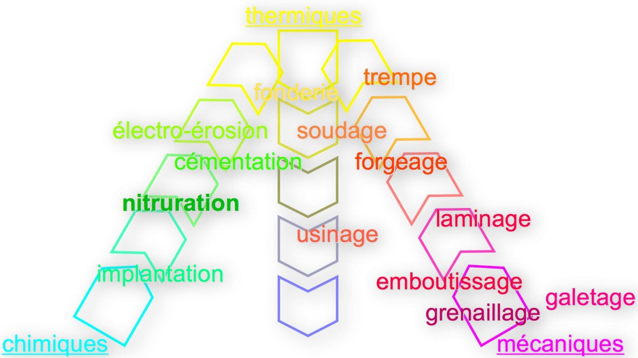
- Nitride medium
  - Solid
  - Gazeous (amoniac – $NH3$)
  - Liquid
  - Ionic
- Transformation as function of material compositon







Processus physico-chimiques

Paramètres technologiques → Gradients de microstructure → État initial avant fonctionnement