EDEXCEL NATIONAL CERTIFICATE
UNIT 12 – ENGINEERING MATERIALS
OUTCOME 4

4. MODES OF FAILURE

***Ductile and brittle fracture*:** effects of gradual and impact loading, effects of grain size, effects of temperature, transition temperature, appearance of fracture surfaces
***Material fatigue*:** cyclic loading, stress concentrations, stress v loading cycles curve, fatigue limit, endurance limit, appearance of fracture surfaces
***Material creep*:** primary, secondary and tertiary creep, effects of temperature, strain v time curve, creep limit, effect of grain size
***Degradation*:** stress corrosion in metals; solvent attack, radiation damage and ageing of polymers; deterioration of ceramics due to thermal shock and sustained high temperatures

<u>CONTENTS</u>

Self assessments are mainly in the form of separate assignments.

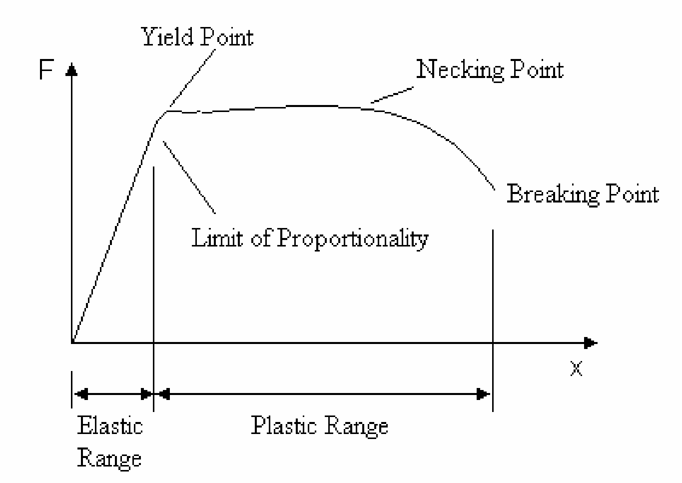
1. INTRODUCTION

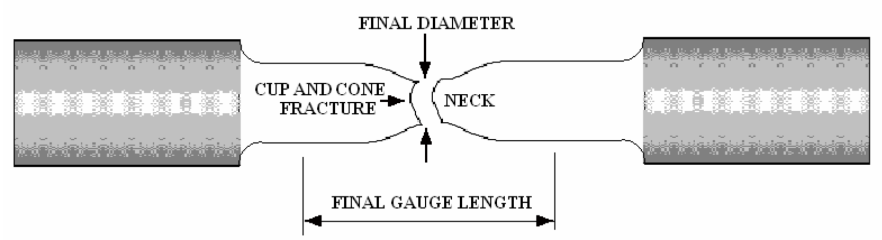
Materials fail in many ways and this tutorial covers some of the main points. Failure is normally considered to occur when the component/structure/product is no longer fit for its intended purpose. This may be because the material has parted and failure by breakage has many aspects. Failure might also occur because the material has deformed without breaking. The failure might be due to wear and degradation so that that the component will no longer function. Standard tests covered in the earlier tutorials are conducted to find the properties of the material so let's start by examining the sort of failure that might be predicted by a tensile test.

2. DUCTILE FAILURE

The diagram shows a typical stress – strain graph for a ductile material.

Failure in a component may be considered to occur when the material reached the yield stress level or the break point. If the material is ductile, the material will yield locally and narrow at the point where it is going to fail. When it breaks, the neck will be clear and a cup and cone will form at the actual fracture point.





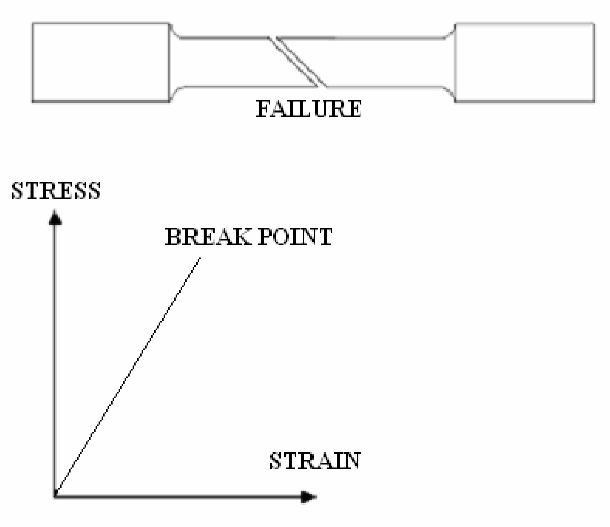
TYPICAL DUCTILE FAILURE

The results obtained may well be affected by the speed at which the specimen is stretched and the temperature of component. The properties listed by standards organisations and manufacturers will usually specify the temperature and strain rate that gave the data.

