Matériaux avancés

Advanced Materials

Residual Stresses Origin

Origines des contraintes résiduelles

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Outline

Simple example

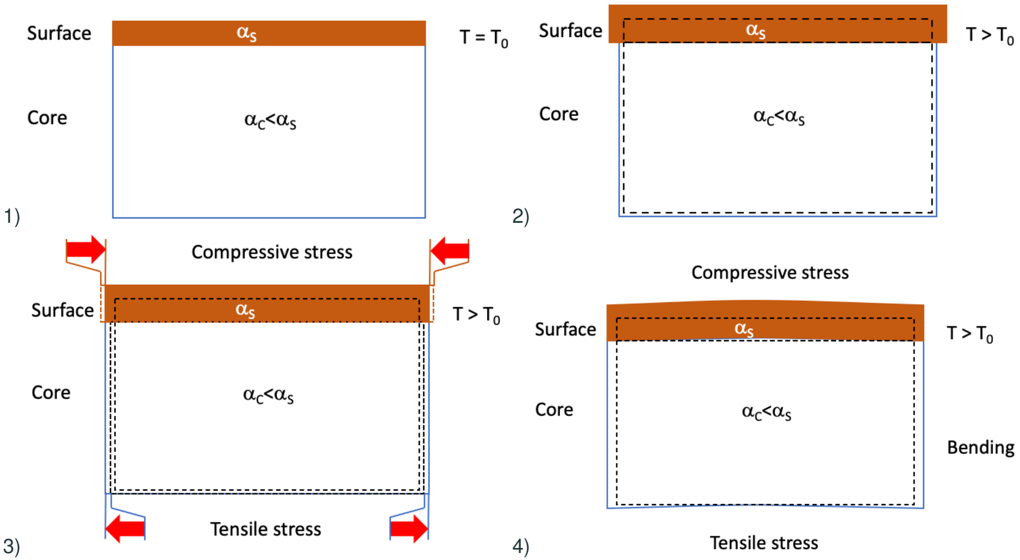
Element of continous mechanics

Residual Stress Relaxation

Simple example

Origin of residual stresses

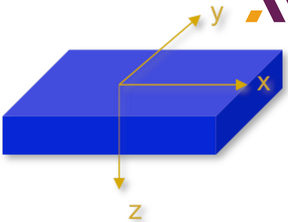
Coating under temperature modification – Stress generation



Element of continous mechanics

Origin of residual stresses

Element of continous mechanics – Basic equations



- Equilibrum equations

$$\text{div}\underline{\underline{\sigma}} = 0 \Leftrightarrow \sigma_{ij,j} = 0 \text{ with i=x,y,z and j=x,y,z}$$

- Compatibilty equations

$$\text{inc}\underline{\underline{\sigma}} = 0 \Leftrightarrow \epsilon_{ii,jj} + \epsilon_{jj,ii} - 2\epsilon_{ij,ij} = 0 \text{ for the contitnuity of fiber curvature}$$

$$\left(\epsilon_{ki,j} + \epsilon_{ij,k} - \epsilon_{jk,i}\right)_j - \epsilon_{ii,jk} = 0 \text{ for the contitnuity of rotation}$$

- Geometry effect to solve partial differential equation using limit conditions and initial conditions
  - direct integration (for simple geomtry)
  - finite elements methods
  - initial conditions and **origin of deformation must be taken into account** (function of material)

Origin of residual stresses

Element of continous mechanics – Origin of deformations

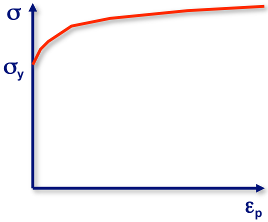
- Deformations
  - $$\underbrace{\underline{\underline{\epsilon}}}_{\text{total deformation}} = \underbrace{\underbrace{\underline{\underline{\epsilon}}^e}}_{\substack{\text{elastic deformation} \\ \text{due to applied or residual stress}}} + \underbrace{\underline{\underline{\epsilon}}^l}_{\text{free stress deformation}}$$
  - $$\underline{\underline{\epsilon}}^l = \underbrace{\underbrace{\underline{\underline{\epsilon}}^d}_{\text{deviatoric deformation}}}_{\text{with } \mathrm{tr}\underline{\underline{\epsilon}}^d = 0} + \underbrace{\underbrace{\underline{\underline{\epsilon}}^s}_{\text{spherical deformation}}}_{\text{with } \mathrm{tr}\underline{\underline{\epsilon}}^s = \epsilon^s_{xx} + \epsilon^s_{yy} + \epsilon^s_{zz} \neq 0}$$
    $$\begin{pmatrix} \epsilon^d_{xx} & 0 & 0 \\ 0 & \epsilon^d_{yy} & 0 \\ 0 & 0 & -2\epsilon^d_{zz} \end{pmatrix} \qquad \begin{pmatrix} \epsilon^s_{xx} & 0 & 0 \\ 0 & \epsilon^s_{yy} & 0 \\ 0 & 0 & \epsilon^s_{zz} \end{pmatrix}$$
- Microstructure effect

