

## Question 1

### 1. Creep deformation

Creep deformation is very particular behaviour of a material. This term is used to describe the permanent deformation of a material at high temperature over time, at a level of stress that would not cause any permanent deformation at room temperature. As a consequence if the strain of a material depends only on the stress at low temperature, as the temperature is raised, strain also depends on time and temperature.

This behaviour can be summed up in a single equation:<sup>1</sup>

$$\epsilon = f(\sigma, t, T) \quad (\text{equation 1})$$

The temperature at which creep deformation can be observed also varies a lot depending on which material is considered. Indeed, temperature is considered high for a material if it is close enough to its melting point. As a general rule, creep starts when:

$T > 0.3$  or  $0.4T_M$  for metals

$T > 0.4$  to  $0.5T_M$  for ceramics<sup>2</sup>

For example, aluminium which has a melting point around 900°C starts to creep a 300°C but diamond which as a melting point around 3500°C will not creep before approximately 1500°C.

Furthermore, creep tests can be run on specimens in order to precisely understand their creep behaviour. A lot of different materials creep (metals, ceramics or polymers for instance) and a typical creep curve can be seen on figure 1 below.

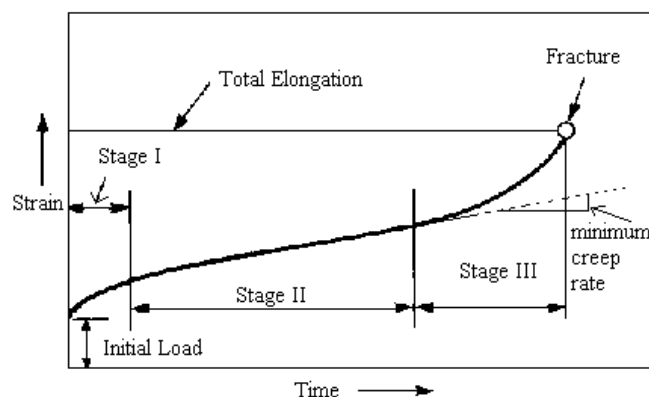


Figure 1: A typical creep curve for metals ceramics and polymers<sup>3</sup>

As it is shown on that figure, strain time-dependence is obvious. The material goes through different stages and the second one (also called the steady state) is the most important to understand the creep behaviour of a material.

<sup>1</sup> Ashby, M. F., Jones D. R., (2005), *Engineering Materials 1*, Butterworth Heinemann, p. 274

<sup>2</sup> Ashby, M. F., Jones D. R., (2005), *Engineering Materials 1*, Butterworth Heinemann, p. 274

<sup>3</sup> <http://www.materialsengineer.com/CA-Creep-Stress-Rupture.htm>, viewed 9 Nov 2008

Also, it is established that calculating the strain rate of a material during this regime is possible using the following equation:<sup>4</sup>

$$\dot{\epsilon}_{ss} = A\sigma^n e^{-\left(\frac{Q}{RT}\right)} \quad (\text{equation 2})$$

Where A, n and Q have to be found experimentally because they vary from a material to another.

As an interesting example of creep deformation, glaciers should be considered. Indeed, because of ice has a low melting point (0°C), glaciers close to that temperature quickly creep and this is why they are able to move and spread. Figure 2 shows this behaviour.



Figure 2: Volume diffusion creep in glacier<sup>5</sup>

## **2. Why may a creep fracture occur at a low macroscopic failure strain compared to the tensile ductility?**

Sometimes creep fractures can happen at unexpected and low values of strain.

Indeed, if for instance a certain stress is applied on a specimen over time at a certain temperature, like we said it is going to creep. Creation of voids can occur on boundaries which lie normal to the tensile stress. Obviously, these voids are microscopic sources of higher values of stress within the bulk of the material. As a consequence they grow quickly by diffusion processes<sup>6</sup> until they link, which lead to failure, even if at the macroscopic scale the strain of the specimen was far from its tensile ductility.

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<sup>4</sup> Ashby, M. F., Jones D. R., (2005), *Engineering Materials 2*, Butterworth Heinemann, p. 279

<sup>5</sup> <http://christieatthecape.blogspot.com/2008/05/in-search-of-columbia-glacier.html>, viewed 14 Nov 2008

<sup>6</sup> Askeland, D. R., (2003), *The science and Engineering of Materials*, Wiley, p. 790

### 3. Creep experiments

As it has been said before, the three constants A, n and Q of equation 1, have to be found experimentally. This is what is going to be done in this section.

Creep experiments carried out on metals samples at a constant temperature (527°C) but different applied stresses gave the following data for the steady state creep rate,  $\dot{\epsilon}_{ss}$ :

Table 1: Results under constant temperature

Stress, $\sigma$ (MPa)	$\dot{\epsilon}_{ss}$ ( $s^{-1}$ )
100	$4 \times 10^{-11}$
200	$1,3 \times 10^{-9}$
300	$9,7 \times 10^{-9}$

Experiments on similar samples at constant stress (150MPa) but at different temperatures gave the following results for the steady state creep rate,  $\dot{\epsilon}_{ss}$ :

Table 2: Results under constant stress

Temperature, $T$ (°C)	$\dot{\epsilon}_{ss}$ ( $s^{-1}$ )
527	$3 \times 10^{-10}$
652	$1.2 \times 10^{-8}$
727	$7.9 \times 10^{-8}$

As a reminder, the general equation established to calculate the strain rate is equation 2

- The constant Q is going to be calculated first:

If the data of table 2 is considered:

A,  $\sigma$  and n are constant. As a consequence, 
$$\frac{\dot{\epsilon}_{ss1}}{\dot{\epsilon}_{ss2}} = \exp\left(-\frac{Q}{RT_1} + \frac{Q}{RT_2}\right)$$

