The Creep of Solder

In order to permanently change the shape of a material, it is necessary to apply a stress which exceeds a critical value called the *yield stress*. Permanent deformation is called *plastic deformation.* If the applied stress is less than the yield stress then the material only deforms *elastically*, so that any strain is recovered on the removal of the stress; *e.g.* when a rubber band is stretched and released.

However, there are circumstances where the diffusion of atoms can lead to plastic deformation even when the applied stress is less than the yield stress. Such deformation is called *creep*, where the plastic strain is dependent not only on the stress but also on time.

Creep in solids occurs at "high" temperatures where atoms are mobile. However, a temperature which is high for one material may not be for another. For example, 550 K is a temperature at which solid-state diffusion can occur very rapidly in lead (which melts at 600 K), whereas at the same temperature, atoms are hardly mobile in iron which melts at 1810 K. To avoid this difficulty, we define a *homologous temperature*, which is the actual temperature divided by the melting temperature (in Kelvin). Metals and ceramics tend to creep rapidly when the homologous temperature is greater than about 0.4.

Creep tests are usually carried out by loading a sample and observing the development of strain as a function of time, for a given temperature and stress. The measured strain (e) is then plotted against time (t) as illustrated in Fig.1. The curve consists of three portions: the primary and tertiary portions are relatively small transients which will be neglected in this practical. The central steady-state part is prolonged and the most important in practice, because it determines how long the material can be used safely. In the steady-state regime, the rate at which strain occurs (*i.e.* the slope of the $e-t$ curve) is given by

$$\frac{de}{dt} = C\sigma^n \tag{1}$$

where σ is the stress, C is a proportionality constant and n is known as the stress-exponent. In this practical, we shall be measuring steady-state creep and the stress-exponent for solder, which is a metallic alloy made from a mixture of lead and tin.

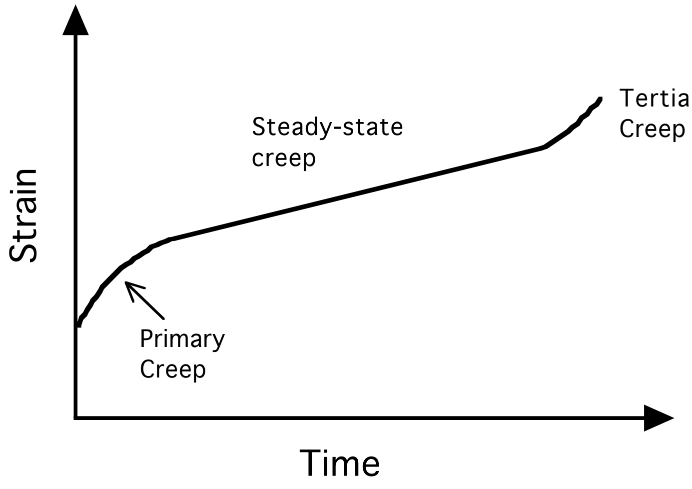

Fig.1: Creep deformation curve illustrating the steady-state creep regime

The Nature of Lead - Tin Solder

Solder is a metallic alloy which is used extensively in the electronics industry to make electrically conducting connections between wires and components such as integrated circuits, resistors, capacitors *etc*. Components like these can be fatally damaged by excessive heat, so that any material used in making soldered connections must have a low melting temperature.

Both lead and tin have low melting temperatures (Fig.2). However, a Pb–Sn mixture containing 61.5 wt.% tin has a eutectic composition and, therefore, the minimum melting temperature of all combinations of lead and tin. This "60 – 40" mixture melts at 183°C. The mixture also has the advantage that it solidifies at the eutectic temperature, rather than over a range of temperatures. This means that a mechanically rigid joint is achieved very quickly. Both of these features are a great advantage in making electrical connections to sensitive components.

For the purposes of the present experiment where we are interested in creep, room temperature (about 300 K) corresponds to a homologous temperature of 0.66. This means that with a suitable design of experimental apparatus, it is possible to observe creep deformation in a time scale which is realistic for a Part IA practical!

