

# Fatigue, Creep and Wear Characteristics of Engineering Materials

## 1. Fatigue

In materials science, **fatigue** is the progressive, localised, and permanent structural damage that occurs when a material is subjected to cyclic or fluctuating strains at nominal stresses that have maximum values less than (often much less than) the static yield strength of the material. The resulting stress is thus well below the ultimate tensile stress, or even the yield stress of the material, yet still cause catastrophic failure. Fatigue should not be confused with cyclic overload, such as the bending of a paperclip. A metal paperclip can be bent past its yield point (i.e., bent so it will stay bent) without breaking, but repeated bending in the same section of wire will cause the material to fail.

Fatigue is the catastrophic failure due to dynamic (fluctuating) stresses. It can happen in bridges, airplanes, machine components, etc. The characteristics are:

- long period of cyclic strain
- the most usual (90%) of metallic failures (happens also in ceramics and polymers)
- is brittle-like even in ductile metals, with little plastic deformation

it occurs in stages involving the initiation and propagation of cracks

### Stages of failures due to fatigue :

I. crack initiation at high stress points (stress raisers)

II. propagation (incremental in each cycle)

III. final failure by fracture

$$N_{\text{final}} = N_{\text{initiation}} + N_{\text{propagation}}$$

### Stage I - propagation

- slow
- along crystallographic planes of high shear stress
- flat and featureless fatigue surface

### Stage II - propagation

crack propagates by repetitive plastic blunting and sharpening of the crack tip.

- . Crack Propagation Rate (not covered)

## **1.1. Fatigue Properties**

Fatigue cracking is one of the primary damage mechanisms of structural components. Fatigue cracking results from cyclic stresses that are below the ultimate tensile stress, or even the yield stress of the material. The name “fatigue” is based on the concept that a material becomes “tired” and fails at a stress level below the nominal strength of the material. The facts that the original bulk design strengths are not exceeded and the only warning sign of an impending fracture is an often hard to see crack, makes fatigue damage especially dangerous.

The fatigue life of a component can be expressed as the number of loading cycles required to initiate a fatigue crack and to propagate the crack to critical size. Therefore, it can be said that fatigue failure occurs in three stages – crack initiation; slow, stable crack growth; and rapid fracture.

As discussed previously, dislocations play a major role in the fatigue crack initiation phase. In the first stage, dislocations accumulate near surface stress concentrations and form structures called persistent slip bands (PSB) after a large number of loading cycles. PSBs are areas that rise above (extrusion) or fall below (intrusion) the surface of the component due to movement of material along slip planes. This leaves tiny steps in the surface that serve as stress risers where tiny cracks can initiate. These tiny crack (called microcracks) nucleate along planes of high shear stress which is often  $45^\circ$  to the loading direction.

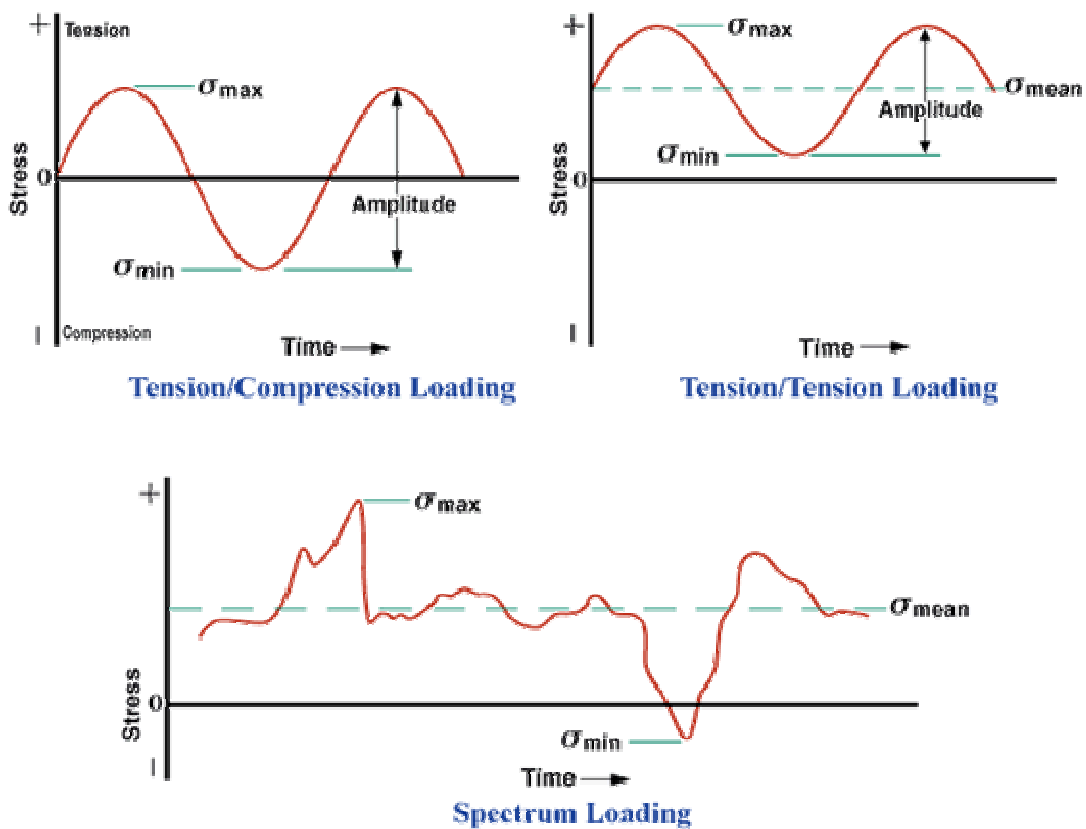
In the second stage of fatigue, some of the tiny microcracks join together and begin to propagate through the material in a direction that is perpendicular to the maximum tensile stress. Eventually, the growth of one or a few crack of the larger cracks will dominate over the rest of the cracks. With continued cyclic loading, the growth of the dominate crack or cracks will continue until the remaining uncracked section of the component can no longer support the load. At this point, the fracture toughness is exceeded and the remaining cross-section of the material experiences rapid fracture. This rapid overload fracture is the third stage of fatigue failure.