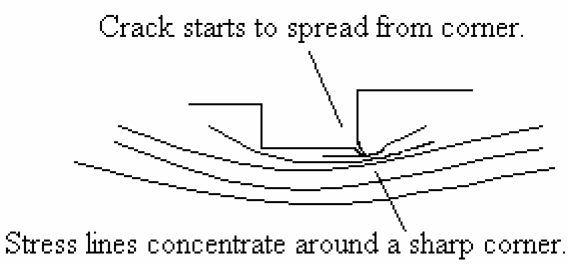
3. BRITTLE FAILURE

A material such as cast iron can be strong and brittle. The breaking stress may be high but once it starts to fail it does so suddenly with no further resistance. On the other hand some polymers are weak but tough. They will easily yield when stretched but require a lot of energy and stretching to make it break.

Brittle materials exhibit no yield point and a typical stress – strain graph is shown. Failure is quite sudden and no neck appears to warn of impending failure. The break in a tensile test specimen is often a 45^{o} plane as shown.



A crack must start at some imperfection in the material such as a machining groove on the surface. These raise the local stress level. Sharp corners and undercuts in a machined component will do the same. In a tough ductile material, there will be yielding and resistance to the crack spreading. In a brittle material, the crack, once started, continues to spread very rapidly.



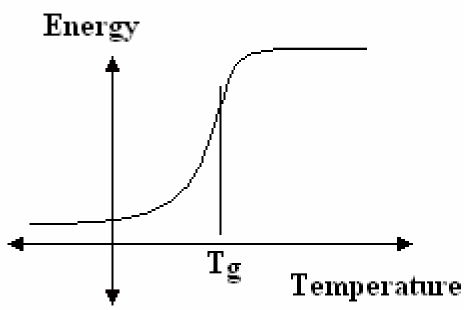
Grinding and polishing a brittle material makes it less prone to cracking. Glass, when polished, exhibits a very high strength but the slightest surface blemish makes it crack easily. This is why glass fibres are so strong but sheet glass so brittle.

Brittle materials are very prone to cracking through sudden impacts that create a crack at a sharp corner. This is why notched specimens are used in impact testing. The Izod and Charpy notched bar test (previous tutorial) determine how sensitive a material is to crack propagation from a sharp corner.

Most materials become brittle when they are extremely cold but some materials, especially certain types of carbon steels and polymers, may well change from ductile to brittle at temperatures found in nature. There have been some spectacular structural failures in bridges, oil rigs and ships due to the steel becoming brittle at near zero temperatures. This is made worse by the presence of sharp corners (e.g. hatch in ships deck) and by the changes in the steel composition brought about during welding.

TRANSITION TEMPERATURE

Notched bar tests are conducted over a range of temperatures to determine where a material becomes brittle and this is one of the properties that should be seriously considered in material selection. A typical graph of absorbed energy against temperature from a notched bar test is shown. The transition temperature is denoted T_g. It is usually taken as the point at which 50% of the fracture is brittle.



qThe ductile-brittle transition is exhibited in BCC metals, such as low carbon steel, which become brittle at low temperature or at very high strain rates. FCC metals, however, generally remain ductile at low temperatures. (see outcome 1 tutorials for crystal type explanation)

FRACTURE APPEARANCE

Much can be told by examining the fracture surface. Brittle polymers produce smooth glassy surfaces and brittle metals show a fine granular surface. Ductile materials show a rough fibrous surface.

THERMAL SHOCK

Brittle materials, especially ceramics, are prone to fracture by sudden changes in temperature. A sudden change can cause rapid and unequal expansion or contraction that set up tensile stresses in the material causing it to break. For example, putting a drinking glass or glass bottle in boiling water will often result in it breaking.

You will find more information at web sites such as
http://www.doitpoms.ac.uk/tlplib/ductile-brittle-transition/ductile-to-brittle.php

4. **FATIGUE FAILURE**

Fatigue is a phenomenon that occurs in a material that is subject to a cyclic stress. Although the peak stress in each cycle is less than that needed to make the material fail in a tensile test, the material fails suddenly and catastrophically after a certain number of cycles.

