

Creep

Objective

The objective of this laboratory is for you to observe and quantify creep deformation in an elemental polycrystalline metal and a polymer.

Preparation

Read sections 13.1-13.11 of Meyers and Chawla; the introductory section of the journal article on Al(Sc) alloys; and the introductory section of the 2010 journal article on polyethylene creep.

Equipment and samples

- Creep apparatus with linear-variable-differential-transformer (LVDT); micrometer for calibrating the LVDT.
- Samples of Al and polyethylene rods.
- Computer, data acquisition board, plotting software.

Introduction

A. Elastic, Plastic and Creep Deformation

These notes emphasize creep deformation of metals; for more details about the microscopic mechanisms of creep deformation of polymers, see section 13.11 of Meyers and Chawla.

When a material is subjected to a load at elevated temperatures it begins to irreversibly change its dimensions by creep deformation. Creep is distinguished from low temperature deformation by its time dependence. When load is first applied to a component, it undergoes virtually instantaneous elastic, and sometimes plastic strain, but zero creep strain. As time proceeds, however, the material continues to strain owing to creep. The total deformation (strain) can be expressed as,

$$\varepsilon = \varepsilon_{el}(\sigma) + \varepsilon_{pl}(\sigma) + \varepsilon_c(\sigma) \quad (1)$$

Where ε_{el} , ε_{pl} and ε_c are the elastic, plastic and creep components of strain, respectively.

Creep strain is obtained by integrating the expression,

$$\varepsilon_c = \int_0^t \dot{\varepsilon} dt \quad (4)$$

Creep can also be important even if the creep strain is relatively small. For example, strings on a guitar or a violin gradually loosen their tension with time, requiring the musicians to retune their instruments. More serious consequences can occur when bolts loosen during high temperature service. Note that the component does not actually change its dimension, but the stress on the component decreases. This form of creep is termed stress relaxation. To see how this occurs, we will assume for the moment that the creep rate can be expressed as,

$$\dot{\epsilon}_c = B\sigma^n \quad (5)$$

Since the total strain in this situation is constant, i.e. $d\epsilon/dt = 0$, we can differentiate eqn.(1) with respect to time and obtain,

$$\frac{1}{E} \frac{d\sigma}{dt} = -B\sigma^n \quad (6)$$

where the plastic strain has been neglected. By integrating from $\sigma = \sigma_i$ at $t = 0$ to $\sigma = \sigma_f$ at $t = t$, we obtain,

$$\frac{1}{\sigma_f^{n-1}} - \frac{1}{\sigma_i^{n-1}} = (n-1)BEt \quad (7)$$

This function is plotted in Fig. 1. Notice that the elastic strain decreases with time as the creep strain increases. Since the elastic stress is proportional to the elastic strain, the elastic stress decreases with time. For this reason, bolts that are used in high temperature applications must be occasionally re-tightened.

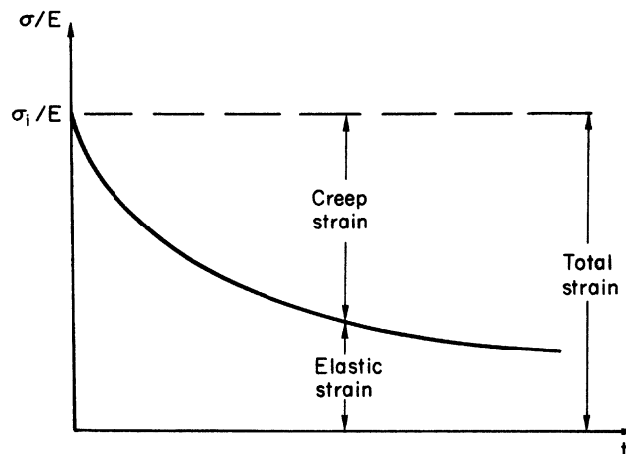


Figure 1. Replacement of elastic strain by creep strain with time at high temperature [1].

