

## 8. TIME DEPENDENT BEHAVIOUR: CREEP

In general, the mechanical properties and performance of materials change with increasing temperatures. Some properties and performance, such as elastic modulus and strength decrease with increasing temperature. Others, such as ductility, increase with increasing temperature.

It is important to note that atomic mobility is related to diffusion which can be described using Ficks Law:

$$D = D_0 \exp -\frac{Q}{RT} \quad (8.1)$$

where D is the diffusion rate,  $D_0$  is a constant, Q is the activation energy for atomic motion, R is the universal gas constant (8.314J/mole K) and T is the absolute temperature. Thus, diffusion-controlled mechanisms will have significant effect on high temperature mechanical properties and performances. For example, dislocation climb, concentration of vacancies, new slip systems, and grain boundary sliding all are diffusion-controlled and will affect the behaviour of materials at high temperatures. In addition, corrosion or oxidation mechanisms, which are diffusion-rate dependent, will have an effect on the life time of materials at high temperatures.

Creep is a performance-based behaviour since it is not an intrinsic materials response. Furthermore, creep is highly dependent on environment including temperature and ambient conditions. Creep can be defined as time-dependent deformation at absolute temperatures greater than one half the absolute melting. This relative temperature ( $\frac{T_{(abs)}}{T_{mp(abs)}}$ ) is known as the homologous temperature. Creep is a relative phenomenon which may occur at temperatures not normally considered "high." Several examples illustrate this point.

a) Ice melts at  $0^\circ\text{C}=273\text{ K}$  and is known to creep at  $-50^\circ\text{C}=223\text{ K}$ . The homologous temperature is  $\frac{223}{273} = 0.82$  which is greater than 0.5 so this is consistent with the definition of creep.

b) Lead/tin solder melts at  $\sim 200^\circ\text{C}=473\text{ K}$  and solder joints are known to creep at room temperature of  $20^\circ\text{C}=293\text{ K}$ . The homologous temperature is  $\frac{293}{473} = 0.62$  which is greater than 0.5 so this is consistent with the definition of creep.