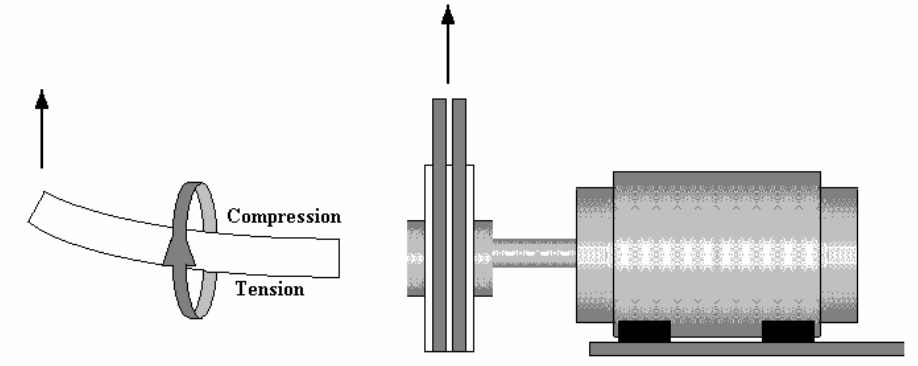
Here are some examples of things that are subject to cyclic stress.

- ***Railway lines that bend every time a wheel passes over it.***
- ***Gear Teeth.***
- ***Springs.***
- ***The suspension cable on a suspension bridge every time a vehicle passes over it.***
- ***The skin and structural members of an aeroplane every time it flies.***
- ***A shaft with a pulley belt drive.***
- ***The connecting rod in a reciprocating engine.***
- ***The stub axle on a vehicle wheel.***

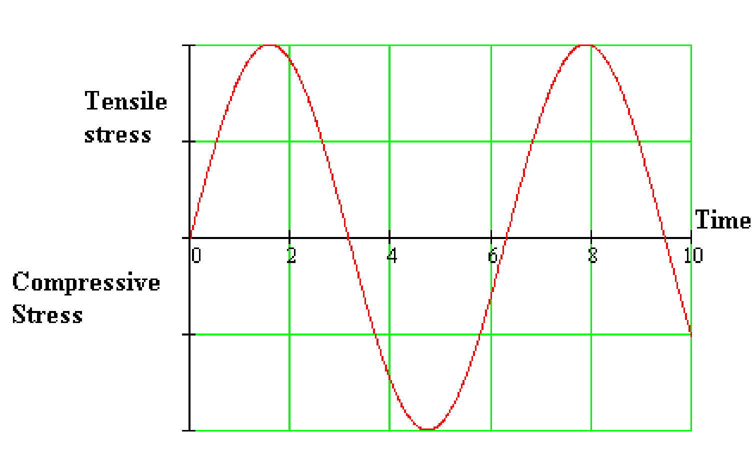
The properties to look for in material selection are ***fatigue strength*** and ***endurance limit*** which are explained in the following.

STRESS FLUCTUATION

Consider the case of an electric motor with a pulley drive on its shaft.

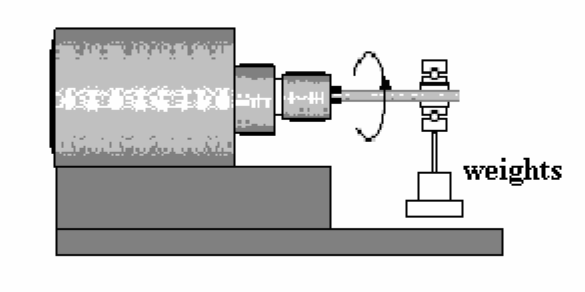


The shaft bends as shown producing tension on one side and compression on the other. As the shaft rotates, any given point on the surface experiences a direct stress that changes from tension to compression once every revolution. The alternating or fluctuating stress causes the failure.
A stress - time graph is likely to be sinusoidal in a case like this.



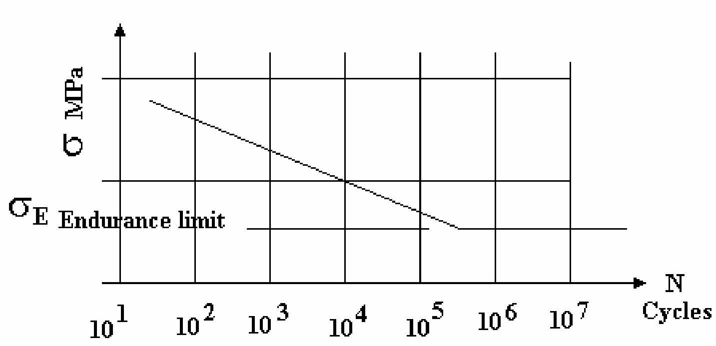
The fatigue life of a component depends on the values of the fluctuation, the mean stress level and the way the stress varies with time. This is not covered here.