## **1.2 Factors Affecting Fatigue Life**

In order for fatigue cracks to initiate, three basic factors are necessary. First, the loading pattern must contain minimum and maximum peak values with large enough variation or fluctuation. The peak values may be in tension or compression and may change over time but the reverse loading cycle must be sufficiently great for fatigue crack initiation. Secondly, the peak stress levels must be of sufficiently high value. If the peak stresses are too low, no crack initiation will occur. Thirdly, the material must experience a sufficiently large number of cycles of the applied stress. The number of cycles required to initiate and grow a crack is largely dependant on the first to factors.

In addition to these three basic factors, there are a host of other variables, such as stress concentration, corrosion, temperature, overload, metallurgical structure, and residual stresses which can affect the propensity for fatigue. Since fatigue cracks generally initiate at a surface, the surface condition of the component being loaded will have an effect on its fatigue life. Surface roughness is important because it is directly related to the level and number of stress concentrations on the surface. The higher the stress concentration the more likely a crack is to nucleate. Smooth surfaces increase the time to nucleation. Notches, scratches, and other stress risers decrease fatigue life. Surface residual stress will also have a significant effect on fatigue life. Compressive residual stresses from machining, cold working, heat treating will oppose a tensile load and thus lower the amplitude of cyclic loading

The figure shows several types of loading that could initiate a fatigue crack. The upper left figure shows sinusoidal loading going from a tensile stress to a compressive stress. For this type of stress cycle the maximum and minimum stresses are equal. Tensile stress is considered positive, and compressive stress is negative. The figure in the upper right shows sinusoidal loading with the minimum and maximum stresses both in the tensile realm. Cyclic compression loading can also cause fatigue. The lower figure shows variable-amplitude loading, which might be experienced by a bridge or airplane wing or any other component that experiences changing loading patterns. In variable-amplitude loading, only those cycles exceeding some peak threshold will contribute to fatigue cracking.



- To sum the factors That Affect Fatigue Life

- Mean stress (lower fatigue life with increasing  $\sigma_{\text{mean}}$ ).
- Surface defects (scratches, sharp transitions and edges).

Solution:

- polish to remove machining flaws
- add *residual compressive stress* (e.g., by shot peening.)
- case harden, by carburizing, nitriding (exposing to appropriate gas at high temperature)

- **. Environmental Effects**

- Thermal cycling causes expansion and contraction, hence thermal stress, if component is restrained. Solution:

- eliminate restraint by design
- use materials with low thermal expansion coefficients.

- Corrosion fatigue. Chemical reactions induced pits which act as stress raisers. Corrosion also enhances crack propagation. Solutions:

- decrease corrosiveness of medium, if possible.
- add protective surface coating.
- add residual compressive stresses.

### 1.3. S-N Fatigue Properties

#### Cyclic Stresses

These are characterized by *maximum*, *minimum* and *mean stress*, *the stress amplitude*, and the *stress ratio* (Fig. 8.20).

- **The S—N Curve**

$S-N$  curves (stress-number of cycles to failure) are obtained using apparatus like the one shown in Fig. 8.21. Different types of  $S-N$  curves are shown in Fig. 8.22.

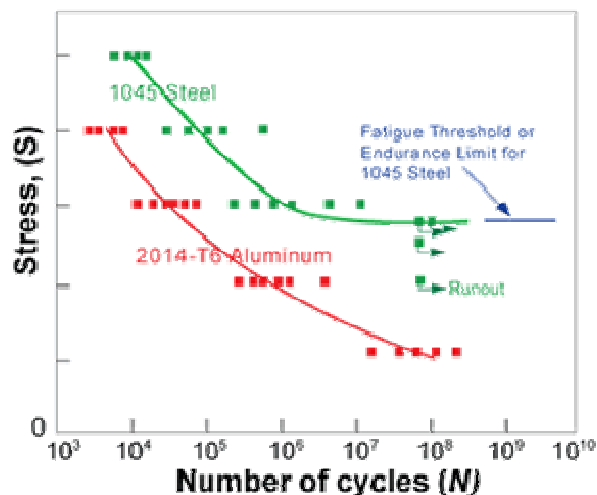
**Fatigue limit** (endurance limit) occurs for *some* materials (like some ferrous and Ti alloys). In this case, the  $S-N$  curve becomes horizontal at large  $N$ . This means that there is a maximum stress amplitude (the fatigue limit) below which the material never fails, no matter how large the number of cycles is.