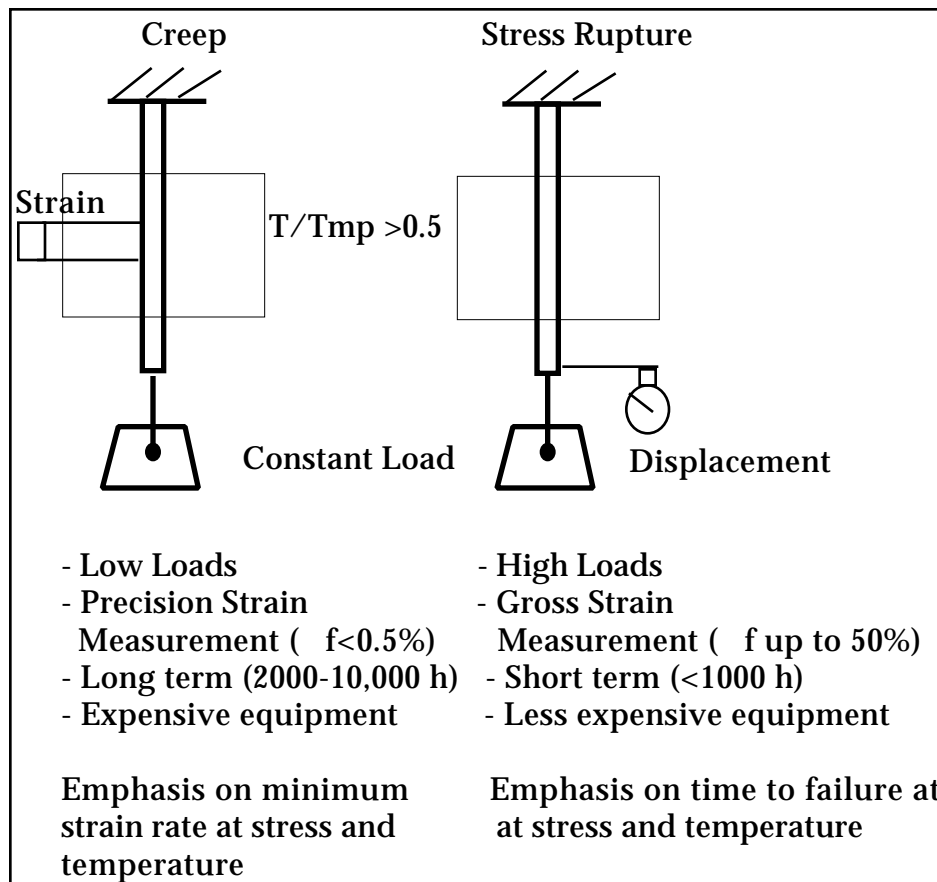


Figure 8.1 Comparison of creep and stress rupture tests

- c) Steel melts at  $\sim 1500^{\circ}\text{C} = 1773\text{ K}$  and is known to creep in steam plant applications of  $600^{\circ}\text{C} = 873\text{ K}$ . The homologous temperature is  $\frac{873}{1773} = 0.50$  which is equal to 0.5 so this is consistent with the definition of creep.
- d) Silicon nitride melts/dissociates at  $\sim 1850^{\circ}\text{C} = 2123\text{ K}$  and is known to creep in advanced heat engine applications of  $1300^{\circ}\text{C} = 1573\text{ K}$ . The homologous temperature is  $\frac{1573}{2123} = 0.74$  which is greater than 0.5 so this is consistent with the definition of creep.

Conceptually a creep test is rather simple: Apply a force to a test specimen and measure its dimensional change over time with exposure to a relatively high temperature. If a creep test is carried to its conclusion (that is, fracture of the test specimen), often without precise measurement of its dimensional change, then this is called a stress rupture test (see Fig 8.1). Although conceptually quite simple, creep tests in practice are more complicated. Temperature control is critical (fluctuation must be kept to  $< 0.1$  to  $0.5^{\circ}\text{C}$ ). Resolution and stability of the extensometer is an important concern (for low

creeping materials, displacement resolution must be on the order of 0.5 μm). Environmental effects can complicate creep tests by causing premature failures unrelated to elongation and thus must either mimic the actual use conditions or be controlled to isolate the failures to creep mechanisms. Uniformity of the applied stress is critical if the creep tests are to be interpreted. Figure 8.2 shows a typical creep testing setup.

The basic results of a creep test are the strain versus time curve shown schematically in Fig. 8.3. The initial strain,  $\epsilon_i = \frac{\sigma}{E}$ , is simply the elastic response to the applied load (stress). The strain itself is usually calculated as the engineering strain,  $\epsilon = \frac{L - L_0}{L_0}$ . The primary region (I) is characterized by transient creep with decreasing creep strain rate ( $\frac{d\epsilon}{dt} = \dot{\epsilon}$ ) due to the creep resistance of the material increasing by virtue of material deformation. The secondary region (II) is characterized by steady state creep (creep strain rate,  $\dot{\epsilon}_{min} = \dot{\epsilon}_{ss}$ , is constant) in which competing mechanisms of strain hardening and recovery may be present. The tertiary region (III) is characterized by increasing creep strain rate in which necking under constant load or consolidation of failure mechanism occur prior to failure of the test piece. Sometimes quaternary regions are included in the analysis of the strain-time curve as well, although these regions are very specific and of very short duration.

