Creep Deformation of Metals

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Aims

On completion of this tutorial package, you should:

- Have a sound understanding of the mechanisms of creep
- Know about stress exponents and activation energies and how to obtain them from experimental data
- Be familiar with a particular set-up for experimental study of the creep characteristics of a metal, available in wire form
- Begin to understand how materials can be designed to minimise creep

Before you start

It may be helpful to complete the TLPs Introduction to Dislocations and Introduction to Mechanical Testing, although these go into more detail than is necessary for the purposes of this TLP.

Introduction

When a material is subjected to a stress that is greater than or equal to its yield stress, the material deforms \textit{plastically}. When the stress is below this level, then in principle it should only deform elastically.

However, provided the temperature is relatively high (see later for the meaning of this), plastic deformation can occur even when the stress is lower than the yield stress. This deformation is time-dependent and is known as \textit{creep}.

During loading under a constant stress, the strain often varies as a function of time in the manner shown below:
This TLP focuses primarily on steady-state creep. In practice, this often dominates the creep behaviour – for example, the period during which it occurs is usually much greater than those for primary or tertiary creep.

There are two broad mechanisms by which steady state creep takes place: diffusion creep and dislocation creep.

**Creep mechanisms**
Diffusion Creep

Diffusion creep occurs by transport of material via diffusion of atoms within a grain. Like all diffusional processes, it is driven by a gradient of free energy (chemical potential), created in this case by the applied stress. For example, an applied tensile stress creates regions of high hydrostatic tension at the extremities of each grain, along the loading direction. In what might be termed the “equatorial” regions of the grain, the hydrostatic stress is lower. Since atoms have a lower free energy in these “polar” regions of high hydrostatic stress (ie “low pressure” regions), they will tend to diffuse towards such regions and this motion will lead to elongation of the grain along the loading direction. Since this occurs on the scale of the individual grains, diffusion distances are shorter in fine-grained materials, which thus tend to be more susceptible to creep.

Click here for more information on Diffusion

There are two types of diffusion creep, depending on whether the diffusion paths are predominantly through the grain boundaries, termed Coble creep (favoured at lower temperatures) or through the grains themselves, termed Nabarro-Herring creep (favoured at higher temperatures).

Note: This animation requires Adobe Flash Player 8 and later, which can be downloaded here.

Dislocation Creep

Dislocation creep is a mechanism involving motion of dislocations. This mechanism of creep tends to dominate at high stresses and relatively low temperatures.

Dislocations can move by gliding in a slip plane, a process requiring little thermal activation.

This is discussed in the Introduction to Dislocations TLP.

However, the rate-determining step for their motion is often a climb process, which requires diffusion and is thus time-dependent and favoured by higher temperatures. Obstacles in the slip plane, such as other dislocations, precipitates or grain boundaries, can lead to such situations.

Note: This animation requires Adobe Flash Player 8 and later, which can be downloaded here.

Effects of stress and temperature on creep rate
Dependence on Temperature

Diffusion is governed by an Arrhenius equation:

\[ D = D_0 \exp\left(-\frac{Q}{RT}\right) \]

Since all mechanisms of steady-state creep are in some way dependent on diffusion, we expect that creep rate will have this exponential dependence on temperature:

\[ \dot{\varepsilon} \propto \exp\left(-\frac{Q}{RT}\right) \]

Creep occurs faster at higher temperatures. However, what constitutes a high temperature is different for different metals. When considering creep, the concept of an homologous temperature is useful.

The homologous temperature is the actual temperature divided by the melting point of the metal, with both being expressed in K. In general, creep tends to occur at a significant rate when the homologous temperatures is 0.4 or higher.

Dependence on stress

The applied stress provides a driving force for dislocation movement and diffusion of atoms. As the stress is increased, the rate of deformation also increases. In general, it is found that

\[ \dot{\varepsilon} \propto \sigma^n \]

where \( n \) is termed the stress exponent. Prediction of the value of \( n \) from first principles is not easy, but its value does depend on which mechanism of creep is operating. For example, for diffusion creep its value is approximately 1, while for dislocation creep it is usually in the range 3-8.
Creep rate equation

The equation governing the rate of steady state creep is:

$$\dot{\varepsilon} = A\sigma^n \exp\left(-\frac{Q}{RT}\right)$$

$Q$ = activation energy;  $n$ = stress exponent;  $A$ = constant;

This can be rearranged into the form:

$$\ln \dot{\varepsilon} = \ln A + n \ln \sigma - \frac{Q}{RT}$$

The activation energy $Q$ can be determined experimentally, by plotting the natural log of creep rate against the reciprocal of temperature.
The stress exponent $n$ can be determined by plotting the strain rate as a function of stress.
The creeping coil experiment - variable stresses in a single specimen

In order to determine the value of \( n \) from a single experiment, it is necessary to have a range of stress levels acting within a single specimen. This is achieved by making the sample into a coil. The stress is provided by the weight of the coil itself, so that the upper part of the coil experiences more stress than the lower parts.
The stress in a particular turn of the coil is proportional to its number, \( N \), where the turns are numbered beginning from the bottom turn and ending at the top. The shear stress \( \tau \) in each turn varies from zero at the centre of the turn (axis of the coil) to a maximum value at the edge of the coil, given by:

\[
\tau \propto \frac{\rho ND^2}{w} \quad \text{(Derivation)}
\]

The coil is then allowed to creep over a fixed amount of time (e.g. one minute) and at the end of this time the spacings, \( s \), between the turns are measured giving information about the dependence of strain rate on stress.

The local shear strain \( \gamma \) in each turn is given by:
The average local strain rate is thus related to the spacing between turns, \( s \), and the time, \( t \), by:

\[
\gamma \propto \frac{s\omega}{D^2} \tag{Derivation}
\]

It should be noted that, strictly, the above analysis applies only while the material remains elastic. As with all cases in which a moment (bending or twisting) is applied, such that the stress distribution is non-uniform, the situation becomes more complex after the onset of plastic deformation. The distribution of strain remains linear along the radius of the wire, but the associated distribution of stress tends to become more complex. For the creeping coil geometry, papers have been published covering various aspects – eg see IG Crosland et al, “The Use of Helically Coiled Springs in Creep Experiments with Special Reference to the Case of Bingham Flow”, J. Phys. D: Applied Physics, vol.6 (1973) p.1040-1046, and Measurements of Creep at High Temperatures using Helical Springs, FD Boardman et al, J. Strain Analysis, vol. 1 (1966) p.140-144. In fact, provided primary creep can be ignored (which is often doubtful), the procedure described here should be reasonably accurate as a method of estimating the stress exponent, as long as it is of the order of unity, ie not very large.

**Experimental set-up**

In order to create a temperature-controlled environment, the coil is placed inside a Perspex tube. Once the temperature in the tube has stabilised, the coil is allowed to creep under its own weight for one minute. The videos below show qualitatively how creep rate varies with