

MECE3245 Materials Science Lab

Creep Test

1. INTRODUCTION

Many machines and structures, particularly those associated with energy conversion, such as turbines, nuclear reactors, steam and chemical plants - operate at high temperature. At temperatures greater than 0.4 to 0.5 of the melting temperature (when the temperature is expressed in degrees Kelvin) materials will slowly deform under loads which would not cause any plastic deformation at room temperature. This deformation is called creep. The strain, ε instead of depending only on the stress, σ also depends on temperature, T and time, t .

$$\varepsilon = f(\sigma, t, T) \quad (1)$$

Creep testing applies a constant load to a specimen while measuring the specimen's elongation, or strain. This strain is plotted against time to form a creep curve. This curve usually contains three regimes, after the initial elastic strain. The first is primary creep where the strain rate, $d\varepsilon/dt$, is initially rapid and then decreases with time. Then the specimen enters into secondary creep, in which the creep rate is constant. This constant creep rate is called as the steady-state creep rate, $\dot{\varepsilon}_{ss}$, or minimum creep rate, $\dot{\varepsilon}_{min}$ (since it is the slowest creep rate during the test). Finally, the specimen enters into tertiary creep, in which the creep rate continually increases until the specimen breaks. The failure event is called creep rupture or creep fracture, characterized by the time to fracture, t_f . Some metals do not exhibit a well-defined secondary creep state. Instead, the primary creep passes directly into tertiary creep. The point at which this change occurs is the slowest creep rate. Although accurately called as minimum creep rate, it is frequently called as steady-state creep rate. In conformity to the more commonly observed creep behavior in designing components that operate at high temperatures, two items must be considered. First excess creep deformation must be prevented because this will lead to interference between components. Second, the component must not be allowed to fail by creep rupture. In designing against creep deformation, $\dot{\varepsilon}_{min}$ or $\dot{\varepsilon}_{ss}$ is commonly used. Primary creep may be included with the initial elastic strain or treated as a function of time. Tertiary creep is usually not considered since failure by excessive elongation usually occurs prior to tertiary creep.

We will concentrate on $\dot{\epsilon}_{ss}$, since this is the most common approach. The stress dependence of $\dot{\epsilon}_{ss}$, at a constant temperature is usually given by a power-law relationship,

$$\dot{\epsilon}_{ss} = B\sigma^n \quad (2)$$

where n is a material constant called the creep exponent and B is a function of temperature. When plotted on log-log coordinates, the data falls along a straight line whose slope is given by n .

The temperature dependence of $\dot{\epsilon}_{ss}$ at a constant stress is usually given by an Arrhenius rate equation,

$$\dot{\epsilon}_{ss} = Ce^{-\frac{Q}{RT}} \quad (3)$$

where C is a function of stress, Q is the activation energy for creep, R is the universal gas constant and T is in degrees Kelvin. Note that as the temperature increases, the rate increases exponentially. The value of Q is found by plotting the natural logarithm of $\dot{\epsilon}_{ss}$ vs. $(1/T)$. The data should fall along a straight line with a slope of $(-Q/R)$.

The general relationship between $\dot{\epsilon}_{ss}$, and T is

$$\dot{\epsilon}_{ss} = A\sigma^n e^{-\frac{Q}{RT}} \quad (4)$$

where A , n and Q are material constants that vary from material to material, and have to be found experimentally.

In addition to controlling excess elongation at high temperatures, it is necessary to prevent creep rupture. To do this, plots of σ vs. $\log t_f$ or $\log \sigma$ vs. $\log t_f$ are constructed at various temperatures. These plots may or may not yield a linear relationship between the variables.

