

Transformation et comportement des matériaux

Materials behaviour and processing

Residual stresses in processing

Contraintes résiduelles

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ARTS ET MÉTIERS – Aix-en-Provence

Introduction

Residual stress

Order of residual stresses

Mechanical surface treatments

Shot Peening

Harmenning

Sand blasting

Finishing treatment

Others machining process

Thermomechanical Surface Treatments

Machining

Thermal Surface Treatments

Thermochemical Surface Treatments

Carburising

Nitriding

Introduction

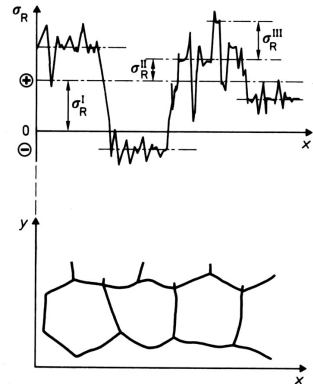
- Origine of strain incompatibility
 - Spherical strain $\underline{\epsilon}_s$
 - Expansion liked or not liked to phase transformation : carburizing, surface quenching, coatings,...local plastification is possible
 - precipitation linked to the creation of new phasis : nitriding, carburizing,...
 - Deviatoric strain $\underline{\epsilon}_d$
 - Plasticity (mechanical processing) : shot peening, burnishing, sand blasting,...
 - Deviatoric and spherical strain
 - Plasticity due to a temperature gradient : machining, grinding
- Aim
 - Against tensile stress in operation
 - The origin of strain incompatibility is linked to the microstructure gradient \Rightarrow 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)

Stress

Stress generation

Origin of stresses – Scale notion

- Different order of stress
 - Macroscopical scale : engineer scale and continuous medium mechanic scale (> some 1/10 of mm)
 - Mesoscopical scale : linked to the heterogeneities (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 equilibrium of macroscopical and microscopical stresses)



– joints de grains

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

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

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

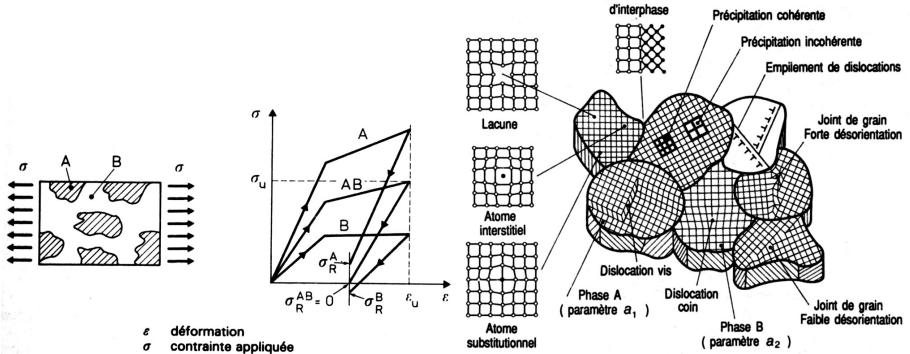
$$\sigma_R^{II} = (\sigma_R - \sigma_h - \sigma_R^I)_{\text{un point}}$$

avec dA élément de surface

Stress generation

Origine of stresses – Order II and order III of stresses

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

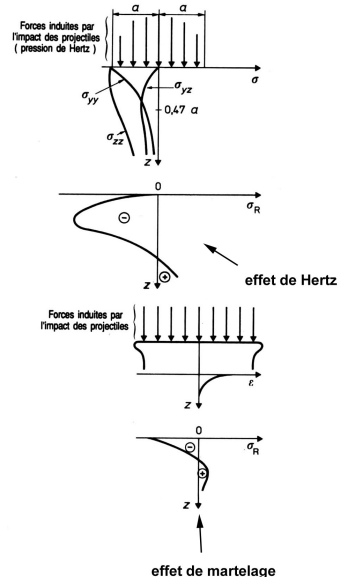


Mechanical surface treatments

Stress generation

Shot peening (*Grenailage de précontrainte*) – Principle

- 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 substrate 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 substrate 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 shotpeen 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*)



