



# **Mechanical Properties of Materials, Processing and Design**

#### **Topic 3. Creep behaviour**



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# **3.1. INTRODUCTION**

- Elastic-plastic behavior:  $\varepsilon = f(\sigma)$ .
- This behavior is typical of 'low' temperatures.
- At 'high' temperatures, the variables 't' and 'T' play a role:  $\epsilon = f(\sigma, t, T)$ .
- This behavior can take place, for example, in structural components of energy conversion facilities (nuclear and thermal power stations, etc.), which operate at high temperatures.







# **3.1. INTRODUCTION**

• From a structural point of view, we can distinguish two situations:



- Creep and relaxation are the 'two sides of the same coin'.
- Both phenomena are strongly affected by **temperature**.





# **3.1. INTRODUCTION**

- What does 'high' and 'low' temperature mean?
- The temperature at which materials begin to creep depends on the melting temperature (<u>absolute scale</u>), T<sub>M</sub>.

 $T > 0.3 T_M - 0.4 T_M$  for metals.

 $T > 0.4 T_M - 0.5 T_M$  for ceramic materials.

 In polymers, the phenomenon is controlled by the glass transition temperature (T<sub>G</sub>). Most polymers flow at room temperature (> T<sub>G</sub>). Below this glass transition temperature, polymers become hard and brittle in some occasions, and the phenomenon disappears.





# **3.1. INTRODUCTION**

#### SOME VISCOUS BEHAVIOR EXAMPLES:

- At room temperature, concrete shows a viscous behavior that entails prestressing losses.
- The lamp filaments, made out of tungsten, break due to creep phenomenon (temperature of about 2000 °C).
- Lead pipes undergo creep at room temperature.
- Displacement in glaciers is caused by a flow process.







# **3.1. INTRODUCTION**







# 3.1. INTRODUCTION IMPORTANCE OF VISCOUS BEHAVIOR:



- a) Displacement limit (service limit state, SLS).
- **b)** Fracture (ultimate limit state, ULS).
- c) Relaxation limits (SLS or ULS).
- d) Buckling (ULS).





# 3.1. INTRODUCTION IMPORTANCE OF VISCOUS BEHAVIOR:

**EXAMPLE**: two components susceptible to undergo creep under in-service conditions.







# **3.2. VISCOSITY**

- Isaac Newton (1642-1727) was the first to propose a viscous behavior model (*Philosophiae Naturalis Principia Mathematica*).
- The experiment consisted of a small plate floating on water the plate being subjected to a constant horizontal force.







# 3.2. VISCOSITY

#### **REPRESENTATIVE VALUES OF VISCOSITY:**

- Both gases and liquids are viscous fluids; as discussed later on, even solids are viscous fluids.
- In general, gas viscosity is lower that that of liquids.
- Gas viscosity increases with temperature; theoretically:

$$\eta \propto \sqrt{T}$$

• Liquid viscosity decreases with temperature.

Gas	T (ºC)	η (Pa⋅s)
N <sub>2</sub>	25	1.78·10 <sup>-5</sup>
H <sub>2</sub> O	100	1.26·10 <sup>-5</sup>
H <sub>2</sub> O	200	1.64·10 <sup>-5</sup>
Aire	25	1.12·10 <sup>-5</sup>

Líquido	T (ºC)	η (Pa⋅s)
Vidrio	500	1.10 <sup>12</sup>
Betún	100	1.10 <sup>8</sup>
Polímero	200	1.10 <sup>3</sup>
Jarabe	25	1.10 <sup>2</sup>
Miel	25	1.10 <sup>1</sup>
Glicerol	25	1·10 <sup>-1</sup>
Aceitre de oliva	25	1·10 <sup>-2</sup>
H <sub>2</sub> O	25	1.5·10 <sup>-3</sup>
H <sub>2</sub> O	100	3.10-4





### **3.3. NEWTONIAN AND NON-NEWTONIAN BEHAVIOR**

• Fluids clasification by viscous behavior:

Newtonian:  $\tau = \eta \dot{\gamma}$ Dilatant:  $\tau = K(\dot{\gamma})^n$  n > 1

Newtonian plastic:  $\tau = \tau_y + \eta \dot{\gamma}$ 

Pseudoplastic:  $\tau = K(\dot{\gamma})^n$  n < 1Plastic:  $\tau = \tau_v + K\dot{\gamma}^n$ 







# 3.3. NEWTONIAN AND NON-NEWTONIAN BEHAVIOR

#### Suggested exercises:

1) The following table provides the data obtained in a test performed on a clay. Model its behavior as a Bingham body, determining its apparent viscosity and critical shear. Compare with the real behavior and with that of a pseudoplastic model.