For other materials (e.g., non-ferrous) the  $S-N$  curve continues to fall with  $N$ .

Failure by fatigue shows substantial *variability*.

Failure at low loads is in the elastic strain regime, requires a large number of cycles (typ.  $10^4$  to  $10^5$ ). At high loads (plastic regime), one has low-cycle fatigue ( $N < 10^4 - 10^5$  cycles).

There are two general types of fatigue tests conducted. One test focuses on the nominal stress required to cause a fatigue failure in some number of cycles. This test results in data presented as a plot of stress ( $S$ ) against the number of cycles to failure ( $N$ ), which is known as an  $S-N$  curve. A log scale is almost always used for  $N$ .



The data is obtained by cycling smooth or notched specimens until failure. The usual procedure is to test the first specimen at a high peak stress where failure is expected in a fairly short number of cycles. The test stress is decreased for each succeeding specimen until one or two specimens do not fail in the specified numbers of cycles, which is usually at least  $10^7$  cycles. The highest stress at which a runout (non-failure) occurs is taken as the fatigue threshold. Not all materials have a fatigue threshold (most nonferrous metallic alloys do not) and for these materials the test is usually terminated after about  $10^8$  or  $5 \times 10^8$  cycles.

Since the amplitude of the cyclic loading has a major effect on the fatigue performance, the S-N relationship is determined for one specific loading amplitude. The amplitude is expressed as the R ratio value, which is the minimum peak stress divided by the maximum peak stress. ( $R = \sigma_{\min} / \sigma_{\max}$ ). It is most common to test at an R ratio of 0.1 but families of curves, with each curve at a different R ratio, are often developed.

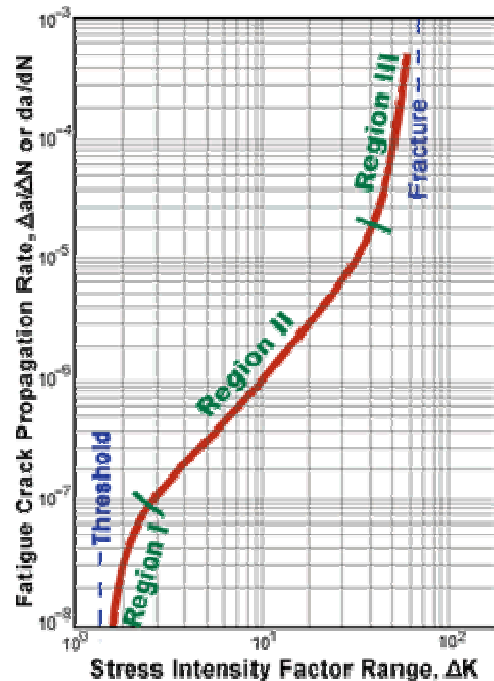
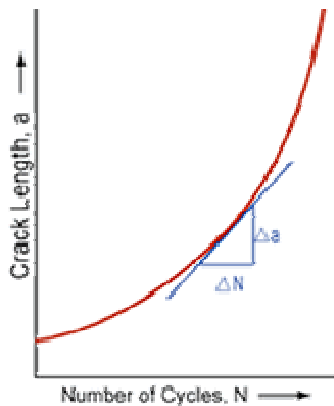
A variation to the cyclic stress controlled fatigue test is the cyclic strain controlled test. In this test, the strain amplitude is held constant during cycling. Strain controlled cyclic loading is more representative of the loading found in thermal cycling, where a component expands and contracts in response to fluctuations in the operating temperature.

It should be noted that there are several shortcomings of S-N fatigue data. First, the conditions of the test specimens do not always represent actual service conditions. For example, components with surface conditions, such as pitting from corrosion, which differs from the condition of the test specimens will have significantly different fatigue performance. Furthermore, there is often a considerable amount of scatter in fatigue data even when carefully machined standard specimens out of the same lot of material are used. Since there is considerable scatter in the data, a reduction factor is often applied to the S-N curves to provide conservative values for the design of components.

#### **1.4. Fatigue Crack Growth Rate Properties**

For some components the crack propagation life is neglected in design because stress levels are high, and/or the critical flaw size small. For other components the crack growth life might be a substantial portion of the total life of the assembly. Moreover, preexisting flaws or sharp design features may significantly reduce or nearly eliminate the crack initiation portion of the fatigue life of a component. The useful life of these components may be governed by the rate of subcritical crack propagation.