$\underline{\underline{\epsilon}}^s$	$\underline{\underline{\epsilon}}^d$
expension	plasticity
precipitation	creep
...	...
volume variation	dislocation motion, diffusion

Origin of residual stresses

Element of continous mechanics – Constitutive law of the material

- Elasticity
  - $\underline{\underline{\sigma}} = \underline{\underline{\underline{\underline{C}}}} : \underline{\underline{\epsilon}} \Leftrightarrow \sigma_{ij} = C_{ijkl}\epsilon_{kl}$ with $\underline{\underline{\underline{\underline{C}}}}$ elastic tensor
  - $\underline{\underline{\epsilon}} = \underline{\underline{\underline{\underline{S}}}} : \underline{\underline{\sigma}} \Leftrightarrow \epsilon_{ij} = S_{ijkl}\sigma_{kl}$ with $\underline{\underline{\underline{\underline{S}}}}$ stiffness tensor
  - $\underline{\underline{\underline{\underline{C}}}} = \underline{\underline{\underline{\underline{S}}}}^{-1}$
- Plasticity
  - $\underline{\underline{\sigma}} = g(\underline{\underline{\epsilon}}^p)$ if $\sigma^{eq} > \sigma_y$
  - g constitutive law of the material (generaly non linear)
  - σ^{eq} equivalent stress (von Mises, Tresca,...)
  - σ_y yield stress



Origin of residual stresses

Element of continous mechanics – Constitutive law of the material

- Equations to solve

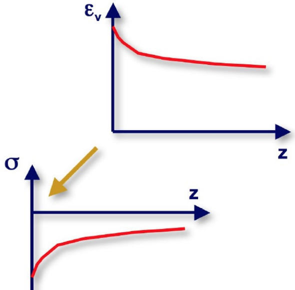
$$\left.\begin{array}{l}\boxed{\sigma_{ij,j}} = 0 \\ \epsilon_{ii,jj} + \epsilon_{jj,ii} - 2\epsilon_{ij,ij} = 0 \\ \left(\epsilon_{ki,j} + \epsilon_{ij,k} - \epsilon_{jk,i}\right)_{,j} - \epsilon_{ii,jk} = 0\end{array}\right\} \text{part geometry}$$

$$\epsilon_{ij} = \boxed{\epsilon^e_{ij}} + \epsilon^d_{ij} + \epsilon^s_{ij} \;\} \text{ stress origine} \Leftrightarrow \text{mechanical processings or surface treatments}$$

$$\boxed{\sigma_{ij}} = C_{ijkl}\epsilon^e_{kl} \;\} \text{ elasticity}$$

$$\boxed{\sigma_{ij}} = g(\epsilon^p_{kl}) \;\} \text{ plasticity}$$

- Relationship between residual stress and microstruture effect : free-stress strains gradient effect (in-depth)



Residual Stress Relaxation

Residual stress relaxation

Origin – Use of material

- Equations to solve

$$\left.\begin{aligned} &\boxed{\sigma_{ij,j}} = 0 \\ &\epsilon_{ii,jj} + \epsilon_{jj,ii} - 2\epsilon_{ij,ij} = 0 \\ &\left(\epsilon_{ki,j} + \epsilon_{ij,k} - \epsilon_{jk,i}\right)_{,j} - \epsilon_{ii,jk} = 0 \end{aligned}\right\} \text{part geometry}$$

$$\epsilon_{ij} = \boxed{\epsilon^e_{ij}} + \epsilon^d_{ij} + \epsilon^s_{ij} \;\Big\}\; \text{stress origine} \Leftrightarrow \text{use of material}$$

$$\boxed{\sigma_{ij}} = C_{ijkl}\epsilon^e_{kl} \;\Big\}\; \text{elasticity}$$

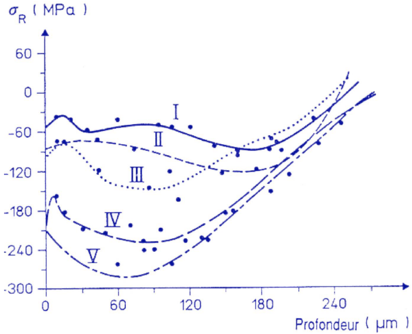
$$\boxed{\sigma_{ij}} = g(\epsilon^p_{kl}) \;\Big\}\; \text{plasticity}$$