$ au \left(N{\cdot}m^{-2} ight)$	$d\gamma/dt \left(s^{-1} ight)$
20	4
25	10
32	20
36	30
40	50





#### **3.4. CREEP AND RELAXATION**

#### Creep

#### ε $\varepsilon_0^e = \sigma_0 / E$ ε, $\varepsilon_v = f(t)$ def. remanente $\varepsilon_0$ $(\varepsilon_0^p + \varepsilon_{vp})$ $\varepsilon_0^e + \varepsilon_0^p$ t σ $\sigma_0$ = cte. $\sigma_0$ descarga t

#### Relaxation





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# **3.5. EVOLUTION OF STRAIN DURING CREEP**

**<u>CREEP TEST</u>**: consists on a specimen subjected to constant load and constant (high) temperature inside an oven. Throughout the test, strain is recorded and graphically plotted as a function of time.



#### **Experimental difficulties:**

- Rigorous control of T.
- Appropriate extensometry.
- Insulation (environmental chamber).
- Connection to the testing machine.





## **3.5. EVOLUTION OF STRAIN DURING CREEP**



## Characteristic design parameters:

 $t_{f}$  (Life span at creep).  $\dot{\mathcal{E}}_{ss}$  (Strain velocity at steady state).

Primary / transient:  $d\dot{\varepsilon}/dt < 0$ Secondary / steady:  $\dot{\varepsilon} = cte. = \dot{\varepsilon}_{ss}$ 

Tertiary:  $d\dot{\varepsilon}/dt > 0$ 



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# **3.5. EVOLUTION OF STRAIN DURING CREEP**

**EXAMPLE:** creep behavior of the austenitic steel AISI 316L.







# 3.5. EVOLUTION OF STRAIN DURING CREEP INFLUENCE OF STRESS AND TEMPERATURE:



Time

#### By increasing the stress or the temperature:

- Instantaneous initial strain increases.
- Strain velocity rate increases in the steady state regime.
- Life span decreases



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# 3.5. EVOLUTION OF STRAIN DURING CREEP INFLUENCE OF STRESS AND TEMPERATURE:







## 3.5. EVOLUTION OF STRAIN DURING CREEP

#### **EXAMPLE**: experimental results for the AISI 316 L steel.







# 3.5. EVOLUTION OF STRAIN DURING CREEP ATOMIC LEVEL JUSTIFICATION:

• Steady state creep: 
$$\dot{\varepsilon}_{ss} = A\sigma^n e^{-(Q/RT)}$$

- Influence of T: Arrhenius law: it is a very common type of law, which works very well to explain diverse phenomena:
  - Rate of oxidation-corrosion / diffusion rate / multiplication of bacteria in a Petri plate, etc.
- The law states that the rate of the process increases exponentially with temperature.
- Arrhenius law in creep is due to the diffusion processes taking place in the material as a consequence of the stress applied and the temperature.



# 3.5. EVOLUTION OF STRAIN DURING CREEP LOW TEMPERATURE CREEP:

#### EXAMPLE:

#### EHE-2008 STANDARD OF STRUCTURAL CONCRETE

#### 38.9 Relajación del acero para armaduras activas

La relajación  $\rho$  del acero a longitud constante, para una tensión inicial  $\sigma_{pi} = \alpha f_{max}$  estando la fracción  $\alpha$  comprendida entre 0,5 y 0,8 y para un tiempo *t*, puede estimarse con la siguiente expresión:

$$\log \rho = \log \frac{\Delta \sigma_p}{\sigma_{pi}} = K_1 + K_2 \log t$$

donde:

Pérdida de tensión por relajación a longitud constante al cabo del tiempo *t*, en horas Coeficientes que dependen del tipo de acero y de la tensión inicial (figura 38.9) El fabricante del acero suministrará los valores de la relajación a 120 h y a 1.000 h, para tensiones iniciales de 0,6, 0,7 y 0,8 de  $f_{máx}$  a temperatura de 20±1°C y garantizará el valor a 1.000 h para  $\alpha$  = 0,7. Con estos valores de relajación pueden obtenerse los coeficientes  $K_1$  y  $K_2$ para  $\alpha$  = 0,6, 0,7 y 0,8.