Aircraft fuselage structure is a good example of structure that is based largely on a slow crack growth rate design. Many years ago, the USAF reviewed a great number of malfunction reports from a variety of aircraft. The reports showed that the preponderance of structural failures occurred from 1) built-in preload stresses, 2) material flaws and 3) flaw caused by in-service usage. These facts led to a design approach that required the damage tolerance analysis to assume a material flaw exists in the worst orientation and at the most undesirable location. The analysis helps to ensure that structures are designed that will support slow stable crack growth until the crack reaches a length where it can reliably be detected using NDT methods.



The rate of fatigue crack propagation is determined by subjecting fatigue-cracked specimens, like the compact specimen used in fracture toughness



testing, to constant-amplitude cyclic loading. The incremental increase in crack length is recorded along with the corresponding number of elapsed load cycles acquire stress intensity (K), crack length (a), and cycle count (N) data during the test. The data is presented in an “a versus N” curve as shown in the image to the right. Various a versus N curves can be generated by varying the magnitude of the cyclic loading and/or the size of the initial crack.

The data can be reduced to a single curve by presenting the data in terms of crack growth rate per cycle of loading ( $Da/ DN$  or  $da/dN$ ) versus the fluctuation of the stress-intensity factor at the tip of the crack ( $DK_I$ ).  $DK_I$  is representative of the mechanical driving force, and it incorporates the effect of changing crack length and the magnitude of the cyclic loading. (See the page on fracture toughness for more information on the stress-intensity factor.) The most common form of presenting fatigue crack growth data is a log-log plot of  $da/dN$  versus  $DK_I$ .

The fatigue crack propagation behavior of many materials can be divided into three regions as shown in the image. Region I is the fatigue threshold region where the  $Dk$  is too low to propagate a crack. Region II encompasses data where the rate of crack growth changes roughly linearly with a change in stress intensity fluctuation. In region III, small increases in the stress intensity amplitude, produce relatively large increases in crack growth rate since the material is nearing the point of unstable fracture.

### **1.5. Characteristics of fatigue failures**

The following characteristics are common to fatigue in all materials:

- The process starts with a microscopic crack, called the *initiation site*, which then widens with each subsequent movement, a phenomenon analysed in the topic of fracture mechanics.
- Failure is essentially probabilistic. The number of cycles required for failure varies between homogeneous material samples. Analysis demands the techniques of survival analysis.
- The greater the applied stress, the shorter the life.
- Damage is cumulative. Materials do not recover when rested.

- Fatigue life is influenced by a variety of factors, such as temperature and surface finish, in complicated ways.
- Some materials (e.g., some steel and titanium alloys) exhibit an *endurance limit* or *fatigue limit*, a limit below which repeated stress does not induce failure, theoretically, for an infinite number of cycles of load. Generally speaking, a steel or titanium component being cycled at stresses below their endurance limit will fail from some other mode before it fails from fatigue. Most other non-ferrous metals (e.g., aluminium and copper alloys) exhibit no such limit and even small stresses will eventually cause failure.
- As a means to gauge fatigue characteristics of non-ferrous and other alloys that do not exhibit an endurance limit, a *fatigue strength* is frequently determined, and this is typically the stress level at which a component will survive  $10^8$  loading cycles.
- Factors that affect fatigue-life

## 1.6. Factors that affect fatigue life

Magnitude of stress including stress concentrations caused by part geometry.

Quality of the surface; surface roughness, scratches, etc. cause stress concentrations or provide crack nucleation sites which can lower fatigue life depending on how the stress is applied. On the other hand, surface stress can be intentionally manipulated to increase fatigue life. For example, shot peening is widely used to put the surface in a state of compressive stress which inhibits surface crack formation and thus improves fatigue life. Such techniques for producing surface stress are often referred to generically as *peening*, whatever the mechanism used to produce the stress. Other more recently introduced surface treatments, such as laser peening and ultrasonic impact treatment, can also produce this surface compressive stress and can increase the fatigue life of the component. This improvement is normally observed only for high-cycle fatigue. Little improvement is obtained in the low-cycle fatigue régime.

Material Type. Certain materials, such as steel, will never fail due to fatigue if the stresses remain below a certain level. Other materials, such as aluminum, will eventually fail due to fatigue regardless of the stresses the material sees.

Surface defect geometry and location. The size, shape, and location of surface defects such as scratches, gouges, and dents can have a significant impact on fatigue life.

Significantly uneven cooling, leading to a heterogeneous distribution of material properties such as hardness and ductility and, in the case of alloys, structural composition. Uneven cooling of castings, for example, can produce high levels of tensile residual stress, which will encourage crack growth.

Size, frequency, and location of internal defects. Casting defects such as gas porosity and shrinkage voids, for example, can significantly impact fatigue life.

In metals where strain-rate sensitivity is observed (ferrous metals, copper, titanium, etc.) strain rate also affects fatigue life in low-cycle fatigue situations.

For non-isotropic materials, the direction of the applied stress can affect fatigue life.

Grain size; for most metals, fine-grained parts exhibit a longer fatigue life than coarse-grained parts.

Environmental conditions and exposure time can cause erosion, corrosion, or gas-phase embrittlement, which all affect fatigue life. Corrosion fatigue is a problem encountered in many aggressive environments.

