Creep Failure

If we apply stress to a material at an elevated temperature, the material may stretch and eventually (finally) fail, even though the applied stress is less than the yield strength at that temperature. A time dependent permanent deformation under a constant load or constant stress and at high temperatures is known as **Creep**. A large number of failures occurring in components used at high temperatures can be attributed to creep or a combination of creep and fatigue. Essentially, in creep the material begins to flow slowly. Diffusion, dislocation glide or climb, or grain boundary sliding can contribute to the creep of metallic materials. Polymeric materials also show creep. In ductile metals and alloys subjected to creep, fracture is accompanied by necking[1], void nucleation[2] and coalescence (merging), or grain boundary sliding[3].
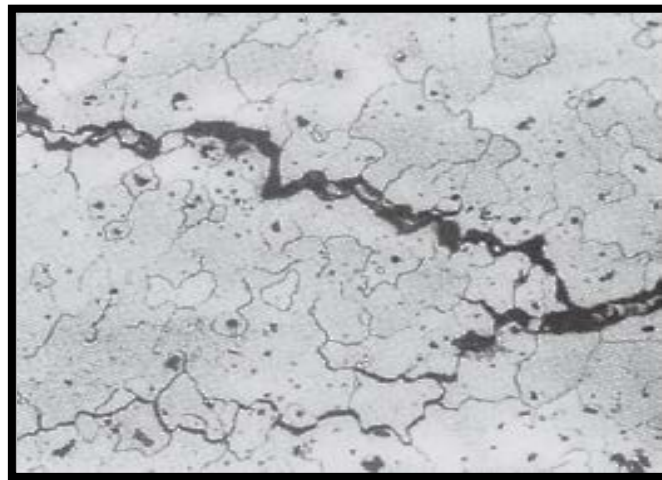

Figure 1. Creep cavities formed at grain boundaries in an austenitic stainless steel (X_{500}).

A material is considered failed by creep even if it has not actually fractured. When a material does actually creep and then ultimately break, the fracture is defined as **stress rupture**. Normally, ductile stress-rupture fractures include necking and the presence of many cracks that did not have an opportunity (chance) to produce final fracture. Furthermore, grains near the fracture surface tend to be elongated. **Ductile stress-rupture failures** generally occur at high creep rates and relatively low exposure temperatures and have short rupture times. **Brittle stress-rupture failures** usually show little necking and occur more often at smaller creep rates and high temperatures. Equiaxed grains are observed near the fracture surface. Brittle failure typically occurs by formation of voids at the intersection of three grain boundaries and precipitation of additional voids along grain boundaries by diffusion processes (Figure 1).

Stress-Corrosion: Stress-corrosion is a phenomenon in which materials react with corrosive chemicals in the environment. This leads to formation of cracks and lowering of strength. Stress-corrosion can occur at stresses well below the yield strength of the metallic, ceramic, or glassy material due to attack by a corrosive medium. In metallic materials, deep, fine corrosion cracks are produced, even though the metal as a whole shows little uniform attack. The stresses can be either externally applied or stored residual stresses. Stress-corrosion failures are often identified by microstructural examination of the nearby metal. Ordinarily, extensive branching of the cracks along grain boundaries is observed (Figure 2). The location at which cracks initiated may be identified by the presence of a corrosion product.