B. Three Stages of Creep

The creep response of a material can be divided into three stages, primary (sometimes referred to as transient creep), secondary (or steady state), and tertiary (or final). The full creep response of a material is illustrated in Fig. 2, where strain is plotted as a function of time. Although there are three stages of creep, usually only steady state creep is of importance since the other two stages are brief; they do not contribute much to the overall strain or service life of a component. How the deformation takes place during primary creep is not well understood, but it seems clear that changes in the microstructure are taking place that make the material increasingly more difficult to deform. This is not unlike the strain hardening observed at room temperature during tensile testing. The strain rate usually falls to a constant rather quickly. During tertiary creep, flaws develop in the microstructure, typically voids along the grain boundaries. As these voids accumulate, the strain rate accelerates, and fracture soon occurs. Of most concern for materials design, therefore, is the second stage of creep.

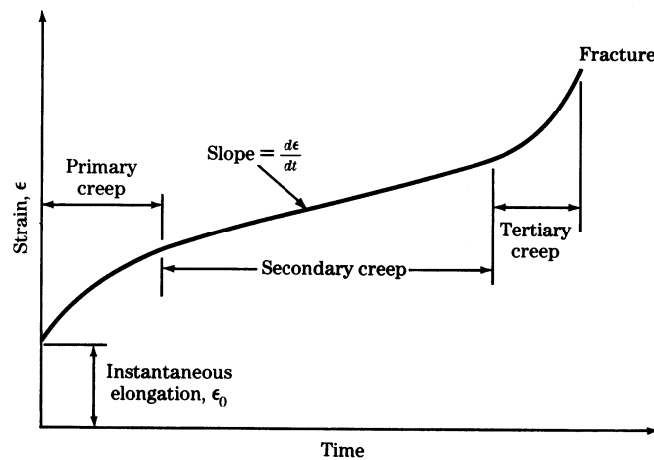


Figure 2. Three stages of creep deformation [2].

C. Steady State Creep

Various mechanisms of creep deformation have been identified. All of them, however, depend on diffusion, and this is why creep is basically a high temperature phenomenon. What denotes "high temperature?" Guitar strings creep at room temperature, while ceramic components are often resistant to creep to over 1500 °C. Since diffusion is involved, it is generally useful to refer to the homologous temperature, T_H , which is the ratio of the actual temperature to the melting point, $T_H = T/T_m$. As a rule of thumb, high temperature generally means $T_H > 0.5$.

We will be concerned in this laboratory only with power law creep, which is expressed by Eq. (5). Generally $3 < n < 8$, where n is the *stress exponent*. The full expression for creep in the steady state regime is given by,

$$\dot{\epsilon}_c = A \left(\frac{\sigma}{\mu} \right)^n D_0 \exp\left(\frac{-Q}{k_B T} \right). \quad (8)$$

Where μ is the shear modulus and k_B is the Boltzmann's constant (1.381×10^{-23} J/°K). Notice in eqn.(8) the terms $D_0 \exp(-Q/k_B T)$, which is simply the diffusion coefficient, and σ^n . The object of the present laboratory is to determine the values of the stress exponent, n , and activation enthalpy for creep, Q . The latter can be compared to the activation enthalpy for diffusion to check if creep and diffusion are indeed related.

Session 1: Creep deformation of pure polycrystalline Al

- Calibrate the LVDT using a micrometer
- Measure the dimensions of the sample with micrometer and caliper.
- Measure the creep strain of an aluminum sample (1100-Al) as a function of time for different applied loads and at different temperatures. You will want to measure the temperature of the clamps at both ends of the sample and use the average of these temperatures to determine the temperature of your sample. At temperatures near 400 C, you will need to use a mass of approximately 1 kg. Near 530 C, you will need to use a mass of approximately 400 g. The best approach will probably be to systematically increase and decrease the mass at constant temperature.
- Analyze the dependence of creep strain-rate on temperature and train to determine the activation energy Q for creep and the stress exponent n . Convert displacements and loads to strains and stresses.