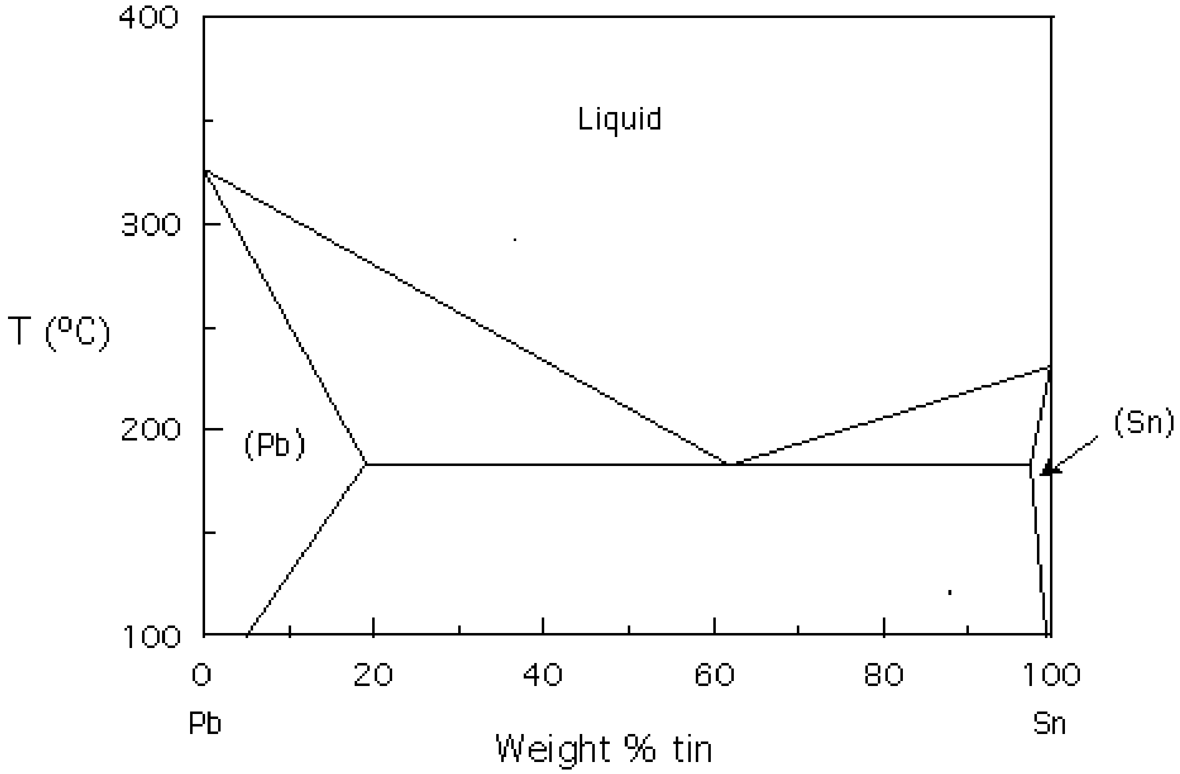

Fig.2: The lead - tin phase diagram

SINCE YOU WILL BE HANDLING LEAD,
you must wash your hands with soap and water before leaving the Department.

Creep Testing

Creep tests are normally carried out using tensile specimens of the kind illustrated in Fig.3a. The sample is loaded whilst in a furnace at a controlled temperature; the deformation (hence strain) and time are recorded continuously. It is necessary to do many tests like this in order to obtain the strain rate as a function of stress.

An alternative method is to use one sample but with a gradient of stress. Fig.3b illustrates this method in which a coil made out of the material of interest is exposed to the right temperature. The stress arises from the weight of the sample itself. This means that there is no stress on the lowest part of the coil, a maximum stress at the highest part, and a proportional stress in all intermediate positions.

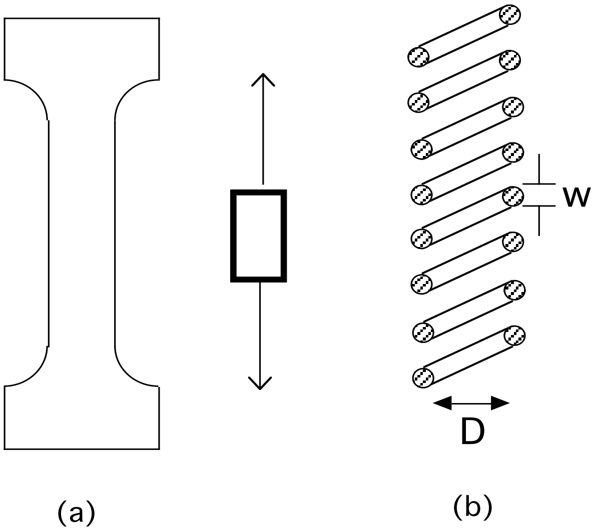

Fig.3: (a) Standard tensile specimen. (b) Coiled specimen.

If the turnings in each coil are numbered N beginning with the lowest turning and ending at the top, then the shear stress in each turning varies from zero at its centre to a maximum value τ at its surface where

$$\tau \propto \frac{ND^2}{w}. \tag{2}$$

where D is the diameter of the coil and w the diameter of the wire which makes the coil (Fig.3b).

The deflection of the coil (a measure of the shear strain) when loaded can be measured in terms of the spacing s between adjacent turns (Fig.4). It is found that the local shear strain γ is given by:

$$\gamma \propto \frac{sw}{\pi D^2}. \tag{3}$$

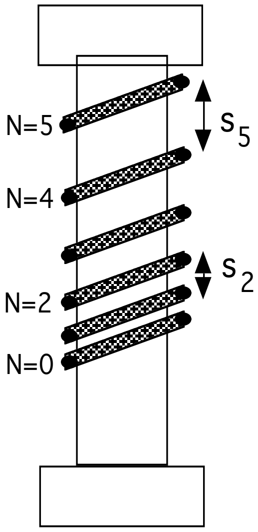

Fig.4: A deformed coil

On allowing the coil to creep, the spacing of the turns at the top (where the weight of the underlying coils is largest) will increase most (Fig.4). This spacing, divided by the time, is a measure of the strain rate for that particular value of stress, so that the strain rate is given by

$$\frac{d\varepsilon}{dt} \quad \frac{sw}{\pi D^2} \tag{4}$$

It follows that a single experiment can give all the data required for a plot of the strain rate versus the stress.