Dislocation Climb: High temperatures permit (allow) dislocations in a metallic material to climb. In climb, atoms move either to or from the dislocation line by diffusion, causing the dislocation to move in a direction that is perpendicular, not parallel, to the slip plane (Figure 2). The dislocation escapes from lattice imperfections, continues to slip, and causes additional deformation of the specimen even at low applied stresses.
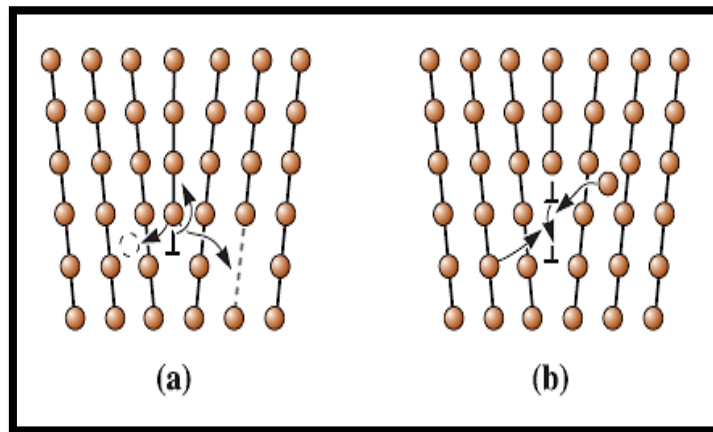

Figure 2. Dislocations can climb (a) when atoms leave the dislocation line to create interstitials or to fill vacancies or (b) when atoms are attached to the dislocation line by creating vacancies or eliminating interstitials.

Evaluation of Creep Behavior: To determine the creep characteristics of a material, a constant stress is applied to a heated specimen in a creep test. As soon as the stress is applied, the specimen stretches elastically a small amount e_0 (Figure 3), depending on the applied stress and the modulus of elasticity of the material at the high temperature. Creep testing can also be conducted under a constant load and is important from an engineering design viewpoint.
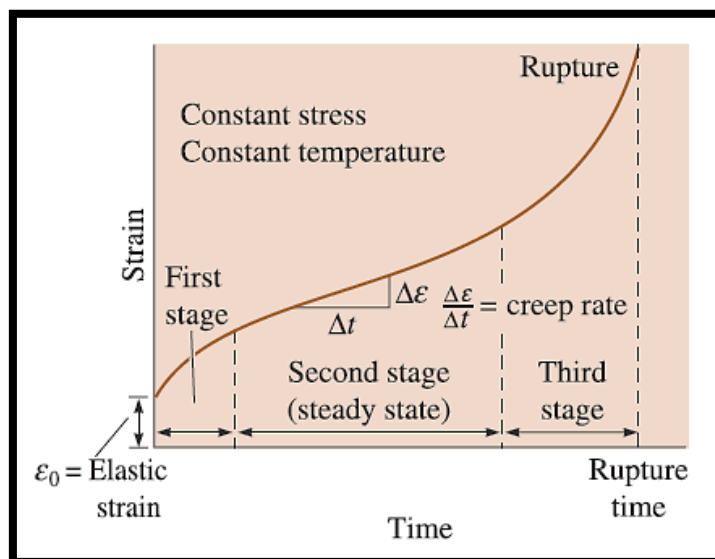

Figure 3. A typical creep curve showing the strain produced as a function of time for a constant stress and temperature.

Creep Rate and Rupture Times: During the creep test, strain or elongation is measured as a function of time and plotted to give the creep curve (Figure 3). In the first stage of creep of metals, many dislocations climb away from obstacles, slip, and contribute to deformation. Eventually, the rate at which dislocations climb away from obstacles equals the rate at which dislocations are blocked by other imperfections. This leads to second-stage, or steady-state, creep. The slope of the steady-state portion of the creep curve is the creep rate:

$$\text{Creep rate} = \frac{\Delta \text{ strain}}{\Delta \text{ time}}$$

Eventually (Finally), during third-stage creep, necking begins, the stress increases, and the specimen deforms at an accelerated rate until failure occurs. The time required for failure to occur is the **rupture time**. Either a higher stress or a higher temperature reduces the rupture time and increases the creep rate (Figure 4). The combined influence of applied stress and temperature on the creep rate and rupture time (t_r) follows an Arrhenius relationship:

$$\text{Creep rate} = C\sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

$$t_r = K\sigma^m \exp\left(\frac{Q_r}{RT}\right)$$

where **R** is the gas constant, **T** is the temperature in Kelvin, **C**, **K**, **n**, and **m** are constants for the material, **Qc** is the activation energy for creep, and **Qr** is the activation energy for rupture. In particular, **Qc** is related to the activation energy for self-diffusion when dislocation climb is important. Relative creep resistance of three magnesium alloys, namely AZ91D, AS21, and MRI153M is shown in Figure 4(b).
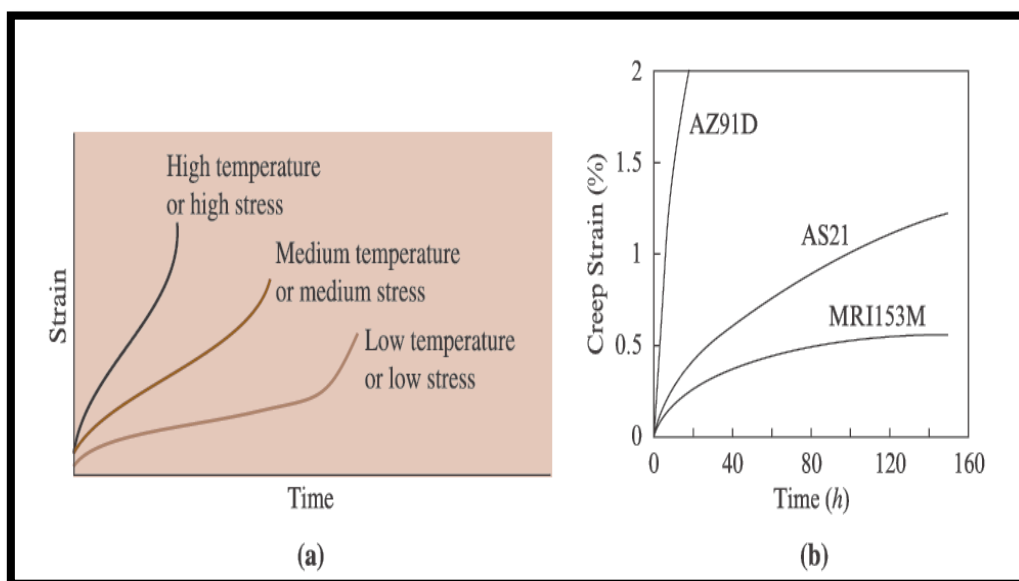

Figure 4. (a) The effect of temperature or applied stress on the creep curve. (b) Relative creep resistance of Mg alloys AZ91D, AS21, and MRI153M.

In creep of polycrystalline materials, other factors (including grain boundary sliding and nucleation of micro cracks) are particularly important. Often, a non-crystalline or glassy material is present at the grain boundaries; the activation energy required for the glass to deform is low, leading to high creep rates compared with completely crystalline ceramics. For the same reason, creep occurs at a rapid rate in ceramic glasses and amorphous polymers.

The stress exponent (**n**) and the creep activation energy (**Qc**) encountered in equation above for Mg alloys MRI 151, MRI 153, and As_{21} are shown in Table 1.

In Mg alloys containing Al, an intermetallic compound (**$Mg_{12}Al_{12}$**) can form at grain boundaries, and this causes the creep resistance to be lowered. The creep resistance is enhanced by adding small concentrations of alkaline earth metals, such as **Ca** or **Mg**. These metals react with Al preferentially and form other intermetallic (i.e., Al_2Ca and Al_2Mg). These intermetallics have melting temperatures greater than (**1000°C**). This translates into enhanced creep resistance, as grain boundary sliding is suppressed.

TABLE 1. Creep exponent (**n**) and activation energy (**Qc**) for some Mg Alloys.

Alloy	Stress Exponent (n) $T = 135°C$, stress 85–110 MPa	Activation energy (Q_c) kJ/mol (90 MPa, 130–150°C)
MRI 151	7.0	175
MRI 153	7.6	181
AS21	19.5	166

(Source: A.M. Russell and K.L. Lee in Structure-Property Relations in Nonferrous Metals, Publ. Wiley, (2005), page 176.)