## **3.6. DESIGN FOR CREEP**

- Structural components may fail due to SLS (Service Limit State) or ULS (Ultimate Limit State).
- SLS analysis can be addressed using previously seen strain rate models.
- Traditionally, ULS analysis is based on experimental data from which charts, tables or graphs are developed.



Nickel alloys comparison: (A) TD-Nickel, (B) MA 6000, (C) directionally-solidified Mar-M200 and (D) single-crystal PWA 454.





# **3.6. DESIGN FOR CREEP**

- In a creep problem we can find three different variables: T,  $t_r$ ,  $\sigma$ .
- By fixing two of them (e.g.,  $\sigma$  and T) it is possible to determine the third one.







# **3.6. DESIGN FOR CREEP**

- The engineering goal is to predict the long-term behavior from 'short-term' <u>tests</u>.
- The usual way to make life predictions when creep might happen is to use data obtained from short duration tests, but at temperatures higher than the in-service temperature.

#### <u>Two important rules</u>:

- Testing time must exceed, at least, 10% of life span of the component.
- It is necessary to ensure that the **same deformation mechanism** acts in both the test and service.
- In the scientific literature, <u>several methods of analysis</u> are presented; the most important ones are the following:
  - I. Monkman-Grant method.
  - II. Larson-Miller method.
  - III. Sherby-Dorn method.





# **3.6. DESIGN FOR CREEP**

## **MONKMAN-GRANT METHOD:**

- This type of relationship is based on the observation that the strain is the macroscopic manifestation of the accumulated damage due to creep.
- Therefore, fail will occur when the accumulated damage in the material (in the form of voids and fissures of creep) reaches a certain critical value.
- Monkman-Grant equation:

$$\dot{\varepsilon}_{ss} t_f = C \approx \varepsilon_f$$



(Feltham and Meakin, 1959).





# **3.6. DESIGN FOR CREEP**

## LARSON-MILLER AND SHERBY-DORN METHODS:

 Assume that a series of creep tests with σ = constant and T = variable, are performed, recording the time to failure t<sub>r</sub> (or to a certain strain).

$$\dot{\varepsilon}_{SS} = A(\sigma)e^{\frac{-Q}{RT}} \implies \varepsilon \approx A(\sigma)t e^{\frac{-Q}{RT}} \implies \log t = \log\left[\frac{\varepsilon}{A(\sigma)}\right] + \frac{Q\log e}{R}\frac{1}{T}$$
• Therefore, for tests with  $\sigma$  = constant a linear relationship is obtained in the representation (log t) Vs. (1/T).





# **3.6. DESIGN FOR CREEP**

### LARSON-MILLER AND SHERBY-DORN METHODS:

- Two extreme cases can be considered:
  - **a)** Q = Q ( $\sigma$ ), C  $\neq$  C ( $\sigma$ ): LARSON MILLER.
  - **b)**  $Q \neq Q(\sigma)$ ,  $C = C(\sigma)$ : SHERBY DORN.







# **3.6. DESIGN FOR CREEP**

#### LARSON-MILLER AND SHERBY-DORN METHODS:



- Two tests at the same stress and different temperature show the same value of  $\mathsf{P}_{\mathsf{LM}}.$
- The relationship  $P_{LM}(\sigma)$  is obtained experimentally.
- Typically, C ~ 20-22 for metals.
- The usefulness of P<sub>LM</sub> is that it allows <u>accelerated creep tests</u> (same stress and higher temperature) to be performed.



# **3.6. DESIGN FOR CREEP**

**EXAMPLE**: P<sub>LM</sub> dependence for a wide variety of Nickel alloys.







# **3.6. DESIGN FOR CREEP**

#### Suggested exercises:

- Using the attached graph, determine the maximum working stress at a temperature of 1100 °C to avoid fracture for 10h.
- 2) What would be the maximum stress for T=500°C and a life span of 10000h?
- Obtain the life span for a stress of 250 MPa and a temperature of 870 °C.









# **3.7. ANALYSIS OF RELAXATION**

- At a constant stress, strain increases over time: **CREEP**.
- At a constant strain, stress decreases over time: **RELAXATION**.