Measurement of Creep Data

The main equipment needed is the "dumbell" illustrated in Fig.5. You are provided with two samples of 60/40 solder, with two different diameters (0.71 and 1.22 mm). Wind each of these into a tight-fitting coil around the mandrel provided, but do not use excessive force during this operation. Begin the experiment using the coil made from the thinner solder and then repeat all the measurements using the other, thicker, solder wire.

1. Remove the cover of the dumbell, and place one coil onto the central section. Taking care to keep the dumbell in a horizontal position, replace the cover and thread the end of the wire nearest to it through the hole in the central section (Fig.5) so that the position of the end of the coil is secured. Keep the dumbell in a horizontal position until you are ready to make the measurements described below. The coil does not creep whilst in a horizontal position, and the elastic component of the strain is also removed.

2. You may begin the experiment by starting the stop-watch and turning the dumbell into a vertical position, with the loose-fitting cover at the top. The coil will steadily unwind. The experiment can be stopped when the lowest turning of the coil reaches within about 1 cm of the base. Turn the dumbell into a horizontal position as soon as the experiment is stopped.

3. Take a double sheet of "duplicate" paper and place it so that the pressure-sensitive sheet is in contact with the whole length of the coil. Rub the top sheet gently (to avoid altering the coil spacing) with a soft pencil (or the mandrel itself) to make an impression of the coil on the pressure-sensitive sheet. The rubbing direction should be perpendicular to the mandrel (parallel to the coils). Remove the paper and measure the turn spacing s as a function of the turn number N, noting that $N = 0$ at the bottom of the coil (Fig.4). See section "Analysis of results" before measuring since entering data directly into a table with appropriate columns which facilitate subsequent analysis.

4. Turn the dumbell, with the distorted coil into a vertical position, but in an upside down orientation in order to reverse the creep. Note the time taken for the coil to return into its original configuration. Steady-state creep occurs at a constant strain rate. A constant strain rate cannot be obtained if the material work hardens during deformation. The times taken for forward and reverse deformation should therefore be equal.

5. Once again, turn the dumbell upside down, but this time blow warm air across the coil using the hair-dryer provided. Do not attempt to make any measurements, simply observe what happens. Note the large effect of temperature on the creep rate.

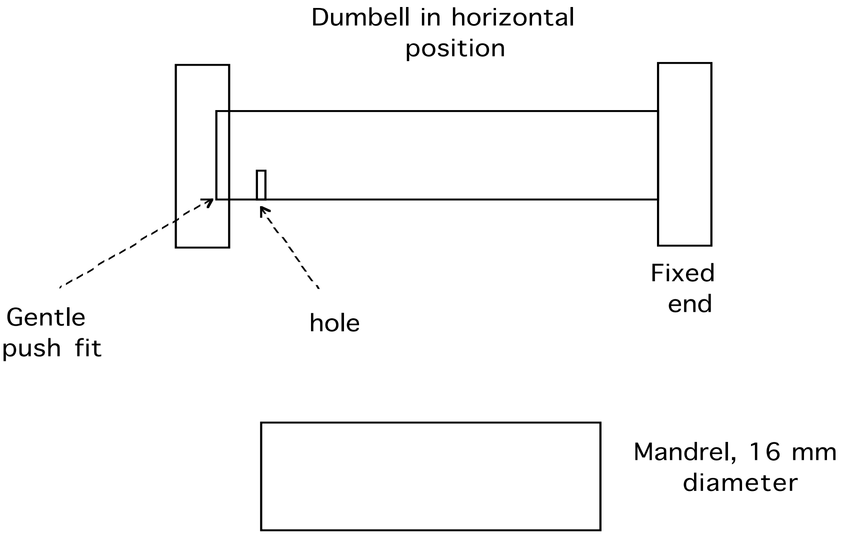

Fig.5: The creep test equipment

Analysis of the Results

The following analysis should be carried out on the data from both coils. Consider what data are needed for the final graphs and draw up an appropriate table with necessary columns before commencing measurements and analysis of results.

1. Obtain a measure of the strain rate by multiplying each value of s by w/t and a measure of the stress as a function of position in the coil by multiplying each value of N by $1/w$,

2. Plot a graph of $\ln(sw/t)$ versus $\ln(N/w)$.

3. Assuming that the errors in the measurement of w and of t are small compared with those in your measurements of N and s, deduce expressions for □s and □N. Hence estimate the error in s and in N and add error bars to your graphs.

4. Is the observed behaviour consistent with steady-state creep? Obtain a value of the stress exponent n.

5. Would you expect pure lead or pure tin to creep at a higher rate than 60/40 solder in an identical environment?

Harry Bhdeshia, Mike Ashby