1-3 CREEP

Creep is time-dependent permanent deformation that is often due to diffusion processes rather than dislocation motion. Engineers need to consider creep in cases in which ceramic components will be used in load-bearing applications at high temperature. It is necessary to specify a particular maximum strain that is acceptable during the anticipated lifetime of the component.

In general, creep behavior of ceramics is similar to that of metals. However, in ceramics it usually occurs at higher temperatures, typically $>0.5 \ T_m$. In comparison, creep is a consideration in aluminum alloys at 100°C and in polymers at room temperature. Creep is particularly important in ice, which creeps extensively at low temperatures. The creep of ice is responsible for the movement of glaciers and the spreading of the Antarctic ice cap. Figure 1.17 shows a general creep curve. There are three regimes:

- Transient or primary creep: Following spontaneous elastic strain the creep rate (also referred to as the creep strain rate) decreases with time from an initially high value. This stage of creep is often represented by an equation of the form

$$\varepsilon = \beta T_m$$

(1.12)

$\beta$ is a constant and $m$ varies from 0.03 to 1.0 depending on the material, stress, and temperature. In some ceramics (e.g., SiC fibers) this may be the only stage shown.

- Steady-state or secondary creep: Strain increases linearly with time, the creep rate is constant, and deformation may continue for a long time. This is the most important regime. The equation for secondary creep is

$$\varepsilon = Kt$$

(1.13)

$K$ is a constant that depends on stress and temperature. The mechanisms for this stage are discussed in the next sections.

- Tertiary creep: a rapid increase in creep rate just before failure. This stage is often missing for ceramics.
The creep behavior of a ceramic is determined by measuring the strain rate as a function of load. In the simplest approach a load is attached to the sample, which is heated, and the deformation is measured as a function of time. Because of the problems we mentioned earlier in performing tensile tests on ceramics the load is usually applied by bending. The disadvantage of bending tests is the inhomogeneous stress state that changes during creep deformation. The creep behavior of ceramics is different if the load is applied in tension or compression and compressive creep tests may, although rarely, be performed. There are three mechanisms for creep and we will describe each of these in the following sections.

1-3.1 DISLOCATION CREEP

In this mechanism creep occurs by dislocation motion, i.e., glide and climb. For the climb-controlled process the creep rate can be expressed as

\[ \dot{\varepsilon} = \frac{\alpha D_n \mu b}{kT} \left( \frac{\sigma}{\mu} \right)^a \]  

(1.14)

which we can simplify by taking all of the "constants" into a temperature-dependant constant \( \Gamma \):

\[ \dot{\varepsilon} = \Gamma \sigma^a \]  

(1.15)

This is a simple power law equation and when \( n > 1 \) we refer to it as power law creep. For climb \( n \) is in the range 4–5; for a glide-controlled process \( n = 3 \).
1-3.2 DIFFUSIONCONTROLLED CREEP

In this mechanism creep is due to atomic diffusion. There is no dislocation motion. If we consider the single crystal shown in Figure 1.18 Nabarro (1948) showed that vacancies would move from the faces under tension to those under compression. There will be a counterflow of atoms and we obtain a permanent shape change as a result. For Nabarro–Herring creep the creep rate is given by

\[ \dot{\varepsilon} = \frac{\alpha D_1 \sigma \Omega}{d^2 kT} \]  

(1.16)

In this case the constant, \( \alpha \), depends on the extent of grain-boundary sliding as determined by Herring (1950). For simple tension test measurements under steady-state conditions \( \alpha = 13.3 \). We assume the following:

- The main source and sink for vacancies are grain boundaries.
- We are in equilibrium.
- There is no cavitations.

The following important points apply to Nabarro–Herring creep:

- The temperature has to be high enough to allow significant vacancy diffusion.
- Diffusion is considered to occur through the bulk of the material.
- Because of the \( d^{-2} \) dependence the creep rate will increase with decreasing grain size (shorter diffusion distance).
- The creep rate is proportional to the applied stress (at least for lower stresses).
- There is a linear dependence between strain rate and stress.

At lower temperatures and for fine-grained ceramics grain boundary diffusion may be the dominant path. In these situations the process is termed Coble creep (Coble, 1963) and the creep rate is:

\[ \dot{\varepsilon} = \frac{150 \Omega \delta D_{gb} \sigma}{\pi d^3 kT} \]  

(1.17)

The important points to note from Eq. 1.17 are that

- Creep rate varies as \( d^{-3} \); hence it is important for very fine-grained ceramics.
- \( D_{gb} > D_L \), so Coble creep is favored at lower temperatures.

Nabarro–Herring and Coble creep can take place in parallel so that actual creep rates will involve both components and both diffusion coefficients. In ceramics we also
have a situation in which both anions and cations are diffusing adding further complications to the creep rate equations. If there is a large difference in the diffusion rates then the creep rate is controlled by the slower diffusing species along the faster diffusing path.