FATIGUE TESTING



A fatigue test should ideally reproduce the same stress levels and fluctuations as in service. The most common form of test is the Wohler Test. In this test, the specimen is held in a chuck with a weight pan suspended from the end as shown. Each revolution bends the specimen so that the surface stress fluctuates between equal tensile and compressive values with a mean level of zero. The maximum stress is easily calculated. The test is repeated with different weights and hence different stress levels. It is rotated until it fails and the number of revolutions is counted. This is the number of stress cycles to failure.

S – N GRAPHS

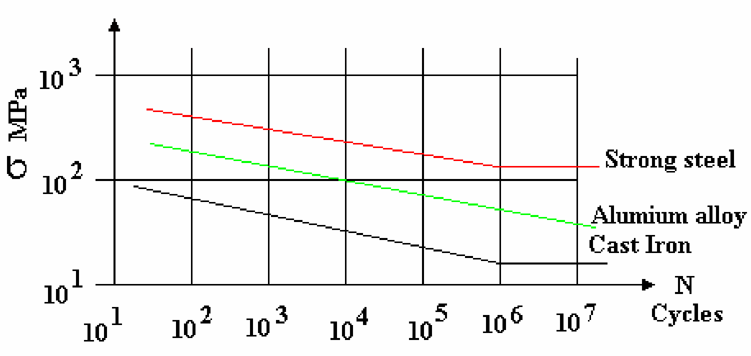


Test data is presented on a S - N graph. S stands for stress and N for the number of cycles. The symbol used for stress is σ (sigma). The graph is normally plotted with logarithmic scales as shown. This tends to straighten out the graphs. The diagram shows a typical result for steel.

FATIGUE STRENGTH

The fatigue strength is the stress level that produces failure after a specified number of cycles.

ENDURANCE LIMIT



The lower limit σ_E is called the endurance limit. If the stress level is below this limit, it will never fail. Non-ferrous materials have no endurance limit. The diagram shows approximate fatigue characteristics of three materials. Research shows that for ferrous materials the endurance limit is approximately proportional to the tensile strength σ_u.
A conservative relationship is $\sigma_E = 0.3\sigma_u$

For materials with no clear endurance limit, σ_N values are stated instead. This is the number of cycles required to produce failure at the specified stress amplitude.

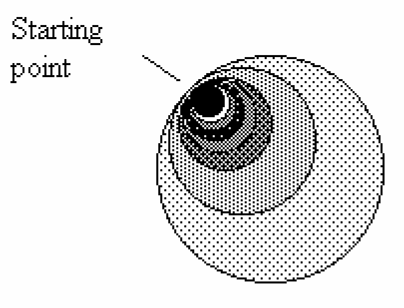
WORKED EXAMPLE No.1

Determine the fatigue strength of a strong steel that gives a life of 10 000 cycles. Use the graph above. What is the endurance limit?

SOLUTION

From the graph, the stress corresponding to 10 000 (10^4) on the red graph is approximately 300MPa. The endurance limit is approximately 200 MPa.

CRACK FORMATION



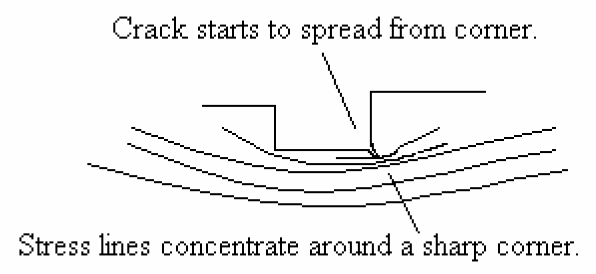
The crack usually starts at some surface defect or feature that produces a stress concentration. For example, an undercut in a shaft for a circlip or a hole for a pin would cause stress concentration. Any fault in the material such as a slag inclusion will also initiate a crack. Undercuts should have rounded corners to reduce this to a minimum. If the material is ductile, the initial crack will not spread easily and the crack opens up and closes as the stress fluctuates. This wears the surface of the crack smooth. As the crack progresses, new material is exposed which starts to wear smooth.

When the crack has spread enough to reduce the cross sectional area of the material to a point where it can no longer carry the load, sudden failure occurs. Often the fracture has an OYSTER SHELL appearance due to the early stages being worn smoother than the later stages.

Cracks spread more easily in brittle material, especially at cold temperatures and failure is sudden.

FATIGUE NOTCH SENSITIVITY

In ductile materials, the crack will start at some point that causes a stress concentration. The diagram shows the stress concentration at the corner of a groove.



