Transformation et comportement des matériaux

Materials behaviour and processing

Creep of materials

Fluage des matériaux

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Outline

Creep (*Fluage*) | Phemenology

Temperature Effect | Definition

Definitions

- Under **mechanical loading @ room temperature** which do not generate **permanante strain**, materials are starting to creep in **non revesible** way when the **temperature increases**
- Low temperature : $\underline{\epsilon}_p = f(\underline{\sigma})$, strain is independent of time → **plasticity**
- Hight temperature : $\underline{\epsilon}_v = f(\underline{\sigma}, t, T)$, strain is function of time and temperature → **visco-plasticity**
- Creep is a slow and continue deformation function of **time**, **temperature** and **applied stress**

What temperature ?

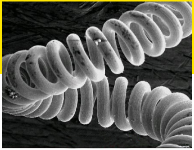
- The temperature when creep starts is linked to the **Melting temperature** T_m of material
- For organic polymers creep occurs when temperature is greather than the glass transition temperature T_g

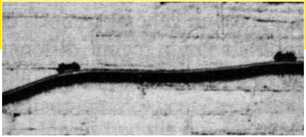
Creep	Metals	Ceramics	Polymers
T≥	0,3–0,4 T_m	0,4–0,5 T_m	T_g

Temperature in Kelvin (K)

Creep | Phemenology

Temperature Effect | Exemples



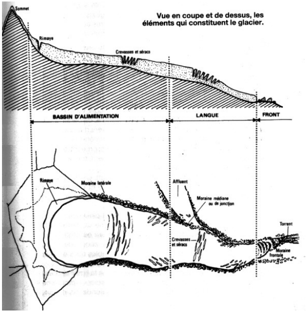


Tungsten

- $T_m > 3\ 000$ K
  - Room temperature $T = 300$ K : very low temperature
  - Tungsten filament lamp $T = 2\ 000$ K : hight temperature
  - Creep of filament under this self-weight, light off is due to shortcircuit between the wires

Lead

- $T_m = 600$ K
  - Room temperature $T = 300$ K : hight temperature
  - Slow creep under this self-weight



Ice

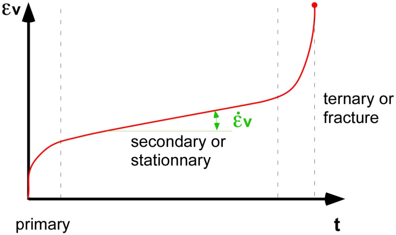
- T_m K
  - $T \lesssim T_m$: very hight temperature
  - Creep of glaciers

Creep | Phemenology

Phemenologic Laws – Schematisation

Definition

- Tensil test with a constant loading @ temperature

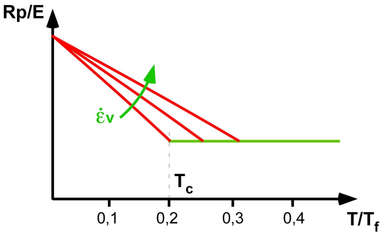


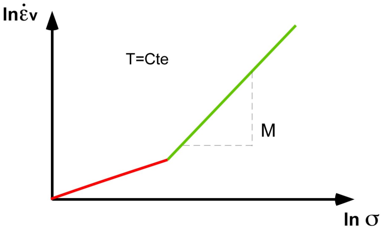
- $\dot{\epsilon_v} \nearrow$ – Primary creep
  - Observed @ low temperature ($T \leq 0.3T_m$)
  - Empiric law : $\epsilon_v = A \ln(1 + \frac{t}{t_0})$
- $\dot{\epsilon_v} \rightsquigarrow$ – Secondary or stationary creep
  - Important when $T > 0,3T_m$
  - Norton law : $\frac{d\epsilon_V}{dt} = \dot{\epsilon_V} = \left(\frac{\sigma - \sigma_S}{K}\right)^M$
- $\dot{\epsilon_v} \nearrow$ – Ternary or crack creep
  - High increasing speed of strain, important damage (void, localized deformation) and failure (final crack)

Creep | Phemenology

Phemenologic Laws – Secondary Creep

- Athermic stage
  - Experimently $\frac{R_p}{E} = f(T, \dot{\epsilon}_v)$ for $T > T_c \approx 0,2 - 0,3T_m$
- Stress dependance
  - $0,3T_m < T < T_m$: Norton law $\dot{\epsilon}_v = \left(\frac{\sigma - \sigma s}{K}\right)^M$ with σ_s internal stress threshold
  - $T > 0,5T_m$: $\sigma_s = 0$ $\dot{\epsilon}_v = \left(\frac{\sigma}{K}\right)^M$ with $M = 3 - 8$ function of material
  - $T > 0,7T_m$ and low applied stress : $M = 1$ whatever material