Stress generation

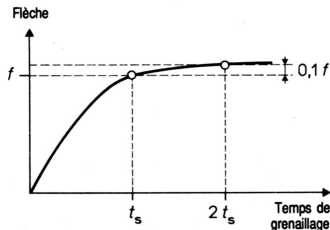
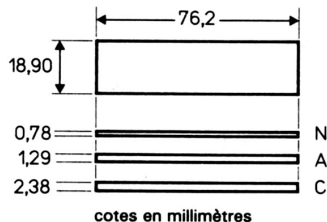
Shot peening – Almen intensity

- Almen strip

- Parallelepipedic thin plate in SAE1070 (XC65) steel clamped on tick holder
- Disposed closed to the shot peened area
- Deformation of specimen (generated stress effect)
- Characterize the shot peening intensity (by ex. F20A)

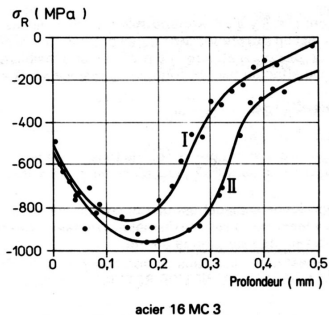
- Saturation curve

- 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)



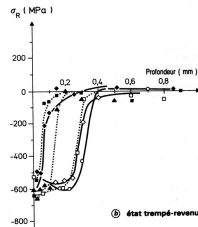
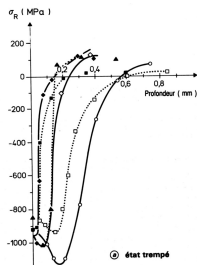
Stress generation

Shot peening – Stress : effect of the shot peening parameters 1/2



diamètre des billes : 0,6 mm
vitesse de projection : 81 m.s⁻¹

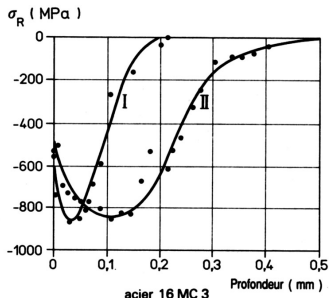
I taux de recouvrement de
II taux de recouvrement de



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

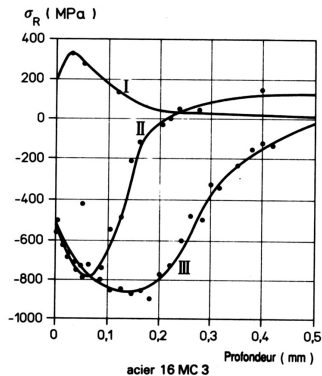
Stress generation

Shot peening – Stress : effect of the shot peening parameters 2/2



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



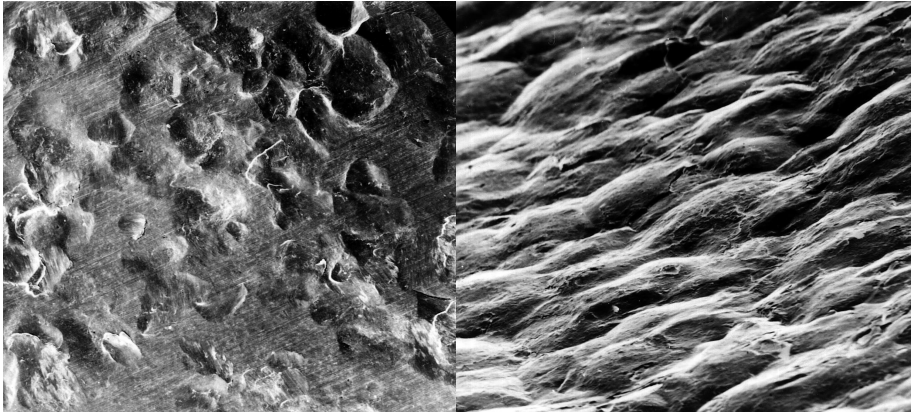
diamètre des billes : 0,6 mm
taux de recouvrement : 100 %

I pas de grenailage
II vitesse de projection de 23 m.s⁻¹
III vitesse de projection de 81 m.s⁻¹