- Creep and relaxation phenomena are two sides of the same coin.
- The material responds with the <u>same constitutive law for two different</u> <u>structural problems</u>: in the creep problem, static boundary conditions are imposed whereas in relaxation kinematic conditions are applied.





σ

# **3.7. ANALYSIS OF RELAXATION**

- To understand the phenomenon, we discretize the time into small intervals  $\Delta t$ .
- It is considered that changes occur in between those intervals.

$$\begin{cases} t = 0 \\ \sigma(t = 0) = \sigma_0 \\ \dot{\varepsilon}(t = 0) = C \sigma_0^n \end{cases}$$
$$\begin{cases} t = \Delta t \\ \Delta \varepsilon_V = \dot{\varepsilon}(t = 0) \Delta t = C \sigma_0^n \Delta t \\ \Delta \varepsilon_E = -\Delta \varepsilon_V \\ \Delta \sigma = -E C \sigma_0^n \Delta t \\ \sigma(t = \Delta t) = \sigma_1 = \sigma_0 - E C \sigma_0^n \Delta t < \sigma_0 \\ \dot{\varepsilon}(t = \Delta t) = C \sigma_1^n < \dot{\varepsilon}(t = 0) \end{cases}$$



$$\begin{cases} t = 2 \Delta t \\ \Delta \varepsilon_{V} = \dot{\varepsilon} (t = \Delta t) \Delta t = C \sigma_{1}^{n} \Delta t \\ \Delta \varepsilon_{E} = -\Delta \varepsilon_{V} \end{cases}$$
$$\Delta \sigma_{1} = -E C \sigma_{1}^{n} \Delta t \\ \sigma (t = \Delta t) \equiv \sigma_{2} = \sigma_{1} - E C \sigma_{1}^{n} \Delta t < \sigma_{1} \\ \dot{\varepsilon} (t = \Delta t) = C \sigma_{2}^{n} < \dot{\varepsilon} (t = \Delta t) \end{cases}$$





#### **3.7. ANALYSIS OF RELAXATION**

• It can be written:  $\sigma_{i+1} = \sigma_i - E C \sigma_i^n \Delta t$ 

$$\frac{\sigma_{i+1} - \sigma_i}{\Delta t} = -EC\sigma_i^n \implies \begin{cases} \sigma_i = \sigma(t) \\ \sigma_{i+1} = \sigma(t + \Delta t) \end{cases} \implies \frac{\sigma(t + \Delta t) - \sigma(t)}{\Delta t} = -EC\sigma^n(t)$$

$$\lim_{\Delta t \to 0} \frac{\sigma(t + \Delta t) - \sigma(t)}{\Delta t} = \frac{d\sigma}{dt} = -EC\sigma^n \quad \Rightarrow \quad \frac{d\sigma}{\sigma^n} = -ECdt \quad \Rightarrow \quad \int_{\sigma_0}^{\sigma(t)} \frac{d\sigma}{\sigma^n} = \int_{0}^{t} -ECdt$$







# **3.7. ANALYSIS OF RELAXATION**

#### Suggested exercises:

1) Obtain the evolution of the tightening stress in a bolt initially prestressed to a stress  $\sigma_i$ . The objective of the bolt is to keep two plates together. The plates are supposed to be non-deformable.



$$\frac{1}{E}\frac{d\sigma}{dt} + C\sigma^{n} = 0 \qquad \sigma(t) = \left[\sigma_{i}\right]^{1-n} - (1-n)ECt \right]^{1/1-n}$$





# **3.8. CREEP MICROMECHANISMS**

#### Metal and ceramic materials:

- Two creep mechanisms can be distinguished: <u>dislocation</u> (power law in stresses) and <u>diffusion</u> (linear law in stress).
- As both mechanisms depend on **diffusive phenomena**, dependence on temperature is given in both cases by the Arrhenius equation.

#### **Dislocation creep:**

- Plastic strain is a consequence of the displacement of dislocations. This movement must overcome: a) Intrinsic strength of the crystal net,
  b) The obstacles that prevent them to move forward (solute atoms, precipitates, other dislocations).
- The diffusion of atoms (assisted by the stress state and the temperature) can unlock the dislocations, thereby allowing the increment of deformations.





#### **Dislocation creep:**

- Consider a dislocation blocked in an obstacle.
- Unless dislocation is blocked in the middle plane, it experiences a lifting/climb force. This reaction tends to displace the dislocation out its slip plane.
- The dislocation will be able to overcome the obstacle if the atoms in the bottom of the dislocation can diffuse through the network.