The ratio of the raised stress level to the normal stress level is called the stress concentration factor.

$$k_f = \frac{\sigma}{\sigma_o}$$

There are ways of determining values of k_f for specified cases but this is not covered here.

WORKED EXAMPLE No.2

The fatigue strength of a material in a standard test for a specified number of cycles is 250MPa. The material has a surface notch with a sensitivity factor of 1.4. Calculate the fatigue strength in this case.

SOLUTION

$\sigma = \sigma_o / k_f = 250 / 1.4 = 178.6$ MPa

WORKED EXAMPLE No.3

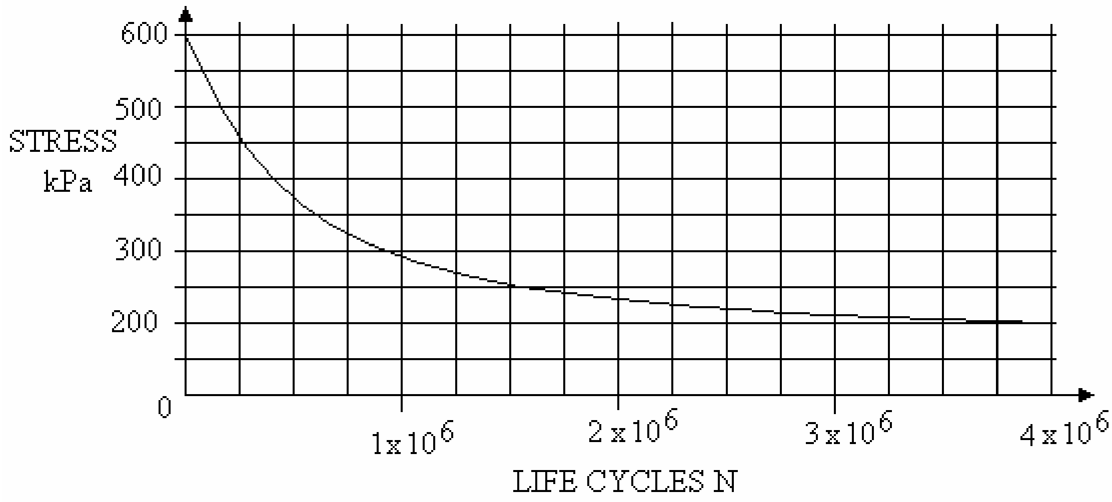
A shaft 50 mm diameter is subject to a bending moment of 3000 Nm. On the surface, there is a notch with a stress concentration factor of 1.6. Calculate the stress produced at this notch.

SOLUTION

$I = \pi D^4/64 = \pi(0.05)^4/64 = 306.8 \times 10^{-9}$ m^4
$\sigma_o = My/I = 3000 \times 0.025/ 30.68 \times 10^{-6} = 244.5$ MPa
$\sigma = \sigma_o \times k = 244.5 \times 1.6 = 391.1$ MPa

WORKED EXAMPLE No.4

The S – N graph shown is for a certain material. Determine the stress level that will produce a life cycle of 750 000. State the endurance limit of this material.



SOLUTION

From the graph the stress level corresponding to 750 000 cycles is 325 kPa. The endurance limit is 200 kPa.

OTHER FACTORS AFFECTING THE FATIGUE LIFE

Fatigue failure may be accelerated by any of the following:

- Stress concentrations factor
- The way the stress fluctuates
- Corrosion
- Residual surface stress
- Surface finish
- Temperature
- Bulk mass (size) of the component

Stress concentrations were mentioned earlier and are caused by keyways, holes, grooves, undercuts, corners or any surface mark.

Corrosion takes many forms and weakens the metal. Surface deterioration may set up stress raising factors. Corrosion of some metals spreads along the grain boundary and so weakens the material. It has been known for a component to fail in fatigue because a chemical marker had been used to write part numbers on the surface and the chemicals etched into the surface and weakened the grain boundaries in that region.

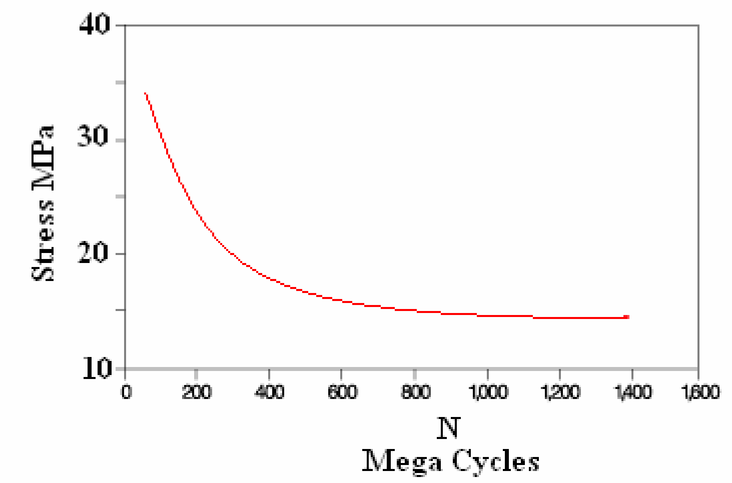
Residual surface stresses can be set up by bending the material thus leaving a permanent stress in it. If the surface has a residual compressive stress, this is beneficial and may be produced by shot blasting or peening.