These plots are adequate if the design life is within the range of the experimental data. However, many design lives are much longer than this range. Design lives of 10 to 30 years are common. Since one cannot wait this long to obtain the experimental data before starting the design, some means of extrapolating the data to long lives is necessary. A common method of doing this is the use of time-temperature parameters which relate the stress and temperature to the time to failure. The most widely used parameter is the Larson-Miller parameter,

$$\text{L-M Parameter} = T [C' + \log t_f] \quad (5)$$

where C' is a constant. C' is approximately equal to 20 when the temperature is expressed in degrees Kelvin and the time is expressed in hours. This parameter is plotted against the stress to obtain a master curve of the creep rupture behavior. By knowing the L-M Parameter for a given stress it is possible to determine the time to failure at a given temperature. By running experiments at the design stress, but at a higher temperature, creep rupture will occur in a reasonable length of time, and the L-M Parameter can be found by using Equation (5). These

calculations must be treated with caution, since they will be in error if the physical mechanism of creep rupture at the lower temperature is different from that at the higher temperature.

Creep deformation occurs by the diffusion of atoms, which is faster at higher temperatures. Since diffusion occurs most rapidly at grain boundaries, creep deformation is concentrated here. This leads to separation of the grains along their boundaries, producing an intergranular fracture surface.

2. EXPERIMENTAL PROCEDURE

In this lab, the creep behavior of Chromel (80% Ni - 20% Cr) alloy will be studied. Creep curves and the time to failure will be measured for different combinations of stress and temperature. The specimen is in the shape of a wire and will be loaded by dead weights. Five tests will be run. The actual values of σ and T to be used will be given to you by the lab assistant. Since you will be using a micrometer in this laboratory, you are expected to know how to read it.

- (1) Measure the length of the furnace. This length will be the original length of the wire for the purpose of calculating strain. This length is approximately equal to the length of the hot section of the wire in which the creep strain occurs.
- (2) Cut a piece of the wire and measure its diameter d as the average of five measurements.
- (3) Zero the clock.
- (4) Make sure the furnace is switched off.
- (5) Insert the wire through the insulation tube, and attach the wire to the frame.
- (6) Slip the extensometer disk onto the wire.
- (7) Support the weight and attach it to the end of the wire.
- (8) Pack the top and bottom of the tube with an insulating material.
- (9) Attach the extensometer to the wire using the extensometer disk.
- (10) Support the weight and energize the power supply. The maximum voltage the furnace can take is 60 V.
- (11) Adjust the temperature. Wait until the thermocouple reading stabilizes. Record the temperature.

- (12) Release the weight and record time. Record the elongation from the dial gauge every 15 seconds during the first five minutes and every 30 seconds thereafter. Note that the temperature is constant during the test.
- (13) Record the time at which the specimen fractures.
- (14) Repeat steps 2-13 for each experiment to be run. After the experiment, examine the fractured specimens using a stereo-microscope or a magnifying glass. Make a sketch of the side and end of the specimen near the fracture surface.
- (15) Experimental conditions:

Test #	Load (kg)	Temperature (°F)
1	$W_1+W_2+W_3$	1680
2	$W_1+W_2+W_3$	1690
3	$W_1+W_2+W_3$	1700
4	W_1+W_2	1700
5	W_1+W_3	1700

Values of different weights mentioned above are: $W_1 =$; $W_2 =$; $W_3 =$. Test #1-3 correspond to experiments where stress/load is constant and temperature is varying. Test #3-5 correspond to experiments where temperature is constant and load is varying.

3. ANALYSIS

Be sure to show sample calculations.

- (1) Make a data table showing the temperature, wire diameter, weight and stress for each experiment. This will be Table I.
- (2) Construct creep curves:
 - (a) For each experiment, compute the strain from the elongation. Present the data in a table containing the time, the elongation and the strain. The units of time should be minutes. These will be Tables IIa through IIe.
 - (b) Plot the creep curves for each experiment. You may put more than one curve on each graph, but you will need several graphs to properly display the data. Draw a smooth curve through the data.
 - (c) From these curves, measure $\dot{\epsilon}_{\min}$ or $\dot{\epsilon}_{ss}$. To do this you must find the minimum creep rate along the creep curve. On each curve, draw a line showing how you found this rate.
 - (d) Make a table showing the stress, temperature, $\dot{\epsilon}_{ss}$ and t_f . This will be Table III.