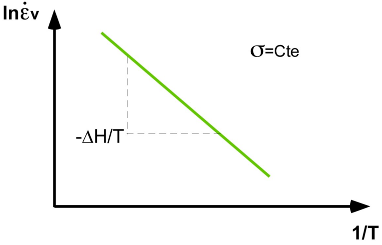


Creep | Phemenology

Phemenologic Law – Secondary Creep

- Temperature Dependance
  - For a constant applied stress and $T > 0.5T_m$, $\dot{\epsilon}_v$ follows Arrhenius law $\dot{\epsilon}_v = C \exp \frac{-\Delta H}{RT}$
  - R universal gaz constant, ΔH thermal activation enthalpy that can be equal to autodiffusion enthalpy ΔH_A in the case of pure metal

Metal	M	ΔH	ΔH_A
		kJ.mol^{-1}	
Al	4.4	142.1	142.1
Cu	4.8	202.3	196.9
Ni	4.6	278	279.2
Zn	6.1	90.3	101.6



- Time dependance
  - Morgan-Grant law : $\dot{\epsilon}_v^q t_R = C$ with $q \approx 1$
  - Failure time life : $t_F = C \left(\frac{\sigma}{K}\right)^M \exp\left(-\frac{\Delta H}{RT}\right)$
- Design of creep resistant workpiece
  - For a choosen time life t and use conditions for temperature and applied stress :
    - Creep strain ϵ_v must be compatible with the use of workpiece (ex. engine blade)
    - Creep ductility ϵ_{vF} (failure deformation) must be grather than ϵ_v
    - Failure time life t_R must be grather than use time life t (with security factor)

Creep | Microstructural

Creep Mechanism

A good creep behaviour must be obtain with high melting temperature T_m of material

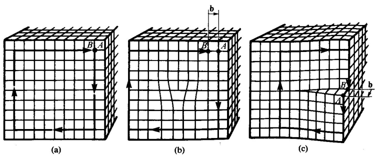
- Low temperature $T < 0,3T_m$: plasticity domain
  - Creep is negligeable
  - Material can be permanantly deformed if the applied stress σ is sufficient to activate the motion of dislocations in their slide planes to cross intrensec defects (internal friction, Frank dislocations) or other defetcs (solute atoms, precipitates).
- Mean temperature $0,3T_m < T < 0,7T_m$: dislocation creep domain
  - Dislocation released by the atom diffusion can cross the defects by changing their sliding planes by climbing. Their mouvements generate a continue and permanent deformation of secondary creep that is produced under applied stress σ. This stress is less important than the stress that induces plastitcity @ low temperature (with thermal activation)
- High temperature $T > 0,7T_m$: diffusion creep domain
  - Creation of permanent deformation by modifying the shape of the grain due to the high speed of atom diffusion in the grain, anisotropic diffusion in relation with the direction of applied stress σ

Summarize

- Dependance in temperature of creep is always controled by the diffusion (thermal actived)
- Dependance in stress of creep is controled by :
  - The crossing of defects for dislocation creep (Norton law with M exponent)
  - The control of atom diffusion flux by the stress σ for diffusion creep ($\dot{\varepsilon}_v \approx \sigma$, $M = 1$)

Creep | Microstructural

Dislocation Creep – Principle



- Bypass of the defects
  - Bypass of the defects by the dislocation is characterized by the energy gap q_0 and the range L

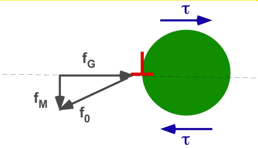
	q_0	L	Defect
Low	$< 0,2\mu b^3$	$1 - 10b$	Internal friction, solid solution
Mean	$0,2 - 1\mu b^3$	$100 - 1000b$	Frank network, cutted precipitates
High	$\leq \mu b^3$	$100 - 1000b$	Bypass precipitates

b Burgger vector moludus $\approx a$ lattice parameter, μ shear modulus $\frac{E}{2(1+\nu)}$

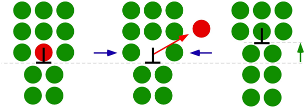
  - For temperature $T > 0,3T_m$, crossing defects
    - is low for short range and is reversible
    - is high for long range and is non reversible
  - Creep is controled by strong defects : precipitates and Frank network
- Internal stress
  - When the defects are crossing, sliding can not be start only if applied stress $\sigma > \sigma_s$ mean internal stress due to the high rage actions of the others dislocations
  - σ_s is function of temperature (by elastic modulus) and deformation rate $\dot{\epsilon}_v$ wich control the evolution the dislocation cells of Frank network