Stress generation

Shot peening – Effect on roughness

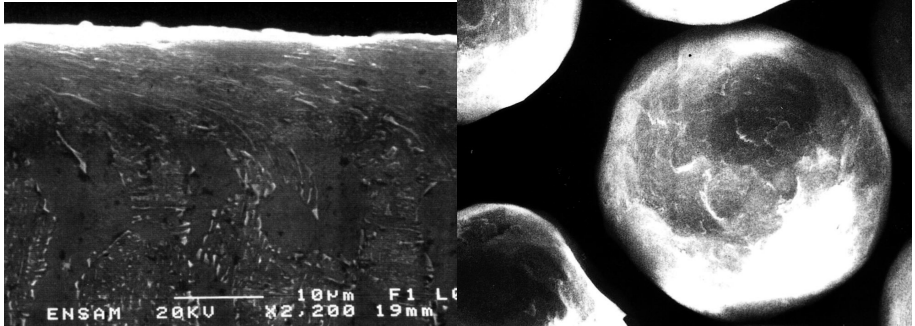
- Surface plastic deformation \Rightarrow roughness modification
- Avantages : elimination of machining stripes, homogeneity of roughness anisotropy
- Inconvenient : creation of microcracks, important damage of the surface



Shot peening effect on workpiece (TiAl6V4)

Stress generation

Shot peening – Effect on roughness 2/2



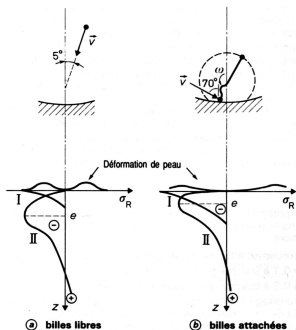
Effect of shot peening on the surface of workpiece (TiAl6V4) and on the media (BA300)

- Process evolution : ultrasonic shot peening
 - US transducer 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
 -

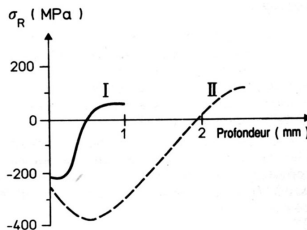
Stress generation

Harmenning

- 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



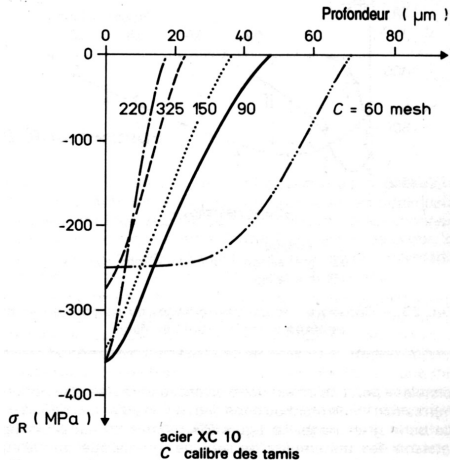
taux de recouvrement 200 %
acier Z2 CN 18-10

- après grenailage à billes libres avec calibre de billes de 0,6 mm et intensité *Almen* 10 A
- après martelage avec pistolet à percussion à 6 coups par seconde et par carré de $5 \times 5 \text{ cm}^2$ et intensité *Almen* 12 A

Stress generation

Sand blasting

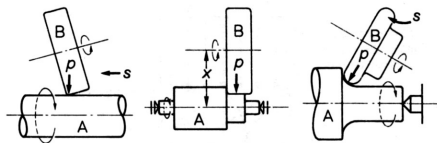
- Non controlled media (size, form,...) with low dimension (10-100 μm) in silica, alumina,...
- Use : decapping, cleaning
- It is not a mechanical surface treatment