- Use of material
  - phase transformation due to temperature change, deformation, ...
  - new free-stress strain fields (plasticity, micro plasticity, ...)
  - new boundaries by machining, cutting, ...
- Residual stress field modification / stress relaxation
  - it is not a local phenomenon
  - whole geometry of the part / sample must be taken into account (structural effect on re-equilibrum)
  - notion of residual stress relaxation (stress field go to none) or residual stress redistribution or modification

Residual stress relaxation

Shot peening – Temperature effect

- Thermal relaxation
  - 45SiCrMo6 steel (spring steel)
  - I) 64h/160℃, II) 4h/160℃, III) 2h/150℃, IV) 2h/100℃, V) reference



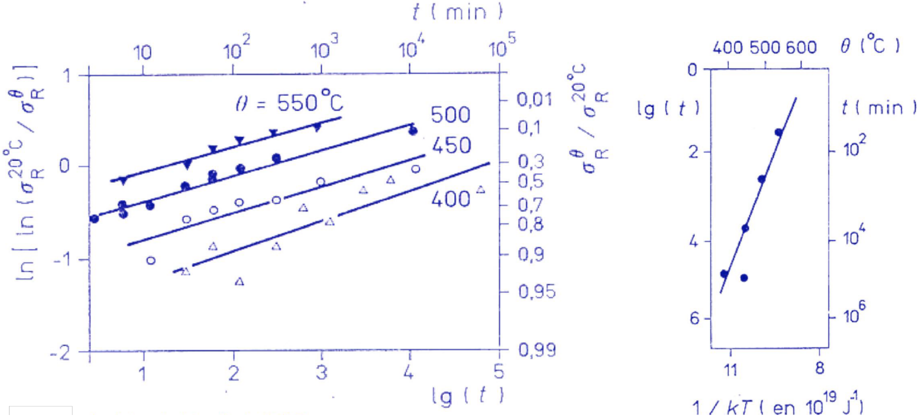
- Origne
  - dislocation mouvement
  - plastic strain relief
  - thermal activate processus
- Equation

$$\epsilon^d_{ij} = \epsilon^r_{ij}(T, t, ...)$$

Residual stress relaxation

Shot peening – Temperature effect

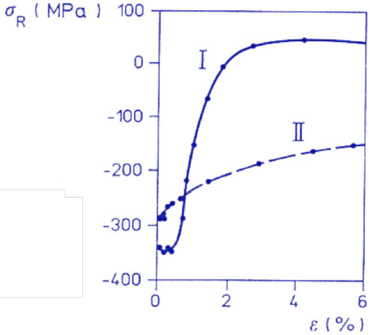
- Exemple of a model (Vöhringer 1983)
  - $\frac{\sigma_R^{\theta}}{\sigma_R^{20°C}} = \exp\left(-Ct^m \exp\left(\frac{-Q}{kT}\right)\right)$
    $\sigma_R^{20°C}$ residual stress @ 20°C
    σ_R^{θ} residual stress @ the temperature θ
    $Q = 4.10^{-19}$J