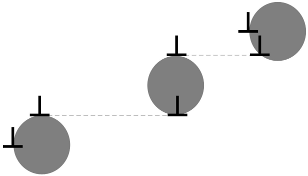
Creep | Microstructural

Dislocation Creep – Mechanism



- Strong defects : precipitates
  - The reaction f_0 [1] of precipitate on dislocation anchored
    - The load $f_e = \tau b$ for dislocation sliding in their plane
    - The load f_M for dislocation climbing
  - $T < 0,3T_m$: classical plasticity $\tau > \tau_{OR}$ crossing by bypass the defect in sliding plane
  - $T > 0,3T_m$: thermal activation that produce the atomic diffusion and the climbing of dislocations under f_M load
- Climbing mechanism





- Sliding mechanism
  - Sliding if $\sigma > \sigma_s$ mean internal stress due to the long range action of the others dislocations
- Speed of macroscopic creep $\dot{\epsilon}_v$
  - $\sigma \nearrow \rightarrow f_M \nearrow \rightarrow$ flux of unanchored dislocation $\nearrow \rightarrow$ sliding speed $\nearrow \rightarrow \dot{\epsilon}_v \nearrow$
  - $M \ggg 1 \rightarrow$ when $\sigma \nearrow$ and $\dot{\epsilon}_v \nearrow$ quickly

Dislocation Creep is Important for Stress σ Close to the Yield Stress σ_y

1. $\vec{f_0} = \vec{f_e} + \vec{f_M}$

Creep, microstrutural

Diffusion Creep – Principle

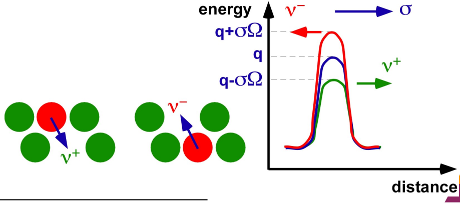
- Under the action of thermal activation energy, gap frequencies ν^+ et ν^- of energy barrier q are equal

$$\nu = \nu^+ = \nu^- = \nu_0 \exp\frac{-q}{kT} \rightarrow <\nu> = \nu^+ - \nu^- = 0 \quad \text{(k Bolztman constant)}$$

- Action of stress σ give to the atome with the volume Ω, mechanical energy $\sigma\Omega$ producing diffusion flux facilitating the gap in the direction of applied stress

$$\nu^+ = \nu_0 \exp - \frac{q - \sigma\Omega}{kT} \quad \nu^- = \nu_0 \exp - \frac{q + \sigma\Omega}{kT} \quad <\nu> = \nu^+ - \nu^- = 2\nu_0 \exp - \frac{q}{kT} \operatorname{sh}\frac{\sigma\Omega}{kT}$$ [2]

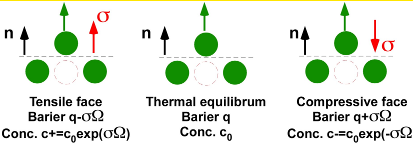
- Applied stress σ control the diffusion flux $D = D_0 \exp - \frac{\Delta H}{kT} \operatorname{sh}\frac{\sigma\Omega}{kT}$



2. $\operatorname{sh}x = (e^x - e^{-x})/2$ hyperbolic sinus

Creep, microstrutural

Diffusion Creep – Mechanics

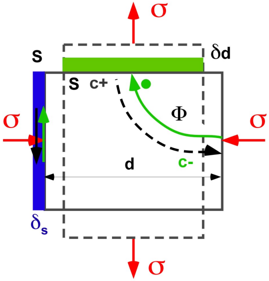


- Void diffusion
  - Void creation = Atome ejection
  - Diffusion of voids and atoms
  - Void flux is opposed to the atom flux
  - Creep speed : $\dot{\epsilon}_v = \Phi \frac{b^3}{d^3}$ with Φ void flux across S
- Volume diffusion $T > 0,7T_m$ (Herring-Nabarro)

$$S = d^2 \; \dot{\epsilon}_v \approx \frac{D}{d^2} \frac{\sigma b^3}{kT}$$

- Grain boundaries diffusion $0,5T_m < T < 0,7T_m$ (Coble)