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# **3.8. CREEP MICROMECHANISMS**

#### **Dislocation creep:**

- This process is called *climbing* of the dislocation. Since it requires atomic diffusion, it is developed for temperatures above 0.3T<sub>M</sub>:
  - T = (0.3 0.5)  $T_M$ , core diffusion.
  - $T = (0.5 0.99) T_M$ , bulk diffusion.

#### T/T<sub>M</sub> = 0.3-0.5: Core difussion



 $T/T_{M} = 0.5-0.99$ : Bulk difussion



Atoms diffuse away from the bottom of the half plane. At high  $T/T_M$  this takes place mainly by bulk diffusion through the crystal





#### **Dislocation creep:**

- When a dislocation is unlocked by the climbing mechanism, it can move forward (due to its stress state) until it gets stuck again.
- The process is repeated again in this new obstacle. This explains the progressive and continue nature of creep.
- This explains, as well, the expression of strain rate by an Arrhenius law.







#### **Dislocation creep:**

#### Influence of T:

• The dislocation creep is assisted by diffusion processes; the temperature dependence of the diffusion coefficient determines the influence of the temperature on the strain rate.

$$D = D_0 e^{-Q/RT} \implies \dot{\varepsilon} = A(\sigma) e^{-Q/RT}$$

#### Influence of $\sigma$ :

• It is a consequence of the climbing force: As stress increases, the climbing force increases, more dislocations are unlocked and the strain rate increases.

$$\dot{\varepsilon} = A\sigma^n e^{-Q/RT} = C\sigma^n; \quad n = 3-8$$





#### Diffusion creep:

- Under low stresses (unable to unlock the movement of dislocations) an alternative mechanisms can occur.
- Elongation of the grains by diffusion (in matrix or grain boundary).
- There is no movement of dislocations.







# **3.8. CREEP MICROMECHANISMS**

#### Diffusion creep:

- Reduced T/T<sub>M</sub>: atomic diffusion predominant in grain boundary (fast difussion path): <u>COBLE CREEP</u>.
- High T/T<sub>M</sub>: atomic diffusion through the matrix (the crystal lattice 'relaxes' thanks to the thermal agitation): <u>NABARRO-HERRING CREEP</u>.

# Influence of T:

• Strain rate is proportional to the diffusion coefficient, D.

#### Influence of $\sigma$ :

• Stress acts as a 'driving force' of the diffusion process (plays the same role as the concentration gradient of Fick's law).

$$\dot{\varepsilon} = \frac{A}{d^{2-3}} \sigma e^{-Q/RT}$$





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# 3.8. CREEP MICROMECHANISMS INFLUENCE OF $\sigma$ AND T: EXPERIMENTAL RESULTS:





# 3.8. CREEP MICROMECHANISMS INFLUENCE OF $\sigma$ AND T: EXPERIMENTAL RESULTS:







Log (dɛ/dt) vs. 1/T for: (a) Ni $-AI_2O_3$ , (b) Ni $-67Co-AI_2O_3$ , Showing the variation of activation energy below and above 0.5 T<sub>M</sub> (Hancock, Dillamore and Smallman, 1972).







# 3.8. CREEP MICROMECHANISMS INFLUENCE OF $\sigma$ AND T: EXPERIMENTAL RESULTS:



Log (dɛ/dt) vs. log $\sigma$  for: (a) Ni $-AI_2O_3$ , (b) Ni $-67Co-AI_2O_3$ , (Hancock, Dillamore and Smallman, 1972).





# 3.8. CREEP MICROMECHANISMS SUMMARY:



Diffusion creep is dominated by two processes. At high temperatures lattice diffusion controls the rate (*Nabarro-Herring creep*). Grain boundary diffusion (*Coble creep*) takes over at lower temperatures.



Power-law creep is mainly based on diffusion controlled dislocation climb processes. Diffusion may occur along dislocation cells or through the lattice.





#### Behavior maps:

- Competition between mechanisms depending on the conditions ( $\sigma$  and T).
- Diagrams available for metals and ceramic materials: they facilitate the task of selecting materials for high temperature applications.







# **3.8. CREEP MICROMECHANISMS**

#### Behavior maps:





#### **3.8. CREEP MICROMECHANISMS**

#### Final instability:



Some microvoids appear in the grain boundaries