*TERMS IN CREEP EQUATIONS*

- \( \alpha \) a constant,
- \( D_L \) lattice diffusivity,
- \( k \) Boltzmann’s constant,
- \( b \) Burgers vector
- \( T \) absolute temperature,
- \( \sigma \) applied stress,
- \( \mu \) shear modulus,
- \( m \) grain size exponent
- \( n \) stress exponent,
- \( \Omega \) atomic volume,
- \( d \) grain size,
- \( D_{gb} \) grain boundary diffusivity
- \( \delta \) grain boundary width.
- \( A \) dimensionless constant.
- \( D \) diffusion coefficient.

![Figure 1.18 Illustration of Nabarro–Herring creep.](image)

1-3.3 GRAIN-BOUNDARY SLIDING

Some ceramics have an intergranular film (IGF) formed during fabrication, often due to the addition of a sintering aid. If this phase softens at high temperature then we get creep by grain-boundary sliding. The glass viscosity, \( \eta \), which is a function of temperature, controls the creep rate. As the temperature increases the viscosity decreases, and this is usually represented by an empirical relation known as the Vogel–Fulcher–Tammann (VFT) equation or sometimes simply the Fulcher equation:

\[
\ln \eta = A + \frac{B}{T - T_0}
\]

(1.18)

\( A, B, \) and \( T_0 \) are constants for a particular glass. The VFT equation works very well except at temperatures close to the glass transition temperature, \( T_g \). There are several mechanisms that can result in a permanent change in shape. In one mechanism the glass is squeezed out of the boundaries during compression flowing to those under
tension. Proof of this mechanism comes from high-resolution TEM, which can be used to directly measure the thickness, \( w \), of the IGF. In these cases

\[
\dot{\varepsilon} = \frac{\alpha \omega^3 \sigma}{\eta_0 d^3}
\]  

(1.19)

Another proposed mechanism is that of dissolution and reprecipitation, which is illustrated in Figure 1.19. Here grains dissolve in the liquid at points of high stress, and this solute then diffuses through the liquid and precipitates at regions of low stress. In this case the creep rate is

\[
\dot{\varepsilon} = \frac{\alpha \omega \Omega^2}{\eta_0 d^3}
\]  

(1-20)

This latter mechanism is similar to what happens during liquid-phase sintering. The requirements include the following:

- The solid must have a certain amount of solubility in the liquid.
- The liquid must wet the solid.

The composition of the IGF is important in determining overall creep behavior. For example, using \( \text{Y}_2\text{O}_3 \) as a sintering aid for silicon nitride ceramics has been found to be superior to using \( \text{MgO} \). Other important aspects of the microstructure are the grain size and the volume fraction of liquid present.

**FIGURE 1.19** Illustration of the dissolution–precipitation mechanism that could be operative in ceramics containing a glassy phase at the GB.

### 1-3.4 TERTIARY CREEP AND CAVITATION

Tertiary creep represents the final stage of creep deformation and involves an acceleration of the creep rate followed by failure of the component. This stage does not occur in all ceramics, and as previously noted certain ceramics exhibit only primary creep. Tertiary creep involves the formation of cavities that lead to crack
formation, often along grain boundaries. The cracks can propagate rapidly, particularly under tensile loading.

Although the nucleation of cavities does not seem to be well understood at present, it is clear that cavitations depends on microstructure. Porosity and second-phase particles, which are sources of stress concentration, can act as nucleation sites for cavitations and subsequent crack growth. Remember pores can be found in most ceramics; even “pore-free” materials such as hot pressed alumina may contain small pores. Cavitations also occur in ceramics with IGFs. Nucleation of the cavities will usually occur at regions where the IGF is not homogeneous, e.g., non-wetted regions, gas bubbles, and impurity particles. Figure 1.20 shows cavity size distribution data for two polycrystalline alumina. One is Lucalox (there is no glassy phase) and the other is 99% pure alumina with a glassy phase. The data were obtained using small-angle neutron scattering. For Lucalox the number of pores increases with increasing creep strain but their size does not increase—nucleation is the dominant process. For the alumina with a glassy phase both the number and size of the pores increase with creep strain—we are getting both nucleation and growth.

**FIGURE 1.20** (a) Cavity-size distribution as a function of creep strain in alumina without a glassy phase (Lucalox). (b) Cavity-size distribution as a function of creep strain in alumina with a glassy phase (AD99).
1-3.5 CREEP DEFORMATION MAPS

From the previous sections you can see that there are a large number of creep mechanisms. These can be expressed by one general equation:

$$\dot{\varepsilon} = \frac{AD\mu b}{kT} \left( \frac{b}{d} \right)^m \left( \frac{\sigma}{\mu} \right)^n$$  \hspace{1cm} (1.21)

The various creep mechanisms give rise to different values of the exponents, $m$ and $n$. For a given ceramic a specific creep mechanism may dominate at certain temperatures and stresses. This can be represented on a creep deformation map as illustrated in Figure 1.21a for a general case and in Figure 1.21b for the specific case of Al$_2$O$_3$. These maps are based on a large amount of experimental data.

*FIGURE 1.21* (a) Schematic of creep deformation map for a polycrystalline ceramic. (b) Creep deformation map for Al$_2$O$_3$. 