Therefore, 
$$Q = \ln\left(\frac{\dot{\epsilon}_{ss1}}{\dot{\epsilon}_{ss2}}\right) * \left(\frac{RT_1 T_2}{T_1 - T_2}\right)$$

Numerical calculation gives three possible values (depending on which  $T_1$  or  $T_2$  are chosen) but the mean value for Q is:

$$Q \approx 185 \text{ kJ mol}^{-1}$$

- Calculation of the constant n:

If the data of table 1 is considered,

A,  $\sigma$  and T are constant. As a consequence, 
$$\frac{\dot{\epsilon}_{ss1}}{\dot{\epsilon}_{ss2}} = \left(\frac{\sigma_1}{\sigma_2}\right)^n$$

Therefore calculation gives a mean value for n:

$$n \approx 5$$

- Calculation of the constant A:

Q and n have already been calculated and are now going to be used to find the numerical value of A.

So far,  $\dot{\epsilon}_{ss} \approx A \sigma^5 \exp\left(-\frac{185000}{8.31 \cdot T}\right)$

As a consequence,  $A \approx \dot{\epsilon}_{ss} * \left[\sigma^5 \exp\left(-\frac{185000}{8.31 \cdot T}\right)\right]^{-1}$

Using the steady state creep rates values of table 1 and 2, we finally have the following numerical results:

Table 3: Results of the A constant calculation

Temperature, T (K)	Stress (MPa)	$\dot{\epsilon}_{ss} (s^{-1})$	A
800,15	100	$4 \times 10^{-11}$	$4,85 \times 10^{-39}$
800,15	200	$1,3 \times 10^{-9}$	$4,92 \times 10^{-39}$
800,15	300	$9,7 \times 10^{-9}$	$4,84 \times 10^{-39}$
800,15	150	$3 \times 10^{-10}$	$4,78 \times 10^{-39}$
925,15	150	$1.2 \times 10^{-8}$	$4,46 \times 10^{-39}$
1000,15	150	$7.9 \times 10^{-8}$	$4,83 \times 10^{-39}$

Which lead to a mean value for A of:

$$A \approx 4.78 \times 10^{-39}$$

As a consequence the general expression for the dependence of the steady state creep rate on stress and temperature is:

$$\dot{\epsilon}_{ss} \approx 4.78 \times 10^{-39} \sigma^5 \exp\left(-\frac{185000}{8.31T}\right) \quad (\text{equation 3})$$

#### **4. Estimate the time to failure of a sample**

The sample considered here is subjected to a stress of 250MPa and at a temperature of 627°C (900.15 K). Equation 3 is going to be used to estimate the time of failure:

Calculation gives:

$$\dot{\epsilon}_{ss} \approx 4.78 \times 10^{-39} (250 \times 10^6)^5 \exp\left(-\frac{185000}{8.31 \times 900.15}\right) \approx 8.5 \times 10^{-8} s^{-1}$$

Therefore,  $\frac{d\epsilon_{ss}}{dt} \approx 8.5 \times 10^{-8} s^{-1}$

Finally,  $\epsilon_{ss} \approx 8.5 \times 10^{-8} t$

All the samples failed at a creep strain of 0.12. As a consequence:

$$t \approx \frac{0.12}{8.5 \times 10^{-8}} \approx 1.4 \times 10^6 \text{ s} \approx 16.2 \text{ days}$$

It has to be kept in mind that it is an approximated value. The quality of the approximation is determined by the accuracy of the experimental results.

**I.5. Comment briefly, on the risk involved in using the creep rate expression to predict the material response under conditions where the creep life would be many years.**

Everything that has been said all along this question is based on calculations and extrapolations.

First of all, it is obvious that there is always a slight error of accuracy because constant values are different for each material and are determined by creep experiments. As a consequence, as the prediction goes further in the future, it is more and more risky to rely on the results that have been calculated.

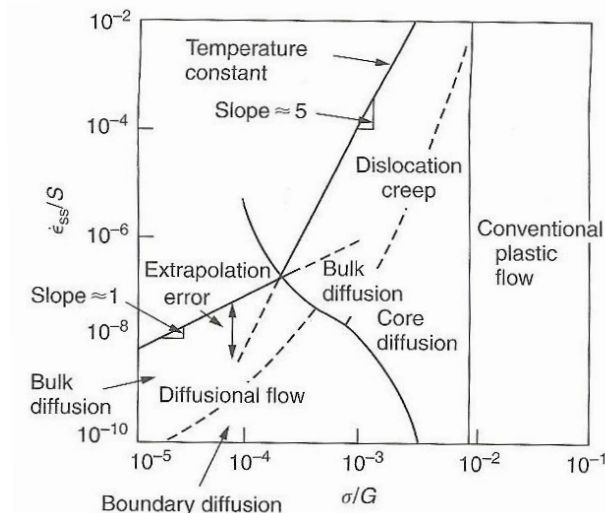


Figure 2: Deformation mechanisms at different strain-rates and stresses

Furthermore, deformation mechanisms may vary (dislocation creep, diffusion flow or core and bulk diffusion...), with the variation of strain-rates and stress<sup>7</sup>. Indeed, figure 2 shows that extrapolation errors can easily be done if the procedure considered is located near two types of mechanism. Considering this, extrapolation for a long period of time (typically many years) is very risky.

As a conclusion, all of this has to be taken into account when designing with materials otherwise catastrophic incidents could for example happen if the material is used as a high performance structure. The safest way is to completely avoid creep behaviour by selecting a material which is going to be used below its critical temperature of  $0.3T_M$ .

<sup>7</sup> Ashby, M. F., Jones D. R., (2005), *Engineering Materials 1*, Butterworth Heinemann, p. 304