The operating temperature over which the part is exposed to affects fatigue life.

### **1.7. Design against fatigue**

Dependable design against fatigue-failure requires thorough education and supervised experience in structural engineering, mechanical engineering, or materials science. There are three principal approaches to life assurance for mechanical parts that display increasing degrees of sophistication:

1. Design to keep stress below threshold of fatigue limit (infinite lifetime concept);

2. Design (conservatively) for a fixed life after which the user is instructed to replace the part with a new one (a so-called *lived* part, finite lifetime concept, or "safe-life" design practice);
3. Instruct the user to inspect the part periodically for cracks and to replace the part once a crack exceeds a critical length. This approach usually uses the technologies of nondestructive testing and requires an accurate prediction of the rate of crack-growth between inspections. This is often referred to as damage tolerant design or "retirement-for-cause".

## **1.8. Stopping fatigue**

Fatigue cracks that have begun to propagate can sometimes be stopped by drilling holes, called drill stops, in the path of the fatigue crack.. However, it is not recommended because a hole represents a stress concentration factor of about 2. There is thus the possibility of a new crack starting in the side of the hole. It is always far better to replace the cracked part entirely. Several disasters have been caused by botched repairs to cracked structures.

## **2. Creep**

Creep is the term used to describe the tendency of a material to move or to deform permanently to relieve stresses. Material deformation occurs as a result of long term exposure to levels of stress that are below the yield or ultimate strength of the material. Creep is more severe in materials that are subjected to heat for long periods and near melting point. The rate of this damage is a function of the material properties and the exposure time, exposure temperature and the applied load (stress). Depending on the magnitude of the applied stress and its duration, the deformation may become so large that a component can no longer perform its function — for example creep of a turbine blade will cause the blade to contact the casing, resulting in the failure of the blade. Creep is usually a concern to engineers and metallurgists when evaluating components that operate under high stresses or temperatures. Creep is not necessarily a failure mode, but is instead a damage mechanism. Moderate creep in concrete is sometimes welcomed because it relieves tensile stresses that may otherwise have led to cracking.

Rather than failing suddenly with a fracture, the material permanently strains over a longer period of time until it finally fails. Creep does not happen upon sudden loading but the accumulation of creep strain in longer times causes failure of the material. This makes creep deformation a "time-dependent" deformation of the material.

Creep deformation can be obtained in reasonable time frames under very high temperatures i.e., temperatures around half of the absolute temperature of the melting point. This deformation behaviour is important in systems for which high temperatures are endured, such as nuclear power plants, jet engines, heat exchangers etc. It is also a consideration in the design of magnesium alloy engines. Since the relevant temperature is relative to melting point (usually at temperatures greater than half the melting temperature), creep can be seen at relatively low temperatures depending upon the alloy. Plastics and low-melting-temperature metals, including many solders creep at room temperature, as can be seen markedly in older lead hot-water pipes. Planetary ice is often at a high temperature (relative to its melting point), and creeps. Virtually any material will creep upon approaching its melting temperature. Glass windows are often erroneously used as an example of this phenomenon: creep would only occur at temperatures above the glass transition temperature (around 900°F/500°C).

An example of an application involving creep deformation is the design of tungsten lightbulb filaments. Sagging of the filament coil between its supports increases with time due to creep deformation caused by the weight of the filament itself. If too much deformation occurs, the adjacent turns of the coil touch one another, causing an electrical short and local overheating, which quickly leads to failure of the filament. The coil geometry and supports are therefore designed to limit the stresses caused by the weight of the filament, and a special tungsten alloy with small amounts of oxygen trapped in the grain boundaries is used to slow the rate of Coble creep.

Steam piping within fossil-fuel fired power plants with superheated vapour work under high temperature (1050°F/565.5°C and high pressure (often at 3500 psig/ 24.1 MPa or greater). In a jet engine temperatures may reach to 1000°C, which may initiate creep deformation in a weak zone. Because of these reasons, understanding and studying creep deformation behaviour of engineering materials is very crucial for public and operational safety.

Creep is the time-varying plastic deformation of a material stressed at high temperatures. Examples: turbine blades, steam generators. Keys are the time dependence of the strain and the high temperature.

- **. Generalized Creep Behavior**

At a constant stress, the strain increases initially fast with time (primary or transient deformation), then increases more slowly in the secondary region at a steady rate (creep rate). Finally the strain increases fast and leads to failure in the tertiary region. Characteristics:

- *Creep rate:*
- *Time to failure.*

### **Stages of creep**

Initially, the strain rate slows with increasing strain. This is known as primary creep. The strain rate eventually reaches a minimum and becomes near-constant. This is known as secondary or steady-state creep. It is this regime that is most well understood. The "creep strain rate" is typically the rate in this secondary stage. The stress dependence of this rate depends on the creep mechanism. In tertiary creep, the strain-rate exponentially increases with strain.