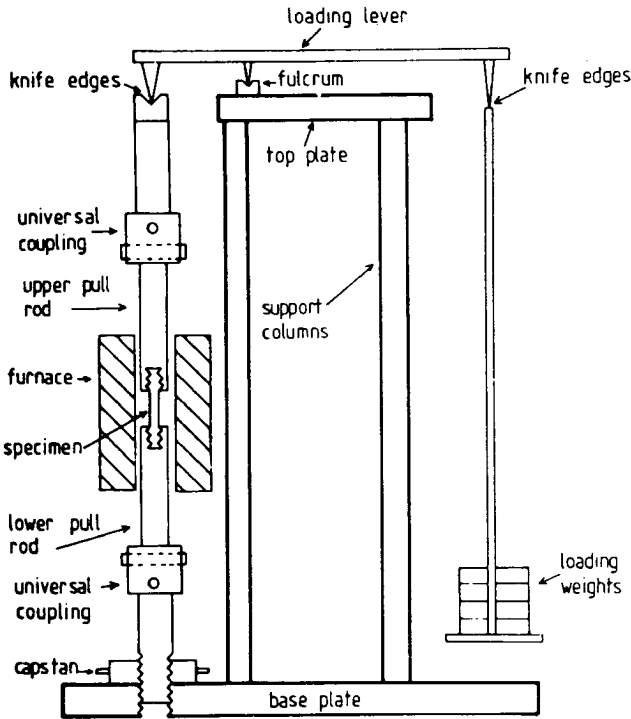


Figure 8.2 Typical creep test set-up

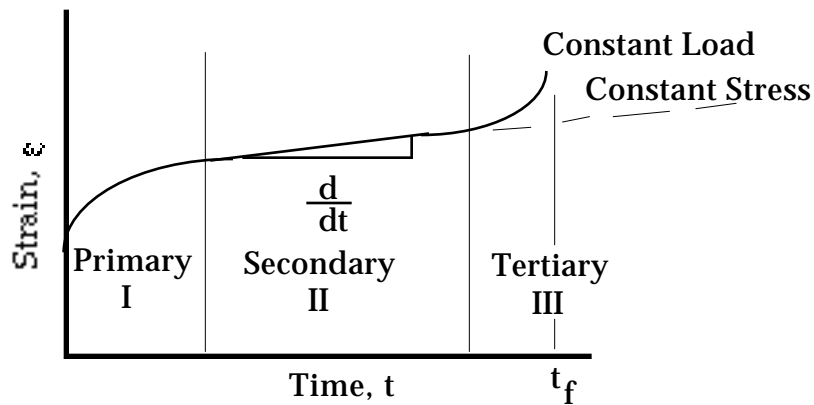


Figure 8.3 Strain time curve for a creep test

In principle, the creep deformation should be linked to an applied stress. Thus, as the specimen elongates the cross sectional area decreases and the load needs to be decreased to maintain a constant stress. In practice, it is simpler to maintain a constant load. When reporting creep test results the initial applied stress is used. The effect of constant load and constant stress is shown in Fig. 8.3. Note that in general this effect (dashed line for constant stress) only really manifests itself in the tertiary region, which is beyond the region of interest in the secondary region. The effects of increasing temperature or increasing stress are to raise the levels and shapes of the strain time curves as shown in Figure 8.4. Note that for isothermal tests, the shapes of the curves for increasing stress may change from dominant steady state to sigmoidal with little steady state to dominant primary. Similar trends are seen for iso stress tests and increasing temperature (see Fig. 8.4).

Creep mechanisms can be visualized by using superposition of various strain-time curves as shown in Fig. 8.5. An empirical relation which describes the strain-time relation is:

$$= \epsilon_i \left( 1 + t^{1/3} \right) \exp(kt) \quad (8.2)$$

where  $\epsilon_i$  is a constant for transient creep and  $k$  is related to the constant strain rate. A "better" fit is obtained by:

$$= \epsilon_i + \epsilon_t (1 - \exp(-rt)) + t \dot{\epsilon}_{ss} \quad (8.3)$$

where  $r$  is a constant,  $\epsilon_t$  is the strain at the transition from primary to secondary creep and  $\dot{\epsilon}_{ss}$  is the steady-state strain rate. Although no generally-accepted forms of nonlinear strain-time relations have been developed, one such relation is:

$$= \epsilon_i + B \epsilon_t^m + D (1 - \exp(-a t)) \quad (8.4)$$

where  $B$ ,  $m$ ,  $D$ ,  $a$  and  $b$  are empirical constants.