Stress generation

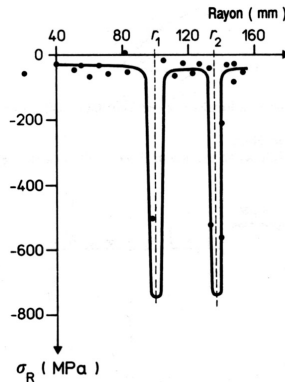
Burnishing

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



A pièce
B galet
p pression

s avance
x écartement des axes suivant
le diamètre de la pièce à réaliser

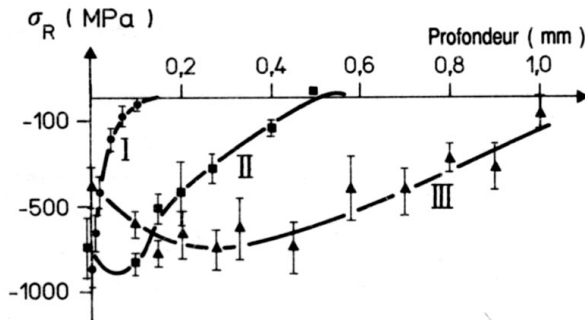


Dimensions de la scie circulaire :

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

Stress generation

Shot peening / sand blasting / burnishing comparison



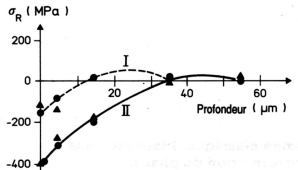
alliage *Hastelloy X*

- I sablage
- II grenailage d'intensité *Almen 10-12A*
- III martelage

Stress generation

Polishing

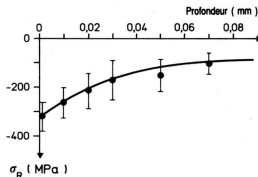
- Obtention of better roughness
- Eliminate of machining stripes
- Generation of compressive residual stress
- Low affected depth



● 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_h^{\parallel} MPa	σ_h^{\perp} MPa	$b(2\theta)$ °	σ_h^{\parallel} MPa	σ_h^{\perp} MPa	$b(2\theta)$ °
rectifiée $Ra=1 \mu\text{m}$	+ 65 (± 30)	- 190 (± 30)	2,70	- 350 (± 25)	- 350 (± 25)	2,75
Fraisée $Ra=3,2 \mu\text{m}$	- 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_h^{\parallel} contrainte résiduelle longitudinale
 σ_h^{\perp} contrainte résiduelle transversale
 θ angle de Bragg (§ 6,223)

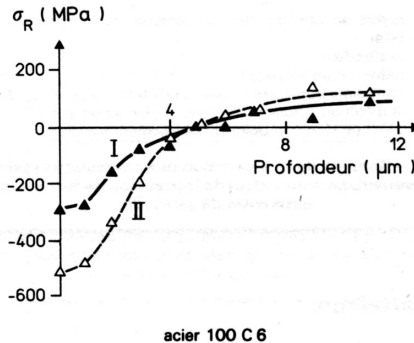
- Self-hooping¹
 - Pressure higher to the use pressure in the case of thick tube
 - Creation of plastic deformation for the interior of the tube
 - Application : cannon tubes
- Preconformage
 - Used when loading is well known
 - Plastic deformation in order to stabilize yield stress of material
 - Application : 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

Thermomechanical Surface Treatments

Residual stress generation

Grinding

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

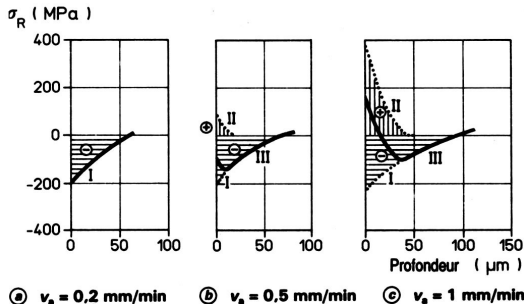


- I contrainte résiduelle parallèle aux stries de rectification
II contrainte résiduelle perpendiculaire aux stries de rectification

Residual stress generation

Usinage

- Mechanical and thermal aspects
- Anisotropy of the stresses (machining transverse direction \neq 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



v_s vitesse d'avance de meule

I contrainte d'origine mécanique (frottement)