- (3) Follow the directions:
- (a) Show that by using the natural logarithm, Equation (3) can be written in the form
- $$y = kx + m$$
- where k and m are constants.
- (b) For the experiments at a constant stress plot $\ln \dot{\epsilon}_{ss}$ vs. $1/T$, where T is in degrees Kelvin. The strain rate should be the y-axis and units must be (minute)⁻¹. The data should be spread out over the graph instead of being grouped in a tight cluster.
- (c) Draw a straight line thru this data and find C and Q in Equation (3). C is constant for a given stress.
- (4) Follow the directions:
- (a) By using logarithm, show that Equation (2) can be written in the form
- $$y = kx + m$$
- where k and m are constants.
- (b) For the experiments at constant temperature, make a graph of $\log \dot{\epsilon}_{ss}$ vs $\log \sigma$. The strain rate should be the y-axis. The units must be (minute)⁻¹ and psi. The data should be spread out over the graph.
- (c) Draw a straight line through this data and find B and n in Equation (2). B is constant at a given temperature.
- (d) Plot $\log \sigma$ vs. rupture lifetime (min.) for the experiments at constant temperature.
- (5) Follow the directions for Larson-Miller Parameters:
- (a) Compute the Larson-Miller Parameter for each of your tests. Time should be in hours and temperature in degrees Kelvin. Assume C' is equal to 20. Be sure to show a sample calculation.
- (b) Make a table giving the stress, temperature, time to failure and the Larson-Miller Parameter. This will be Table IV.
- (c) Plot the Larson-Miller Parameter versus $\log \sigma$. You may wish to make your own logarithmic scale, since the range of the stresses is quite small. Draw a smooth curve through all of the data.

4. QUESTIONS

- (1) (a) Show that

$$A = \frac{B}{e^{-Q/RT}} \quad \text{and} \quad A = \frac{C}{\sigma^n}$$

- (b) What value of $\dot{\epsilon}_{ss}$ would you expect at 800 °C and 16000 psi? (Hint: A, B and C in Equations. (1-3) are related to each other.)

- (2) Using your Larson-Miller curve, what temperature should you use for a life of 20 years at the lowest stress level?
- (3) With increasing stress or temperature, what changes will you notice in a typical creep curve?
- (4) Does Chromel have a well-defined secondary creep stage? Explain your answer.
- (5) Creep data usually exhibit a large amount of scattering. How much scatter existed in your data? This can be estimated from your graphs in 3, 4 and 5 of the analysis section. Be specific in your answer.
- (6) Put your sketch of the fractured specimen here, and describe the features shown.
- (7) Creep deformation mechanisms all involve the diffusion of atoms, explaining increased transport at higher temperatures.
 - (a) What is diffusion and how does it occur?
 - (b) Why does it occur most rapidly at grain boundaries?
- (8) Primary creep is typified by a continuously decreasing creep rate. Give reasons.
- (9) Why is the creep rate constant during the secondary creep state? What causes the tertiary creep state to appear? [Hint: Use the effect of both strain hardening and the creep damage to the microstructure].
- (10) Give the approximate temperature at which creep deformation becomes an important consideration for each of the following metals; nickel, copper and lead.
- (11) Steady-state creep rate data are given below for nickel at 200 °C:

$\dot{\epsilon}_{ss}$ (hour ⁻¹)	σ (MPa)
24×10^{-2}	69
25×10^{-3}	55

If it is known that the activation energy for creep is 140,000 J/mol, compute the steady-state creep rate at a temperature of 250 °C and a stress level of 48 MPa (7000 psi).

5. REFERENCES

Askeland, D.R., *The Science and Engineering of Materials*, PWS Engineering, 1984, pp. 138-143, 718-719.

Dieter, G.E., *Mechanical Metallurgy*, McGraw-Hill 1961, pp. 335-347, 354-359.

Van Vlack, L.H., *Elements of Materials Science and Engineering*, Addison-Wesley, 1985, pp. 187-188, 520-521.

Wulff, J., *Structures and Properties of Materials*, Vol. 3, pp. 16-19, 113-118, 133-136.