If a surface is very smooth, there are no points for a crack to start and no stress raisers. Polishing a component improves its fatigue life. For example, the connecting rods on racing car engines are designed to have the minimum mass possible and so are designed with a very small stress safety margin. This would leave them prone to fatigue failure and polishing them makes fatigue failure less likely. On the other hand, rough surface finishes say from turning on a lathe, reduce the fatigue life. Components have been known to fail in fatigue simply because a part number was engraved on the polished surface.

Hot temperatures cause surface oxidation and degradation and so reduce the fatigue life. Thermal expansion and contraction is itself a cause of fatigue stress For example, the leading edges of aeroplanes get hot in flight and cool at other time causing expansion and contraction. Aeroplane body panels are often shaped by shot blasting so inducing a compressive stress on the surface to counteract fatigue.

SELF-ASSESSMENT EXERCISE

1. A shaft 80 mm diameter is subject to a cyclic bending moment of ±800 Nm. On the surface, there is a notch with a stress concentration factor of 1.3. Calculate the stress fluctuation produced at this notch. S – N graph for the material is shown. What is the expected life of the shaft. (±20.7 MPa and about 300 Mega Cycles)



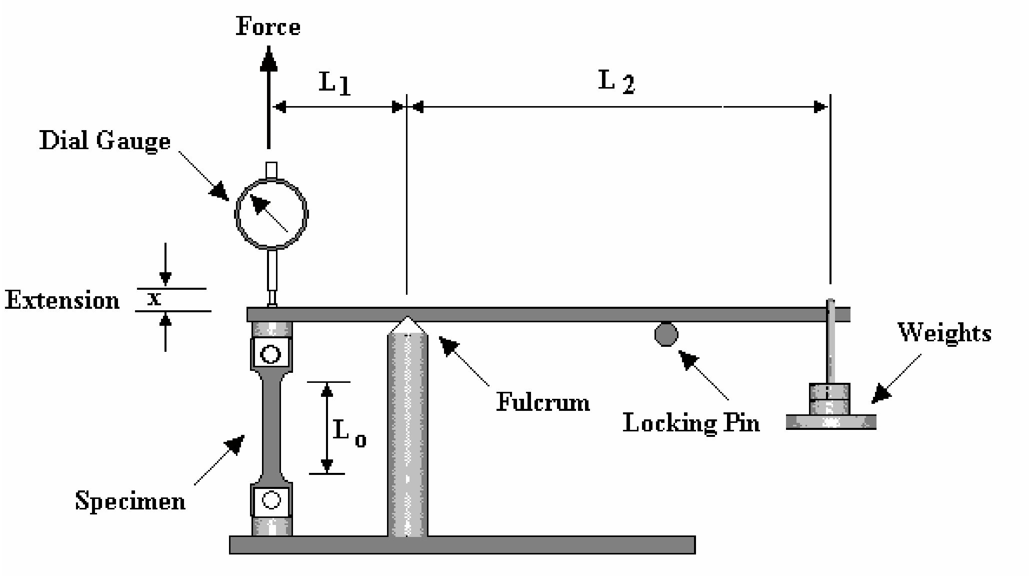
5. CREEP

Creep is a phenomenon where some materials grow longer over a period of time, when a constant tensile stress is applied to it. The material may well fail although the tensile stress is well below the ultimate value.

TEST MACHINE

A simple laboratory test machine is illustrated below. The specimen (usually lead or polymer) is fitted into the clamps with a pin at each end. The weights (W) create the tensile force (F) through a simple lever such that $F = W L_2/L_1$. A dial gauge may be used to measure the extension of the specimen although an electronic instrument may also be used for recording directly into a computer.