Session 2: Creep deformation of polyethelyene

- Measure the dimensions of the sample.
- Measure the creep strain of a polymer sample as a function of time for different applied loads and at different temperatures. The TAs will provide guidance on the masses and temperatures that are appropriate. Compare the creep deformation of polyethylene to the creep deformation of the simple metal that you studied in session 1.

Instrument procedures

Creep Apparatus

The creep apparatus is sketched below in Fig. 3. A specimen is clamped to heavy rods and placed into a furnace. Thermocouples are placed near the top and the bottom of the specimen. Weights are added to the bottom support rod outside of the furnace. A linear variable displacement transducer (LVDT) is attached to the bottom support to measure the displacement. It is important that the support rods

have high creep resistance as the LVDT measures the total displacement of the sample and the rods. We use stainless steel rods. The LVDTs have a sensitivity of $\approx 1 \mu\text{m}$.

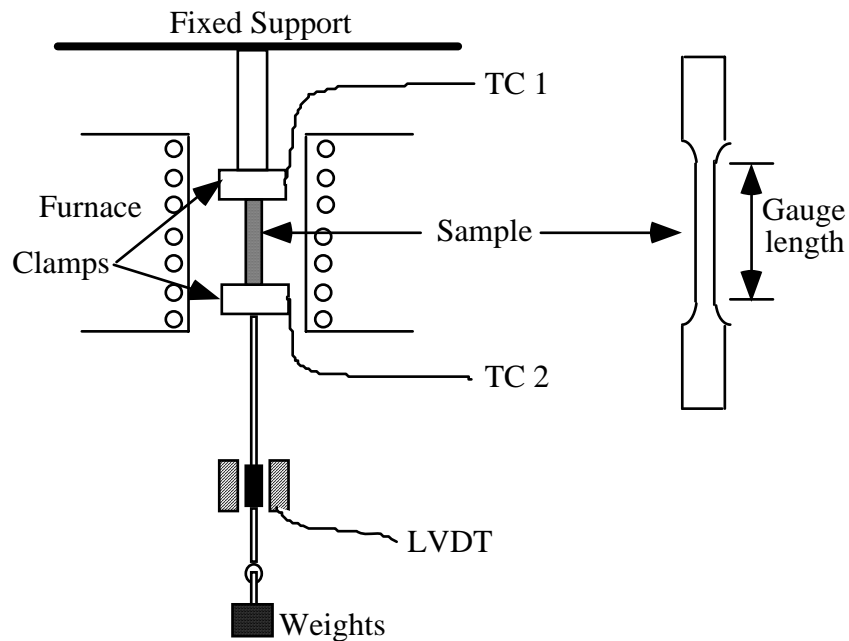


Figure 3. Creep apparatus.

Calibration of LVDT

Before you begin the experiment, the LVDT must be calibrated. Essentially the LVDT measures the change in the inductance of a coil of wire as a ferromagnetic core moves through its center. The LVDT calibration is done as follows: (a) Place one end of the ferromagnetic core of the LVDT on a micrometer head and the other end through the LVDT transformer coils; (b) Adjust the micrometer head and the position of the ferromagnetic core in the transformer coils until the LVDT output reads about -1200 mV/V ; (c) Then record the LVDT output at regular intervals (every 1 mm) of the micrometer head movement until the LVDT output reads around $+1200 \text{ mV/V}$. The LVDTs you will be using in this laboratory should be linear within this range; (d) A graph between the LVDT output and the micrometer head readings will result in a straight line and the slope of which will give you the LVDT calibration.

References

1. M.F. Ashby and D.R.H. Jones, *Engineering Materials: An Introduction to their Properties and Application*, Pergamon Press, 1st Ed, New York, 1980.

2. W.F. Smith, *Foundations of Materials Science and Engineering*, McGraw-Hill, Inc., 2nd Ed, New York, 1993.