II contrainte d'origine thermique

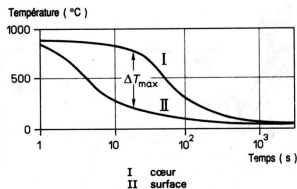
III contrainte résultante

Thermal Surface Treatments

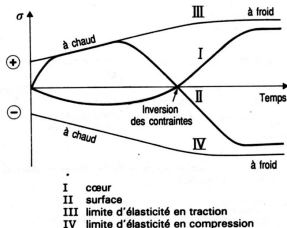
Residual stress generation

Superficial quenching – without phase transformation 1/2

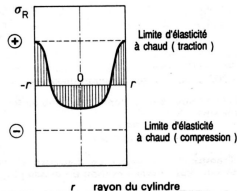
- Free stress deformation of dilation (temperature gradient) \Rightarrow plastic deformation \Rightarrow residual stresses
- Temperature effects
- Possibility of shrinkage cracks creation by local plastification of the material (yield stress)



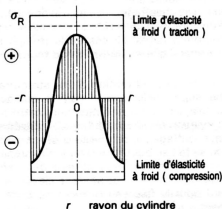
(a) évolution de la température en fonction du temps



(b) évolution des contraintes en fonction du temps



(c) contrainte résiduelle au cours de la trempe

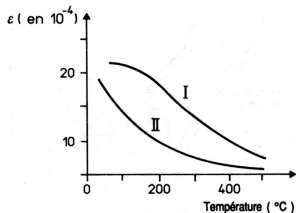


(d) contrainte résiduelle après la trempe

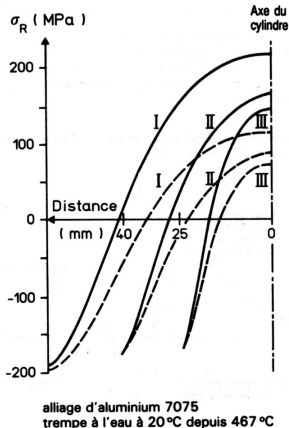
Residual stress generation

Superficial quenching – without phase transformation 2/2

- Geometry effect
- Material effect



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



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

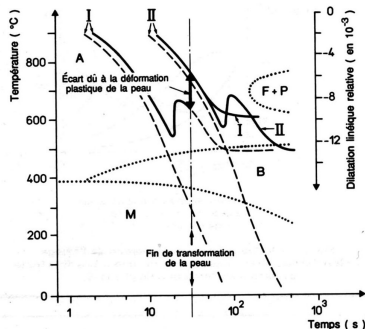
--- contraintes résiduelles circonférentielles
— contraintes résiduelles longitudinales
 r rayon du cylindre plein

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

Residual stress generation

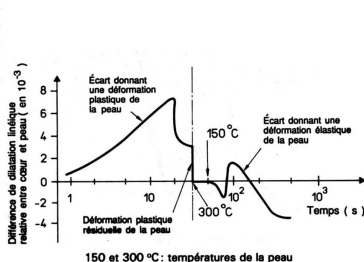
Superficial quenching – with phase transformation 1/2

- Stress free deformation due to phase transformation (austinite \Rightarrow martensite) : volume deformation \Rightarrow residual stresses
- Application : stell (special grade)



A austénite courbes TRC I peau
 B bainite --- courbes de refroidissement II cœur
 F ferrite — courbes de dilatation relative
 M martensite
 P perlite

Ⓐ évolution de la température et de la dilatation relative en fonction du temps



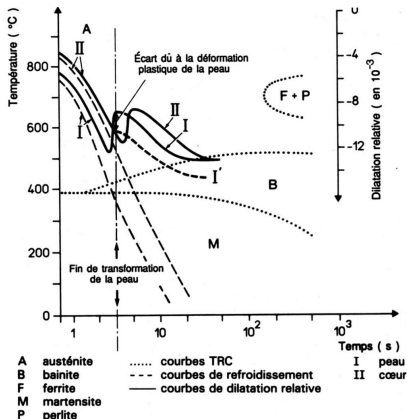
Ⓑ évolution des déformations de la peau en fonction du temps