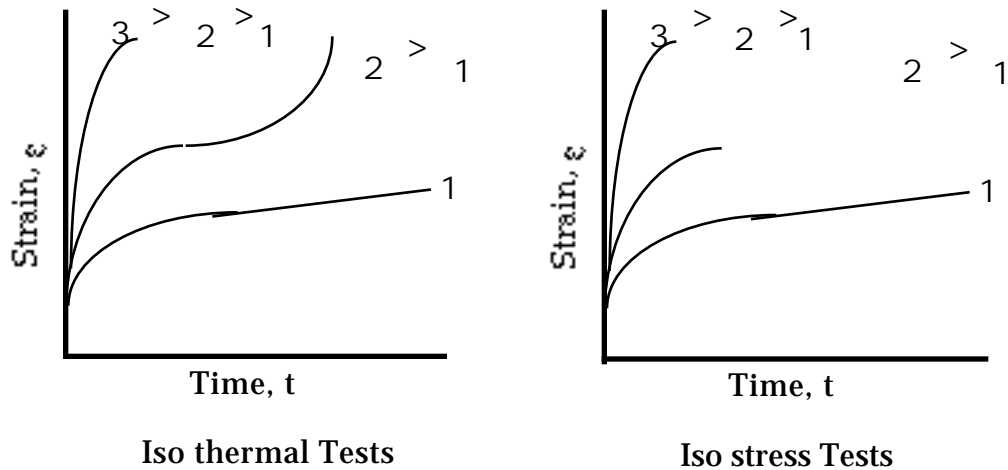


Figure 8.4 Effect of stress and temperature on strain time creep curves

In this relation, if  $t > t_{\text{transient}}$  then

$$\epsilon = \epsilon_i + B \sigma^m t + D \quad (8.5)$$

and the strain rate is the steady-state or minimum strain rate:

$$\frac{d\epsilon}{dt} = \dot{\epsilon}_{ss} = B \sigma^m \quad (8.6)$$

The steady state or minimum strain rate is often used as a design tool. For example, what is the stress needed to produce a minimum strain rate of  $10^{-6}$  m/m / h ( or  $10^{-2}$  m/m in 10,000 h) or what is the stress needed to produce a minimum strain rate of  $10^{-7}$  m/m / h ( or  $10^{-2}$  m/m in 100,000 h). An Arrhenius-type rate model is used to include the effect of temperature in the model of Eq. 8.6 such that:

$$\dot{\epsilon}_{ss} = \dot{\epsilon}_{\min} = A \sigma^n \exp \frac{-Q}{RT} \quad (8.7)$$

where  $n$  is the stress exponent,  $Q$  is the activation energy for creep,  $R$  is the universal gas constant and  $T$  is the absolute temperature.

To determine the various constants in Eq. 8.7 a series of isothermal and iso stress tests are required. For isothermal tests, the exponential function of Eq. 8.7 becomes a constant resulting in

$$\dot{\epsilon}_{ss} = \dot{\epsilon}_{\min} = B \sigma^n \quad (8.8)$$

Equation 8.8 can be linearized by taking logarithms of both sides such that

$$\log \dot{\epsilon}_{ss} = \log \dot{\epsilon}_{\min} = \log B + n \log \sigma \quad (8.9)$$