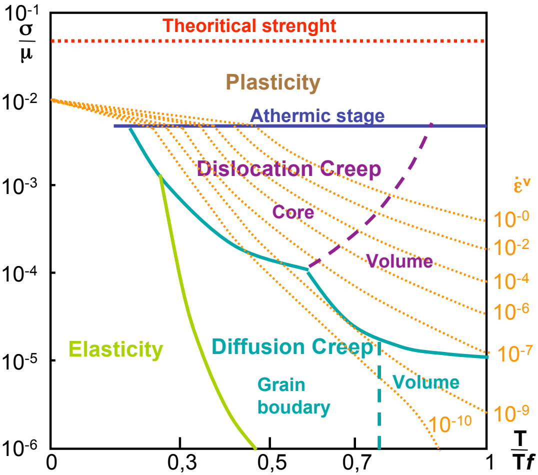
$$S = d\delta_s \; \dot{\epsilon}_v \approx \frac{D\delta_s}{d^3} \frac{\sigma b^3}{kT}$$



- Diffusion Creep
  - $\dot{\epsilon}_v \approx \sigma$: newtonian viscous behavior (Norton $M = 1$)
  - $\dot{\epsilon}_v \approx D = D_0 \exp -\frac{Q}{kT}$: creep speed $\nearrow$ with T
  - $\dot{\epsilon}_v \approx \frac{1}{d^2}$: creep speed $\nearrow$ when grain size $\searrow$

Creep, microstrutural

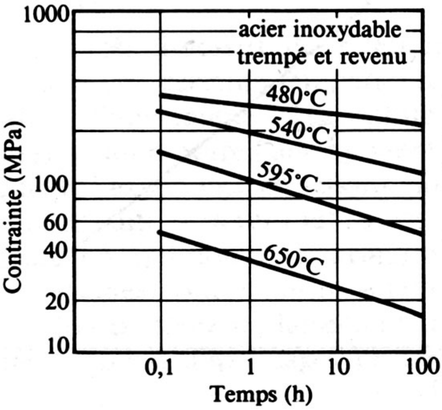
Creep Map

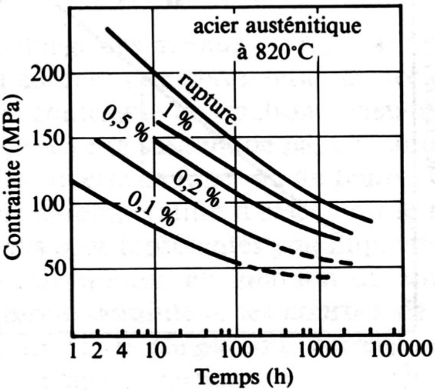


- avec $\sigma = \sqrt{\frac{1}{2}\mathrm{Tr}(\underline{\sigma}_D^2)}$ et $\dot{\epsilon}^v = \sqrt{2\mathrm{Tr}(\underline{\dot{\epsilon}}^2)}$ (s^{-1})

Creep, microstrutural

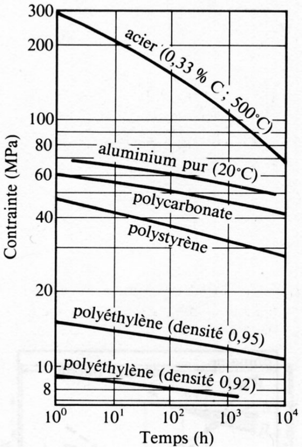
Numerical data – Stainless Steels

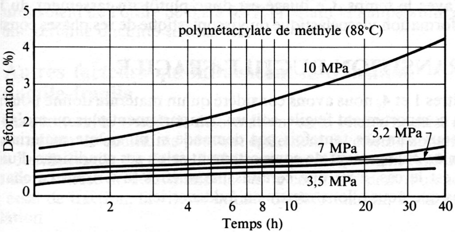




Creep, microstrutural

Numerical data – Organic polymers

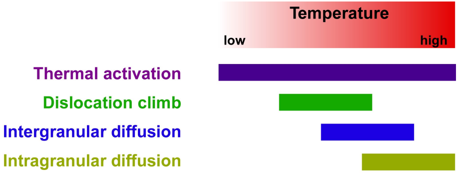




Creep

Sumarize

- Phenomenological aspects : 3 stages
  - Primary
  - Secondary or stationary
  - Tertiary or crack
- Temperature influence



- Influence of melting or transition temperature of the material
- Influence of the microstructure (defects against motion of dislocations)
  - Dislocation creep is important under high stress
    - Decreasing the motion of dislocation by incresing the defetcs (**stables** precipitates @ used temperature)
    - Materials with high intrensec friction of cristalline network (covalentes bonding – oxydes, silicates, carbites et nitrates)
  - High diffusion creep (small grains, low stress @ high temperature)
    - Increase the size of grains using adapted heat treatments
    - Force intergranular diffusion to reduce grain boundaries sliding

Creep

Creep exemple

Creep of a commemorative marble panel – Récollets abbey, Béthune, Pas-de-Calais, France - © André Lardon