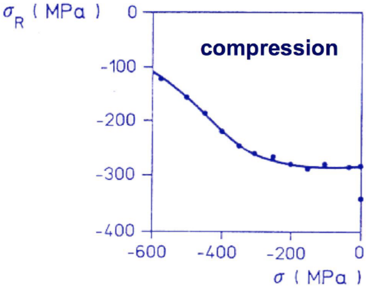
Residual stress relaxation

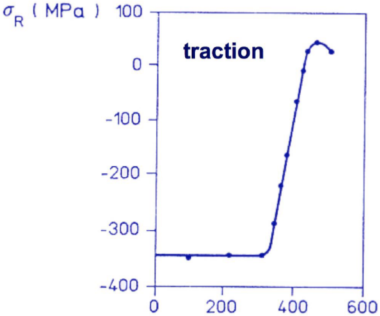
Shot peening – Mechanical effect

- 2024 aluminum alloy under uniaxial plastic deformation



Applied stress : I) compressive, II) tensile





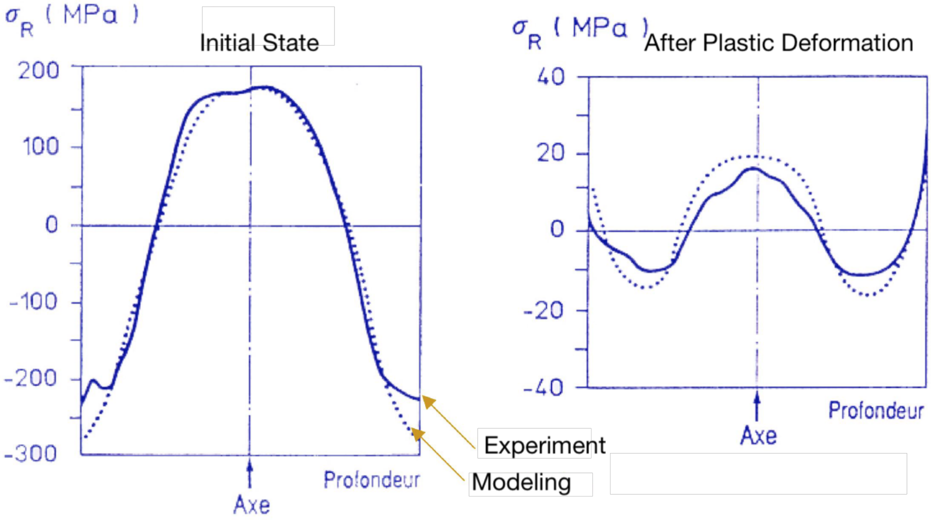
- Origne
  - plastic deformation → increasing of dislocation density
- Equation

  $\epsilon_{ij}^{d} = \epsilon_{ij}^{p}(\sigma)$

Residual stress relaxation

Thick plate after quenching – Uniaxial plastic deformation

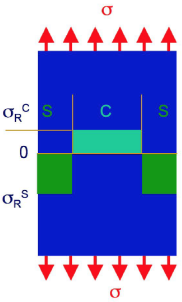
- 7075 aluminum alloy, water cooling @ 20℃, 70 mm thickness

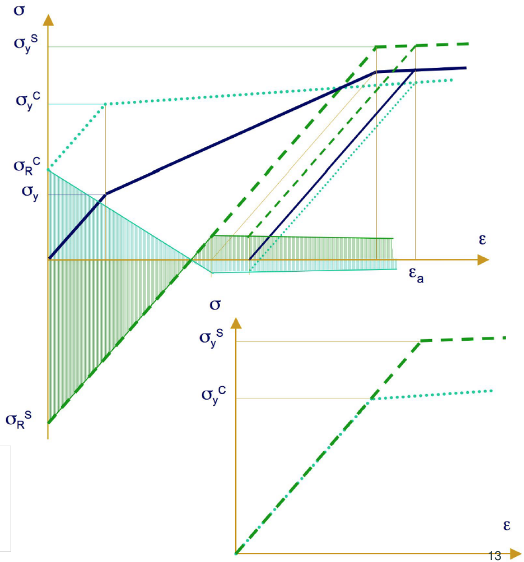


Residual stress relaxation

Thick plate after quenching – Uniaxial plastic deformation

- plastic deformation under tensile stress
  - not the same mechanical behaviour between the surface (S) and the core (C) of the material
  - yield stress (σ_y^C, σ_y^S) and hardening coefficient

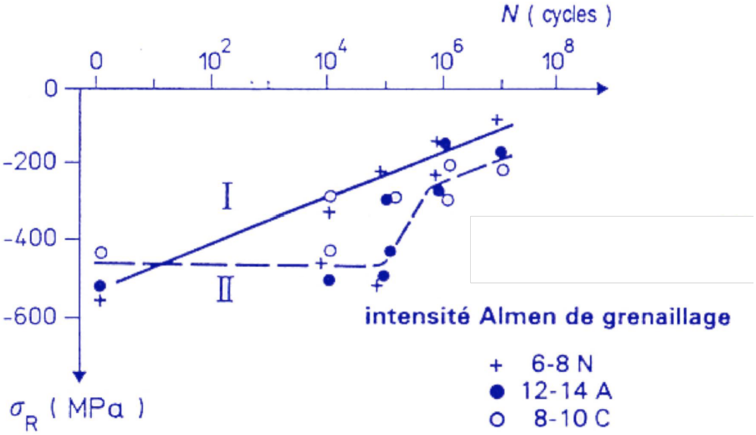




Residual stress relaxation

Shot peening – Cyclic loading effect (fatigue)

- 35CrMo4 steel quenched and tempered



Applied stress : I) ±330 MPa, II) ±230 MPa,

- Origne
  - Oligocyclic fatigue $\sigma > \sigma_y$, equivalent to uniaxial loading
  - @ the microscopic scale : microplasticity and dislocation mobility → if stable rearrangement, no important stress relaxation