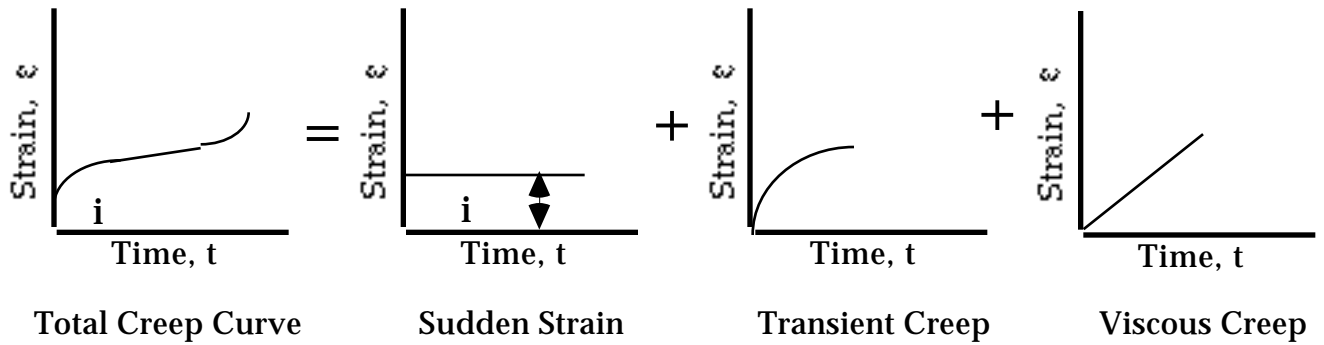


Figure 8.5 Superposition of various phenomenological aspects of creep

Log-log plots of  $\dot{\epsilon}_{\min} = \dot{\epsilon}_{ss}$  versus  $\sigma$  (see Fig. 8.6) often results in a bilinear relation in which the slope,  $n$ , at low stresses is equal to one indicating pure diffusion creep and  $n$  at higher stresses is greater than one indicating power law creep with mechanisms other than pure diffusion (e.g., grain boundary sliding).

For iso stress tests, the power dependence of stress becomes a constant resulting in

$$\dot{\epsilon}_{ss} = \dot{\epsilon}_{\min} = C \exp \frac{-Q}{RT} \quad (8.10)$$

Equation 8.10 can be linearized by taking natural logarithms of both sides such that

$$\ln \dot{\epsilon}_{ss} = \ln \dot{\epsilon}_{\min} = \ln C - \frac{Q}{R} \frac{1}{T} \quad (8.11)$$

Log-linear plots of  $\dot{\epsilon}_{\min} = \dot{\epsilon}_{ss}$  versus  $\frac{1}{T}$  (see Fig. 8.7) results in a linear relation in which the slope,  $\frac{-Q}{R}$ , is related to the activation energy,  $Q$ , for creep.

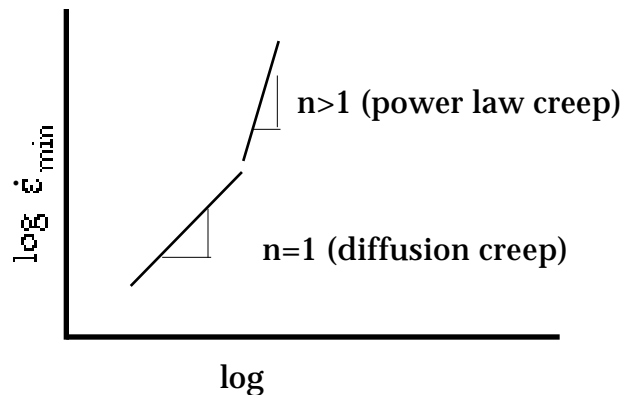


Figure 8.6 Log-log plot of minimum creep strain rate versus applied stress showing diffusion creep and power law creep.

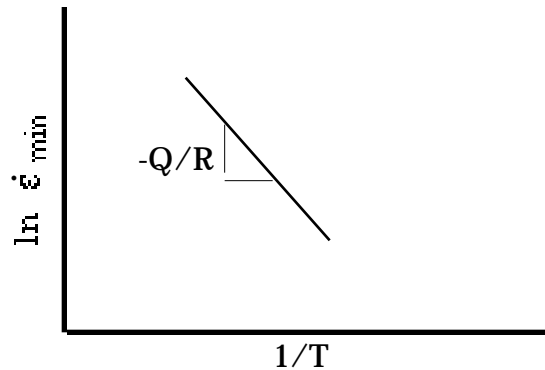


Figure 8.7 Log-linear plot of minimum creep strain rate versus reciprocal of temperature showing determination of activation energy.