### **General creep equation**

$$\frac{d\epsilon}{dt} = \frac{C\sigma^m}{d^b} e^{-\frac{Q}{kT}}$$

where C is a constant dependent on the material and the particular creep mechanism, m and b are exponents dependent on the creep mechanism, Q is the activation energy of the creep mechanism,  $\sigma$  is the applied stress, d is the grain size of the material, k is Boltzmann's constant, and T is the temperature.

### **Dislocation creep**

At high stresses (relative to the shear modulus), creep is controlled by the movement of dislocations. When a stress is applied to a material, plastic

deformation occurs due to the movement of dislocations in the slip plane. Materials contain a variety of defects, for example solute atoms, that act as obstacles to dislocation motion. Creep arises from this because of the phenomenon of dislocation climb. At high temperatures vacancies in the crystal can diffuse to the location of a dislocation and cause the dislocation to move to an adjacent slip plane. By climbing to adjacent slip planes dislocations can get around obstacles to their motion, allowing further deformation to occur. Because it takes time for vacancies to diffuse to the location of a dislocation this results in time dependent strain, or creep.

For dislocation creep  $Q = Q_{\text{self diffusion}}$ ,  $m = 4-6$ , and  $b=0$ . Therefore dislocation creep has a strong dependence on the applied stress and no grain size dependence.

Some alloys exhibit a very large stress exponent ( $n > 10$ ), and this has typically been explained by introducing a "threshold stress,"  $\sigma_{th}$ , below which creep can't be measured. The modified power law equation then

becomes:  $\frac{d\epsilon}{dt} = A (\sigma - \sigma_{th})^n e^{\frac{-Q}{RT}}$  where  $A$ ,  $Q$  and  $n$  can all be explained by conventional mechanisms (so  $3 \leq n \leq 10$ ).

### **Stress and Temperature Effects**

Creep becomes more pronounced at higher temperatures (Fig. 8.37). There is essentially no creep at temperatures below 40% of the melting point.

Creep increases at higher applied stresses.

The behavior can be characterized by the following expression, where  $K$ ,  $n$  and  $Q_c$  are constants for a given material:

### **Alloys for High-Temperature Use**

These are needed for turbines in jet engines, hypersonic airplanes, nuclear reactors, etc. The important factors are a high melting temperature, a high elastic modulus and large grain size (the latter is opposite to what is desirable in low-temperature materials).



Some creep resistant materials are stainless steels, refractory metal alloys (containing elements of high melting point, like Nb, Mo, W, Ta), and superalloys (based on Co, Ni, Fe.)

### **Nabarro-Herring Creep**

Nabarro-Herring creep is a form of diffusion controlled creep. In N-H creep atoms diffuse through the lattice causing grains to elongate along the stress axis. For Nabarro-Herring creep  $k$  is related to the diffusion coefficient of atoms through the lattice,  $Q = Q_{\text{self diffusion}}$ ,  $m=1$ , and  $b=2$ . Therefore N-H creep has a weak stress dependence and a moderate grain size dependence, with the creep rate decreasing as grain size is increased.

Nabarro-Herring creep is found to be strongly temperature dependent. For lattice diffusion of atoms to occur in a material, neighboring lattice sites or interstitial sites in the crystal structure must be free. A given atom must also overcome the energy barrier to move from its current site (it lies in an energetically favorable potential well) to the nearby vacant site (another potential well). The general form of the diffusion equation is  $D = D_0 \text{Exp}(E_a / KT)$  where  $D_0$  has a dependence on both the attempted jump frequency and the number of nearest neighbor sites and the probability of the sites being vacant. Thus there is a double dependence upon temperature. At higher temperatures the diffusivity increases due to the direct temperature dependence of the equation, the increase in vacancies through Shottky defect formation, and an increase in the average energy of atoms in the material. Nabarro-Herring creep dominates at very high temperatures relative to a material's melting temperature.

### **Coble Creep**

Coble creep is a second form of diffusion controlled creep. In Coble creep the atoms diffuse along grain boundaries to elongate the grains along the stress axis. This causes Coble creep to have a stronger grain size dependence than N-H creep. For Coble creep  $k$  is related to the diffusion coefficient of atoms along the grain boundary,  $Q = Q_{\text{grain boundary diffusion}}$ ,  $m=1$ , and  $b=3$ . Because  $Q_{\text{grain boundary diffusion}} < Q_{\text{self diffusion}}$ , Coble creep occurs at lower temperatures than N-H creep. Coble creep is still temperature dependent, as the temperature increases so does the grain boundary diffusion. However, since the number of nearest neighbors is effectively limited along the



interface of the grains, and thermal generation of vacancies along the boundaries is less prevalent, the temperature dependence is not as strong as in Nabarro-Herring creep. It also exhibits the same linear dependence on stress as N-H creep.