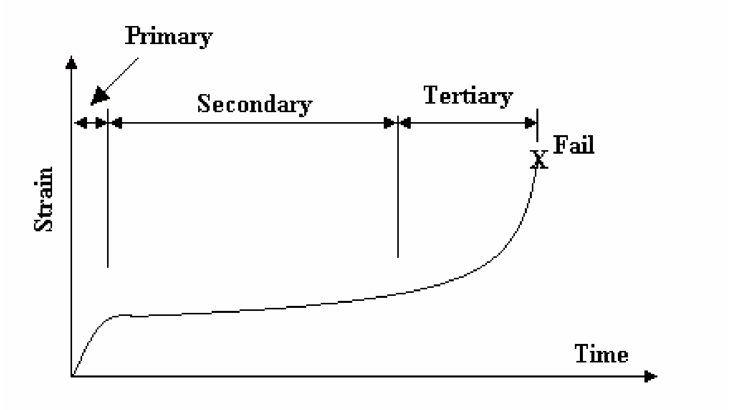
The specimens are normally rectangular in section as they are cut from thin plate.
The tensile stress is $\sigma = F/A$. A is the cross sectional area.
The strain is $\varepsilon = x/L_o$ where x is the extension and Lo the gauge length of the specimen.



The lever is locked in place by a locking pin. A weight is added and the dial gauge is adjusted to zero. The locking pin is removed and a stop watch started at the same moment. Recordings are taken of extension and time. These are plotted to produce an extension time graph. A better machine would use electronic instruments and plot the graph automatically.

TYPICAL RESULTS

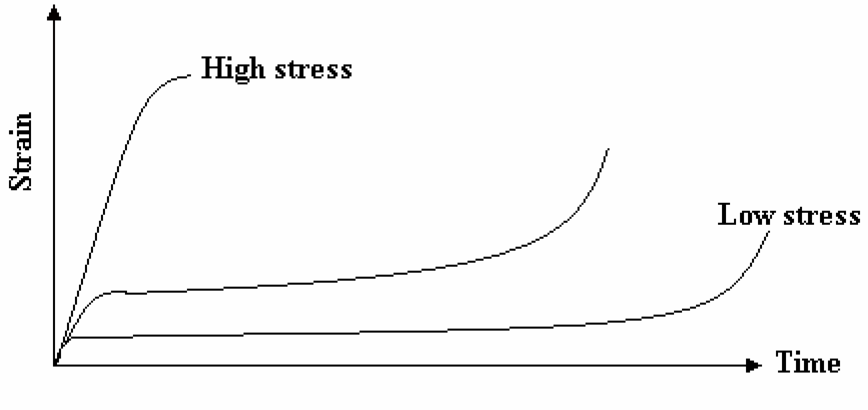
A typical result for a lead specimen is shown below.



CREEP CHARACTERISTICS

Creep usually occurs in three stages called ***primary***, ***secondary*** and ***tertiary***. In the primary stage extension is fast but this stage is not always present. In the second stage the extension is at a constant rate and relatively slows. In the tertiary stage the extension quickens again and leads to failure.

The creep rate is affected by the stress level. Higher stress levels increase the creep rate.



FACTORS AFFECTING CREEP

Most materials will not creep at all until a certain stress level is applied. This level is called the ***LIMITING CREEP STRESS***.

Metals like lead creep very easily at room temperatures and so do polymers. This is made much worse when the polymer is warmed.

PROLONGED HIGH TEMPERATURE
The limiting creep stress of metals is reduced at high temperatures. This is a very important factor in the design of turbine blades. In gas turbines, the blades are subject to high temperatures and prolonged periods of centrifugal force that causes them to creep. If the tip of the blades touches the casing, a catastrophic failure will occur. Much research has been conducted into finding creep free materials for turbines.

Test machines for high temperature creep use a heated oven to surround the specimen.

Ceramic materials are much less likely to exhibit creep tendencies and there is research into composite ceramics for high temperature components. Even so, a sheet of glass in a window for a very long time will measurably thicken at the bottom due to its own weight.