The goal in engineering design for creep is to predict the behaviour over the long term. To this end there are three key methods: stress-rupture, minimum strain rate vs. time to failure, and temperature compensated time. No matter which method is used, two important rules of thumb must be borne in mind: 1) test time must be at least 10% of design time and 2) creep and/or failure mechanism must not change with time, temperature or stress.

Stress-rupture This is the "brute force method" in which a large number of tests are run at various stresses and temperatures to develop plots of applied stress vs. time to failure as shown in Fig. 8.8. While it is relatively easy to use these plots to provide estimates of stress rupture life within the range of stresses and lives covered by the test data, extrapolation of the data can be problematic when the failure mechanism changes as a function of time or stress as shown by the "knee" in Fig. 8.8.

Minimum strain rate vs. time to failure This type of relation is based on the observation that strain is the macroscopic manifestation of the cumulative creep damage. As such, it is implied that failure will occur when the damage in the material in form of creep cavities and cracks resulting from coalesced creep cavities reaches a critical level. This critical level of damage is manifested as the failure which can be predicted from the minimum strain rate and the time to failure such that.

$$\dot{\epsilon}_{\min} t_f = C \quad f \quad (8.12)$$

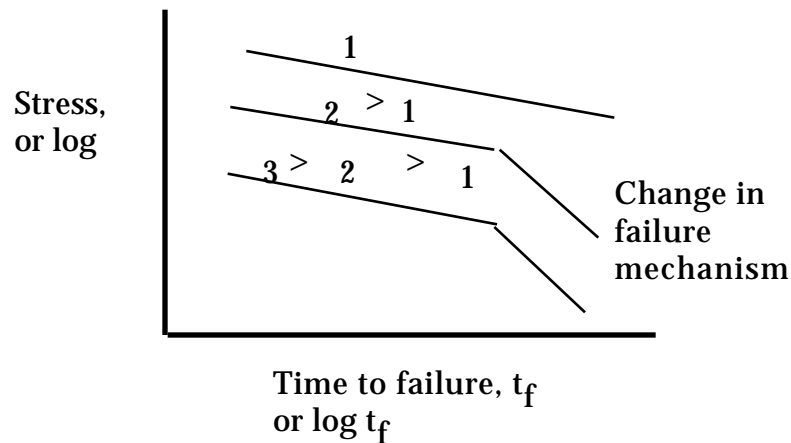


Figure 8.8 Stress rupture plots for various temperatures

Equation 8.12, known as the Monkman-Grant relation, should give a slope of -1 on a log-log plot of  $\dot{\epsilon}_{min}$  versus  $t_f$  regardless of temperature or applied stress for a particular material. It then becomes a simple matter to predict a time to failure either by measuring the minimum strain at a given stress and temperature or predicting the minimum strain rate from Eq. 8.7 for the given temperature and stress once the A and Q are determined. Having found the minimum strain rate, the time to failure can be found from the Monkman-Grant plot for the particular material.

Temperature-compensated time In these methods, a higher temperature is used at the same stress so as to cause a shorter time to failure such that temperature is traded for time. In this form of accelerated testing it is assumed that the failure mechanism does not change and hence is not a function of temperature or time. In addition, assumptions can be made that Q is stress and temperature independent. Two of the more well-known relations are Sherby-Dorn and Larson Miller.

In the Sherby-Dorn method,  $P_{SD}$  is the temperature compensated time such that:

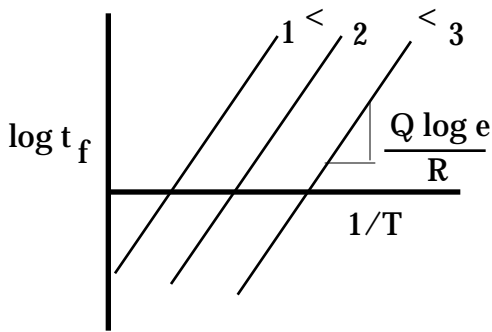
$$P_{SD} = \log t_f - \frac{\log e Q}{R T} \quad (8.13)$$

where  $P_{SD}$  is the Sherby-Dorn parameter and Q is assumed independent of temperature and stress. In this method, a number of tests are run at various temperatures and stresses to determine the times to failure and activation energy. A "universal" plot (see Fig. 8.9) is then made of the stress as a function of  $P_{SD}$ . The allowable stress for an combination of time to failure and temperature (i.e.,  $P_{SD}$ ) can then be determined from the curve.