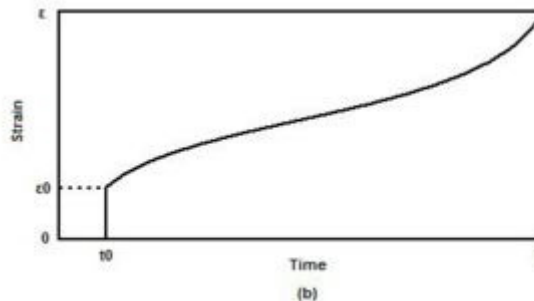
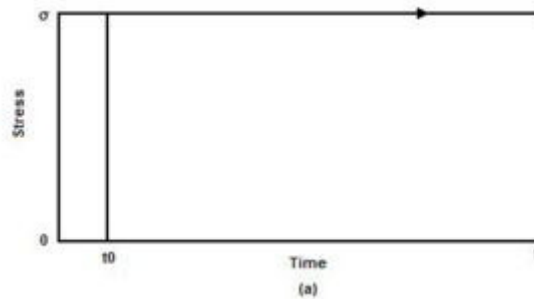
### Creep of Polymers

Creep can occur in polymers and metals which are considered viscoelastic materials. When a polymeric material is subjected to an abrupt force, the response can be modeled using the Kelvin-Voigt Model. In this model, the material is represented by a Hookean spring and a Newtonian dashpot in parallel. The creep strain is given by:

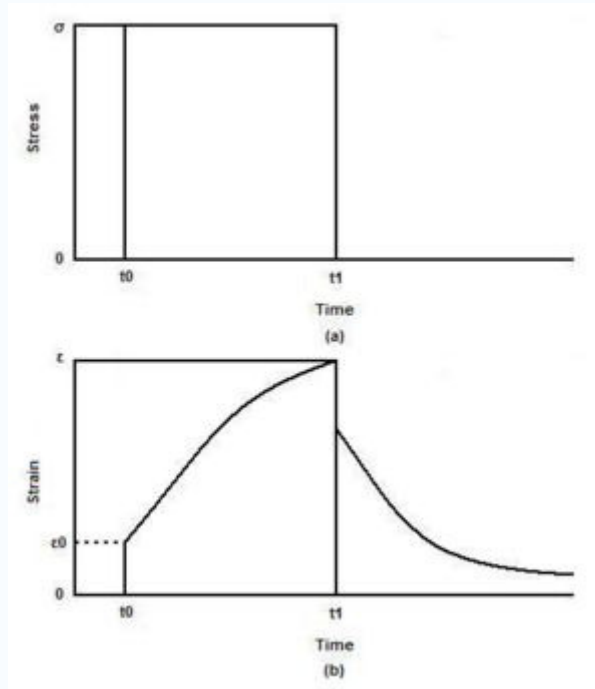
$$\epsilon(t) = \sigma C_0 + \sigma C \int_0^\infty f(\tau)(1 - \exp[-t/\tau])d\tau$$

Where:

- $\sigma$  = applied stress
- $C_0$  = instantaneous creep compliance
- $C$  = creep compliance coefficient
- $\tau$  = retardation time
- $f(\tau)$  = distribution of retardation times



Applied stress (a) and induced strain (b) as functions of time over an extended period for a viscoelastic material.



Applied stress (a) and induced strain (b) as functions of time over a short period for a viscoelastic material.

When subjected to a step constant stress, viscoelastic materials experience a time-dependent increase in strain. This phenomenon is known as viscoelastic creep.

At a time  $t_0$ , a viscoelastic material is loaded with a constant stress that is maintained for a sufficiently long time period. The material responds to the stress with a strain that increases until the material ultimately fails. When the stress is maintained for a shorter time period, the material undergoes an initial strain until a time  $t_1$ , after which the strain immediately decreases (discontinuity) then gradually decreases at times  $t > t_1$  to a residual strain.

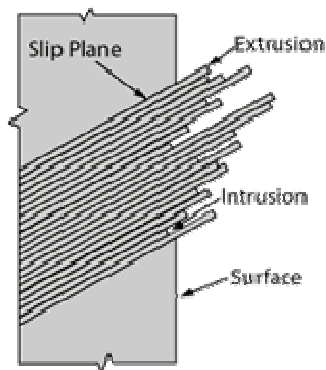
Viscoelastic creep data can be presented in one of two ways. Total strain can be plotted as a function of time for a given temperature or temperatures. Below a critical value of applied stress, a material may exhibit linear viscoelasticity. Above this critical stress, the creep rate grows disproportionately faster. The second way of graphically presenting viscoelastic creep in a material is by plotting the creep modulus (constant applied stress divided by total strain at a particular time) as a function of

time.<sup>[1]</sup> Below its critical stress, the viscoelastic creep modulus is independent of stress applied. A family of curves describing strain versus time response to various applied stress may be represented by a single viscoelastic creep modulus versus time curve if the applied stresses are below the material's critical stress value.

