

Objective:

The objective of this lab is for you to observe and quantify creep deformation in a polycrystalline metal. From analysis of the creep data, you will find out how creep behavior is related to atomic processes.

Preparation

Read sections of 13.1-13.11 of Meyers and Chawla, the journal articles by Coble-1962 and Herring-1950, and Deformation-Mechanism Maps. (All on Compass website)

Equipment and samples

- Creep apparatus with linear-variable-differential-transformer (LVDT) and the micrometer calibrating the LVDT;
- Al samples suitable for applying uniform stress in tension;
- Computer, data acquisition board, and plotting software.

Introduction:

A. Elastic, Plastic and Creep Deformation:

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. You will recall from our first laboratory on tensile testing,

$$\sigma = E \cdot \varepsilon_{el} \quad (2)$$

and

$$\sigma = K \cdot \varepsilon_{pl}^n \quad (3)$$

Creep strain is obtained by integrating the expression,

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

Creep can also be important even though a component does not change its spatial dimensions. 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,

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

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

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

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.

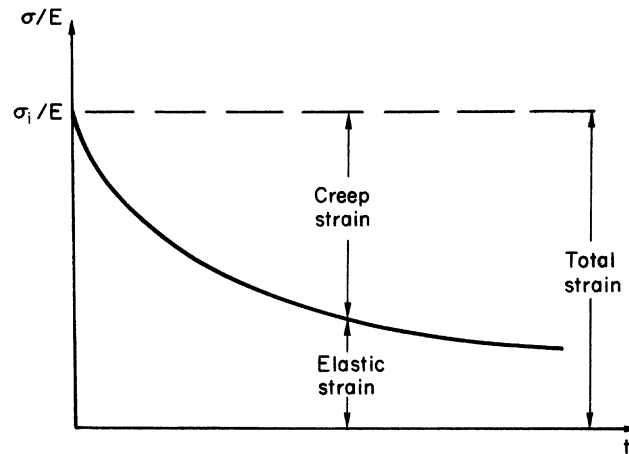


Fig. 1. Replacement of elastic strain by creep strain with time at high temperature (1).

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 you observed at room temperature during your 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.

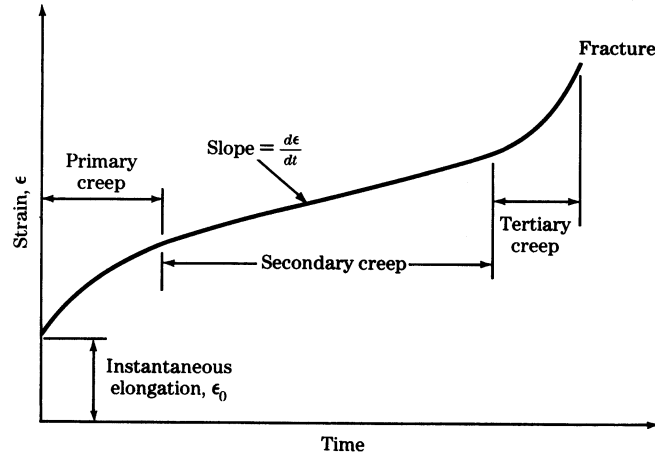


Fig. 2. Three stages of creep deformation (2).

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 eqn.(5). Generally $3 < n < 8$, where n is the *stress exponent*. The full expression for creep in the steady state regime is given by,

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

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

Laboratory Procedure:

You will measure the creep strain of an aluminum sample (1100-Al) as a function of time for different applied loads and at different temperatures. From these measurements, you will determine the stress exponent and activation energy for creep deformation.

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 $\sim 1 \mu\text{m}$.

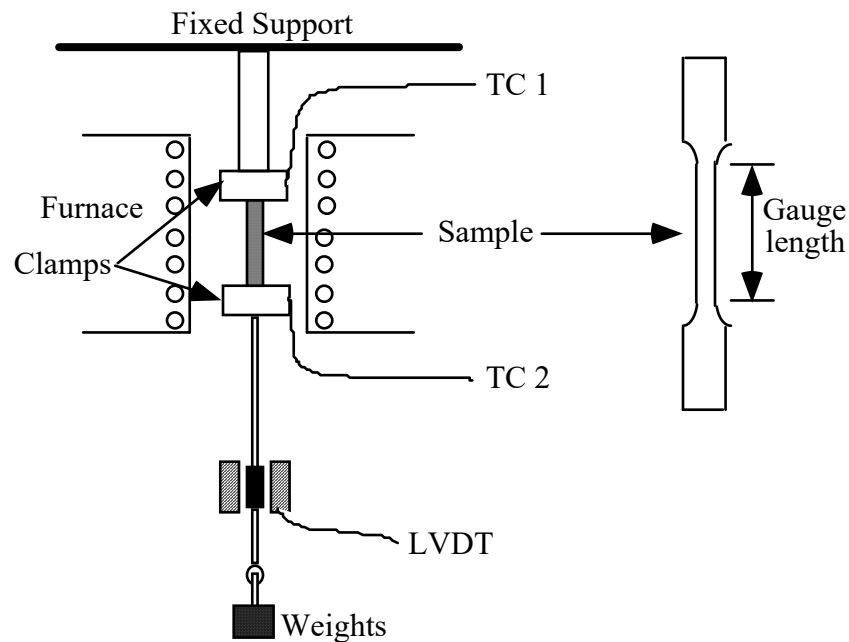


Fig. 3. Creep apparatus.

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:

- Place one end of the ferromagnetic core of the LVDT on a micrometer head and the other end through the LVDT transformer coils;
- Adjust the micrometer head and the position of the ferromagnetic core in the transformer coils until the weight hanger is clear of the LVDT. Make

sure the 0's on the micrometer are lined up; (c) Record the LVDT output voltage at regular intervals (every 0.5-1 mm) of the micrometer head movement until you've obtained 7-10 points; (d) A graph between the LVDT output and the micrometer head readings will result in a straight line, and the slope of this line will give you the LVDT calibration factor.

Creep Curves:

Measure the displacement of your sample by LVDT and convert the displacement into strain so that you will have the strain as a function of time – a creep curve for your sample. Obtain the creep curves at three different stress levels for a given temperature to determine the stress exponent. Determine the activation energy by performing the creep tests at three different temperatures while holding the mechanical load constant. A total of five (5) samples will therefore be tested, since one test can be used as a baseline for both stress exponent and activation energy calculations. You will select both the temperatures and loads tested for the samples.

Hints: A good place to start is 400°C with 1000 grams of weight. This should take approximately 1 hour for a test. Slight changes in temperature and load can sometimes lead to large changes in creep behavior. Tests of less than 30 minutes generally do not yield good steady-state creep rates. Remember that the melting temperature of Al is 660°C.

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.