acier 15 CDV 6
 trempé à l'eau

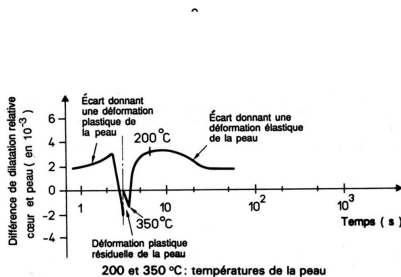
Residual stress generation

Superficial quenching – with phase transformation 2/2

• 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

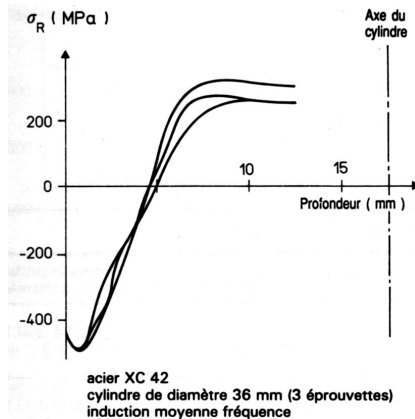
acier 15 CDV 6
trempé à l'eau

Tempe Superficial quenching with phase transformation – 10 mm diameter cylinder

Residual stress generation

Superficial quenching – Induction

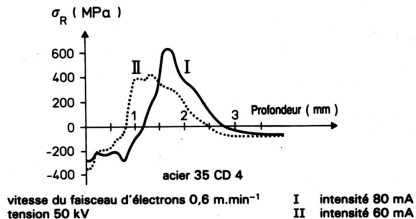
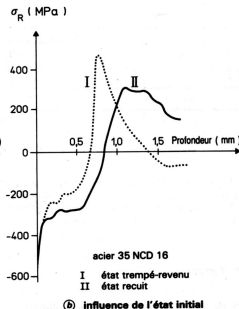
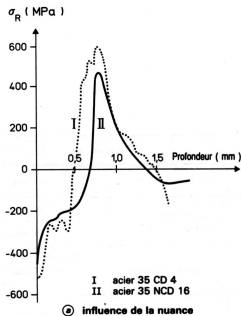
- Creation of Foucault current with an inductor
- Metallic material
- Simple geometry of parts
- Application : cranshaft, sawtooth



Residual stress generation

Superficial quenching – High energy beam processing (laser, electron)

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

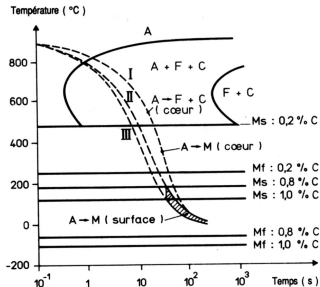


Thermochemical Surface Treatments

Residual stress generation

Carburising – Principle

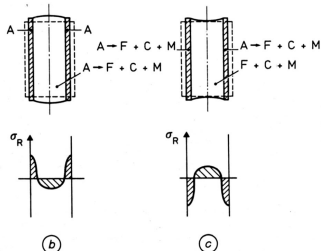
- Carbon content increasing of the material ($T \geq A_{C3}$) \Rightarrow low carbon steels
- Quenching \Rightarrow austenite-martensitic transformation \Rightarrow volume variation



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



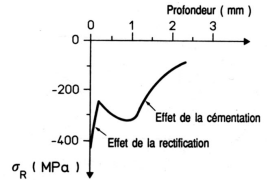
--- pièce initiale
▨ couche superficielle cémentée

- (b) contraintes résiduelles après transformation
 $A \rightarrow F + C + M$ du cœur
- (c) contraintes résiduelles résultant de la transformation
 $A \rightarrow F + C + M$ en surface (état final)

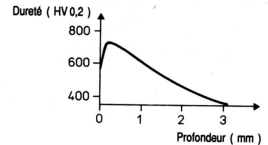
Residual stress generation

Carburising – Effets

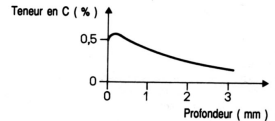
- Increasing of surface hardness
- Affected depth around 1 mm
- Problem due to the non transformed austenite (in generally it is good for mechanical behaviour)
- Be careful to the deformation of the parts during quenching (quenching under pressure)
- Decarburising during tempered treatment (indispensable)