Additionally, the molecular weight of the polymer of interest is known to affect its creep behavior. The effect of increasing molecular weight tends to promote secondary bonding between polymer chains and thus make the polymer more creep resistant. Similarly, aromatic polymers are even more creep resistant due to the added stiffness from the rings. Both molecular weight and aromatic rings add to polymers' thermal stability, increasing the creep resistance of a polymer. (Meyers and Chawla, 1999, 573)

Both polymers and metals can creep.<sup>[2]</sup> Polymers experience significant creep at all temperatures above  $\sim -200^{\circ}\text{C}$ , however there are three main differences between polymeric and metallic creep. Metallic creep:<sup>[2]</sup>

- is not linearly viscoelastic
- is not recoverable
- only significant at high temperatures



### 3. Thermal shock

**Thermal shock** is the name given to cracking as a result of rapid temperature change. Glass and ceramic objects are particularly vulnerable to this form of failure, due to their low toughness, low thermal conductivity, and high thermal expansion coefficients. However, they are used in many high temperature applications due to their high-melting point .

Thermal shock occurs when a thermal gradient causes different parts of an object to expand by different amounts. This differential expansion can be understood in terms of stress or of strain, equivalently. At some point, this stress overcomes the strength of the material, causing a crack to form. If nothing stops this crack from propagating through the material, it will cause the object's structure to fail.

Thermal shock can be prevented by:

1. Reducing the thermal gradient seen by the object, by
  1. changing its temperature more slowly
  2. increasing the material's thermal conductivity
2. Reducing the material's coefficient of thermal expansion
3. Increasing its strength
4. Increasing its toughness

Borosilicate glass such as Pyrex is made to withstand thermal shock better than most other glass through a combination of reduced expansion coefficient and greater strength, though fused quartz outperforms it in both these respects. Some glass-ceramic materials include a controlled proportion of material with a negative expansion coefficient, so that the overall coefficient can be reduced to almost exactly zero over a reasonably wide range of temperatures.

#### **4. Wear**

In materials science, **wear** is the erosion of material from a solid surface by the action of another solid. The study of the processes of wear is part of the discipline of tribology. There are four principal wear processes:

1. Surface fatigue :
2. Adhesive wear
3. Abrasive wear
4. Corrosive wear

The definition of wear does not include loss of dimension from plastic deformation, although wear has occurred despite no material removal. Also this definition fails to include impact wear where there is no sliding motion or cavitation (also corrosion) where counterbody is a fluid..

Wear can possibly be better defined as a process in which interaction of surface(s) or bounding face(s) of a solid with the working environment results in the dimensional loss of the solid, with or without loss of material. Wear environment includes loads (types include unidirectional sliding, reciprocating, rolling, impact), speed, temperatures, counterbodies (solid, liquid, gas), types of contact (single phase or multiphase in which phases involved can be liquid plus solid particles plus gas bubbles). In standard wear test (e.g., those formulated by respective subcommittees under ASTM Committee G-2) results, the loss of material during wear is expressed in terms of volume. The volume loss gives a truer picture than weight loss particularly when comparing wear resistance properties of materials with large variations in density. For example, weight loss of WC+Co (density = 14g/cc) as 14g and that of Al alloy (density = 2.7g/cc) as 2.7g shall result in same wear in terms of volume loss of 1cc. For engineering components the working life is over when the dimensional losses exceed the specified tolerance limits.

Wear along with other aging processes, such as, fatigue, creep and fracture toughness cause progressive degradation of materials with time leading to failure of material at an advanced age. Under normal operating parameters, the property changes during usage normally occur in three different stages as follows:-

- Primary or early stage or run-in period, where rate of changes can be high.
- Secondary or mid-age process where a steady rate of aging process is maintained. The useful or working life is comprised mostly of the life span at this stage.
- Tertiary or old-age stage, where rapid rate of aging leads to early failure.

With increasing severity of environmental conditions, such as, higher temperatures, strain rates, stress and sliding velocities, the secondary stage is shortened and the primary stage tends to merge with the tertiary stage, thus drastically reducing the working life. Surface engineering processes are used to minimize wear and extend working life of material. References

1. R. Chattopadhyay; Surface Wear- Analysis, Treatment, and Prevention, ASM-International, OH, USA, 2001, ISBN no 0-87170-702-0.
2. R. Chattopadhyay, 'Advanced Thermally Assisted Surface Engineering Processes' Kluwer Academic Publishers, MA, USA (now Springer, NY), 2004, ISBN 1-4020-7696-7, E-ISBN 1-4020-7764-5.

### **Adhesive wear**

Adhesive wear is also known as scoring, galling, or seizing. It occurs when two solid surfaces slide over one another under pressure. Surface projections, or asperities, are plastically deformed and eventually welded together by the high local pressure. As sliding continues, these bonds are broken, producing cavities on the surface, projections on the second surface, and frequently tiny, abrasive particles, all of which contribute to future wear of surfaces.

### **Abrasive wear**

When material is removed by contact with hard particles, abrasive wear occurs. The particles either may be present at the surface of a second material or may exist as loose particles between two surfaces. Abrasive wear can be measured as loss of mass by the Taber Abrasion Test according to ISO 9352 or ASTM D 1044.

### **Corrosive wear**

Often referred to simply as “corrosion”, corrosive wear is deterioration of useful properties in a material due to reactions with its environment.

One form of high temperature corrosive (oxidative) wear can lead to the formation of compacted oxide layer glazes, which under certain circumstances reduces wear.