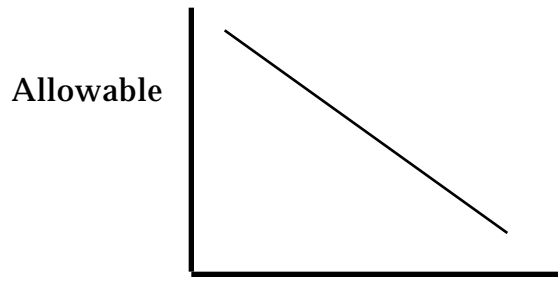
In the Larson-Miller method,  $P_{LM}$  is the temperature compensated time such that:

$$P_{LM} = \frac{\log e Q}{R} = T(\log t_f + \log C) \quad (8.14)$$





Experimental Results



$$P_{SD} = \log t_f - \frac{\log e}{R} \frac{Q}{T}$$

"Universal" Sherby Dorn Relation

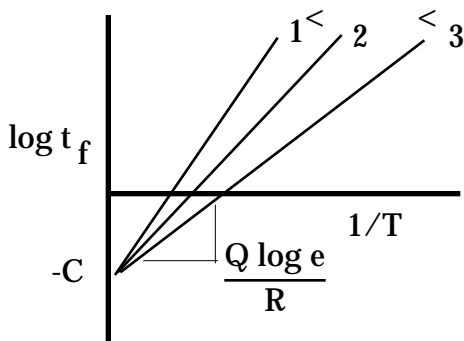
Figure 8.9 Summary of Sherby-Dorn relation

where  $P_{LM}$  is the Larson-Miller parameter,  $Q$  is assumed to a function of stress only, and  $C$  is a constant of  $\sim 20$  for most materials. In this method, a number of tests are run at various temperatures and stresses to determine the times to failure and activation energy. A "universal" plot (see Fig. 8.10) is then made of the stress as a function of  $P_{LM}$ . The allowable stress for an combination of time to failure and temperature (i.e.,  $P_{LM}$ ) can then from the curve.

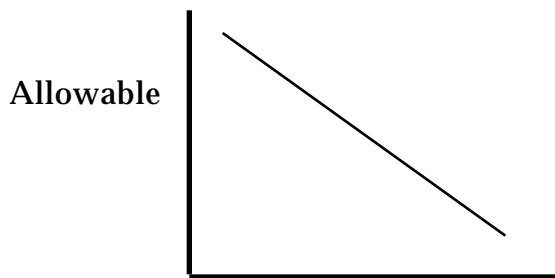
An example of the application of the Sherby-Dorn relation is as follows. For a certain aluminum-magnesium alloy the stress- $P_{SD}$  relation is found to be

$$= f(P_{SD}) = -11.3P_{SD} - 124 \quad (25 \quad 85 \text{ MPa}) \quad (8.15)$$

The design problem is to determine the allowable stress to give 2000 h life at 200°C. For this alloy, the activation energy,  $Q$ , is 150.5 kJ/mole. Using  $Q=150,500$  J/mole,  $R=8.314$  J/mole K,  $t_f=2000$  h, and  $T=473$  K,  $P_{SD}$  is calculated as -13.21. Substituting this value of  $P_{SD}$  into Eq. 8.15 gives an allowable stress of 25 MPa.



Experimental Results



$$P_{LM} = T (\log t_f - C)$$

"Universal" Larson-Miller Relation

Figure 8.10 Summary of Larson-Miller relation