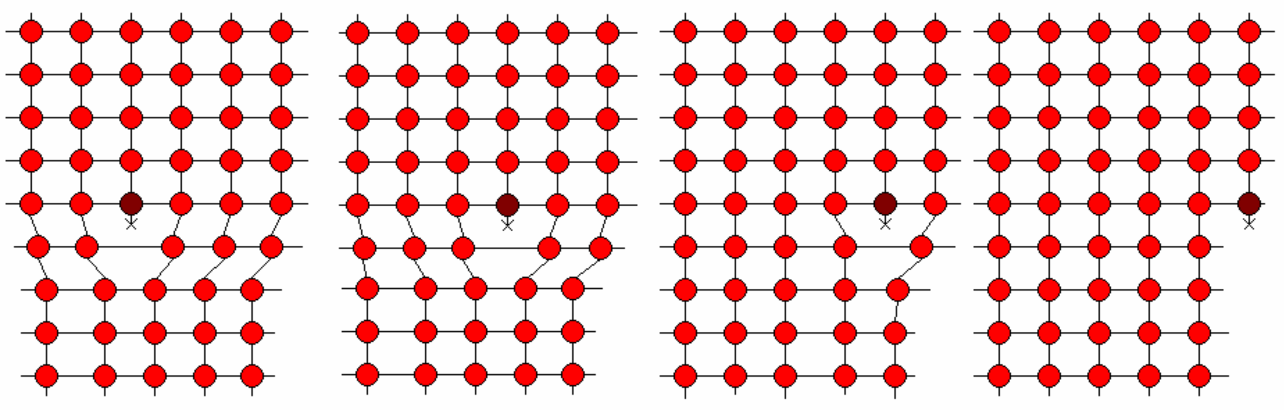
Another way of indicating creep properties are to state the stress values that produces a certain % extension within a stated time. For example: not more than 0.5 % within the first 24 hours.

CREEP MECHANISM

To understand the mechanism of creep you need to have a good knowledge of metallurgy. Here is a very basic description. There are three basic mechanisms.

DISLOCATION SLIP AND CLIMB.

In crystalline materials, dislocations slip through the stressed crystal lattice. A molecule with a free bond forms the dislocation as shown. When the material is stressed the bonds can jump as shown until the molecule with the free bond is at the edge. Dislocations can move in either direction or climb when they meet obstacles such as impurities. Generally, they accumulate at the crystal boundary.



GRAIN BOUNDARY SLIDING.

As dislocations gather at the grain boundary, voids are created and these change into ruptures as the material starts to fail. In the tertiary stage of creep the grain slip at their boundaries.

DIFFUSION FLOW.

At low stress and high temperatures, atoms diffuse from the sides of the grains to the top and bottom thus making them longer

6. DEGRADATION

Many aspects of failure through degradation have been covered in the preceding work. Here is a summary of the main points.

CORROSION

Corrosion through oxidation and electrolytic attack only applies to metals and failure can result when the corrosion makes the component/structure/product no longer fit for purpose or because it has so weakened the structure that the material breaks. Corrosion is generally accelerated by prolonged high temperature.

STRESS CORROSION

This is a form of failure due to the presence of corrosion and tensile stress in the material. The tensile stress opens up the crack and allows the corrosion to penetrate deeper. The cracks are usually on the microscopic level and follow the grain boundaries in the material. Failure occurs at stress levels between normal tensile failure and the fatigue threshold. The tensile stress may be the result of residual stresses produced by welding or some other reason.
You can read much more about this and see some good pictures and case examples at
http://www.corrosion-doctors.org/Forms/scc.htm

SOLVENT

A solvent is a liquid that dissolves another substance. Solvents as a material are useful for cleaning, forming a base for paint, varnishes, lacquers, industrial cleaners, and printing inks and so on. Organic solvents are often toxic, contribute to air pollution and are inflammable. Their use has declined.

Polymers are prone to solvents attack that weaken it and destroys it so great care must be exercised in material selection concerning the substances the polymer will come into contact with. For example, the rubber or plastic seals used on engineering pipe systems must not fail because of attack from the liquid in the pipes. The compatibility of a range of materials with chemicals is easily found on web sites such as http://www.upchurch.com/TechInfo/polymerInfo.asp

A search engine for compatible materials is http://www.upchurch.com/TechInfo/chemComp.asp

Clearly ceramics do not dissolve and are often used to contain solvents.

RADIATION

Polymers used for medical equipment and elsewhere, will degrade as a result of exposure to radiation such as Gamma and X rays and electron-beam.
It has long been known that radiation exposure can lead to significant alterations in the materials. Radiation affects the polymer molecules causing dissociation and other things that lead to failure. This may take days, weeks, or months after irradiation to have an affect. Resulting changes can be embrittlement, discoloration, odour generation, stiffening, softening, enhancement or reduction of chemical resistance, and an increase or decrease in melt temperature.

Because the effects of ionizing radiation depend greatly on polymer chemical structure, the dose necessary to produce similar significant effects in two different materials can vary.

A common undesirable effect resulting from the irradiation of some polymers is discoloration (usually yellowing). Discolouration also occurs with prolonged exposure to ultra violet light and plastics used for outdoor applications (such as motor car parts and double glazing) will discolour or fade with time so additives are used in manufacture to prevent this.

You will find further “in depth reading” at http://www.devicelink.com/mddi/archive/00/02/006.html