(a) contraintes résiduelles



(b) dureté



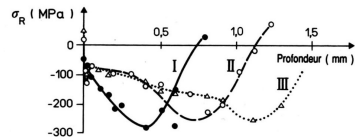
(c) teneur en carbone

acier 16 NC 6

Residual stress generation

Carburising – Influences of material

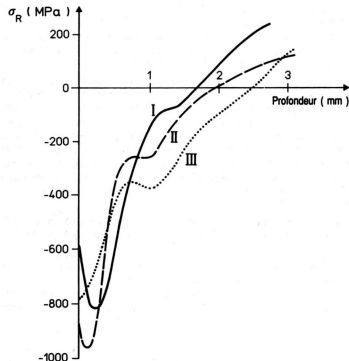
- Carbon medium
 - Solid
 - Gaseous (hydrocarbur – CH_4)
 - Liquid
 - Ionic (in development)
- Transformation is fonction of material composition
- Special grades developed (0,1% to 0,2% of carbon)



cémentation gazeuse
température de trempé 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 trempé 880 °C

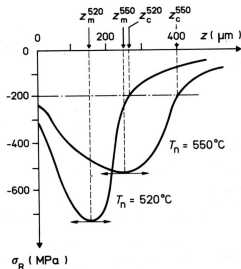
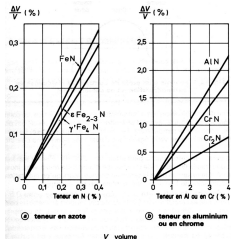
I épaisseur cémentée 0,2 mm
II épaisseur cémentée 0,4 mm
III épaisseur cémentée 0,8 mm

Ⓑ acier XC 18 (d'après Koch)

Residual stress generation

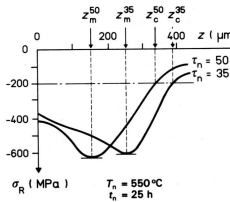
Nitriding – Principle

- Nitride medium
 - Solid
 - Gazeous (amoniac – NH_3)
 - Liquid
 - Ionic
- Transformation as function of material composition



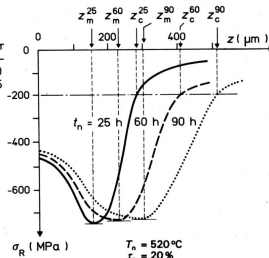
③ influence de la température T_n

$t_n = 25$ h
 $t_n = 20$ h



④ influence du taux de dissociation τ_n

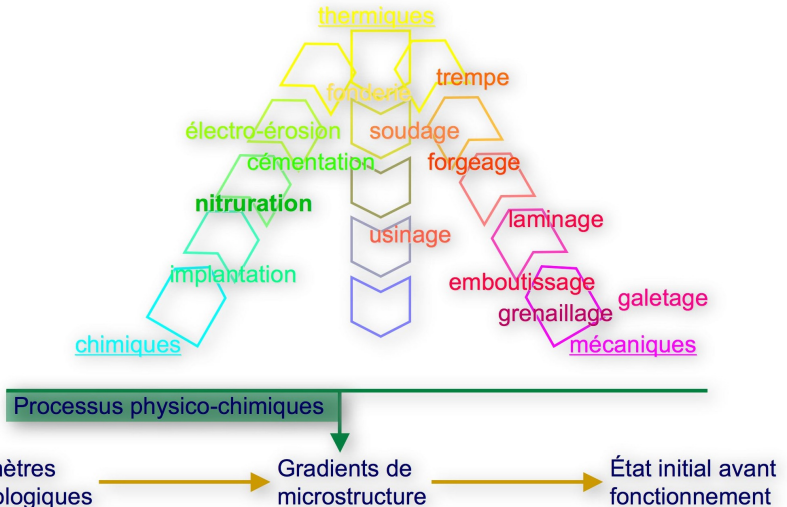
acier 32 CDV 13
 z profondeur



⑤ influence de la durée t_n

Residual stress generation

Sumarize



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- Précontraintes et traitements superficiels, J.Barralis, L.Castex, G.Meader, Techniques de l'Ingénieur, traité Matériaux métalliques, M 1 180.
- A Review of Residual Stress Measurement Methods - A Guide to Technique Selection, F A Kandil, J D Lord, A T Fry and P V Grant, NPL Report MATC(A)O4, ISSN 1473-2734.
- Residual stress Part 1 – Measurement techniques, P. J. Withers and H. K. D. H. Bhadeshia, Materials Science and Technology April 2001 Vol. 17
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